OXFORD UNIVERSITY

AN INTRODUCTION TO THE POSSIBLE SUBSTRUCTURE OF
QUARKS AND LEPTONS

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Louis Lyons

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Abstract

After an introductory discussion of the history of substructure and of the motivations for examining the possible compositeness of quarks and leptons, experiments which could be relevant to the non-point-like nature of these fermions are reviewed. Where possible the data are used to deduce limits on the substructure energy scale.

Starting with very early ideas about quark and lepton substructure, we go on to summarize some of the specific models which have recently been proposed. They are very varied, but a general discussion is given about common topics which such models consider (e.g. the nature of the binding mechanism, the problem of the masses of the composite systems, the way in which fermion generations arise, whether to make weak intermediate bosons composite, etc.). In considering individual models, emphasis is placed on what specific predictions can be tested experimentally.

We conclude that experiments in the near future could significantly increase the energy range in which substructure can be probed. This may then provide a more realistic basis on which to judge whether quarks and leptons are composite.

Louis Lyons

Nuclear Physics Laboratory

Oxford

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* This is one of a series of articles on "Quarks and Hadronic Interactions". Reviews of quarks search experiments and of lepton pair production have already appeared in Progress in Particle and Nuclear Physics 7 (1981) 157 and 169 respectively. This article is to appear in volume 10 (1983).

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Quarks and Leptons

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An Introduction to the Possible Substructure of

Quarks and Leptons

Quarks were introduced in 1964 to explain the structure of "elementary" particles⁽¹⁾. The charged leptons and neutrinos are regarded as point-like, and can be used to probe other objects. Thus quarks and leptons are the smallest scale structure of matter at present known to us. Within the last few years, however, the question of whether this is the ultimate, truly elementary level has been raised. In this article, we review the subject of the possible substructure of quarks and leptons.

The substructure of this article is as follows. In section 1, we take a brief historical look at previous discoveries of substructure, with a view to understanding what the significant pointers might be to the onset of a new level; with this aim in mind, we also review the salient quark and lepton properties. Experimental evidence that is relevant to quark and lepton substructure is examined in section 2. Where feasible, experimental limits are converted into corresponding bounds on the scale of possible substructure. Sections 3 and 4 deal with the early models of quark and lepton substructure, and with the more recent developments respectively. Finally (section 5), the successes and problems of substructure models are summarised, and some questions and hopes for the future are mentioned.

This review of necessity presents a personal viewpoint of the subject, with the main emphasis being experimental i.e. what evidence there may at present be for substructure or which are the most hopeful processes in which to search for composite effects, and what are the

testable consequences of models of substructure. I thus apologise in advance to those whose contributions to this field I have omitted to mention either because they fell outside the scope of this review or because, in this fast developing field, I am unaware of their work.

Previous reviews of this field, all with a much more theoretical bias than this one, have been written by Harari⁽²⁾, Terazawa⁽³⁾, Reskin⁽⁴⁾, Preskill⁽⁵⁾, Barbieri⁽⁶⁾ and Peccei⁽⁷⁾. Many of the early references can be found in an article by Greenberg⁽⁸⁾.

1. Levels of Substructure

1.1 Substructure as Historic Aim

The physical world is full of objects with very different sizes, appearances and properties. It has long been an aim of thinking man to explain this amazing variety in terms of some simpler elements. The rules of what constitutes a satisfactory theory of substructure have changed throughout the ages, but one seemingly constant demand is that the different elementary objects at the substructure level should number at most a few*.

The first scientific approach to substructure was Dalton's atomic theory. This was motivated qualitatively by the desire to find a simple way of understanding the enormous number of chemical compounds known, but quantitatively to explain the laws of chemical combination. It thus effectively provided an interpretation of the masses of the composite systems. Furthermore it became a dynamic theory - as Kinetic Theory, it elucidated the properties of gases. The ultimate verification came with the determination of Avogadro's number, which was equivalent to a measurement of atomic masses and radii.

The fact that the relative masses of different atoms were simple ratios was unexplained on the Atomic Theory. The growth in the number of different atoms from ~20 in Dalton's day to over 100 today also

* The Greeks used Air, Fire, Earth and Water as the basic elements. Examination of their initial letters indicates that not only did the Greeks understand the essential principal of substructure, but they also had a good command of the English language.

suggested that atoms were perhaps not as indivisible as Dalton had supposed. The Mendele'ev classification of atoms also pointed to some underlying simplicity of structure. The final clue was the observation by Thompson that electrons were a constituent of many different substances. The eventual proof of substructure in this case came with Rutherford's demonstration that the atom was not a uniform sphere but that the mass was concentrated in a central region, whose size he later measured. The subsequent Bohr model of the atom opted out of the problem of how atoms remained stable, but explained the existence of the many excited states of atoms, as well as providing a very successful fit to the energies of the excited states of atomic hydrogen.

The next level of substructure - from the nucleus to individual nucleons - was an obvious step. Nuclei were not point like but had a finite extent, their masses bore simple relations to each other, and constituents to build the nucleus (the proton and the electron) already existed. The fact that such a model had serious problems did not detract from the substructure idea; they were resolved with the subsequent discovery of the neutron and the emergence of the neutron-proton picture of the nucleus. With a model of nuclei having a common substructure, radioactive transmutations and nuclear reactions should occur by the exchange of constituents, and these were indeed observed.

At the birth of the nuclear atom, only 2 constituents were required for a complete description of the whole of nature. Gradually other "elementary particles" were discovered, and by now the list contains several hundred entries. Indeed there are now more "elementary particles" than chemical elements. Surely such a large number of

particles cannot be really elementary? This was resolved with the invention of the quark model, which succeeded in explaining not only the vast number of existing particles, but also the non-existence of various undiscovered ones (the so-called exotics). Apart from this success in the field of the spectroscopy of strongly interacting particles, as the parton model it also provided at first qualitative explanations and then some quantitative ones about elementary particle dynamics. At its inception, the model required just 3 quarks, and was thus second only to the proton-electron model in economy.

An overview of the subject of substructure in these various historical phases is given in Table 1. We turn to the properties of quarks in the next section, where we also consider the other basic fermions, the leptons. We first note that previous substructure models have had most of the following features in common:-

- 1) Quantum Numerology. The composite system contained a large number of states. The model could explain why these existed and why others did not.
- 2) Spectroscopy. Quantitative explanations could be provided for excited states.
- 3) Dynamics. Reaction mechanisms and properties of composite systems could be understood.
- 4) Extended structure. Direct observation of the non point like behaviour of composites gave evidence for substructure.

It is also apparent that early theoretical difficulties with substructure have not ruled out the models completely. Indeed with hindsight we can see that their subsequent resolution has often lead to

a deeper understanding of the physics involved.

1.2 Brief history of quarks, leptons, etc.

In 1964, at the time of the invention of the Quark Model, only 3 different types of quarks were needed, viz: up, down and strange*. The spectroscopy corresponding to the charm quark c was discovered⁽⁹⁾ from 1974 onwards, and that of the bottom quark b from 1977⁽¹⁰⁾. It is expected that the top quark t is waiting to be discovered at energies soon to become available. Thus there now exist 5 (and perhaps soon 6) different "flavours" of quarks.

Meanwhile the number of quarks has increased by a further factor of 3, since each flavour is supposed to exist as three different "colours"⁽²⁵¹⁾. This concept was originally introduced as a hidden quantum number device to explain how baryons could contain 3 identical quarks in the same state with parallel spins. Subsequently it proved useful numerically in explaining the rates of e^+e^- annihilation to hadrons and τ^0 decay to $\gamma\gamma$; each of these depends on the number of different quarks that can contribute. Thus the current number of quarks is 15.

The fact that no free quark has unambiguously been observed⁽¹¹⁾ is not taken as a serious impediment to the model. Indeed it is now confidently believed by most theoretical physicists in the field (although, despite considerable effort, no proof has yet been produced) that quarks are "confined": their interaction is such that they can never be separated from each other. In the language of colour, only

* Quarks are henceforth referred to by the initial letter of their name.

colourless states (e.g. $q\bar{q}$ or qqq) can exist in the free state. Quarks, on the other hand, are coloured and so cannot exist alone. This would also explain why qq or $4q$ states are not observed.

The well established leptons (e , μ , ν_e and ν_μ) have also been augmented recently with the discovery⁽¹²⁾ of the τ in 1975, and with the observation⁽¹³⁾ that its neutrino is not the same as the ν_e or ν_μ .

Apart from these quarks and leptons, fundamental bosons also exist and transmit the various forces of nature among the fundamental fermions. A catalogue of these, together with the fermions, is shown in Table 2. Clearly the list is long. We return to the question of whether these are all the truly elementary particles of nature in section 1.4.

1.3 Are quarks and leptons similar or different?

Quarks or leptons appear to be very different types of objects. Quarks experience the strong interactions which are responsible for the existence of the numerous "elementary" particles, and indeed they may well be confined; leptons are affected only by the electro-weak interactions and are readily observable in the free state. Quarks have fractional electric charge and also possess the mysterious property of colour, while leptons are integrally charged and colourless. Finally the separate empirical rules of baryon and lepton conservation apply to quarks and to leptons respectively.

Despite such obvious divergences, several similarities are emerging. First there is the historical fact that the known quarks and leptons have increased in parallel, and are indeed grouped together in

generations (see Table 2). Thus in the early 1930s the known particles consisted of up and down quarks on the one hand (admittedly, then in the form of protons and neutrons), and electrons and neutrinos on the other; all these are essential for the functioning of the Universe. The period up to the mid 1970s saw the discovery of the redundant fermions - the strange and charm quarks, and the muon and its neutrino. Currently the luxury items are being discovered - the bottom (and hopefully, soon the top) quark and the tau lepton and its neutrino. Are these extra fermions also required for the Universe's existence or is their purpose merely to amuse and torment high energy physicists?

The second group of similarities relates to various properties of the fermions. Thus both sets have spin $\frac{1}{2}$ and their charges are simply related (e.g. $e_e = 3e_q$). In fact the sum of the charges of all particles within a given generation is zero (provided we count each flavour of quark 3 times to allow for the different colours); this feature is necessary in order to produce cancellation among the anomalous triangle diagrams⁽¹⁴⁾, which would otherwise cause problems with the renormalisability of weak interactions. Again the quarks and leptons couple to the electro-weak interaction in similar manners.

It is quite possible that the future will relate quarks and leptons even more firmly. Thus if Grand Unification Theories are successful in linking the strong and electro-weak interactions, the present differences between quark and lepton interactions would be relegated to an insignificant low energy symmetry breaking phenomenon. Within such a scheme, quarks and leptons are assigned to the same fundamental representation of the relevant group. A consequence of Grand Unification Theories is that quarks can decay into leptons, with neither

baryon nor lepton number being individually conserved, but instead some linear combination of them. Also there are relationships among the masses of quarks and leptons.

An alternative, though possibly related, approach has been to try to discover what type of substructure could explain the proliferation of fermions. Most of these attempts have ascribed to the quarks and leptons similar or common substructures. Such models are described in sections 3 and 4.

Finally we note that models relating quarks and leptons have a long history. Thus originally, for want of alternatives, nuclei were considered as bound states of protons and electrons; this picture died with the discovery of the neutron. More recently, attempts have been made to treat leptons as quarks⁽¹⁶⁾ or as constituents of quarks⁽¹⁷⁾, to consider lepton number as a fourth colour⁽¹⁸⁾ or to classify leptons and quarks in the same multiplet^(18,19) (see also sections 3.1 and 3.2). A few of the papers on the subject of quark-lepton relationships are listed in Table 4.

Although the real test of how intimately quarks and leptons are related (and whether the distinction itself will disappear) must await the future, it is clear that a discovery of a new set of leptons would intensify the search for a correspondingly new family of quarks.

1.4 Psychology and aims of substructure

We have seen that in the past each level of substructure has started its existence with a small number of basic entities, but that as time has passed these have proliferated, and this in turn has been the

signal that a new level of substructure is waiting to be discovered. It is thus tempting to speculate that the observed multiplicity of quarks and leptons (not to mention the various bosons) means that they too may possess substructure. This could, however, be a reflection of the psychology of physicists, rather than being relevant to any basic property of matter. Indeed it is conceivable that Nature has chosen a large number of fundamental entities, and that the simplicity (if any) resides in the mathematical equations describing the existence and behaviour of the particles⁽²⁰⁾.

Before completing this introductory section, we list what we believe should be the rules for a useful model of substructure.

i) Model Defined

The model should be defined in terms of what are the substructure elements (henceforth called preons), and what are the interactions between them. It should also be clear whether the model is to explain both quarks and leptons (in general we expect this to be so), and which if any of the bosons of Table 2 are composite.

ii) Quantum Numerology

The model should provide a natural explanation of the observed composites (i.e. flavours and colours of quarks, and the generation structure of quarks and leptons). It should also explain the non-appearance of unobserved quarks and leptons (e.g. colour sextets, colourless fractionally charged fermions, spin 3/2 fermions, etc.) as well as other possible preon combinations. Most models hide behind the

complication of calculating the masses of composites; unwanted states can simply be assumed to be too heavy to have been observed to date.

iii) Mass formulae

The known fermions, with masses from <50 eV to ~ 5 GeV, provide a challenge for any composite theory. A mass formula would also predict when (if ever) new quarks and leptons were to be found, as well as being consistent with the absence of further quarks and charged leptons up to ~ 16 GeV.

iv) Dynamics

The model should explain the dynamics of the composite systems in terms of that of the fundamental preons. This includes the nature of the strong interactions of quarks and the weak interactions of leptons; possible nucleon decay processes*, the nature of mass generation, Cabibbo-Kobayashi-Maskawa mixing and possible neutrino mixing effects*, conceivable generations changing or even unusual generation conserving reactions* (see section 4.2), etc.

v) Predictions

The models should produce some testable predictions. These could be the masses of new conventional fermions (e.g. the top quark, or the next generation charged lepton), or of new types (e.g. spin $3/2$ or colour sextets). Other possibilities are for reactions that have yet to

* With these unseen processes, the model must merely ensure that they occur at a sufficiently low rate.

be observed, such as the rates or branching ratios of nucleon decay modes; the energy range in which substructure effects might be directly observable; the total number of generations that exist, etc. An untestable model is intrinsically unsatisfactory.

v) Economy

We regard economy in terms of the number of preons and the extra ad hoc assumptions as desirable, but realise that this is an aesthetic judgement that Nature may not share.

2. Experimental Limits on Substructure

In this section we review the experimental data which could show evidence for quark and lepton substructure. Where possible, we convert the experimental limits into lower bounds on the effective mass scale Λ of the substructure; this can be changed into an equivalent size L of the fermions via

$$L(\text{in } 10^{-16} \text{ cm}) = (0.2 \Lambda(\text{in TeV}))^{-1}$$

Since most of the limits are model dependent, we aim to specify in so far as is possible what assumptions are used in the calculations. It should also be kept in mind that the scale (or even the existence) of substructure could differ for the different fundamental fermions, e.g. for quarks and for leptons; or for the fermions of different generations.

2.1 Magnetic Moments

According to Dirac, the magnetic moment μ_D of a point like spin $\frac{1}{2}$ particle of mass m is given by

$$\mu_D = \frac{e\hbar}{mc}$$

or expressing it as $g/2$ times the relevant magneton $e\hbar/mc$,

$$g = 2.$$

Corrections to this arise from the emission and reabsorption of virtual photons. These can be calculated from quantum electrodynamics. The strong interactions will also produce corrections which will be much more important for quarks than for leptons; even the weak interactions have a small effect. These processes (see Fig.1) give the fermion an effective size, which is responsible for the modification to the point like value of g . We emphasise that this is not substructure in the sense that we mean it. Any substructure would show up as additional corrections to g .

The g values for atoms are of order 10^5 larger than an atomic magneton. This is thus evidence for substructure, and is explained by the magnetic moment being due to the atomic electrons. The proton's magnetic moment is ~ 2.79 nucleon magnetons, and the neutral neutron has a non-zero magnetic moment of ~ 1.91 nucleon magnetons; these are understood in terms of the 3 quark structure of nucleons.

It thus appeared that if quarks and leptons had a composite structure, this could manifest itself as significant deviations of g from the point like values (corrected for QED and strong interaction effects).

2.1.1 The electron

The magnetic moments of the electron and of the positron have been measured with extreme accuracy by observing single particles held in a Penning trap (21). The value of

$$a = \frac{g-2}{2}$$

$$\text{is } a_{e^-} = (1\,159\,652\,200 \pm 40) \cdot 10^{-12}$$

$$\text{and } a_{e^+} = (1\,159\,652\,222 \pm 50) \cdot 10^{-12}$$

These are to be compared with a calculated value (22,23)

$$a_{\text{theory}} = (1\,159\,652\,460 \pm 127 \pm 75) \cdot 10^{-12}$$

where the first error comes from the quoted uncertainty in the value of α as determined from the Josephson effect, and the second comes from the calculational accuracy. The evaluation includes 8th order QED effects, which involve the calculation of 891 Feynman integrals; hadronic and weak effects are also allowed for, but make only a small ($\sim 1 \cdot 10^{-12}$) contribution to a .

Kinoshita and Lindquist point out that there could be a larger error on α from theoretical uncertainties in the interpretation of the Josephson effect, and that the discrepancy between theoretical and experimental values of a should be taken as setting an upper limit on, rather than providing evidence for, substructure.

With the quoted errors, we set the limit on possible substructure contributions to a as

$$\delta a < 0.5 \cdot 10^{-9}$$

This limit could be improved (or perhaps evidence for substructure discovered) by a better determination of α .

2.1.2 The muon

The magnetic moment of the muon has been measured with great accuracy in a series of experiments at CERN using muons trapped in a storage ring (24). The precession of the moment in the magnetic field is monitored by the direction of preferential emission of the decay electron. By watching decays at a fixed location on the ring, the precession and cyclotron frequencies are compared in order to yield (g-2) directly. The result is that

$$a_\mu = (1165924 \pm 9)10^{-9}$$

compared with a theoretical calculation (55) of

$$a_{th} = (1165921 \pm 8)10^{-9}$$

The theoretical value includes corrections from 6th order QED processes, strong interactions and weak interactions; the hadronic contribution, estimated as $(67 \pm 9)10^{-9}$, is significant. The agreement with the predicted value is superb, leaving the maximum value of the extra possible contributions to a from other effects (including substructure) in the range $(-20 \text{ to } +26)10^{-9}$.

There are no plans to improve the accuracy of this measurement in the immediate future, but a new calculation of the theoretical value is in progress (25).

2.1.3 u, d and s quarks

In the absence of free quarks (26,27), their magnetic moments cannot be directly measured. They can, however, be deduced from those of the baryon octet of SU(3) via the quark model. The ratio

$$\mu_p/\mu_n = \frac{2.793}{-1.913} \approx \frac{-3}{2}$$

where an exact value of $-\frac{3}{2}$ would imply $\mu_u = -2\mu_d$. This would be expected for equal mass u and d point-like quarks of charge ratio -2. The absolute values of the nucleon magnetic moments together with the assumption of Dirac values for the quark magnetic moments require $\mu_u = 336 \text{ MeV}$ ($=m_d$ by assumption) (28). This compares with a value of 363 MeV as usually input to mass formulae.

This simple picture also gives

$$\mu_S = \mu_A$$

The measured Λ magnetic moment then implies that $m_S = 538 \text{ MeV}$ if we again assume a Dirac moment. This too is within 10% of a value that one would use for a mass fit of strange baryons. Again the model is in difficulty in reproducing the exact values of the magnetic moments of the other baryons (28).

The disagreement at the level of 10% should not be taken as positive evidence for substructure, but could be due to either an anomalous moment from the strong interactions (53) or to the simplicity of the quark model assumptions (e.g. allowing for configuration mixing effects results in some improvement). Since the origin of the discrepancies is by no means certain, we thus should regard the possible contribution of substructure to the quarks magnetic moments as being limited only at the 10-20% level. In order to improve this limit,

* If we were to relax the $m_u=m_d$ assumption in order to reproduce the μ_p/μ_n ratio exactly, we would require $m_u > m_d$, while mass formulae normally require $m_u > m_d$. Again this shows that the simple model for baryon magnetic moments in terms of the constituent quarks' should not be taken literally.

better experimental data on baryon magnetic moments would be useful only in so far as they might help in understanding why the current values are inconsistent (at the 10% level) with a simple quark model, and which if any of the possible modifications is relevant.

2.1.4 Other particles

If neutrinos possessed a magnetic moment, they would lose energy in their passage through matter. Thus the ν_e magnetic moment is limited by the experimental facts that at least some of them succeed in escaping from the sun, and that no energy loss was detected in a large scintillator close to the pulsed reactor⁽²⁹⁾; the value is less than 10^{-9} electron magnetons. If the neutrino were made of charged fermion constituents, it is possible that it could have a magnetic moment, and as the mass of the neutrino is $\lesssim 50\text{eV}$, its magneton is at least 10^4 times as large as the electron's. In the strong binding approximation, however, the anomalous moment (which for a neutral particle is the total moment) is at best $O(m/\Lambda)$, and so no useful limit on the scale of substructure is derived.

The experimental cross section for

$$\bar{\nu}_\mu e + \bar{\nu}_\mu e$$

limits the magnetic moment of the muon neutrino to be less than 10^{-8} electron magnetons⁽³⁰⁾. This reaction is discussed again in section 2.4 in relation with the neutrino's charge radius.

No direct measurements of the magnetic moments of the τ lepton or the c or b quarks exist, although Shaw⁽²⁴⁶⁾ has analysed the reactions $e^+e^- \rightarrow \tau^+\tau^-$ and $e^+e^- \rightarrow \text{hadrons}$ in terms of the τ and quark anomalous

magnetic moments; and an analysis of radiative transitions among hidden charmed states and among hidden bottom states is in progress⁽³¹⁾.

2.1.5 Interpretation of magnetic moments

As the experimental values of g , especially for the electron and muon, are consistent with expectations, it was considered that this could be evidence against substructure at all⁽³²⁾, or at very least impose severe constraints on a substructure model. Thus point-like values of g could be obtained if the composite system was built of 3 constituents, each having mass $1/3$ of the composite system, and similarly for electric charge⁽³³⁾.

Subsequently several authors⁽³⁴⁻³⁷⁾ have shown that it is possible to restore the g value to approximately 2 even for composite models, in situations where the binding is strong i.e. when the size of the composite system is small compared with its inverse mass. The previously known systems of atoms, nuclei and elementary particles, whose g values differ from 2, are in this sense only weakly bound, and hence their magnetic moments readily reveal the system's composite structure.

The magnitude of the corrections to $g=2$ is model dependent, and can be affected, for example, by whether the composite system of mass m consists of a fermion and a boson, or of 3 fermions. With fermionic constituents obeying a chiral symmetry, the correction to $g=2$ is $O(m/\Lambda)^2$, whereas otherwise it is $O(m/\Lambda)$. These are, however, only order of magnitude calculations, and in specific cases, it is conceivable that the coefficient could be zero, in which case the observed $g \neq 2$ values

would not give any limit on Λ . An example of this would be the Lipkin case of $1/3$ mass and charge constituents. The model of Kim and Song⁽²⁴²⁾ also predicts small anomalous moments, even for small values of Λ .

In the absence of such accidents, and assuming that the corrections to $g-2$ are $O(m/\Lambda)$, the muon magnetic moment leads to

$$\Lambda > 4 \cdot 10^3 \text{ TeV},$$

while for $O(m/\Lambda)^2$

$$\Lambda \geq 0.6 \text{ TeV}$$

(Farley himself quotes a limit of 0.04 TeV for a possible modification of the muon's form factor arising from substructure effects).

The corresponding numbers for the electron are 10^3 TeV and 0.02 TeV respectively. For the u d and s quarks the corrections could be $\sim 20\%$, so the limit on the substructure of these quarks is only $\Lambda \geq 10^{-3}$ TeV.

Clearly such limits for the electron and muon are model dependent, while those for the quarks are insignificantly low.

2.2 Other QED tests for leptons

The reactions

- (a) $e^+e^- \rightarrow e^+e^-$
- (b) $\rightarrow \mu^+\mu^-$
- (c) $\rightarrow \tau^+\tau^-$
- (d) $\rightarrow \gamma\gamma$

have been studied at energies up to 35 GeV, and compared with QED calculations (including corrections for hadronic vacuum polarisation and electroweak interference effects) for point like particles.

Modifications to these predictions could be produced by any substructure possessed by the fermions, which could manifest itself as a form factor $1+s/\Lambda^2$ in the relevant amplitude^{*,†}. The recent data by the experimental groups CELLO, JADE, MARK J, PLUTO and TASSO are reviewed by Dittman and Hepp⁽³⁸⁾, by Branson⁽³⁹⁾ and by Mess and Wiik⁽⁴⁰⁾. The different sets of data naturally produce somewhat different values of Λ for a given reaction, but fairly typical values are that Λ is greater than 120, 120, 100^{**} and 45 GeV for reactions (a)-(d) respectively. The lower limit on Λ is lower for reaction (d) than for the other reactions as the corrections of order s/Λ^2 vanish, and the modification to the cross-section is proportional to s^2/Λ^4 .

Lane⁽²⁷⁰⁾ obtains a larger limit for Λ (~ 750 GeV) for the electron by assuming that there would be a hypercolour contribution to reaction (a) from the preons within the electrons; this is of strength $\sim 1/\alpha$ compared with the usual γ exchange process. Reactions (b) and (c) are currently also being analysed in this way.

* For the process $e^+e^- \rightarrow e^+e^-$, there may also be a form factor of the type $1+g^2/\Lambda^2$. The effect of both form factors can be expressed as a modification of the cross-section $\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{QED}} (1+\delta(s, \cos\theta))$. Further details can be found in the article by Dittman and Hepp⁽³⁸⁾.

† In some models, the form factors are $(1+s/\Lambda^2)^n$, where n is a small integer. To the extent that $\Lambda \gg s$, we can regard the data as determining Λ^2/n rather than Λ^2 and n separately. Thus for $n \neq 1$, the limits we quote would be multiplied by $1/n$.

** A similar limit is set by Shaw⁽²⁴⁶⁾, who analyses the τ production angular distribution in terms of a possible anomalous magnetic moment of the τ .

Although the limits on Λ for the electron and muon are lower than those quoted in Table 5 as deduced from the magnetic moments, the ambiguities in theoretic interpretation are smaller here. Furthermore the reaction (c) provides evidence on the point-like structure of the τ for which no corresponding direct measurement of the magnetic moment exists.

2.3 $e^+e^- \rightarrow \text{hadrons}$

The reaction

$$e^+e^- \rightarrow \text{hadrons}$$

is assumed to take place via the intermediate states

$$e^+e^- \rightarrow \gamma + q\bar{q}$$

with the quarks then fragmenting into the observed hadrons. For point like electrons and quarks, the cross-section relative to $\mu^+\mu^-$ production should then be

$$R_{ee} = \sum e_q^2$$

where the summation runs over the different coloured quarks, and those flavours which can be excited at the centre of mass energy $\sqrt{s}$ of the reaction. Corrections to this simple formula will arise from QCD effects; virtual gluon emission will give an effective structure to the quarks. The effect has been calculated, and varies but slowly with s ; we ignore it.

Further modifications could be produced by non point like behaviour of the fundamental fermions. Parametrising this as a factor $(1 + s/\Lambda^2)^{-2}$ in the cross-section, we find that the data for $\sqrt{s} > 12$ GeV is consistent with $\Lambda > 200$ GeV; similar values have been obtained by individual groups fitting their own data (41,253). We consider that the

possible systematic uncertainties associated with individual measurements of R_{ee} are unlikely to produce a bias in the energy dependence of the cross-section, and so we feel justified in treating the errors on individual measurements as independent in our determination of Λ . We also ignore the possibility that the approximate constancy of R_{ee} as a function of energy is due to a temporary balance caused by a decrease due to quark substructure being compensated by an increase due to crossing the threshold for $t\bar{t}$ production.

We note that the limit this provides on quark substructure is significantly better than that from the baryon magnetic moments, and it includes charm and bottom quarks as well. [The limit is, however, an average over all quarks, and if it were assumed that the u d s and c were essentially point-like, while the b alone possessed significant structure, the limit for it would be 60 GeV].

In principle the inverse reactions

$$q\bar{q} \rightarrow e^+e^-, \mu^+\mu^+$$

should also provide information on possible fermion substructure. These processes contribute to the Drell-Yan production of lepton pairs in hadronic interactions. The theoretical predictions thus also depend on the structure functions for quarks and antiquarks within hadrons, as deduced from deep inelastic lepton scattering experiments. Furthermore the different role played by soft gluon emissions in the Drell-Yan and deep inelastic scattering processes enhances the predicted Drell-Yan cross section by a factor of ~ 2 (as calculated according to lowest order QCD calculations) compared with the naive prediction (42). Together with experimental normalisation uncertainties of at least $\pm 20\%$, these factors mitigate against using the Drell-Yan process to study fermion

substructure.

We look forward to new data on hadronic production in e^+e^- collisions at energies in the region of ~ 100 GeV which should be available with new accelerators working later in this decade. These would enable possible substructure on the scale of ~ 1 TeV to be studied.

2.4 Deep Inelastic Lepton Scattering Experiments

Experiments involving the inelastic scattering of charged and neutral leptons from nucleons have played a crucial role in the development of the quark model. It was the observation that the cross-section exhibited scaling (i.e. was independent of Q^2) which originally suggested the existence of point like scattering centres within the nucleon, and this complemented the quark model explanation for hadron spectroscopy. Later the observation of scaling violations (i.e. the dependence of cross-section on Q^2) was important in helping develop the ideas which lead to Quantum Chromodynamics (QCD). Furthermore, these scaling violations were also responsible for the first suggestions that quarks were not point like, and hence exhibited substructure (43-45). Admittedly this type of substructure was due to the QCD processes of quarks emitting gluons, which, in analogy with QED processes of virtual photon emission, is not substructure in the sense that we mean it. These papers were significant, however, in pointing out the fact that quarks could be non-point like, and opened the way for the subsequent discussion of composite quarks.

An analysis of the Q^2 dependence of structure functions with a view to investigating fermion substructure is complicated, first of all by the Q^2 dependence expected on the basis of perturbative QCD, and secondly with possible contributions from higher twist terms arising from bound state effects. The current data is such that it is difficult to distinguish perturbative and bound state effects, and the inclusion of extra terms for substructure would render the analysis completely inconclusive.

An analysis of the structure functions as deduced in e^+p and e^-d experiments has been performed by Bodek (46). For the range 2 to 20 GeV² for Q^2 and $x > 0.1$, a limit of > 10 GeV is deduced for the substructure scale, when all the scaling violation is ascribed to this effect, and parametrised as $(1+Q^2/\Lambda^2)^{-2}$. Matumoto obtained $\Lambda > 7$ GeV in a similar analysis (47).

A larger limit could be obtained by allowing for QCD effects before looking for quark substructure (48). This has been done by Norton (49) using the EMC Collaboration's μN data at 280 GeV/c. The structure functions are parametrised as

$$F_2(x, Q^2) = F_2^{QCD}(x, Q^2) [1 + Q^2/\Lambda^2]^{-2}$$

With the QCD scale parameter Λ_{QCD} and Λ as variables, the data require $\Lambda > 85$ GeV. A similar analysis of e^-N data could presumably increase the limit as determined by Bodek.

The point-like nature of neutrinos and quarks leads to a cross-section for νN and $\bar{\nu} N$ scattering rising linearly with s . Deviations from this prediction caused by QCD effects are small, since the major effect is to enhance the quark structure functions of the

nucleon at low x at the expense of a depletion at large x .^{*} If the substructure effects are as assumed in the previous paragraph, the point like cross-section σ_0 is modified to

$$(\sigma/s) \sim (\sigma/s)_0 (1 - s/\Lambda^2)$$

The current data for ν_μ scattering yields $\Lambda > 70 \text{ GeV}$ ⁽²⁶⁷⁾.

An analysis (along the lines of that performed by Norton for the μN data) of the structure functions obtained from νN scattering has been carried out by Wahl using the CDHS group data⁽⁵⁰⁾; his result is that $\Lambda > 100 \text{ GeV}$, with a possible reduction in the limit due to systematic effects. It is to be noted that in weak interaction processes, an upper limit to the range of Λ that can be explored is set by the mass of the intermediate vector boson; according to the Standard Model⁽⁵¹⁾, this is $\sim 90 \text{ GeV}$.

Alternatively limits for neutrinos can be obtained by assuming that neutral current reactions occur via single photon exchange off neutrinos with a charge distribution^{**} (i.e. neglecting Z^0 exchange effects). The old data of Hassert⁽⁵²⁾ on

$$\bar{\nu}_\mu N + \bar{\nu}_\mu X$$

and their limit for

$$\bar{\nu}_\mu e^- + \bar{\nu}_\mu e^-$$

both yield charge radius limits equivalent to $\Lambda > 35 \text{ GeV}$ ^(30,54). Bardin et al also have used an old limit⁽²⁹⁾ on

* In fact the compensation is not complete, and the cross section is expected to fall slowly with increasing energy⁽²⁶⁹⁾. This means that Λ if anything is larger than our estimate.

** This is not identical to the type of substructure discussed in the previous paragraph, where non-point-like effects could be observable even if the neutrino's charge distribution were exactly zero everywhere.

$$\bar{\nu}_e e^- + \bar{\nu}_e e^-$$

to obtain a similar limit on the charge radius of the $\bar{\nu}_e$. By using more recent data on neutral current reactions (e.g. $\bar{\nu}_\mu e^-$ elastic scattering^(56,57)), and allowing for the expected contribution from Z^0 exchange[†], we can increase the limit for ν_μ on Λ by a factor of 2.

2.5 Rare flavour changing processes

2.5.1 $\mu \rightarrow e \gamma$

The current limit on the branching ratio for this process is $< 2.10^{-10}$ ⁽⁵⁸⁾; a proposal has been submitted for a new experiment at Lamf⁽⁵⁹⁾. If the muon is some form of excitation of the electron, we might expect electromagnetic transitions between them. This could also be true if the electron and muon possessed some form of common substructure. It is less apparent that the transition ought to take place in models where the different generation leptons are distinguished by different generation components which could be conserved.

We can attempt to use the absence of the $\mu \rightarrow e \gamma$ reaction to place limits on either the scale Λ of the muon and electron substructure, or on the mass M_B of a hypothetical boson which mediates the reaction by its ability to couple to fermions of different (as well as the same) generations. In the latter case $M_B > 7 \text{ TeV}$ ⁽⁶⁰⁾, while the substructure scale is $> 10^2 \text{ TeV}$ if the matrix element is proportional to $(m_\mu/\Lambda)^2$ ^{*}, or

† In some models⁽⁶¹⁾, however, there is a contribution to Z^0 exchange from such charge distributions.

* Bars⁽⁸⁰⁾ has suggested that the rate is of order $m_\mu^5 m_e^2 / \Lambda^6$, in which case Λ is reduced to 0.6 TeV . The corresponding limits derived later in this section from the processes $\tau \rightarrow \mu \gamma$ and $\tau \rightarrow e \gamma$ would be reduced to 0.2 and 0.04 TeV respectively.

$>10^8$ TeV if it is proportional to $(m_\mu/\Lambda)e^{(62-64)}$. The limits of course involve the assumption that the reaction $\mu\rightarrow e\gamma$ is not forbidden, nor is it particularly suppressed (e.g. by a GIM type mechanism, small mixing angles, etc.). Any such suppression mechanism would reduce the lower limits on Λ or M_B . It is clear that there are many uncertainties in deducing a mass scale from the non-observation of this process.

Some substructure models (147,202) predict that the decay $\mu\rightarrow e\gamma$ should occur. The experimental limit of $<5 \cdot 10^{-8}$ for this process (215) has been deduced by analysing data from experiments looking for the $e\gamma$ mode. Tomozawa (62) has given a very model dependent calculation of the rate for this process in terms of Λ .

The limit for the $\tau\rightarrow e\gamma$ or $\mu\gamma$ branching ratios is $<6 \cdot 10^{-4}$ (65). Combining this with the τ lifetime of $(3.4 \pm 0.7) \cdot 10^{-13}$ secs (66) we deduce that the substructure mass scale for the τ is >1.5 TeV or $>2.5 \cdot 10^3$ TeV for matrix elements proportional to $(m_\tau/\Lambda)^2 e$ or to $(m_\tau/\Lambda)e$ respectively. These limits are subject to the same qualifications as those mentioned above for $\mu\rightarrow e\gamma$.

2.5.2 $\mu\rightarrow 3e$

The present limit is $<2 \cdot 10^{-9}$ (67). A proposal exists at SIN to reduce this to the $\sim 10^{-12}$ level (68). Theoretical estimates (60,69) are dependent on Cabibbo like suppression factors. Assuming these can be ignored, that couplings have normal values and that there is no suppression from the interplay of different mediating bosons, the current limit on the mass of the mediating boson is >10 TeV.

The corresponding limits for $\tau\rightarrow lll$ (where $l=\mu$ or e) are $\sim 4 \cdot 10^{-4}$ (65).

2.5.3 $\mu^+N\rightarrow e^+N$

The best upper limit on this $\mu^+\rightarrow e^+$ conversion process is $<7 \cdot 10^{-11}$ as compared with the ordinary capture process; the target used was sulphur (70). Proposals exist at Triumf and at Langf to reduce this limit by an order of magnitude (71). According to Calm and Harari, this sets a limit of >100 TeV on the mass of a mediating boson (which must now, in contrast to the two previous reactions, be capable of coupling to quarks as well as to leptons). Once again this number could be almost arbitrarily reduced by unsuitable choices of the relevant mixing angles.

The limit on $\mu^+\rightarrow e^+$ conversion (70), again in sulphur, is $<10^{-9}$. This process is allowed as an alternative to $\mu^+\rightarrow e^+$ in some substructure models (214).

2.5.4 $K\rightarrow e$ processes

If quarks and leptons possess common substructure, we can imagine constituent rearrangement processes in which a generation change in the quark sector is balanced by a compensating change among the leptons. Such processes include the reactions

- (a) $K_L^0 \rightarrow \mu^+ e^-$
- (b) $K^+ \rightarrow \mu^+ \nu_e$
- (c) $K^+ \rightarrow \pi^+ \mu^+ e^-$

which are discussed further in section 4.2.5. The current branching

ratios for these processes are $<0.4\%$ for (b) (72,73) and $<5 \cdot 10^{-9}$ for (c) (74). The quoted limit (75) for (a) is $<2 \cdot 10^{-9}$, but the experiment concerned (76) failed to observe the $\mu^+\mu^-$ decay mode; the next best limit (77) is $<6 \cdot 10^{-6}$. It would appear well worth while to attempt to improve the limits for these reactions for which the net change in generation number is zero*. In models where there are specific generation number components (say β_1 , β_2 and β_3 distinguishing the generations), these processes would be mediated by the exchange of $\beta_1\beta_2$ bosons. According to Cahn and Harari, the non-observation of reaction (c) probably sets a limit of >18 TeV on its mass; Zhu (78) calculates a similar limit for this reaction. Robinett's limit based on reaction (a) is >8 TeV (274).

2.5.5 $K_L^0-K_S^0$ mass difference

The $K_L^0-K_S^0$ mass difference is sensitive to contributions from mediating bosons which can couple to both $d\bar{s}$ and $s\bar{d}$ quark combinations. In a substructure approach, whether such bosons exist depends on the particular model employed. Assuming that such a process is allowed, then the experimental value (75) of $3.5 \cdot 10^{-15}$ GeV sets a limit (60,69,80) of around 400 TeV on M_B , subject to the usual comments about suppression factors.

The weaker limit (75) on mixing in the $D^0-\bar{D}^0$ system is partially compensated by the larger mass of the D meson, resulting in a bound on the boson mass $M_B > 50$ TeV (69,80), subject once again to the usual

* This assumes that the same difference in generation number is assigned to the s and d quarks as to the μ^+ and e^+ leptons - see section 4.2.5.

restrictive assumptions.

2.6 Nucleon decay

The subject of proton decay has so far yielded more famous quotations than observed events. Thus Goldhaber (81) observed that one can feel it in one's bones that protons don't decay - if the lifetime were less than 10^{17} years, the radiation damage to our bodies would make us (painfully) aware of the phenomenon. It has also been stated that if the proton were stable, it would not exist (82); baryon non conservation may have been essential for the development of the baryon asymmetry in the early Universe.

With quarks and leptons sharing a common substructure, it is possible that quark and lepton numbers are not separately conserved. Thus in the rishon model* of Harari (83) and Shupe (84), baryon decay proceeds at the fundamental fermion level via rishon rearrangement processes such as

$$u + u + \bar{d} + e^+$$

$$TTV + TTV + TVV + TTT$$

which bears a strong similarity to the standard weak decay

$$u + \bar{d} + \nu + e^+$$

$$TTV + TTV + VVV + TTT$$

Indeed one might suspect that the rates of these processes could on such a model be similar. The observed ratio of the proton and, say, Λ^0 lifetimes of $>10^{47}$ is in stark contrast with this naive expectation. [The current limit on the nucleon lifetime is $>1.5 \cdot 10^{30}$ years (85)].

* "Rishon" is the name that Harari gives to his preons (see section 3.4).

There are (at least) two types of ways of avoiding this embarrassment. The first is to forbid the quark-lepton transition either completely* (for example, by choosing one or more of the components of the quark to differ from those of the lepton, and to be conserved in all reactions), or at least partially; an example of this is the model of Harari and Seiberg⁽⁸⁶⁾ in which their choice of quark and lepton wave function results in the rishons not having the correct helicities to allow the $u\bar{u}d\bar{e}^+$ reaction to proceed (at least, in the limit that symmetry breaking effects are neglected).

The alternative is to adopt a different arbitrary expedient of assigning different masses M_B to the bosons which mediate the baryon decays and the ordinary weak processes. Thus the lowest order processes involving leptoquark exchange result in a lifetime of order $M_B^4 M_p^5$ ⁽⁸⁷⁾, yielding $M_B \gtrsim 10^{15}$ GeV. This is in the region of the energy scale of Grand Unified Theories or perhaps even the Planck mass, and if the substructure scale is anything like this, it will make direct observation of substructure effects impossible for the foreseeable future. On the other hand, in the Harari-Seiberg picture, lowest order diagrams are forbidden, and the next set of processes⁽⁸⁷⁾ yield lifetimes around M_B^8/M_p^9 ; now the limit on M_B is reduced to $\sim 10^7$ GeV, and the dominant decay modes are those with $\Delta(B-L)=2$. If these too can be forbidden, the most likely modes are $p\bar{p}e^+e^-$, etc., with the rate reduced to M_B^{12}/M_p^{13} , with a corresponding lowering of the limit for M_B to $\sim 10^5$ GeV. While we do not recommend that these values should be taken too seriously, they do illustrate the model dependence of the limits on

* In that case, the experimental limit on the proton lifetime provides no information on Λ .

boson masses from the limit on the experimental decay rate. Furthermore, these limits apply to the masses of bosons contributing to the process rather than to the non-point like size of the fundamental fermions themselves; insofar as the bosons would be constituted from the same entities as the fermions themselves, these two mass scales should be related, though the connection could be rather tenuous.

The experimental limits on $n\bar{n}$ oscillations are such that constraints derivable on substructure are much weaker than for the corresponding nucleon decay processes*.

2.7 Exotic Quarks and Leptons

In substructure models, fermions of spin $\geq 3/2$ can exist as spin rearrangement states (provided that quarks or leptons are made from at least 3 spin $1/2$ fermions), or as states in which the constituents possess orbital angular momentum with respect to each other.

In general, radial and orbital excitations occur on the energy scale characteristic of the scale of the substructure. With limits of the order of magnitude discussed earlier in this section, it is perhaps not too surprising that such states have not yet been found. It is by no means clear that spin rearrangements could not occur at low energies (see, however, Section 4.1.13). Their non-observation has led to attempts to suppress such states⁽⁸⁶⁾.

* This is not true for models in which proton decay is forbidden but neutron-antineutron oscillations are allowed⁽⁸⁸⁾.

Other forms of exotic quarks and leptons could exist in specific models of substructure. These include quarks and leptons of unusual charges, or quarks in colour multiplets other than triplets.

The non-observation of the top quark^(40,79) at energies up to ~35 GeV can be taken as excluding most types of exotic quarks in the mass range up to ~17 GeV. Searches for heavy leptons have been reviewed by Perl⁽⁸⁹⁾, by Mess and Wilk⁽⁴⁰⁾ and by Bohm⁽⁷⁹⁾; again no states have been seen up to similar energies. The conservative view is then to limit the substructure scale to being larger than this⁽⁹⁰⁾; if low lying spin rearrangement states are not forbidden, then the substructure scale is very much larger (but again the limit is very model dependent).

We conclude from all the above data that there is as yet no evidence which requires us to give up the idea that quarks and leptons are point-like objects. In Table 5 we present the lower limits on the substructure mass scale as deduced from the various unobserved effects.

3. Early History of Quark and Lepton Substructure

We now consider the early models that were proposed for quark and/or lepton substructure. These range from pictures in which quarks are either replace by, or else built out of, leptons to the rishon model, an approach in which both quarks and leptons (as well as some of the gauge bosons) are built out of just two basic entities. The more recent models, together with the subsequent developments of the rishon model, are described in section 4.

3.1 Leptons as constituents of hadrons

There is a very long history of models in which hadrons are built either entirely or partially out of leptons. These date back to the proton-electron model of the nucleus.

In 1960, Maki⁽⁹¹⁾ and Matumoto⁽⁹²⁾ suggested that the 3 simplest baryons, the proton, neutron and Λ , were made out of the three known leptons ν , e^- and μ^- respectively, bound to a B^+ . Subsequently this picture was enlarged⁽⁹³⁾ to accommodate the ν_μ and a still-to-be-discovered charmed baryon. An alternative picture due to Taketani and Katayama⁽⁹⁴⁾ had the charged leptons as composites of neutrinos with a bosonic charge e^- , while the proton and neutron were $B^+\nu$ and $B^+\nu e^-$ respectively.

After the birth of the quark model, the Japanese school of physicists devised models in which the quarks contained leptons. Thus Hayashi⁽⁹⁵⁾ suggested that the 4 combinations of $B^+\bar{\nu}$ could provide the structure of the u , d , strange and charmed quarks. The desire to understand the $\Delta I = \frac{1}{2}$ rule was a motivation for this approach. A later variant due to Senju⁽⁹⁶⁾ built the charged leptons as 3 fermion composites of a neutrino and two charged objects ϵ_i ; and quarks as a neutrino, ϵ_i and ϵ_b . As in most such models, the quarks could be integrally or fractionally charged depending on whether the charge of ϵ_b is $1/2$ or $1/6$. This may have been the first model in which quarks and (charged) leptons were 3 fermion states with some preons in common. The partons as seen in deep inelastic scattering experiments were taken to be the preons of this model. Senju also emphasised that deep inelastic scattering could provide evidence of fermion substructure. This early

history has been reviewed by Terazawa (225).

A Han-Nambu type model of hadrons built out of both hadronic quarks and leptonic quarks has been suggested by Kalfleisch and Fowler (16). Their two triplets of leptonic quarks are e^+ , $\bar{\nu}_e$ and an extra neutral lepton $\bar{\lambda}_e$; and a similar set μ^+ , $\bar{\nu}_\mu$ and $\bar{\lambda}_\mu$. The hadronic quarks are $\bar{u}$, $\bar{d}$ and $\bar{s}$. Baryons are then composed of one hadronic and two leptonic quarks, while mesons are hadronic quark pairs. The model predicts that the ν s produced in K^+ and π^+ decay differ; this is contrary to observation (72,73).

Even more recently Nowak et al (17) proposed that baryons consist of an extended hadronic core which contains 3 sites to each of which a lepton is bound in a small orbit; mesons consist of a different core with a lepton and an antilepton bound to 2 sites. The motivation for the model is that colour is permanently confined, so it can be ignored; for economy, flavour is identified with the leptons. Higher mass hadrons correspond to excitations of the core, rather than of the lepton orbits around their sites. The model suggests that hadronic cores should have masses of ~ 5 GeV and lifetimes of 10^{-15} secs, that a baryonic core with 2 (instead of 3) leptons should be observed as a narrow peak in the baryon + antilepton mass spectrum, that K^+, μ^+, e should be observed as a result of core decay, etc. The proton is predicted to be stable.

Finally Barut (97) has discussed a model in which all elementary particles are composed of only absolutely stable particles, viz, the proton, electron and neutrinos, bound together by magnetic interactions. The baryons are then $p\bar{e}\bar{\nu}$ composites, and the mesons $\bar{e}\bar{\nu}$. The muon, which

is either some excited state of the electron or an $e\bar{\nu}$ resonance, is utilised as a strangeness component of hadrons. In this simplest version, it is not clear how the decuplet baryons (e.g. Δ^{++} , Ω^- , etc.) are to be constructed, but Barut has now made the model equivalent to the Han-Nambu integrally charged quark model (244). The form of the magnetic interaction can reproduce both strong and weak interaction effects, but a mass formula for leptons predicts that (in the non-relativistic semiclassical approximation) the next lepton after the τ should appear at 10.3 GeV. A $\mu^+\nu_e$ decay mode of the K^+ is to be expected.

Thus many of the above models appear not so much as ways of giving substructure to quarks, but of finding mechanisms for doing away with quarks altogether, or at very least of not considering them as fundamental as the leptons.

3.2 Early ideas about quark and lepton substructure

It was in the early 1970's that the first suggestions, not involving leptons as preons, were made that quarks might be composite.

The problem of the statistics of quarks lead Chang (98) to suggest that a quark was composed of an electric quark and a magnetic one, the latter being a magnetic monopole. Krolkowski (99) introduced the issue of statistics in a different way. He assumed that a quark was composed of a spin $\frac{1}{2}$ boson q and a spin zero fermion c ; the wrong statistics of the preons was responsible for their binding. His motivations included the statistics obeyed by quarks and the fact that half the nucleon momentum appears to be carried by neutral constituents. Subsequent

papers⁽¹⁰⁰⁾ investigated the consequence of such a model for deep inelastic scattering and for strong interactions, and included colour as a preon property.

Another group of papers⁽⁴³⁻⁴⁵⁾ explained the observed scaling violations in deep inelastic scattering or the non constancy of R_{ee} as being due to quark substructure. The paper of Senju⁽⁹⁶⁾ was mentioned in the previous section. Chanowitz and Drell⁽⁴³⁾ and West⁽⁴⁵⁾ invoked the coupling of quarks to gluons to explain their non-point-like nature. This today is classed as a QCD effect, and is not substructure in the sense that we employ it. These papers are significant, however, in raising the question of possible structure below the quark level. Matumoto⁽⁴⁴⁾, however, following his earlier papers⁽¹⁰¹⁾ interpreting deep inelastic scattering in terms of quarks with size, anomalous magnetic moments and excited states, actually suggested that a composite quark structure (with one preon carrying flavour and the other colour) could be responsible for scaling violations.

One of the first suggestions that leptons could possess substructure was made by Zichichi and Massam⁽¹⁰²⁾ as early as 1966. Their reasoning was simply that, just as hadrons are made of hadronic quarks, so leptons may be made of leptonic quarks. In their subsequent searches for quark production, their quoted limits thus distinguish between these two possible quark types⁽¹⁰³⁾. An attempt to build a model of this sort is discussed by Greenberg and Nelson⁽¹⁰⁴⁾. They assume that leptons are built out of three "leptoquarks", which could

* These are to be distinguished from today's leptoquarks which are supposedly responsible for mediating baryon non-conserving reactions.

have either fractional or integral charge. They also examine the possibility that leptoquarks are identical with ordinary quarks; this could lead to a unification of leptonic and hadronic phenomena. Salam and Pati⁽²⁵⁶⁾ had also suggested that leptons might be built out of fractionally charged objects.

3.3 Structural Models

While Greenberg and Nelson pursued the analogy of leptons and hadrons, Pati and Salam considered unifying the leptons with the quarks. They first suggested⁽¹⁸⁾ that the four then known leptons were a fourth colour variant of the four known quark flavours. This would unify the strong with the electro-weak interactions; and would allow the proton to decay and lepton number type to be violated in processes like $K_L^0 \rightarrow \mu e$. They then followed this with the idea that both quarks and leptons could be built out of preons⁽¹⁰⁷⁾. Their simplest version entailed a fermion Q carrying one of the four flavours (u, d, s or c) and a colour quartet boson C (corresponding to the 3 quark colours plus the 4th colour for the leptons). An alternative version⁽¹⁰⁷⁾ had C as a fermion, and the quarks and leptons were made of QC , where δ was an extra neutral singlet fermion added to obtain the correct spin. A similar picture has also been mentioned by Koike⁽¹⁰⁸⁾.

As an alternative to the introduction of charm, Greenberg⁽¹¹⁸⁾ suggested that quarks had a QC structure; Q was a flavour triplet fermion and c a spinless coloured preon. Then mesons were $QCQC$ systems, and radial excitations could produce, among many other states, possible candidates to explain the ψ and ψ' .

Rather than attempting to reproduce the quantum numbers of composite states, Raitio (109) tried to explain dynamical features of hadronic and leptonic reactions. This model builds the normal quarks out of a charged spin $\frac{1}{2}$ preon ψ and a neutral pseudoscalar π , but there also exist excited quarks composed of ψ and a neutral scalar ϕ . Such quarks are assumed to be constituents of hadrons such as $N^*(1470)$ and $\rho(1600)$.

It was a couple of years before the Pati Salam and Strathdee approach was followed by other similar versions. These are all characterised by assigning the various properties of the composite systems to the individual preons. Thus Terazawa (110) chose to build the composites as hcw , where the preons were fermions with the following properties

$h_{1,2,\dots}$ = generation component
 $w_{1,2}$ = flavour doublet
 c_i = colour (for $i=1, 2$ and 3) or leptonic character (for $i=0$)

Thus the up and down quarks are $h_{1i}c_iw_1$ and $h_{1i}c_iw_2$, while the negative muon is $h_{20}c_0w_2$. The gluons are $c\bar{c}$ composites. Terazawa went on to assume a Lagrangian for the w preons, and could then reproduce the Weinberg-Salam model with $\sin^2\theta_w = 1/4$ or $9/20$. The masses of the Higgs and W bosons, being $w\bar{w}$ composites, were given in terms of the w preon mass, thus suggesting that w pair production should become possible not too far above the mass of the W boson. Subsequent developments of this model are discussed in section 4.3.

Ne'eman's substructure model (111) used preons as follows:-

$\beta_{1,2,\dots}$ = generation component boson
 α^0, α^- = flavour doublet fermion
 β_B = coloured boson of charge $2/3$ and baryon number $1/3$, present only in quarks.

Thus the up and strange quarks are $\alpha^0\beta_B\beta_{11}$ and $\alpha^-\beta_B\beta_2$, while the muon is $\alpha^-\beta_2$. Ne'eman also takes into account the handedness of the composites, by assuming that the α^0 and α^- can exist as a left handed doublet and as two separate right handed singlets. He considers that the gauge bosons are elementary.

Another example of this type of structural model is due to Taylor (112). His quarks and leptons have the structures APF and $AF'W$ respectively, where the different fermionic preons are:-

A = ancestor (or generation) component
 F, F' = flavour, with charges $+2/3$ and $-1/3$ for F , and 0 for 1 for F'
 P = pigment (colour triplet)
 W = white (colour singlet)

All the preons are hypercoloured (see 4.1.4), and this is responsible for their binding. The F s are responsible for the electroweak interactions of the composites, and the coloured P s for the QCD ones. In this model, the proton is stable and $\sin^2\theta_w = 1/4$.

Taylor is not satisfied by the reduction in the number of fundamental objects, and suggests that maybe in their turn the A, F, F', P and W can be analysed in terms of sub-preons.

Other somewhat similar structural models, but which have a wider aim than just reproducing the quantum numerology of the known fermions, are discussed in section 4.3. We now turn to the most economical of these early models.

3.4 The Harari-Shupe Model

The most ambitious of the early models for explaining the quantum numerology of the quarks and leptons is due to Shupe⁽⁸⁴⁾ and to Harari⁽⁸³⁾, in that they construct all the first generation fermions from just 2 basic preons. The content of the Harari version of the model is without any form and devoid of structure*. He calls his fundamental subfermions rishons, denoting them by T and V (of charge 1/3 and 0 respectively[†]); Shupe's notation for them is a^+ and a^0 (again in units of 1/3). Then

$$\begin{aligned} u &= TTV & \nu_e &= VVV \\ d &= TTV & e^- &= TTV \end{aligned}$$

with the T and V's being in S states.

The 3 possible orderings of the rishons within the u or the d are assumed to give rise to the 3 colours of the quarks, while leptons are colourless since there are no possible order permutations of their identical rishons. Thus colour is a characteristic which arises naturally at the composite level; it need not be introduced (and is

* Translation of the Hebrew words Tohu and Vohu⁽¹¹³⁾, the names he uses for his fundamental entities.

† Throughout this article, electric charges are given in units of the proton's charge.

indeed not even defined) for rishons. Although this idea has subsequently been rejected by Harari (see Section 4.4), it has been revived by Jarvis and Green⁽²⁸²⁾, whose rishons are not fermions but obey a generalised quantum statistics.

Higher generations are assumed to arise as some low level of excitation. Gluons and the intermediate weak bosons W^+ and Z^0 could be 6 rishon composites and the photon could be either a $T\bar{T}$ or a 6 rishon state (to make it more like the Z^0), or it could be elementary.

The main appeal of this scheme is that it replaces the first generation fermions and several bosons by just 2 basic entities. It also explains naturally why the lepton and quark charges are related ($e_e = 3e_q$), or almost equivalently why the net charge of a fermion generation is zero.

On the other hand, it raises several difficulties*, mainly related to the lack of any dynamics in the theory. For example,

- Where are the spin 3/2 fermions?
- Why are other rishon combinations (e.g. RR , $RR\bar{R}$, etc.) not observed?
- What mechanism produces the second and third generations?
- With such similar substructures, why are quarks but not leptons confined?
- Why are the intermediate bosons (e.g. $W^+ = T\bar{T}VVV$) colourless, given that they can have order permutations of their rishons?
- Since the ν_e and the electron each contain 3 spin 1/2 rishons in an s

* Some of these are common to composite models in general.

state of orbital motion, do the rishons possess a new type of colour (and does this imply yet a further level of substructure)?

g) Do the 3 order permutations of the rishons in the quarks in fact produce colour triplets?

h) The weak interactions have become multiparticle phenomena (see fig.3(a)). Furthermore, at the rishon level, weak interaction processes and baryon number violating reactions have a very similar structure (see fig.3(b) and (c)), despite their very different rates.

It is clear that, in order to proceed further, it is necessary to introduce some dynamics into the model. The attempt of Harari and Seiberg to do this is discussed later in section 4.5.

The problems of the Shupe and Harari schemes have been discussed by Casalbuoni et al(114), who make the T a colour triplet; a similar approach is adopted by Squires(115). Nelson(116) has considered the spin and statistics problem, and Adler(117) has attempted to introduce dynamics into the rishon model via a non local gauge theory.

3.5 Excitation Models

The structural models discussed in sections 3.3 and 3.4 above concentrated in obtaining the correct quantum numbers for the fermions, while ignoring their masses as a problem to be solved when a better understanding of mass generation is obtained. We now turn to models which attempt to reproduce the mass spectrum, while quantum numbers are largely neglected.

Soon after the discovery of the ψ and its interpretation as a $c\bar{c}$ state, Horgoh(119) suggested a harmonic oscillator potential model for the higher quark states. He deduced a mass formula for the vector mesons composed of $q\bar{q}$:

$$E_k = \frac{1}{2}(\epsilon+1)(\epsilon+2)\mu_0$$

With μ_0 as 0.3 GeV, the first few vector mesons occur at 0.9 GeV (ϕ) and 3.6 GeV (ψ), and the $b\bar{b}$ state is successfully predicted at 9 GeV. Unfortunately the $t\bar{t}$ meson should be seen at 18 GeV, and the value of R_{ee} should grow much more dramatically than is seen experimentally.

Kalman(120) used the same expression as Horgoh, but for the energy difference between quarks rather than for the masses of vector mesons. His picture was of the constituents of quarks interacting via a harmonic oscillator potential, with binding occurring only at closed shells. With μ_0 set at 0.33 GeV and a charmed quark mass of 1.65 GeV, $m_D \sim 5.9$ GeV and $m_L \sim 15.9$ GeV (just below the current experimental lower limit). The strange quark is predicted to be somewhat too heavy at 0.67 GeV, and it is not clear why both the u and d quarks (rather than just one) should be found at 0.34 GeV.

A third model of this type is due to Blaha(121). He considers that higher generation quark flavours could arise as a dynamical rearrangement of fermionic degrees of freedom. He predicts a geometric mass spectrum arising from a QCD type interaction between massless basic colour triplet fields called $U\bar{r}$ -3 and $U\bar{r}$ -u (of charge $-1/3$ and $+2/3$ respectively). The low mass fermions (e, μ , u and d) are allowed to be heavier than naively predicted because of the larger value of the coupling constant at lower energies. With the masses of the ϕ , ψ and τ being ~ 1 , 3 and 9 GeV, the expected mass of the $t\bar{t}$ meson is 28.6 GeV,

again below the current limit. If the lepton masses also form a geometric series, the next one will be at 30 GeV; this region remains to be tested.

This type of approach has not been much pursued in the last couple of years*. One problem is that, despite the increase in the number of fermions, there are still not enough to make a convincing fit of their masses in most models. The neutrino masses, as at present known, are trivially zero, the extra colour states of quarks provide no new information, quarks and leptons can have independent masses, and excuses can be found for the lowest mass fermions not to fit predicted values. Another problem that the models suffer from is that, insofar as they are successful in reproducing the masses of the known fermions, they have predicted where the next ones should be found; and often experimental investigation in the relevant energy range has subsequently demonstrated that the required states are in fact absent.

3.6 Group Theoretical Approach

Yet another approach to the substructure question is to try to find a suitable group for the preons. Thus Phillips⁽¹⁵⁵⁾ has investigated groups of the form $SU(m)_F \times SU(m)_C$ where m is twice the number of generations and the subscripts F and C refer to flavour and colour. He assigns the preons f to the irreducible representation of the group.

* Head and Moore-Head⁽¹²²⁾, however, have a potential model for relativistic preons in composite states which is claimed to reproduce the correct masses for $\nu_e, \mu, \pi, K, \rho, \omega, K^*, \phi$, neutron, $\Lambda, \Sigma, \Xi, D, D^*, F$ and F^* . Koppen and Durr use an oscillating potential to reproduce the charged lepton spectrum⁽²⁵⁵⁾, while Caldirola's model utilises a 4 dimensional de Sitter micro-universe involving an elementary time interval⁽²⁷⁸⁾.

With a few assumptions, Phillips deduces that the only possibilities for m are 4, 10, 16.... The value 4 corresponds to the Pati Salam model of quarks and leptons, but $SU(4)_F$ is not large enough to contain the subsequently discovered third generation. Phillips thus chooses $m=10$.

As in the Pati-Salam approach, the last colour corresponds to lepton character, and the rest to quark colours.

The (10,10) representation contains 10 hadronic preons each in 9 colour states, and 10 leptonic ones. The preon charges are $+5/9$ and $-4/9$. The 9 colours are made of 3 colour triplets, each in 3 shades (light, medium and dark). The combination of 3 preons of a given colour but of different shades produces a composite shadeless quark of that colour. Altogether 10 singly flavoured quarks of charge $+2/3$ or $-1/3$ can be formed.

The gauge group of the preon's interactions is $SU(9)_C$. This results in 80 gauge fields, comprising a shade changing octet of supergluons which bind the preons into quarks, plus 72 colour changing gluons.

This model is quite specific in its structure, and correspondingly rich in predictions. We thus expect 2 more generations of fermions, as well as exotic quarks. There is also such a plentiful spectrum of preons that one may suspect that this may not represent the ultimate level of substructure.

In the period when hadrons were being rapidly discovered, the group theoretical classification certainly played a major part in the road to understanding their substructure. It is thus hardly surprising that the

leptons.

- d) Quarks and leptons are made of the same preons. Thus in the Rishon model (83,84) (see section 3.4) fermions are made of preons T and V which carry B-L of $+1/3$ and $-1/3$ respectively. The composites too have only B-L defined, rather than B and L individually.

4.1.3 Substructure Scale Λ

All that is known about Λ is that it should satisfy the experimental limits as specified in section 2. We re-emphasise the warning that many of the limits mentioned there are model dependent, and hence a different model could possibly use a smaller value of Λ .

Despite the fact that a semi-infinite range is available for Λ , popular values tend to cluster in two regions.

Low Λ

Here we include models which favour values of Λ in the range 1-100 TeV (see, for example, refs.123, 128-131 and 279). This puts Λ at around the lowest values consistent with the least model dependent experimental limits (i.e. as derived from the reactions $e^+e^- \rightarrow \bar{\nu}_\ell \nu_\ell$ and the anomalous magnetic moments of the electron and muon), and encourages experimentalists that their search for direct observation of substructure effects may bear fruit in the not-too-distant future*. It has also been argued⁽⁹⁰⁾ that excited states of quarks and leptons (as

* This has been compared to the advice that, if you lose your keys on the way home on a dark night, you should look for them under a lamp-post since if they are anywhere else you will not be able to find them⁽¹³⁴⁾.

opposed to new flavours) could exist at energies as low as $\Lambda/100$, and hence soon become accessible.

From a slightly more theoretical viewpoint, one can observe that the weak interaction coupling constant already defines an energy scale ($G_F^{-1/2} \sim 300$ GeV), and it would be economical to use it for substructure rather than to introduce yet another scale; indeed in models where the weak interactions arise as residual effects of a short range hypercolour force (63,86,123,128,280) such a value of Λ may even be relevant. Similar values have also been suggested in relation to the technicolour version of composite Higgs bosons⁽¹³²⁾, and in order to solve problems associated with the high energy behaviour of processes involving intermediate vector bosons⁽¹³³⁾.

A major problem with this class of models is to explain why processes such as proton decay and neutral current flavour changes occur at such low rates. It is necessary either to forbid them, or to make them highly suppressed (see 4.1.10).

High Λ

The other popular range for Λ is 10^{12} - 10^{16} TeV. These values correspond respectively to the energy at which Grand Unification⁽¹³⁷⁾ may be achieved and to the Planck mass. The latter arises naturally in models where the binding mechanism is gravitation⁽¹³⁸⁾, or where supergravity is involved^(139,140).

At an experimental level, it is easily consistent with even the most conservative limits given in section 2, but it does imply that any reasonably direct observation of substructure effects (e.g. the

group theoretic approach to quarks, leptons and preons continues to be popular. More such articles are mentioned in section 4.3, and in ref.(106).

4. Substructure Today

Having in the previous section reviewed the early history of substructure, we now turn to more recent developments. We first consider several points which apply to substructure models in general. One specific topic, that of generations of fermions, is considered in 4.2. Then in 4.3, we give a brief description of some of the current substructure models, emphasising experimentally testable predictions. A more detailed account of one of these models (that of Harari and Seiberg) is presented in section 4.4.

4.1 General Features of Substructure Models

4.1.1 Which "elementary particles" are composite?

The majority of models consider the observed quarks and leptons all to be composite. There are however variants, such as:-

- a) Either the quarks or the leptons are composite, but not both. This situation can arise simply because only one type of fermion has been considered, rather than from some basic underlying physical reason.
- b) The first generation fermions are elementary while higher generations are composite(222). Generations are discussed further in 4.2.
- c) Left handed fermions are composite, while right handed ones are

elementary(123,150).

- d) The particles of the fundamental 5 representation of $SU(5)$ (i.e. the left handed $\bar{3}$, e^- and ν_e) are elementary, but those of the 10 representation (the left handed u , $\bar{u}$, d and e^+) are composite(124); or vice versa(242).

Next comes the question of the bosons. The photon and gluon (and the hypergluon in those models using hypercolour to bind the preons - see 4.1.4) are usually considered to be elementary; they are probably massless and are the gauge bosons of unbroken local symmetries. Insofar as gravity is included in composite models, this applies to the graviton as well. However, models of composite photons(125), gluons(126) and gravitons(127) have been considered.

The massive bosons include the carriers of the weak interactions, and probably also the Higgs particle. Models are divided on whether they should be regarded as composite or elementary. They are discussed further in 4.1.8.

4.1.2 Quarks - Leptons Difference

A variety of approaches is used to distinguish quarks from leptons. In an order which makes quarks and leptons increasingly similar (and hence which will make nucleon decay intrinsically easier), these include:

- a) Leptons are elementary while quarks are composite.
- b) At least one of the preons in quarks and in leptons are different.
- c) A variant of b) is where a colour quartet of preons exist, the first 3 of which are contained in quarks and the last one in

appearance of a form factor in scattering processes) becomes impossible.

Arguments against a lower value of Λ have been advanced by Masiero⁽¹⁴¹⁾, on the basis of the baryon/photon ratio of the Universe; and by Nanopoulos⁽¹⁴²⁾, using the relation between the b quark and τ lepton masses.

A few models utilise the idea that there may be more than one scale Λ characterising the preons. Thus preons themselves may not be the ultimate form of matter, but could in turn be built out of simpler pre-preons^(155-158,248). This is popular in models with many preons, or as a means of introducing an extra energy scale into the otherwise desert-like region between Λ and the Planck mass.

4.1.4 Binding Mechanism

The suggestions for the mechanism that is responsible for binding the preons within quarks and leptons include almost all known interactions (e.g. gravity⁽¹³⁸⁾, electromagnetism^(143,144) and quantum chromodynamics⁽¹⁴⁵⁾) and hypothetical ones imported from elsewhere (e.g. Higgs exchange^(130,147) and supersymmetry^(139,140,148)).

There is also a new interaction specific to composite models - hypercolour⁽²⁶⁰⁾. In analogy with the colour force between quarks mediated by gluons, hypercolour binds preons via hypergluon exchange; colour and hypercolour are both exact gauge symmetries. The hypercolour interaction is generally assumed to be confining, and hence free preons would be unobservable. [It should be remembered, however, that attempts to demonstrate that colour confinement is a necessary consequence of QCD have to date been unsuccessful]. All "observable" quarks and leptons

are hyperwhite.

The colour group is $SU(3)_C$. The corresponding group for hypercolour is generally taken as $SU(n)_H$, with n being 2⁽¹²⁴⁾, 3^(86,149,214,242,254), 4^(129,279,280), possibly 5⁽²⁷¹⁾, 7⁽¹⁵³⁾ or 9⁽¹⁸⁶⁾ or even larger⁽²⁷¹⁾. Bars has investigated models in which the different preons can belong to different hypercolour representations, with n up to 16⁽⁸⁰⁾. Other possibilities include $SO(3)$ ⁽¹⁶⁹⁾, $O(5)$ ⁽²⁷³⁾, $O(15)$ and $O(17)$ ⁽¹⁸⁶⁾ or F_4 and E_6 ⁽⁸⁸⁾. If hypercolour exists, we can safely presume that someone has chosen the correct group.

Hypercolour models in general predict that leptons will exhibit strong interactions at energies high enough ($\sim \Lambda$) such that their substructure is probed.

Some versions of hypercolour models consider that it may be conceivable to unify hypercolour with colour at some high energy⁽²⁸⁸⁾.

A different approach which utilises new interactions is that of Pati et al⁽¹⁵⁶⁾. They assume that preons can carry two new types of charge, which are analogous to (but not identical with) electric and magnetic charges. Composite fermions are neutral in both these charges. Pati et al remark that maybe the preons themselves are composites of pre-preons, each of which carries only one of these charges.

4.1.5 Composite Masses

4.1.5.1 Massless composites

Composite quarks and leptons are light. This is apparent when their mass M is compared with either the magnitude of the substructure scale Λ (see 4.1.3), or equivalently with the limit on their size R as determined experimentally. The dimensionless product MR for quarks and leptons is compared with those for other composite systems in Table 6; only quarks and leptons have this product less than 1.

The "natural" value that we might expect for MR is unity*. The proton has this order of magnitude. Indeed its size is controlled, depending on our viewpoint, either by virtual pions or by quarks, either of which is lighter than the proton and hence R is somewhat larger than M_p^{-1} . A nucleus containing A nucleons has MR larger by a factor of $A^{4/3}$; this increase is caused by the Pauli Principle not allowing the larger mass nucleus to have a smaller size. Another step up the substructure scale brings us to the hydrogen atom. Here MR is very large, primarily because the size of the atom is determined by the extra-nuclear electron, while the mass is essentially that of the nucleus. This discrepancy should disappear in positronium. Here, however, MR is still larger than unity. In this case the reason is that the quantity that we really expect to be of order unity is pR (where p is the momentum of a constituent) rather than MR ; in the non-relativistic case relevant here, $M \gg p$ and the product MR is thus large.

* It is possible, however, to obtain arbitrarily small values of MR by "fine tuning" of the potential in which the preons are found (see, for example, ref.(255)).

We thus see that in all previously known composite systems, the value of MR is either of order unity or larger; and we understand the reasons for this. It thus becomes a problem to explain why composite fermions are so light*. Indeed a zeroth order approximation to the problem is to regard the fermions as massless, and to leave the problem of why their masses are mostly non-zero for later.

Zero masses suggest the operation of a symmetry principle: the mass of the photon is zero because electromagnetism is gauge invariant. The basic idea behind most explanations of the approximate masslessness of quarks and leptons is Chiral Symmetry, which conserves separately the numbers of left handed and right handed fermions. A mass term in the Hamiltonian for fermions is essentially a helicity flip operator; massless particles travel at the velocity of light and their helicities cannot be changed by Lorentz boosts. Thus a massive fermion corresponds to a chiral symmetry breaking term in the Hamiltonian, while conversely a massless fermion could be produced by forbidding the mass term by invoking Chiral Symmetry.

The options for massless particles now depend on whether the interactions are such that the chiral symmetry of the original theory is spontaneously broken or not.

* In their discussion of the problems of obtaining massless states, Aoki et al.(247) suggest that the simplest way of resolving the difficulties associated with realistic composite models may be to assume that quarks and leptons after all are elementary.

a) Spontaneous Symmetry Breaking

This is analogous to the situation in which a sphere of iron will become magnetised along a particular direction, thereby spontaneously breaking the spherical symmetry of the system.

In the usual strong interactions, the u and d quarks are light and we can consider them as approximately massless. If the strong inter-quark QCD interactions were such that chiral symmetry was not spontaneously broken, then composite fermion states such as the proton would be massless. But this is not so. Quark-antiquark pairs can be produced virtually from the vacuum, they have zero net momentum and angular momentum, and hence non zero helicity. The result is that the vacuum does not have a definite chirality, and hence can absorb chirality, thus destroying the relevant symmetry. Spontaneous symmetry breaking, however, produces massless Goldstone bosons⁽¹⁵⁹⁾; in the QCD case these are the 8 pseudoscalar mesons, which in our limit of massless quarks would be massless composites.

If, as seems plausible, the interactions responsible for preon binding also break a chiral symmetry of the original model, we again expect massless composites, but these are bosons rather than the fermions we observe. Bardeen and Vijnic-Triantafillou⁽¹⁴⁸⁾ have overcome this difficulty by using a supersymmetric theory, in which bosons and fermions can be transformed into each other*. In this case the spontaneous symmetry breaking gives rise to massless Goldstone fermions, which could conceivably be the observed quarks and leptons. A

* Ref.289 lists other articles applying supersymmetry to composite models.

difficulty with this interesting idea is that usually only one Goldstone fermion is generated, while there are many essentially massless composites.

Instead of broken supersymmetry producing Goldstone fermions, Aoki et al⁽²⁴⁷⁾ have suggested another way in which supersymmetry could be relevant. The breaking of some other symmetry in the model gives rise to massless Goldstone bosons, but the unbroken super-symmetry also requires the existence of corresponding massless fermions.

b) Unbroken chiral symmetry

The other, and more popular even if less plausible⁽²⁸¹⁾, route to massless particles is to assume that the preon interactions are such that chiral symmetry remains exact. In that case the spin $\frac{1}{2}$ composite states can be massless, as we wanted for the quarks and leptons.

The major problems in this approach are to demonstrate that in any symmetry breaking, there remains enough chiral symmetry to require massless composites; and to identify which of the possible composites are the ones that remain massless. In this programme, 't Hooft⁽¹⁶⁰⁾ has enumerated two conditions which he considers necessary for the model to maintain its global chiral symmetry, and which help classifying the massless composites. We return to the 't Hooft conditions in 4.1.13.

Alternatively discrete chiral symmetries⁽²⁵⁷⁾, arising from the breaking of some original continuous chiral symmetry, can be utilised to assign different quantum numbers to right and left handed preons. For some combinations of preons, mass terms (involving left and right handed states) are forbidden, and hence these composites may be massless. This

mechanism avoids the necessity of satisfying the 't Hooft anomaly constraints.

The subject of massless composites, chiral symmetries and the 't Hooft conditions have received extensive attention in the last couple of years. A detailed analysis of this topic is beyond the scope of this article, but has been discussed by Peskin⁽⁴⁾. It is worthy of a review in its own right.

4.1.5.2 Finite masses for composites

Having attempted to ensure that fermions are massless, it is now necessary to give them a finite mass. Non-substructure models do this via a Higgs mechanism, and some substructure models⁽⁸⁶⁾ mimic this by hoping that either the preons or the quarks and leptons can bind to form condensates that will fulfil a Higgs role. Other ideas have included colour⁽¹³⁶⁾, technicolour⁽²⁵⁹⁾, electromagnetism^(147,206) and new mechanisms^(161,239). These suggestions have been discussed by Preskill⁽⁵⁾, who emphasises the technicolour approach. He points out that the rich spectrum of charged fermion masses (from $\frac{1}{2}$ MeV to 5 GeV at present) could be imagined as coming from a formula like $\beta^n \Lambda_T$, where Λ_T is the technicolour scale of ~ 10 TeV, β is a small parameter (say ~ 0.1) and n is a positive integer which expresses the degree of mass suppression (see also refs.136 and 149). Then fermions corresponding to the lowest values of n still remain to be discovered, and could exist in abundance.

The next puzzle concerning the mass spectrum is why the neutrinos are massless, or at most very light (or is this the easiest part of the problem to understand?). At first sight it would appear that models with neutrinos made of only neutral preons (e.g. ref.86) have an advantage over those with charged preons (e.g. ref.128), in that in the latter case the neutrinos would have an electromagnetic self-energy (and a non zero charge radius^{*}). In each case, however, the preons interact with each other by some interactions (in both refs.86 and 128, the preons are coloured and hypercoloured) and hence this produces a self energy as well. Exact unbroken chiral symmetry could of course keep composite neutrinos massless, but then why are the other fermions so much heavier? Thus it appears that the masslessness of the neutrinos remains a puzzle. Indeed several substructure models predict a non zero ν mass⁽¹⁶³⁾, although this prediction is hardly a specific signature of substructure.

Most substructure models utilise the idea of fermion generations; the problem of what gives the higher generations their masses may be linked with that of the general issue of fermion masses. Again the intermediate vector bosons are usually considered composite, and their larger masses are also to be explained. Thus there is a rich mass spectrum standing as a challenge for potential theories.

The "advantage" of not being able to calculate masses at present is that exotic composites (for example, colour sextet or octet quarks, or doubly charged leptons), which are predicted by some models but which

* An alternative⁽⁶¹⁾ to the Weinberg-Salam model utilises the non-zero charge radius of the neutrino in order to produce neutral current interactions.

have not yet been seen, can be assumed to be heavy enough not to have been discovered to date. This is intrinsically unsatisfactory. We can hope that a successful model will not only reproduce the known masses but also can demonstrate that unobserved states are either superheavy, or predicted to be seen soon at specific masses.

4.1.6 Preon Properties

(a) Preon Mass

Most models employ the idea of light preons. In order for these not to have been seen as free particles, they are permanently confined, in analogy with the (unproved) confinement of quarks by QCD. In the preon case, the confinement could be provided by the charge associated with the binding mechanism. Thus some models employ hypercoloured preons, with the only entities able to be observed independently being hypercolourless (e.g. quarks and leptons). The case for light constituents has been stated by Dimopoulos (164).

The alternative is very heavy preons (165), perhaps with mass of order of the composite scale Λ . They then need not necessarily be confined; it is merely their large mass which prevents their having been detected to date. Then the observation of free preons may become an experimental possibility (110). The composites can be light, with the binding energy of the very strong binding interaction compensating for most of the preons' mass.

It should be remembered that not all preons need have the same mass. This is especially true in models that employ different types of preons (e.g. fermions and bosons).

(b) Preon electric charge

The simple ratio of the electric charges of the e^- and d quark finds a natural explanation in models like those of Shupe (84) and Harari (83); the e^- contains 3 charged constituents and the d just one, while the other constituents are neutral*. Other models do not explain this ratio but simply replace it by a similar ratio at the preon level. For example, Fritzsch and Mandelbaum (128) use preons whose charges are $1/2$ and $1/6$.

4.1.7 Type of Preons

Models can be divided according to whether the composite spin $\frac{1}{2}$ fermions are made out of 3 spin $\frac{1}{2}$ fermions f , a fermion and a boson b , or purely bosons. It should, however, be noted that the preon content number of composites need not necessarily be conserved (167, 170, 235).

(a) Fermionic preons

This type of picture has been widely employed (168). It has the advantage of utilising less preon types, and correspondingly fewer parameters than fermion + boson versions. One might expect that a rearrangement of spins could lead to spin $3/2$ fermions. These have not yet been observed, presumably because (if they exist at all) they are too heavy. This can to some extent be explained by the fact that it is the spin $\frac{1}{2}$ states which manage to become anomalously light (see 4.1.5). The mass of spin $3/2$ quarks and/or leptons (assumed to be Regge

* It is possible to argue, however, that the choice of exactly zero charge for a preon is unnatural.

recurrences) is estimated by Schnitzer to be in the TeV region⁽²⁴⁰⁾. The phenomenological consequences of spin 3/2 quarks have been investigated by Taylor⁽²⁴¹⁾.

Variants of the 3 fermion model include $2f+f^{(169)}$, a mixture of $3f$ and $2f+f^{(170)}$, and a mixture of $5f$, $4f+f$, etc.⁽¹⁷¹⁾.

(b) Fermion plus boson

This variant has also been very popular⁽¹⁷²⁾. It dispenses of the problem of low mass spin 3/2 states. Models vary in the way in which preon properties (such as electric charge, colour, etc.) are divided between the boson and the fermion.

If the bosonic preon is not fundamental but is itself a fermion pair composite, this type of model then reduces very much to the $3f$ version. The idea that preons may not be the ultimate constituents of matter⁽¹⁵⁵⁻¹⁵⁸⁾ has been discussed in attempts to reduce the number of fundamental constituents, and with a view to introducing more mass scales between 1 TeV and the Planck mass.

An alternative to the fb approach is the fermion + 2 bosons picture⁽¹¹¹⁾ which Ne'eman employs for quarks. This allows different properties (in this case generation number and the quark-lepton distinction, including charge) to be assigned to different preons, and hence distinct composite bosons to be constructed from them. Kuang and Tye also use composites of this type⁽²⁷⁹⁾. In one of their models, Casalbuoni and Gatto⁽¹⁵⁰⁾ construct leptons from a fermion plus 3 bosons.

(c) Boson models

Models exist in which either $2^{(143)}$ or $3^{(156,173)}$ bosons are employed to make the composite fermions. The bosons are taken to be magnetic monopoles⁽¹⁴³⁾, dyons⁽¹⁷³⁾ or the carriers of analogue electric and magnetic charges⁽¹⁵⁶⁾. The hope is that the angular momentum of $\frac{1}{2}$ required for the composite fermion can be obtained from the interaction field.

It thus appears that in building composite fermions, almost every conceivable combination of preons has been employed. One unexplored possibility, however, is a Mendele'ev style classification, with the fermions that differ only in generation number belonging to the same chemical type group, with the neutrinos corresponding to inert gas configurations and the different quark colours to rare earth structures.

4.1.8 Vector Bosons and Higgs Particles

Given that preons are already being utilised to make quarks and leptons, it is in the interest of economy to consider whether other particles, such as the weak bosons and/or the Higgs scalars, can be composites of the same preons. The weak bosons $W^{\pm}$ and Z^0 could be $ff^{(174)}$, $b\bar{b}^{(175)}$, 3 boson⁽¹⁴⁵⁾ or 6 preon⁽¹⁷⁶⁾ composites. These models then are capable of interpreting the weak interactions, due to preon exchanges (see fig.4), as being a residual van der Waals type effect of the very short range preon binding mechanism. With the small size of the composite fermions being responsible for the weakness of the weak interactions, the value of Λ is determined as $\sim G_F^{-1/2} = 300$ GeV.

Such a picture thus not only removes the intermediate bosons from the list of fundamental particles, but also reduces the number of basic interactions. It is then not clear whether a Grand Unified Theory which links a fundamental QCD interaction with a residual weak one is meaningful; with unification energies of 10^{15} GeV, well above the scale of compositeness Λ , the weak interactions (which would apply only for the composite systems) would no longer exist.

If the bosons are b5 composites, they must be in an $L=1$ state. To the extent that their masses are very small compared to Λ , this is not favoured. (However, boson masses of 70-90 GeV and a composite scale of ~300 GeV could be not too unreasonable in this respect). Fritzsche (128) has also argued that with $L=0$, it may be difficult to understand the value of $\sin^2 \theta_w$ (see 4.1.11); Llewellyn-Smith points out that Fritzsche's argument is incorrect (177), but $\sin^2 \theta_w$ may be small anyway.

The 6 preon picture of weak bosons makes weak interaction processes look more complicated at the preon level than at the quark-lepton-boson scale. It is also necessary to explain why the $W^\pm$ and the Z^0 are the lightest of the many possible 6 preon composites.

With the intermediate bosons as composites, we expect in general that there will exist a spectrum of $W^\pm$ and Z^0 s, rather than just one of each as in the Standard Model (51); as usual there is some arbitrariness concerning the mass of these excited states. It is possible that the Z^0 will consist of an almost degenerate pair of states (184). One can also expect weak currents coupling to right handed fermions; the present limit on M_R/M_L , the ratio of the masses of the right and left handed bosons, as derived from the $K_L^0-K_S^0$ mass difference, is $20^{(178)}$, and from

cosmology is $30^{(179)}$. Weak isoscalar composite Ws could also exist.

A contrary view has been put forward by Tosa and Marshak (88), who argue that the gauge picture of weak interactions is too beautiful to spoil by replacing it by a composite effect. In that case the preons themselves are specifically given a weak charge, and the weak currents couple directly to them (88,181). Bars (80) and Shaw (222) also do not employ composite weak bosons.

The compositeness of the Higgs has been suggested not only for reasons of economy. There are corrections (183) to the mass of the Higgs M_H , arising for example from processes involving $f\bar{f}$ loops, which unfortunately diverge with the upper limit P of the internal momentum as

$$\delta M_H^2 \sim P^2$$

Now problems may arise with the Higgs coupling (182) for $M_H \gtrsim 1$ TeV. If we wish to maintain $\delta M_H^2 \ll M_H^2$, it is thus necessary to cut off the contribution to δM_H^2 for $P \gtrsim 1$ TeV. One (but not the only) way to do this is to have the Higgs composite on a scale Λ not larger than 1 TeV.

Models of composite Higgs bosons have been examined by Marinescu and Schmidt (161), by Terazawa (110) and by Georgi (272). Other models utilise condensates of the composite fermions to fulfil the role played by the Higgs (163).

We thus see that the Higgs and/or weak bosons may be composite independently of whether quarks and leptons are; attempts to make composite bosons out of known fermions in fact considerably predate substructure models. If they are all composite, they could be so on different energy scales Λ . The most appealing picture, however, would be if only one composite scale was involved.

Finally we note that Weinberg and Witten⁽¹³⁵⁾ have shown that, subject to suitable conditions, composite or elementary massless particles of spin greater than $\frac{1}{2}$ cannot exist. (The graviton and photon do not satisfy the conditions, and hence are allowed to be massless⁽⁴⁾). This could be a relevant restriction on the compositeness of vector bosons (of mass ~ 100 GeV) in models where the substructure scale is very much larger than 1 TeV.

4.1.9 Dynamics

Most of the early models discussed in section 3 did not attempt to deal seriously with any dynamical questions related to the preons. Their main emphasis was in reproducing the pattern of known quarks and leptons. Since these fermions at present appear as generation repetitions of the u, d, e^- and ν_e , the constraints imposed on such model builders are not severe and numerous varieties of preon models have been suggested.

Models which incorporate dynamics, however, are in principle capable of making more specific predictions, some of which may even be testable experimentally. Thus Terazawa⁽¹¹⁰⁾, by assuming a Lagrangian for his preons, could make his model equivalent to the Weinberg-Salam model of weak interactions, and predicted that the masses of the Higgs H and intermediate bosons $W^\pm$ are related by

$$M_H \sim 2/\sqrt{3} M_W$$

Another attempt to introduce dynamics into preon models, this time for the Stupe-Harari approach (see section 3.4), has been made by Adler, who uses a non-local gauge approach⁽¹¹⁷⁾. Harari himself uses more conventional dynamics (see section 4.4).

The main calculation which we can look forward to is that for the mass spectrum of composites. Not only is a rich spectrum already known, but predictions for other low mass states yet to be discovered will be a crucial test of such a picture. Other predictions relate to proton decay (see 4.1.10) and other flavour changing processes, the existence of right handed weak interaction currents, possible parity violation in strong interactions at high energy, generation mixing effects⁽²⁶⁵⁾ for quarks and possibly for neutrinos, etc.

4.1.10 Proton Decay*

If quarks and leptons are composed of the same constituents, then rearrangement processes can lead to quark-lepton conversions and hence proton decay. This can be regarded either as a success, since according to Grand Unified Theories the proton can be expected to decay; or as a serious problem, since the proton lifetime is at least some 10^{47} orders of magnitude longer than typical weak interaction decays, which are also preon rearrangement processes. It is thus necessary to estimate the lifetime for this decay.

Naive estimates give a lifetime $\sim \Lambda^4/M_p^5$. Thus the proton lifetime can be made long by making Λ large; a value of $>10^{15}$ GeV would do**. Alternatively various mechanisms could be invoked to suppress the basic rishon process^(86,87), with proton decay proceeding only via higher

* A discussion of proton decay in relation to the substructure scale Λ has already been given in section 2.6.

** This, however is not the only viewpoint. Squires⁽¹⁸⁴⁾ has argued that the rishon rearrangement process will not be particularly suppressed compared with elastic scattering of the composites, and then deduces that $\Lambda > 10^{28}$ GeV.

order diagrams involving more powers of Λ . Then a smaller value of Λ would suffice. In that case the dominant decay modes should differ from those normally expected (which have $\Delta B = \Delta L$), and can provide an interesting test of the model.

An alternative is to use at least one different preon in quarks and leptons (186). If these preons are separately conserved in all interactions, then the quark to lepton transition is forbidden, and proton decay does not occur. It would appear that the observation of proton decay would destroy this type of model. This is not necessarily so, since it is conceivable that the fermions are composite on a scale $\Lambda < 10^{15}$ GeV, but at $\sim 10^{15}$ GeV, the preons which distinguish quarks from leptons become unified. In that case proton decay would be a Grand Unification, rather than a substructure, phenomenon.

The question of proton decay in composite models has also been discussed by Tosa and Marshak (88), who suggest that the proton may be stable but $n\bar{n}$ oscillations could occur, and by several other authors (187).

4.1.11 Weinberg Angle

The value of $\sin^2 \theta_w$ can be computed from the structure of a given preon model. Since the current experimental value (188) is 0.215 ± 0.015 , a theory which predicts $1/4$ (86) is not unreasonable, especially when it is remembered that this value applies at an energy Λ . When this is renormalised down to the weak interaction energy scale M_w , the predicted value decreases and can come into even better agreement with experiment.

* Chanda and Roy (185) consider the multipreon nature of the leptoquark and find $\Lambda > 10^{12}$ GeV.

Other theories, however, predict $\sin^2 \theta_w = 3/8$ (162), or $9/20$ (189), and these too can be claimed as a success by invoking a larger substructure scale Λ and hence a bigger renormalisation effect before comparison with experiment.

An alternative viewpoint is adopted by Fritzsch (128), who regards weak interactions as the residual effects of the preon binding interaction. His intermediate bosons are composites, and the photon can mix with the neutral one via the annihilation of its preons. The value of $\sin^2 \theta_w$ is then related to $\psi(0)$, the intermediate boson's wave function at the origin (and hence can be used as a measure of the boson's size). The natural magnitude for $\sin^2 \theta_w$ on such a model is $\sim \alpha$. In order to obtain a large enough value, the W must be spatially small ($m_W \sim 1$, as compared with ~ 5 for a typical hadron). Chen and Sakurai (151) claim that the enhancement occurs because the γ and W are almost degenerate on the mass scale $\Lambda > 1$ TeV.

Fritzsch claims that models of intermediate bosons with non-zero orbital angular momentum between the constituents (123) may have problems as $\psi(0) \sim 0$, and hence the predicted value of $\sin^2 \theta_w$ would be too small; Llewellyn-Smith (177) disagrees with the argument although the conclusion may be correct. The masses of such bosons may also be a difficulty.

4.1.12 Magnetic moments

The fact that the electron and muon magnetic moments are in such excellent agreement with calculations based on a point structure was originally thought to be a serious problem for models of substructure. It is now generally agreed that, in a strong binding limit, the

deviations from the point like value for a composite of mass m will be only of order $(m/\Lambda)^2$ or (m/Λ) , depending on whether the binding does or does not have a chiral symmetry. Thus a large enough value of Λ can suppress any anomalous magnetic moment. It should be noted, however, that the expressions could be more complicated for models with different types of heavy preons with differing masses; and that the constants of proportionality in the above order of magnitude estimates could be small e.g. $4\pi/9\pi$ (190).

A possibly more troublesome effect has been noted by Aoki (191) and by Bander (37). Because the axial current is not conserved, a renormalisation effect can take place between the preon and composite levels such that even if the preons are purely left-handed, the composites need not be completely so. The observed left handed weak couplings of quarks and leptons could thus be a serious constraint for composite models.

4.1.13 't Hooft Anomaly Conditions

A gauge theory for the interactions of massless spin $\frac{1}{2}$ fermions may run into difficulties from the so-called triangle anomaly diagrams, which involve the coupling of 3 of the gauge currents to a fermion loop (see fig.5). Even if a theory possesses chiral invariance, there is a danger that such processes could result in its spontaneous breakdown; we have seen in 4.1.5 that, in order for composite fermions to be light, chiral invariance may be an almost exact manifest symmetry.

't Hooft (160) has argued that in order for spontaneous breakdown not to occur, two conditions must be satisfied.

- 1) The sum of the anomalies for the massless preons must equal that for the massless composites*.
- 2) If any preon has a large mass, all composites containing this preon should be heavy. [The Appelquist-Carrazzone theorem (192)].

These constraints place severe restrictions on models of essentially massless composites. It is generally agreed that some such conditions (193) are necessary to provide a means of preventing the spontaneous breakdown of chiral symmetry, but it is by no means clear that they are sufficient. Indeed Bars (80) has enlarged them to a set of 10 conditions which he believes are necessary. A vast literature has grown up around this subject, both from the point of view of the degree to which conditions are necessary and/or sufficient, and also in their implementation in specific preon schemes. A discussion of this is beyond the scope of this article; it is a subject meriting a review of its own.

Finally we would like to emphasise that most of the models have features which are basic and lead to predictions which if contradicted by experiment would result in the model being discarded; but there can also be additional optional assumptions which, if predictions based on them turn out to be incorrect, can readily be modified or given up without affecting the model as a whole. Thus in the Harari-Seiberg

* Coleman and Grossman (252) have emphasised that only massless spin- $\frac{1}{2}$ states contribute to the anomalies.

approach, the choice of a mechanism for producing generations is not a crucial part of the model, which could thus survive the discovery of a 4th generation of fermions.

4.2 Generations

4.2.1 Existence of Generations

The lightest quarks and leptons are the colour triplet u and d of charge $+2/3$ and $-1/3$ respectively, and the colour singlet charge -1 electron and its neutrino. This array of particles is echoed in the charm and strange quarks, and the muon and its neutrino. Assuming that the top quark exists[†], a third generation of fundamental fermions (including the bottom quark, and the tau lepton and its neutrino) repeats the pattern of the first two. It thus appears that fermions exist in generation groups^{*}, and it is possible that still further generations remain to be discovered.

Table 7 lists the experimental situation concerning the question of how many generations exist. To date 3 generations of quarks and leptons have been observed. An upper limit on the number of different neutrino types (of mass below ~ 200 MeV) is known from the new limit (180) on the $K^+ \rightarrow \pi^+ \bar{\nu}$ branching ratio, which updates the value quoted in ref. (199). In the near future, we can hope that $\bar{\nu}$ decays of Z^0 's produced in $e^+e^- \rightarrow Z^0$ or $Z^0\gamma$ will determine the number of neutrino types (with mass

[†] In the model of Kim and Song, the top quark is predicted not to exist (242).

^{*} Other hints in favour of a generation structure are that the net electric charge of a generation of fermions is zero, and the existence of a mass relationship between the bottom quark and the tau lepton (142).

below ~ 30 GeV) exactly (200,250); the $Z^0\gamma$ mode may well be the easier to use.

Also included in Table 7 is an incomplete list of predictions from specific models concerning the number of generations, as well as suggestions based on various general arguments.

The most stringent of these bounds comes from cosmology, which in fact relates to the number of species of light neutrinos (i.e. of mass ≤ 1 MeV^{††}). This number is constrained by the observed He/H ratio in the Universe to be $\sim 3-4$. Thus if each generation contains a light neutrino, then the number of generations is similarly limited. The only way out of this constraint could be if higher generations have heavier neutrinos, or if the cosmological numerology changes in the future, as it has occasionally done in the past.

If the discrepancy (201) in the observed and calculated solar neutrino fluxes is ascribed to neutrino mixing between the ν_e from the sun and the other types of neutrinos, then the total number of neutrinos species is 3.3 ± 0.7 , provided the neutrino mixing is maximal.

The asymptotic freedom argument is based on the way the strong coupling constant changes with energy:-

$$\alpha_c(s) = \frac{12\pi}{(33-2N) \ln(s/\Lambda_{QCD}^2)}$$

where N is the number of quark flavours. With more than 16 quark flavours, α_c would grow with increasing energy. Thus as we believe that

^{††} Other cosmological arguments (194) suggest that neutrino masses are below ~ 30 eV.

quarks behave as if they are approximately free particles in hard scattering processes at high energies, there should be 16 quark flavours; the restriction to 8 generations thus assumes that each generation contains two flavours of quarks. It is conceivable, however, that more generations exist with very heavy quarks, which do not participate in interactions at current energies. Thus at higher energies, we could enter a regime in which asymptotic freedom did not apply.

Several years ago, Kobayashi and Maskawa demonstrated that to accommodate the CP violating decay of the K^0 in terms of quark mixings required the existence of at least 6 quarks. Although the observed CP violation together with this assumption thus implies the existence of 6 quarks, it is at that level not apparent why it is necessary to have CP violations and why, for example, a 2 or 4 quark situation would be unsatisfactory. It is, however, possible to invoke the Anthropic Principle, which states that the Universe must contain those features necessary for our existence, which is an essential prerequisite for its observation. The existence of an excess of matter over antimatter in the Universe may have required, among other things, CP-violating processes in the early stages of the Universe⁽²⁰³⁾. Thus in order for the Universe to exist as we know it, at least 6 quark flavours may be necessary.

4.2.2 Generations in Composite Models

Models of quark and lepton substructure can be divided according to whether they

- i) try to explain only the first generation fermions, and regard the others as being produced by some other mechanism to be investigated later;
- ii) take the first generation fermions as given, and concentrate on explaining why repeated patterns of generations occur; or
- iii) attempt to explain all known fermions (and any still to be discovered ones) simultaneously.

Another difference is between models where higher generations are exact replicas of the first, and those where they differ in some way (e.g. they include exotic fermions, spins other than $\frac{1}{2}$, have right handed couplings, alternating signs of lepton number, are composite while the first one or two generation fermions are elementary, or do not couple to the first generation).

The most popular number of generations to "predict" seems to be 3, the number currently known. The discovery of more quarks or leptons beyond the t or τ would be embarrassing for such models.

One approach to the question of the number of generations in composite models is that it may be determined by the anomaly conditions (see section 4.1.13). Since a summation over composites is equated to that over the fermionic preons, a relation can emerge between the number of generations on the one hand, and some preon property (like the number of hypercolours⁽¹⁵⁰⁾ or the number of colours⁽⁴⁾) on the other. This of course leaves open the question of how the various generations differ from each other.

We now turn to the various suggestions that have been made to explain the generation structure. The idea that each new quark and lepton flavour of the higher generations could be explained by the introduction of a new preon type is inelegant and against the spirit of the substructure approach; there may also be a problem with explaining how composite weak bosons couple in a universal manner to the different fermions. Other mechanisms include:-

(a) Radial excitations.

The scale Λ on which fermions may exhibit non-point like behaviour is at least 1 TeV. If fermions indeed have substructure, then besides the ground state configuration, there can exist higher levels corresponding to radial excitations and to orbital angular momentum between the constituents. These generally will be of order Λ above the ground state*, and hence are too high in energy to explain the existence of higher generation fermions at excitations of order of 1 GeV. The only possibility for avoiding high masses would be if the $J=1/2$ excitations could be kept approximately massless by the mechanism discussed in 4.1.5. Radial excitations have been utilised by Greenberg (63), Kopper and Durr (255), Squires (115) and by Vijnjic-Triantafillou (202) as being responsible for higher generations.

Greenberg has also discussed the problem of producing at least 3 radial excitations before the first orbital one. In the non-relativistic case, it is difficult to reconcile this with a rapid

* However, Fried and Kang, invoking Messiah, claim that in a long range potential, excitations can exist at energies well below the binding energy (216). Kopper and Durr also can produce tightly bound states in an oscillating potential (255).

increase in mass with generation.

(b) Other excitations

The excitation models of Horgoh, Blaha and Kalman were discussed in section 3.5. Raitio (138) has suggested that gravitational excitations between preons could be responsible, Wu (173) has utilised S3 excitations in a 3 dyon system, while those suggested by Adler (117) are topological, and by Werle (263) are hydrodynamical.

(c) Generation component

Since higher generations look simply like heavier replicas of the first, many models of substructure have attempted to "explain" higher generation particles by incorporating a constituent which exists in (at least) 3 different varieties, and which distinguishes the generations. Thus Terazawa (110) uses constituents h_1, h_2, h_3 , Ne'eman (111) has s_1, s_2, s_3 , while Taylor (112) employs an ancestor component A carrying a family label. Koide (204) utilises h preons as does Terazawa, but leptons contain different $h_i h_j$ combinations while quarks contain $h_i \bar{h}_j$. A less arbitrary variant of this approach is to use the 't Hooft (and possibly other) constraints in order to restrict the number of preons, and hence generations (80, 280).

The alternative is to use just one type of generation component, of which n are to be found in the nth generation fermions. Thus Derman (130) and Veltman (147) utilise Higgs bosons to produce higher generations, while Fritsch and Mandelbaum (128) suggest that hypercolour gluons could be responsible.

In general this type of approach could accomodate an arbitrary number of generations.

(d) Other preons

An attractive idea is to use preons, which are already needed by the model, in order to build higher generations. Greenberg and Sucher⁽⁶³⁾ and Gonzales-Mestres⁽¹⁶⁹⁾ employ pairs of preons, while Harari and Seiberg⁽⁸⁶⁾ suggest using extra quartets of rishons ($\pi\bar{\pi}\bar{V}\bar{V}$), added to their first generation 3-rishon states (see section 4.4). Kobayashi's generation component is S^0 , which is a composite of 4 of his V preons⁽²⁴⁸⁾.

(e) Fine Structure

Some prescriptions for producing fermions result in degenerate states. By assuming that this degeneracy is removed by some interaction, a limited number of generations could be produced. This could involve a recoupling of the spins of the preons (as, for example, in the models of Kakazu⁽²⁰⁵⁾, Wu⁽²⁰⁶⁾, Wetterich⁽¹⁷⁰⁾, Yasue⁽¹⁵⁸⁾ and to some extent Gonzales-Mestres⁽¹⁶⁹⁾); models with composite fermions made of 3 or $\frac{1}{2}$ spin $\frac{1}{2}$ preons could result in 2 or 5 generations respectively by this mechanism. Alternatively it could apply to the spatial configuration of the composite state. Thus in the Salam approach⁽¹⁵⁶⁾ where fermions are made out of 3 different preons, a structure of 2 preons tightly bound with the third at larger distances could produce three generations. Luo and Yang employ 3 different preons ABC with identical properties; their 3 generations are ABC , $\bar{A}\bar{B}\bar{C}$ and $\bar{A}BC$ ⁽²⁵⁸⁾.

(f) Multiple states

A mechanism that generates masses for the fermions could produce a multiplicity of states. Terazawa⁽²⁰⁷⁾ has suggested that masses might arise as solutions of self-consistency equations for mass renormalisation.

Sogami's generations arise as independent solutions of a modified Dirac equation for composite states⁽²⁷⁶⁾.

The existence of generation components of a fermionic nature within composite fermions strengthens the idea that the number of fermions in each generation may be conserved. It may also be applicable in other models with a specific generation component. (It is less clear whether the idea would be useful in other models). We thus investigate the consequences of "Generation Number" and its conservation for quark and lepton reactions.

4.2.3 Flavour Conservation

In lepton physics, as well as the overall lepton number L , the individual lepton types e , μ and τ are separately conserved. The most striking evidence for this is the absence of reactions like

$$\begin{aligned} \mu &\rightarrow 3e \\ \mu &\rightarrow e\gamma \\ \mu N &\rightarrow e N \\ \text{and } \nu_{\mu} p &\rightarrow e p^* \end{aligned}$$

This can be restated by saying that the generation number is conserved,

* Although the experimental limit in this case is far less stringent than for the other processes, it was the non observation of this reaction⁽²⁰⁸⁾ which lead to the confirmation of the existence of the ν_{μ} , and to the idea of the separate conservation of the different lepton types.

i.e. the number of leptons within each generation is separately conserved for any reaction. No violation of this rule has yet been observed.

For the quark sector, in addition to baryon (or quark number) conservation, the separate quark flavours are individually conserved in strong and in electromagnetic interactions. [Charge conservation of course ensures that a certain linear combination of fundamental fermion numbers is constant in any reaction]. In neutral current weak interactions, individual flavours are conserved, but in charged current processes flavour changes are observed. These include reactions in which the charge change within a generation in the quarks is balanced by the opposite charge change (again within a generation) in the leptons.

$$\begin{aligned} \text{e.g. } d &\rightarrow u + e^- + \bar{\nu}_e \\ \text{or } c &\rightarrow s + e^+ + \bar{\nu}_e \quad \text{or } s \rightarrow u^+ + \nu_\mu \end{aligned}$$

Hence although individual flavours are not conserved, the net numbers of fermions in each generation are. In other weak processes generation changes do occur.

$$\begin{aligned} \text{e.g. } \Lambda &\rightarrow p \pi^- \quad (\text{or } s \rightarrow u \bar{u} + \pi^-) \\ \text{or } \Lambda &\rightarrow p e^- \bar{\nu}_e \quad (\text{or } s \rightarrow u \bar{u} + e^- \bar{\nu}_e) \end{aligned}$$

Such processes, however, are ascribed to Cabibbo mixing among the quarks, rather than to basic non-conservation of fermion generations separately. [Thus, somewhat curiously, despite the fact that baryon conservation is established much better than lepton conservation, the rule of the conservation of individual generations is stronger for leptons than for quarks].

We now wish to look at the problem the other way round i.e. which processes would be allowed by "Generation Conservation". But first we must decide how to choose the generation number of antiparticles.

4.2.4 Generation Number of Antiparticles

If we arbitrarily assign generation number +1 to the u, d, e^- and ν_e , what should the corresponding value be for the $\bar{u}, \bar{d}, e^+$ and $\bar{\nu}_e$? The possibilities are ± 1 .

The choice of -1 is clearly favoured by considering various reactions which are allowed or forbidden by the conservation of generation number with the two possibilities. This is done in Table 8. Thus although it may be possible to invoke arguments based on the masses of the mediating particles, it seems abundantly clear that the choice $G(e^+) = -1$ is preferable.

The most convincing argument, however, is that the choice $G(e^+) = -1$ is necessary if we wish to maintain the allowed or forbidden status of a given process as the particles are moved from one side of the reaction to the other. Thus the processes

$$\begin{aligned} \mu^- + e^- &\rightarrow \nu_\mu + \bar{\nu}_e \\ \text{and } \nu_\mu + e^- &\rightarrow \mu^- + \bar{\nu}_e \end{aligned}$$

are both allowed if the generation number of fermions and of anti-fermions are opposite, but the muon's only known decay mode would be generation-number forbidden if they were chosen as the same. This argument simply relies on the fact that quarks and leptons are fermions, and that generation number as we use it is an additive quantum number.

Thus we henceforth consider only the case of opposite generation numbers for fermions and their antiparticles, and tend to view with suspicion models in which the generation number component is the same for particles and antiparticles.

4.2.5 Generation Conservation

We here attempt to see the extent to which the concept of generation number conservation is equivalent to the various separate empirical conservation laws relating to fundamental fermion flavours. We defer consideration of baryon non-conserving processes till the end of this section.

For strong interactions, only quarks are involved. Then generation conservation (together with charge and baryon number conservation) allows reactions in which the net numbers of each quark flavour are individually conserved. In addition, processes like

$$s + u + c + d \quad (\text{e.g. } K^- p \rightarrow D^0 n)$$

are also permitted, but are difficult to distinguish from ordinary weak interaction processes. (A similar effect pertains in purely leptonic processes, like $\nu_\mu e^- \rightarrow \mu^- \nu_e$, which again can take place via weak interactions).

Electromagnetic processes involve real or virtual photons. Since these couple directly only to fermions plus their own antiparticle, electromagnetic reactions will trivially conserve generation number. We now turn to weak interactions.

If we assume that the 3 generation components are different (rather as Terazawa, Ne'eman and Taylor did), and that they differ for quarks and for leptons* (which they did not), then we reproduce the observed situation (disregarding Cabibbo-suppressed transitions). If, however, the generation numbers of the leptons and the quarks in the same generation are identical†, then we can expect interesting reactions which conserve the overall numbers of fermions of each generation, but which do not conserve the quarks and leptons of each generation separately. In models with specific generation components, these processes correspond to the exchange of such components between the quarks and the leptons. A list of some of these reactions is given in Section A) of Table 9. Experimental limits where known are quoted. The rate at which such reactions may be expected to occur depends on the unknown masses of the relevant mediating bosons. Estimates have been made for some of these reactions by Cahn and Harari⁽⁶⁰⁾ (who also consider the generation violating reactions discussed in section 2.5), by Kane and Thun⁽⁶⁹⁾ and by Zhu⁽⁷⁸⁾. Kobayashi⁽²⁴⁸⁾, Kuang and Tye⁽²⁷⁹⁾ and Veltman⁽¹⁴⁷⁾ have also commented on such processes.

Of the experimental numbers quoted, we should note that the limit of $< 2 \cdot 10^{-9}$ on $R_L^0 \rightarrow \mu^+ e^-$ was obtained in an experiment⁽⁷⁶⁾ which set a similar upper limit for the $\mu^+ \mu^-$ decay mode, which is substantially

* This is equivalent to having the numerical values of the generation numbers of d, s, b, e⁻, μ^- and τ^- being completely unrelated.

† In fact, all that is required is that the difference in generation numbers for quarks of different generations is the same as that for leptons of the corresponding generations. In all reactions apart from nucleon decays, the absolute values of the generation numbers of quarks and of leptons are irrelevant.

below the currently accepted value (75) of $(9 \pm 2)10^{-9}$. If we then disregard their limit for μ^+e^+ , the next best number is more than 2 orders of magnitude larger (77).

Concerning those cases where limits do not yet exist, it is conceivable that a dedicated experiment in the near future could investigate Σ^+ branching ratios down to the level of 10^{-7} to 10^{-8} (212), while current limits for rare branching modes are of order 10^{-3} to 10^{-4} (65).

Table 9 also contains (section B) a further list of reactions which would be allowed by overall conservation of generation number, rather than on the numbers of particles of each generation separately. This relies on the assignment

$$G_3 - G_2 = G_2 - G_1$$

where G_i is the generation number of the i^{th} generation fermions. This would apply in models where the second or third generation particles are obtained by adding 1 or 2 of the generation components to the first generation particles.

In section C) we list reactions in which the generation number, in addition to satisfying the above assumption, is conserved modulo 3. This could arise, for example, in the model of Harari and Seiberg (86) where generation number is associated with the axial charge X. This is measurable only modulo 12, and each generation is assumed to be produced by adding a 4 riskon combination with $\Delta X=4$ to the previous one.

It is clearly of interest to try to improve the experimental limits on these so far unobserved processes.

Finally we remark that the simplest nucleon decay involving first generation fermions which automatically conserves generation number is

$$n \rightarrow \nu_e \nu_e \nu_e$$

which is not the easiest of processes to observe. Other possibilities are

$$n \rightarrow \pi^+ e^- \nu_e \nu_e$$

which needs to be distinguished from $n \rightarrow \pi^+ e^-$,

$$p \rightarrow \pi^+ \nu_e \nu_e \nu_e, \text{ etc.}$$

For a general nucleon decay involving only first generation fermions, the change in generation number ΔG is given by

$$\Delta G = -(\Delta(B-L) + 4)g_1$$

where g_1 is the generation number assigned to first generation fermions*. Thus in order to conserve generation number in other possible nucleon decay reactions such as

$$p \rightarrow \pi^0 e^+, e^+ e^- e^+, e^- \pi^+ \pi^+, \text{ etc}$$

$$\text{and } n \rightarrow \pi^- e^+, \pi^+ e^-, \text{ etc}$$

it is necessary to assign generation number 0 to the first generation fermions. This would then allow both B-L conserving and violating decays, but would forbid $p \rightarrow \pi^0 \mu^+$, etc. Such an assignment of generation number, however, would make the ν_e and $\bar{\nu}_e$ interchangeable in any weak interaction process, and we regard this as undesirable. We conclude that as baryon decays have yet to be observed, and as such reactions would violate baryon and lepton conservation, it is probably not worth

* This assumes again that the quarks and leptons of each generation are assigned the same generation numbers. In the riskon model (86) there is an offset of the X-numbers (which are used to define generations) between quarks and leptons, but this model has difficulties in incorporating higher generation fermions in its picture of nucleon decay.

while to try applying generation number conservation to them. It goes without question to say that the observation of baryon decay processes would be of utmost interest, as is the question of whether any linear combination of B and L is conserved in such decays.

Baryon decay processes in composite models were also discussed in 4.1.10.

4.3 Summary of Current Models

In sections 4.1 and 4.2 we have discussed various features which are relevant to substructure models in general. Here we review very briefly some of the specific models recently proposed for quark and lepton structure.

Abbott and Farhi (123)

In this strong coupling confining $SU(2)_L$ model, the left-handed fermions are composite, while the right handed ones are elementary. The basic preons are 24 left-handed coloured and charged fermions ψ (equivalent to the quarks and leptons of the first 3 generations), and a boson doublet ϕ responsible for the weak interactions; the model is thus not economical in terms of the number of preons. The bound state fermions satisfy the 't Hooft conditions and acquire their masses from Yukawa couplings.

The weak interactions arise as residual effects of the hypercolour binding, and have the $SU(2)_L \times U(1)$ symmetry of the preons*. Abbott and

* Indeed Abbott and Farhi consider that models which discover symmetries at the bound state level which do not exist for the preons are incorrect.

Farhi show that this can reproduce the low energy phenomenology of the charged and neutral currents (including V-A character, universality and the absence of strangeness changing neutral currents). The weak interaction does, however, differ slightly from that in the Standard Model; this may enable the model to be tested.

The value of Λ is determined from the strength of the weak interactions to be in the few hundred GeV range[†]; thus direct observation of substructure effects can be hoped for in the near future. The intermediate boson spectrum starts above 100 GeV, with excited states at higher energies; the bosons are composites of pairs of the scalar preons and are broad resonances. With the asymmetry between right and left handed fermions, parity violation in strong interactions is expected.

In a more recent paper, a variant of the model with the scalar preon replaced by a fermion-antifermion pair is investigated (213).

Albright, Schrempf and Schrempf (214)

Albright et al apply the 't Hooft condition of anomaly matching to a composite theory based on $SU(3)_G \times SU(6)_L \times SU(6)_R$. By demanding that at least 3 generations with a $SU(3) \times SU(2) \times U(1)$ structure are produced, a unique solution is found involving 4 generations, of which 2 are standard, but the other 2 are unusual. Thus the 3rd and 4th families have the right handed quarks in $SU(2)_L$ doublets, the 4th set of quarks

† Such a small value of Λ may make it difficult to understand the lack of an observed substructure contribution to the muon's anomalous magnetic moment.

have electric charges $-1/3$ and $-4/3$, and the weak coupling of the 3rd and 4th generation fermions is V rather than $V-A$. This then leads to a prediction that the reaction $e^+e^- \rightarrow \tau^+\tau^-$, in contrast to the $\mu^+\mu^-$ final state, should have no forward-backward asymmetry. Albright also expects a rich spectrum of new exotic states around the mass of the W . These predictions are independent of the value of Λ .

It is suggested that the lepton numbers of alternate generations alternate in sign*. Then processes involving μ^+e^- conversions would be forbidden. For example, $\mu^+\nu_e$ should not be seen, while either $\tau^+\nu_e$ or $\tau^+\mu_\nu$ (depending on whether the τ is assigned as a 3rd or 4th generation fermion) would be allowed, although probably suppressed.

In order to compensate for the matched anomaly of the composite fermions and the preons, a set of spectator particles common to composite and preon levels is required. These are colour singlet objects whose charge and baryon number are identical to quarks*. The authors suggest that these could be what Fairbank is seeing in his search for fractional charge (11).

* This is not meant to imply that reactions, allowed by the modified lepton number being conserved, take place at the usual weak interaction rate. Thus decays like $\pi^+ \rightarrow K^+ \mu^+ \nu_\mu$ or reactions such as $\nu_\mu N^+ X$ are known to be suppressed at the level of ~ 0.1 to 1% of the usual reactions (72, 73, 209); while $\nu_\mu N^+ e^- N^+$ is less than 10^{-9} times the ordinary capture rate (70). Thus in order to be viable, in addition to this modified lepton number being conserved, lepton generation transitions must be either forbidden or else highly suppressed. In the former case, it makes no difference whether μ^+ and e^- have the same or opposite lepton numbers. If only a suppression operates, the new and the conventional lepton assignment can be distinguished, for example, by the observation of either $K^+ \mu^+ \nu_\mu \mu^+ e^+$ or $\pi^+ \mu^+ e^+$; $\tau^+ \nu_e$ or $\mu^+ \nu_e$; or $\mu^+ N^+ e^- N^+$.

Proton decay in this model is predicted to involve generation flip.

Ansel'm (124)

This is a model in which the $SU(5)$ 5 fermions are fundamental, but the decuplet fermions are composites of 3 left-handed fermionic preons called quintets, which belong to the $SU(5)$ 5 representation. Thus the left-handed electron (along with the left handed $\bar{d}$ and ν_e) is elementary, but its right handed partner is composite. Right handed composites are made of left handed quintets, and left handed composites from right handed anti quintets.

Combinations of 3 quintets can result in many exotic fermion combinations. Most of these, Ansel'm argues, are exactly massless (since it is impossible to construct valid mass generating terms for them), and since this may cause problems, they may be unobservable or non-existent. In order to balance the Adler anomalies between composites and preons, Ansel'm is left with 3 generations of fermions plus an unlimited number of charge $2/3$ quarks. The number of generations is equal to the number of hypercolours; they are produced by some unspecified form of excitation.

The substructure scale Λ is chosen as $\sim 10^{15}$ GeV, in order to prevent the proton from decaying too quickly. Then μ^+e^- occurs at an impossibly slow rate; $\mu^+\nu_e$ is forbidden. The left-right asymmetry of the model produces parity violation in strong interactions; because of the large value of Λ , this will presumably be very difficult to detect.

Barbieri, Maiani and Petronzio⁽⁶⁴⁾

The preons are left handed massless spinors $\chi_{i\alpha}$ where i and α go up to n and N respectively. The symmetry group of the spinors is $O(n) \times SU(N)$ and are referred to as metacolour (equivalent to hypercolour) and metaflavour respectively. Generations are formed by binding the hypergluons to a single preon to make hypercolourless states; in this way exactly n generations will be possible. If N were 16, then n must be at least 5 in order to maintain hypercolour asymptotic freedom; there would then be 5 generations. Three preon states may also be bound.

The substructure scale Λ is calculated to be at least 170 TeV, as deduced from the absence of $\mu\tau\tau$.

Barbieri, Mohapatra and Masiero⁽¹²⁹⁾

This is a variant of the Abbott and Farhi model⁽¹²³⁾, with both left and right handed fermions being composite. The preons are fermions F which are responsible for the weak interactions and scalars ϕ possessing colour and charge (compare Greenberg and Sucher⁽⁶³⁾). The F^u and F^d have charges $\frac{2}{3}$; the ϕ are a colour triplet of charge $1/6$ and a colour singlet of charge $-\frac{1}{3}$. The fermions are $F\phi$ composites.

The electroweak interactions are mediated by composite $F\bar{F}$ bosons, and correspond to a left-right extension of the standard model (since otherwise there are problems with anomalies). Parity violation is ascribed to a mass difference between the intermediate bosons coupling to the left and right-handed weak currents. The substructure scale Λ is

100-500 GeV, in order to reproduce the strength of the weak interactions.

The basic Lagrangian is locally invariant under $SU(4)_F \times SU(3)_C \times U(1)_{EM}$, where $SU(4)_F$ refers to the hypercolour binding interaction. By investigating possible dynamics for the model, Barbieri makes the following predictions.

- a) Right handed neutrinos exist in the mass range 10-60 GeV. These should enable neutrinoless double β decay to occur with lifetimes $\sim 10^{22 \pm 2}$ years.
- b) The left handed ν_e has a mass of 5-25 eV
- c) Assuming that at low energies the effective Lagrangian is dominated by the lightest composite bosons, Barbieri can make the weak interactions very similar to those of the standard model.
- d) A massless Goldstone boson (the Majoron) and several charged pseudo Goldstone bosons of mass ~ 10 GeV should exist.
- e) Explicit evidence for substructure should be seen in the 100-500 GeV range.

Bars⁽⁸⁰⁾

In a series of papers, Bars has considered questions relating to chiral symmetry breaking, and the emergence of generation structure in composite models. He has enlarged the 't Hooft conditions by enunciating 10 constraints which a 3 fermion preon model should satisfy. He has investigated all possible models in which the 3 preons can belong to different hypercolour representations, and finds only 4 models (called A B C and D) which satisfy all the conditions. Model A utilises

preons in two different hypercolour representations, and has up to 8 generations; the others have each preon in a different representation and accommodate 4 generations. By utilising a different preon in quarks and in leptons, Bars does not have the problem of proton decay. The selection rules for other flavour changing processes are different for the various models; observation of $K_L^0 \rightarrow \pi^0 \mu^+ \mu^-$ or $K^+ \rightarrow \pi^+ \mu^+ \mu^-$, a substructure contribution to the $K_L^0 \rightarrow \pi^0 \mu^+ \mu^-$ mass difference or $D^0 \rightarrow \pi^0 \mu^+ \mu^-$ mixing could help distinguish between them. Bars also claims that the rate for $\mu \rightarrow e \gamma$ is proportional to $m_\mu^5 m_e^2 / \Lambda^6$, and hence this process will be difficult to observe (and will lower the limit on Λ to below 1 TeV).

An intrinsic feature of these models is that parity violation in strong interactions should occur at energies approaching Λ .

Within model A, there exist exotics (neutral colour sextets and charged octets, and charge 4/3 colour triplets). If these are not too heavy, they could contribute dramatically to the value of R_{ee} . They could conceivably bind in hadrons and hence could be responsible for the fractional charges possibly seen in quark search experiments⁽¹¹⁾.

Bars' preons carry electroweak charges, and he sees no need for the weak bosons to be composite.

As in many other substructure models, the number of preons exceeds the number of composite fermions.

Casalbuoni and Gatto (150,186)

In an extensive series of papers, these authors have adopted a group theoretic approach to investigating possible substructure models. Because of doubts⁽¹⁹³⁾ about the validity of the Appelquist-Carrasone constraint, they have given it up, and replaced it by the requirement that models should ensure that the proton is sufficiently stable, even with a substructure scale in the region 1-100 TeV. They have investigated the problem of assigning baryon and lepton numbers consistently to the preons and to the composites. Their models include various possibilities for the hypercolour group, including $SU(n)$ (where $n=3,4,7$ or 9) and $O(15)$ and $O(17)$; the number of preon hypercolours and the number of quark flavours (or equivalently generations) are related.

Various candidates emerge as possibilities for constructing the composites. An early version made the left handed $\bar{\nu}_d$ u and e^+ out of χ , $a\chi$, $aa\chi$ and $aaa\chi$; χ is an uncharged fermion with $B-L=-1$ while a is a colour antitriplet with charge 1/3 and $B-L=2/3$. [The corresponding right handed particles have structures $\chi b a a a$, $\chi b a a$, $\chi b a$ and χb , where b has charge -1, $B-L=0$ and is colourless]. A more recent suggestion has spinor preons ψ of charge $\pm \frac{1}{2}$, and baryon and lepton number 1/4, and scalar preons ϕ with charge -1/6 and baryon and lepton numbers -1/12 and 1/4 respectively; quarks are $\psi\bar{\psi}$ composites and leptons are $\psi\psi\psi$.

Derman (130) and Veltman (147)

Here the n^{th} generation is supposed to arise from binding n Higgs bosons onto the fundamental preon quartet (U, D, E and N). Since the Higgs is neutral with respect to weak, electromagnetic and colour

interactions, different generations have similar quantum numbers and couplings.

Derman estimates the Higgs mass to be about 10 TeV and the fermionic preons as ~100 GeV; Veltman guesses that the substructure scale Λ is in the few hundred GeV range. In either case, substructure effects should be apparent soon.

The neutrino masses are expected to be non-zero, and neutrino mixing can occur⁽¹³⁰⁾.

Since the Higgs binding is strong, the HH composites could be light. This could be a problem for the model.

The exchange of the Higgs scalar between fermions could result in generation exchange processes discussed in section 4.2 e.g. $K \rightarrow \mu e$ or $\nu_\mu d \rightarrow e \bar{c}$. Higgs decay could lead to processes which violate generation number conservation, such as

$$u \rightarrow e + H + e \gamma \gamma$$

Veltman estimates that the expected rate for this is still below the current experimental limit⁽²¹⁵⁾. He also mentions that above a few TeV, the Higgs itself may be composite.

The potential between a massive fermion and a Higgs scalar has been investigated in more detail by Fried and Kang⁽²¹⁶⁾.

Finally it should be noted that Veltman himself regards this picture as "a very crude model" rather than a serious attempt to describe fermion substructure. He uses it as an educational device for discovering the sort of problems (e.g. with respect to flavour changing

processes) that arise in trying to solve the generation problem in terms of substructure.

Durr and Saller(167)

This work is motivated by Heisenberg's search for a unified quantum field theory of elementary particles. The basic field is a single 4-component Weyl isospinor spinor χ . Durr emphasises that this is a field rather than a particle, since particle number has no meaning in relativistic theory. The basic invariance group is $U(1)_F \times SU(2)_I$, referring to fermionic number and isospin respectively; larger symmetry groups could arise at the composite level. Leptons and quarks are XXX and $XX^* \chi$ composites. The gauge fields and Goldstone bosons are generated dynamically, but composites with spin larger than 2 do not occur. It is hoped that properties like hypercharge and colour arise as structural symmetries at the composite level, rather than being properties of the fields themselves. A unique parameter-free Lagrangian is written down, and can be reduced at the composite level to a form like that of the Standard Model of weak interactions.

It is difficult to obtain testable predictions from the model.

Ellis, Gaillard and Zumino(139)

These authors investigate an $N=8$ extended supergravity approach, in which gravity is included with the other interactions in a supersymmetric theory. A problem with such a model is that, although the basic multiplet of the $N=8$ theory is large and contains objects of spin up to 2, there is still no room in it for the μ and τ leptons, the

b quark or the vector boson W. Ellis et al follow the suggestion of Curbwright and Freund(217) that the elements of the original N=8 supermultiplet are to be taken as preons rather than as quarks, leptons, etc. The graviton may be composite, or it may be the spin 2 preon. The compositeness of fermions and gauge bosons is an output of supergravity theories, rather than input as in most other models.

In some mysterious way, the theory contains a concealed local SU(8) symmetry(218), which Ellis Gaillard and Zumino assume will be spontaneously broken at energies not far below the Planck mass to an SU(5) grand unified group. Many composite states can be constructed, but by devising a prescription for discarding many of these, Ellis finds that the remaining ones correspond to 3 generations of fermions.

Thus the model predicts that fermions (as well as gauge bosons and Higgs scalars) are composite, that the Grand Unified Theory is SU(5) and that only 3 generations exist. Unfortunately our understanding of supergravity dynamics is such that Derendinger Ferrara and Savoy, also studying N=8 supergravity, are able to use a different set of criteria to decide which composites remain approximately massless; they deduce that the number of generations should be even(140).

A further discouraging feature is that the scale of Λ is the Planck mass, so direct observation of substructure effects is out of the question. The proponents of supergravity models, however, consider that the theory is so beautiful and all embracing that Nature would have been ill-advised to ignore it in choosing the fundamental theory.

Fritzsch and Mandelbaum (128)

This is a fermion plus boson preon model. The fermions α and β are colour 3 of charge $\pm\frac{1}{2}$; the bosons x and y are colour 3 and 3 of charge $\frac{1}{6}$ and $-1/2$ respectively. The composite u and d are $\alpha\beta$ and βx ; the electron and its neutrino are αy and βy . Weak interactions are the Van der Waals type residual effects of the hypercolour binding interaction, with the W^+ boson being an $\alpha\beta$ composite. In order to obtain the correct strength of the weak interactions, the substructure scale Λ is ~ 300 GeV.

Higher generations may occur as excitations involving extra hypergluons. In that case decays like $\mu \rightarrow e \gamma$ could occur via a hypergluon $\rightarrow \gamma$ transition. Such processes then need to be suppressed by, for example, an analogue of Zweig's rule(219).

In the Standard Model, mixing between the photon and the weak neutral current arises from spontaneous symmetry breaking; here, in contrast, it is related to the strength of the γ - W^0 transition. This occurs via a process where the W^0 constituents annihilate. Then $\sin^2 \theta_w$ is related to the wave function at the origin of the W^0 , and hence to its size. The experimental value of $\sin^2 \theta_w$, according to Fritzsch and Mandelbaum, then determines the size of the W to be $\sim (M_W)^{-1}$, which they consider to be somewhat small*. For models of this type, they also claim that in order for $\sin^2 \theta_w$ not to be vanishingly small, it is necessary for the intermediate boson to be composed of only two

* Most hadrons have radii r a few times larger than their inverse mass m^{-1} . The only exception is the pion for which $r \sim m^{-1}$, rather as in Fritzsch and Mandelbaum's estimate for the neutral boson.

constituents. The constituents should also be fermions; with bosonic preons, the W needs one unit of orbital angular momentum, which makes $\sin^2 \theta_w$ too small (contrast the model of Abbott and Farhi).

Following Kogerler and Schildknecht(266), Fritzsch et al have investigated whether the experimentally observed equality of the couplings of the weak interaction current to different quark and lepton doublets would be expected in a composite situation. A specific but model independent current algebra approach is used to show that this universality follows from the assumption of the dominance of the lowest lying W poles. In that case the masses of the lightest vector bosons agree with the predictions of the Standard Model.

The Fritzsch and Mandelbaum model predicts that exotic states should exist. For example, colour sextet quarks and colour octet leptons could occur below 50 GeV. Because of the W and Z having hypercolour constituents, excited states should exist at $\lesssim 500$ GeV, and the Z^0 can couple to hadronic channels such that its width could be as large as 10-20 GeV (as compared with ~ 2.4 GeV as calculated conventionally(200)). The masses of the W and Z , however, can agree with the predictions of the Standard Model.

Robinet(274) points out that scalar bosons composed of $\bar{\chi}\chi$ could induce $K_L^0 \rightarrow \mu e$ transitions. The absence of this mode sets a limit of > 8 TeV on the mass of such a boson.

With Λ so small, direct observation of substructure effects can be hoped for soon. For example, since electrons contain constituents with colour, e^+e^- annihilation reactions will start looking like typical

hadronic interactions and the cross-section will become constant at $\sim \Lambda^{-2}$, rather than exhibiting behaviour typical of a one photon intermediate state with a $1/s$ dependence of the cross-section. The excitation of colour octets and sextets should show up dramatically in e^+e^- annihilations at even lower energies.

Gonzalez-Mestres (169)

This model makes quarks and leptons out of 3 fermion-antifermion combinations, with the binding provided by an $SO(3)$ hypercolour. There are two different fermionic preons ψ_1 and ψ_2 of charge $2/3$ and $1/3$ respectively. The electron and its neutrino are given as $\bar{\psi}_1\bar{\psi}_1\psi_2$ and $\psi_2\psi_2\bar{\psi}_1$ respectively. The up quark can be $\psi_1\psi_1\bar{\psi}_1$ or two different combinations of $\psi_1\psi_2\bar{\psi}_2$; the down quark is $\bar{\psi}_2\bar{\psi}_2\psi_2$ or $\bar{\psi}_2\bar{\psi}_1\psi_1$ (twice). The intermediate bosons are combinations such as $\psi\bar{\psi}$ or $3\psi_23\bar{\psi}_2$, $\psi_1\psi_2\psi_2\bar{\psi}_1\bar{\psi}_2$, etc. By adding a $\psi\bar{\psi}$ combination to the first generation, (more than) enough quarks and leptons to form the second generation are produced. The third generation could also be found in $3\psi_2\bar{\psi}$ states; or it could be part of $4\psi_2\bar{\psi}$ combinations. Composites with exotic quantum numbers are possible, and are presumed to be heavier than the known fermions.

This model is very like that of Wetterich(170). Luo and Yang(258) also employ a similar idea.

Greenberg and Sucher (63)

The preons of the Greenberg and Sucher approach are a spin $\frac{1}{2}$ flavour doublet F of charges $+2/3$ and $-1/3$; a neutral scalar antitriplet of colour C ; and a lepto scalar S of charge $2/3$. The first generation quarks are then $F\bar{C}$, while the corresponding leptons are $F\bar{S}$. Higher generations could be produced by adding extra $\bar{C}\bar{C}$ or $S\bar{S}$ pairs. Alternatively, generations could correspond to radial excitations. This, however, may give rise to a conflict, at least if the problem is considered non-relativistically. If the preon potential is written as $\sim r^a$, then the requirement of at least 3 generations (radial excitations) occurring before the first orbital one (which could result in spins of $3/2$ for the composites) implies that $a < -3/2$; while a spectrum growing rapidly in mass with increasing generation number implies a being large and positive*.

Greenberg and Sucher assume that the weak interactions arise as residual effects of the preon binding force, in much the same way as strong interactions between hadrons are related to QCD. Then the intermediate bosons (and the Higgs scalars) are $F\bar{F}$ composites. The photon and gluons could be either fundamental or composite. Other possible preon combinations (such as $\bar{C}\bar{S}$ $C\bar{S}$ etc.) are assumed to lie high in mass.

It is stressed that the successful calculation of a mass spectrum for a preon model will be a crucial test of the substructure approach; this could even precede the direct observation of quark and/or lepton

* Kopper and Durr attempt to overcome this problem by using an oscillating potential in order to fit the charged lepton spectrum.

form factors. A list of problems connected with the mass spectrum of composites is discussed.

The $SU(N)$ preon binding interaction could become unified with the $SU(3)_C$ interaction at very high energies. Another possibility is that, since the model contains both fermionic and bosonic preons, supersymmetry may be relevant.

Harari and Seiberg (86)

This is a dynamical extension of the Shupe and Harari models, and is considered in detail in section 4.4.

Kakazu and Matumoto (205,149)

Kakazu and Matumoto look for a preon model in which the electroweak interactions are associated with only one type of charged preon w , and the other preons are neutral. With the left-handed w s being an $SU(2)_L$ doublet, they must have charges $2/3$ and $-1/3$. The other preon is a colour anti-triplet neutral fermion c . The up and down quarks are then ccw combinations, while the electron and neutrino are $\bar{w}_1\bar{w}_1\bar{w}_2$ and $\bar{w}_1\bar{w}_2\bar{w}_2$. The first two generations of leptons may correspond to two linearly independent chiral configurations of $\bar{w}_1\bar{w}_2$; a similar possibility may apply to the cc pair in quarks. Further generations probably require some form of excitation.

Testable predictions for this model await the introduction of dynamics.

Matumoto⁽¹⁴⁹⁾ has also attempted to produce a reasonable hierarchy of masses to compare with the generation structure of observed quarks and leptons. To achieve this, he uses technicoloured preons and a Harari-Seiberg type structure for generations (see section 4.4), except that it is the third generation which is chosen as the 3-preon state with lower generations containing extra sets of preon combinations. His composites obtain masses via condensates of technibosons (in contrast to the usual technifermion condensates); this helps Matumoto avoid $K^0-\bar{K}^0$ transitions happening at a rate above the experimental limit.

It remains to be shown in this approach why only 3 generations produce low mass composites.

Kim and Song⁽²⁴²⁾

This model unifies the electroweak and colour interactions with $SU(3)$ hypercolour preon binding* in an $SU(8)$ gauge model, derived from an $SO(8)$ extended supergravity; the hypercolour scale is in the few TeV region. The $SU(5)$ decuplet quarks and leptons are kept as elementary, but the 5 fermions are composites of 3 fermionic preons; this is in contrast with the assignments of Ansel'm⁽¹²⁴⁾. In Kim and Song's model, there is no top quark.

As a result of the left hand leptons being composite and the right handed ones being fundamental, the substructure contribution to the anomalous magnetic moments of the leptons is expected to be small, even

* As well as the other articles of ref.288, Casalbuoni⁽¹⁵⁰⁾, Derendinger⁽¹⁴⁰⁾, Ellis⁽¹³⁹⁾, Krolikowski⁽¹⁴⁵⁾, Macrae⁽²²⁰⁾ and Rosa^(88,232) also deal with unification at the preon level.

for low values of Λ . Decays like $\mu \rightarrow e \gamma$ are similarly suppressed. Another prediction is that nucleon decays always give rise to left handed positrons or μ^+ . The model also requires 187 pseudo Goldstone boson of masses > 40 GeV.

Krolikowski^(145,146)

Krolikowski has investigated a QCD model of fermions, in which the preons are a fermion f and a boson b , both of charge $-1/3$ and both being colour triplets. The up and down quarks are $f\bar{b}$ and $\bar{f}(bb)$, while the electron and its neutrino are $f(bb)$ and $\bar{f}\bar{b}$ respectively; here (bb) denotes a P-wave boson pair. The weak interactions are residual effects of the extended composite states, with the W vector boson being $b(bb)$ and the Z being $b\bar{b}$ and $f\bar{f}$. The Higgs too could be $b\bar{b}$ and $f\bar{f}$ scalars. Exotic leptons and colour triplet weak bosons (somewhat of a contraction in terms) are predicted, and some supersymmetric-like partners of the composite fermions can be produced by interchanging b and f .

With heavy preons, a Coulomb-like binding potential can be arranged to give zero mass for the composite neutrino, but the masses of the other fermions could cause problems.

The proton is expected to decay to $e^+ \bar{\nu}_e \bar{\nu}_e$, although the rate is arbitrary.

With the same QCD interaction responsible for the binding of preons in fermions and of quarks in hadrons, Krolikowski suggests that the differences between the colourless leptons and the colourless hadrons must be related to their different compositions.

Krolkowski and Pokorski⁽¹⁴⁶⁾ have considered a scheme for unifying flavours and generations at a lower energy than flavours and colours. Their tentative choice for the generation symmetry group is a chiral SU(3), with the first generation being a singlet and a further 3 forming a triplet. The first generation fermions could remain uncoupled to those of higher ones. Thus processes like $\tau^+ \mu^+ \mu^+ e^-$, $\nu_\mu \beta^- e^- c$ or $\bar{\nu}_\mu \tau^+ \mu^+ e^-$ would not take place, while others such as $\bar{w}^+ \tau^+ \tau^- \mu^+$ could. (Here w^- is the fourth generation charged lepton). In that case the limits suggested in section 2.5 for the bosons mediating flavour changing processes would not apply, since at present they all involve first generation leptons.

Macrae (220)

This is a group theoretic approach. Macrae assumes the existence of 4 generations and then places the complete 64 component fundamental spinor, consisting of 16 entries for each generation, in a Spin(14) representation. This includes a Spin(4) interfamily symmetry. This approach is said to lead naturally to a constituent model with only 4 4-state (or 8 2-state) constituents.

Maki (157)

In this approach, the rishons of the Shupe-Harari picture are themselves composite objects of a Dirac field Λ and a scalar θ , each of charge 1/6. Thus the T is a $\Lambda\theta$ composite, and the V is a 7θ . The relevant gauge group is taken as $SU(3)_C \times SU(3)_F \times SU(2)_D$, where the last factor is a colour interaction, responsible for binding the θ and Λ

into the rishons. Maki takes the Λ as a colour triplet, hypercolour singlet, while the θ is a colour singlet, hypercolour triplet; both are colour doublets. The scale of the interactions is such that

$$\Lambda_C \ll \Lambda_H \ll \Lambda_D$$

Maki expects that exotic $\Lambda\bar{\Lambda}$ and $\theta\theta$ states could be below 1 GeV in mass, and could complicate the search for glueballs. The $\theta\theta$ combination could perhaps be responsible for producing generations; by attaching a $\theta\theta$ combination in turn to each rishon of the 3 rishon composite states, perhaps 3 excited generations could be produced.

Mansouri (221)

An approach based on an SO(10) Grand Unified Group is used by Mansouri. He uses 5 fermionic preons $b_1 \dots b_5$ and their antiparticles. Quarks and leptons are 5 preon composites, containing either b_i or $\bar{b}_i$ for all 5 values of i . The preons obey only Abelian U(1) symmetries. Mansouri claims that the quantum numbers of the b 's can be assigned uniquely in order to reproduce the known $2^5=32$ first generation states (including antiparticles and two helicities). Thus the charges of the b 's are (1/6, 1/6, 1/6, 0, -1/2), B-L is 1/3 for the first 3 and zero for the last 2, whose third components of weak isospin are $\pm 1/4$.

The composite left handed up and down quarks are $[b_1 b_2 \bar{b}_3] b_4 \bar{b}_5$ and $[b_1 b_2 \bar{b}_3] \bar{b}_4 b_5$ respectively, where $[b_1 b_2 \bar{b}_3]$ denotes that the antiparticle of any one of the first 3 preons is involved. The left-handed electron and its neutrino are $\bar{b}_1 \bar{b}_2 \bar{b}_3 b_4 \bar{b}_5$ and $\bar{b}_1 \bar{b}_2 \bar{b}_3 b_4 b_5$. Spin 3/2 and 5/2 states are excluded by assuming that the spins of the b 's tend to be antiparallel, with only the last b 's spin remaining unpaired.

Generations could be produced by assuming the existence of two extra bs (b_6 and b_7) with quantum numbers identical to b_4 and b_5 respectively. It is assumed that, in analogy with atoms and nuclei, a shell structure exists; in this case 5 bs form a stable configuration. Then by allowing the last pair of bs to be b_4b_5 , b_4b_7 , b_6b_5 or b_6b_7 , 4 generations could be produced. Presumably the generation containing b_6b_7 is least like that involving b_4b_5 , and its coupling to it will be weakest.

Gauge bosons and Higgs scalars are also assumed to be composite.

Apart from its treatment of generations and its choice of symmetry group for the preons, this approach resembles that adopted by Yasuè (158).

Montvay (153)

If Λ is taken as $>10^{14}$ GeV because of possible constraints from the proton lifetime, unifying the hypercolour preon interactions with colour, whose scale parameter $\Lambda_c \sim 0.1-1$ GeV, may present difficulties. Montvay attempts to avoid this problem by generalising a model of Casalbuoni and Gatto, such that the hypercolour group is changed from $SU(3)$ to $U(m)$, where m is odd. Quarks and leptons then become composites of m fermionic preons. A group theoretic approach to unification then suggests that m may be 5 or 7.

Pati (144,152,156)

Pati (144) raises the possibility that the binding force between preons could be magnetic in origin, with the preons carrying magnetic as well as electric charges. [This would violate parity and time reversal invariance; such effects should become apparent at energies comparable with Λ . The motivation for such an argument is that, according to Pati, electric forces cannot be strong enough at short distances to bind the preons, unless there are considerably more preons than composite fermions; such a possibility is aesthetically unpleasing. Since the magnetic charge is larger than the electric one, magnetic binding could be strong enough to produce composite states. Pati does, however, acknowledge that hypercolour would be a possible substitute for magnetism as the origin of preon binding.]

With a model like the early one of Pati et al (107) utilising a doublet f , 4 coloured preons c and a spurion s , it is possible to assign magnetic charges such that only fcs combinations are magnetically neutral and can produce fermions as 3 preon composites. [For example, the f c and s can be assigned charges 1, 3 and -4 respectively]. Spin $\frac{1}{2}$ zero composites could be Higgs scalars, and magnetically charged spin $\frac{1}{2}$ composites could play the role of technifermions. The basic Lagrangian of the preons may obey a $U(1)_E \times U(1)_M$ symmetry.

Pati Salam and Strathdee (156) describe a variant of this model in which the $U(1)_E \times U(1)_M$ charges carried by the preons are only analogous to electric and magnetic charges, but not identical to them. These analogue charges for the f c and s could be, for example, $(0,0)$ $(0,h)$ and $(-g,-h)$ in order to have only fcs combinations neutral in both

charges. It is suggested that a single primordial gauge boson couples to both g and h , and that the photon, gluon, weak bosons and perhaps even the graviton are composite. A further unusual suggestion is that f , c and s could all be scalars with the angular momentum $\frac{1}{2}$ of the composite states being associated with the field of g and h ; alternatively and more mundanely the preons could be fermions.

If the composites consist of a preon pair core with a less tightly bound third preon, 3 generations could perhaps be produced by the different possible choice of preons for the core (fc , fs or cs). Generations could alternatively arise from a series of different generation preons s_i . Higgs scalars can be composites of an even number of preons. There can also be $f\bar{f}$, $c\bar{c}$ and $s\bar{s}$ vector states which could produce forward-backward asymmetries in $e^+e^- \rightarrow \mu^+\mu^-$ or $q\bar{q}$ reactions.

It is conceivable that the preons, carrying 2 basic charges g and h , are themselves composites of even more elementary objects which each carry only one charge. This gives rise to the idea of a whole series of preons, pre-preons, etc. each with its own substructure scale, and leading eventually perhaps to very basic "monotheistic" entities.

Pati Salam and Strathdee⁽¹⁵²⁾ also favour the idea that the preons (or pre-preons) may be fields of a supersymmetric theory. Perhaps a single supersymmetric multiplet can be used to build composite preons, with flavour and colour arising only at the preonic level.

Raitio (138)

In an attempt to incorporate gravitation into the realm of particle physics, Raitio builds composite quarks and leptons from maxons, which are heavy fermions of about the Planck mass. The composite scale is thus $\sim 10^{16}$ TeV. Maxons have charges of $1/3$ and zero, and are colour triplet and singlet respectively; they are bound in composites by gravitation. QCD interactions, electromagnetism and gravitation remain exact gauge theories, with the gluon, photon and graviton being massless; weak interactions in contrast are merely maxon rearrangement processes.

Higher generations could arise as gravitational excitations. Then processes like $\mu \rightarrow e + X$ or $c \rightarrow u + X$, where X is a photon or gluon, would not occur because the gravitationally excited states would not emit electromagnetic or strong interaction bosons. In contrast, since the Z^0 is a gravitationally bound state, weak decays can change generations, and hence produce non-zero Cabibbo-like mixings. Apart from the weak bosons, other 6 maxon states should include doubly charged bosons, which Raitio expects to have mass of order 200 GeV.

Apart from the binding mechanism, the model of Squires⁽¹¹⁵⁾ resembles this one.

In a subsequent paper, Lehto and Raitio describe an alternative scheme in which the maxons are massless, and carry technicolour and hypercolour with a binding scale of ~ 100 TeV. The weak interactions are now gauge interactions. In order to satisfy the 't Hooft consistency constraints and for the model to possess asymptotic freedom, Lehto and

Raïtio favour a left-right asymmetric theory.

Shaw and Slansky (222,223,245)

This is an attempt to unify the electroweak and colour forces with those responsible for preon binding; thus neither colour nor the electroweak interactions are regarded as merely effective low energy composite interactions. The group investigated is E6 which contains SO(10) and U_1^c , where the latter is the preon binding mechanism, mediated by a single vector boson. The alarmingly prolific fundamental fields are 78 gauge bosons, 27 left handed fermions and 78 scalars. The 27 fermions include an SO(10) 16 representation, which is identified with the first generation quarks and leptons i.e. these fermions are elementary. Higher generations arise as composites of the fundamental fermions and the fundamental scalars. Many such states are possible. Shaw and Slansky assume that the most tightly bound are those with the most negative products of the U_1^c charges. They thus identify 2 more SO(10) 16s as 2 further generations, and a 144 representation containing a 4th generation and many exotic fermions (such as colour sextet and octet quarks, and doubly charged leptons). The existence of the members of the 144 representation is required in order to make the U_1^c interaction, with its large coupling constant at high energies, unify with the electroweak and colour interactions. These extra states are expected by Shaw and Slansky to lie not too far above the 3rd generation fermions.

Recently Shaw and Daghighian (245) have modified this to an SO(14) model in which both the first and second generations are elementary;

this implies that the limits on the anomalous magnetic moments of the electron and muon are irrelevant as far as the substructure scale Λ is concerned. The spectrum of predicted new composite states is even richer than in the E6 case.

In an earlier model (223), Shaw suggested that the first four flavours of quarks q are elementary, and further flavours could be produced by combining them with a colour octet uncharged boson α bearing a new quantum number which would also be carried by the q_α composite quarks. Bound states $\alpha\bar{\alpha}$ and $q_\alpha q_\alpha$ could also exist. This model was advanced as providing an alternative to the b quark for understanding the T resonance region. Although this version is ruled out, Shaw points out that if more quarks are found it could be resurrected by considering that more than 4 flavours are fundamental and the remaining ones composite.

Squires (115,184)

The motivation for this model, like several others, was to use compositeness to remove the need for Higgs scalars, and to make weak interactions the residual effect of preon hypercolour binding. In the earlier paper, Squires uses T and S preons, which are equivalent to the Shupe-Harari T and V , except that the T is a colour triplet. Thus colour is a preon property rather than arising as a composite effect. Subsequently Squires opted for the S being a colour $\bar{3}$ rather than his original colour singlet; these are then identical to the Harari-Seiberg preon assignments. Squires states that higher families could arise as radial excitations, and presumes that these too can be almost massless

for much the same reason that the first generation fermions are.

Squires investigates the Appelquist-Carrazzone condition for his model in the limit that the colour coupling can be neglected compared with the preon hypercolour binding; this is a question on which Harari adopts a different viewpoint. Squires finds that the light composite states include the first family of fermions, but also many other states.

The difference in the QCD and hypercolour spectra is pointed out. In the former, pseudo scalars (e.g. pions) are lighter than vectors (ρ , ω , etc.) which in turn are lighter than fermions (baryons). In contrast, composite fermions (quarks and leptons) are lighter than vectors ($W^\pm$, Z^0), while the identity of composite pseudoscalars is as yet uncertain.

Recently Squires has reconsidered the weak interactions as residual hypercolour effects. In the ribbon model (see sections 3.4 and 4.4), the neutral vector bosons can be $\pi\pi$ or V_0 . It is then rather natural to find that there exist 2 almost degenerate Z^0 's (compare the ρ and ω in QCD), whose splitting Squires expects to be not more than 10 GeV. It is possible to reproduce the low energy phenomenology of the Standard Model for neutral current interactions. Squires notes that it remains to show why the charged vector bosons have predominantly left handed couplings, and why their masses are small compared to Λ (which Squires favours as being very much larger than 1 TeV).

Proton decay in preon models has also been discussed by Squires (see section 4.1.10).

Tanikawa and Saito (224)

This is a composite model in which quarks and leptons are built out of a fermion f and a boson b . The fermions have charge 0 and -1; the bosons are a neutral colour singlet with lepton number 1, and a charge $2/3$ colour triplet with baryon number $1/3$. The bosons also exist in 3 different varieties for the 3 generations.

The weak interactions are assumed to arise at the composite level from preon exchange duality diagrams. For example, the reaction

$$\bar{\nu}_\mu u + \mu^+ \bar{d}$$

can be viewed as being mediated by a series of W boson ($f_i \bar{f}_j$) exchanges in the t channel; or by a series of lepto quarks ($\bar{b}_i b_j$) in the s channel. Tanikawa and Saito assume B_4 amplitudes⁽²³³⁾ for such processes, and then predict that scaling violations will be observed, that Regge type behaviour will appear at high energies and that the neutrino and antineutrino cross-sections will eventually become equal.

If their individual preons are stable, proton decay and generation changing reactions need not occur.

Terazawa (110,207,225-231)

The original Akama and Terazawa model⁽¹¹⁰⁾ built composite fermions out of 3 types of preons, a weak isodoublet w_i , a colour quartet c_j and a generation preon h_k . In a series of papers, Terazawa and his collaborators have subsequently investigated how such a model (or instead a fermion + boson structure for the composites) can have dynamics incorporated.

Terazawa has considered unified models of all forces including gravitation, in which bosons are $q\bar{q}$ or $f\bar{f}$ composites. An alternative to this approach is one where unification is achieved at the level of the preons.

By assuming a suitable Lagrangian for the preons, the model (227) can be made equivalent to a Yang Mills approach for colour, and to the Weinberg Salam model for the electroweak interactions; the Weinberg angle is predicted as

$$\sin^2 \theta_w = \frac{1}{4(Q^2 + (Q-1)^2)}$$

where Q is the charge of the first w . The intermediate bosons and Higgs mesons are $w\bar{w}$ composites. The Higgs mass M_H is then predicted to be related to the boson $w^\pm$ and preon w masses by

$$M_H \sim \frac{2}{\sqrt{3}} M_{w^\pm} \sim 2 M_w$$

This then implies that the production of free (or perhaps confined) preons in e^+e^- annihilations should be possible not far beyond the 2° mass region; this is reminiscent of the production of charm mesons just above the ψ mass. The production of preons at such a low energy may be in conflict with some of the limits on the substructure scale given in Table 5.

Photons and gravitons are considered as composite too. The the photon mass need not be zero. Gravitation arises as an effective interaction (228), and is almost equivalent to Einstein-Weyl general

relativity. With the suitable choice of the sign of a parameter, gravitation can be made attractive (although it could alternatively have been made repulsive). Terazawa and Akama claim that the model explains why the cosmological constant is so small. The theory requires a short-distance cut-off which is in the neighbourhood of the Planck mass.

The unknown preon dynamics should determine many of the properties of the composite fermions. These properties can thus give some clues to the dynamics. Terazawa considers, for instance, that in order for the composite systems to obey the Dirac equation, the preon dynamics is probably non-linear and non-local (230).

Composite masses should also give information concerning preons. In particular the rapid rise of mass with generation number should be a relevant hint (229). The fact that the first generation fermions are so light leads Terazawa to suggest that they might be Goldstone fermions of a supersymmetry.

Quark mixings are also related to preon dynamics (229). In substructure models, Terazawa finds it natural that the Cabibbo-Kobayashi-Maskawa mixing angles should decrease with increasing mass difference between the quarks. It is also expected that these angles should be functions of momentum transfer. Terazawa also discusses the magnetic moments and the axial charges of composite fermions, as well as more direct experimental signatures of possible substructure.

As an alternative idea to generations corresponding to different preons h_k , Terazawa raises the possibility that they may correspond to

different solutions of a self-consistency equation for renormalised masses⁽²⁰⁷⁾. The particular scheme investigated seems to allow an odd number of generations, which contrasts with Terazawa's previous prediction of 6 generations, based on the mean mass of preons as deduced from the G - α relation of his unified model; a variant of the idea could probably result in an even number.

Thus a wide range of consequences of compositeness have been investigated. Many of these seem to be relevant for a broad class of substructure models. The real test of the Terazawa picture, however, will come when the region above the Z^0 is investigated in e^+e^- collisions to see whether (free or confined) preons can be produced.

Tosa and Marshak (88,232)

By imposing the constraints that

- a) no spin $\frac{1}{2}$ exotics exist;
- b) there are no anomalies in the strong and electroweak sectors; and
- c) there are equal numbers of quark and lepton generations,

Tosa and Marshak find that composite models (of either the 3 fermion or the fermion + boson type) with more than one generation cannot be constructed, if the preons' symmetry is $SU(3)$ for colour and either $SU(2)_L \times U(1)$ or $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ for the electroweak interactions. With $SU(4)_C \times SU(2)_L \times SU(2)_R$, however, they find that the 3 fermion type model can produce 3 generations, after the effect of the Pauli Principle is included. The hypercolour group is F_4 . Their model allows $n-\bar{n}$ oscillations, but proton decay does not occur. Their philosophy is that the gauge picture of weak interactions is too beautiful to spoil by

making the vector bosons composite or the weak interactions residual effects of substructure.

Tosa has also attempted to unify a grand unified group of QCD and the electroweak interactions with a generation group. The only possibility is to have higher generations as repetitions of the first, which Tosa believes hints at substructure.

Visnjic-Triantafillou (202,148)

This is a model (202) in which the composite fermions are made of a fermion and a boson which are heavy. The n^{th} generation fermions correspond to the n^{th} $s_{\frac{1}{2}}$ state; in order to obtain 3 radial excitations before the first orbital one, a potential of the form $V-r^\alpha$ would require $\alpha < -3/2$. Visnjic-Triantafillou assumes that the potential's parameters can be tuned in order to produce light composite states; this may be a sign of some underlying symmetry, but whether it can also be done successfully for the radial excitations is less clear.

With the composite wave function written as

$$\psi = \psi_I \psi_i,$$

the radial parts ψ_i are assumed to be orthogonal for the different generations, and approximately identical for the different flavours; while the internal wave functions ψ_i are orthogonal for the different flavours but identical for the different generations. This then results in no flavour changing neutral currents*, but produces non-zero Cabibbo-Kobayashi-Maskawa mixing angles.

* Greenberg and Sucher⁽⁶³⁾ and Terazawa⁽²²⁹⁾ also deal with the suppression of these processes.

In a subsequent paper with Bardeen⁽¹⁴⁸⁾, Vissic-Triantafyllou considers that his boson and fermion preons could initially be massless particles of a supersymmetry. Spontaneous symmetry breaking could then produce massless bound states as Goldstone fermions (in contrast to the usual Goldstone bosons of a non supersymmetric theory). This is a novel suggestion for keeping the composite fermions approximately massless; some of the problems of this approach have been mentioned by Reskin⁽⁴⁾. Low mass spin 3/2 states are avoided as these cannot be Goldstone particles.

Dynamical symmetry breaking can result in the preons becoming massive while the bound states remain massless (compare models where the light Goldstone pion is made from pairs of heavy nucleons). The heavy preons then need not be confined, and hence could be produced as free particles in interactions at high enough energies. A dramatic rise is expected at these energies in the elastic scattering cross sections for composite fermion-fermion scattering, as well as for reactions like $e^+e^- \rightarrow \mu^+\mu^-$, $\tau^+\tau^-$ or $q\bar{q}$, and for $q\bar{q} \rightarrow \bar{q}l$. Perhaps strong production of lepton pairs in $\bar{p}p$ collisions could be the first indication of compositeness.

Wetterich (170)

The preons of this model are two spin $\frac{1}{2}$ particles, P_1 and P_2 , of charge $+1/3$ and $-2/3$ respectively, forming an isospin doublet. The leptons are then constructed as ppp and the quarks as $\bar{p}\bar{p}\bar{p}$, except that Wetterich considers that the composite states can also contain extra $p\bar{p}$ pairs. Exotic quarks of charge $+5/3$ and $-4/3$ and leptons of charge -2

or $+1$ should also exist. Four normal generations can be produced by the various spin and isospin couplings of the preons; a further 5 unusual generations (with weak isospin 1 and/or spin 5 not equal to $1/2$) are also expected. Gauge bosons are considered to be made of composite fermion pairs, or equivalently as 6p states.

The value of $\sin^2\theta_w$ calculated for this model is 9/20.

Wetterich speculates that perhaps P_1 and P_2 can be identified with the $\bar{d}$ and $\bar{u}$ quarks respectively. Then for example the composite u (which was $P_1\bar{P}_1\bar{P}_2$) becomes $\bar{d}du$, while the neutrino would be $\bar{u}\bar{d}\bar{d}$.

This model bears a strong similarity to that of Gonzales-Mestres, with his ψ_1 and ψ_2 becoming Wetterich's $\bar{P}_2$ and P_1 .

Yamawaki and Yokota (254)

There are 3 types of massless preons c , w and t , which carry colour, electroweak and technicolour interactions respectively. Their charges are $1/12$, $\pm 1/2$ and $-1/4$ respectively; the c have baryon number $1/6$ and the t lepton number $1/2$. Quarks are ccw composites and leptons are ttw ; the binding mechanism is hypercolour.

The approximate masslessness of the composite states is assured by discrete $U(1)_A$ symmetries associated with the conservation of the difference in numbers of left and right handed preons of each type. Different chiral combinations of each type of fermion can be constructed*; these are taken to correspond to different generations.

* This is along the lines of the suggestion by Kakazu (205) for producing 2 generations.

Other composites of 3 preons include exotics and technifermions; condensates of the latter could be responsible for giving non-zero masses to the quarks and leptons (compare ref.(243)).

Conservation of c preons would result in the proton being stable.

Difficulties of the model include the fact that $K^0-\bar{K}^0$ mixing is allowed, and the necessity to exclude the many unwanted states.

Yasue (158,261)

Starting with a model in which quarks and leptons are built of a boson W and a fermion c , Yasue introduces a further level of substructure so that both W and c are composed of spin $\frac{1}{2}$ "subkomas" s . The W consists of two subkomas and c of 3, making the observed fermions $5s$ composites. Each s can exist in two states s and $\bar{s}$ (denoted by $\uparrow$ and $\downarrow$). Then

$$u_i = W_1 c_i \quad d_i = W_2 c_i \quad e^- = W_2 c_0 \quad \text{and} \quad \nu = W_1 c_0$$

where the subscript i on the quarks and on c is a colour index. In terms of subkomas

$$\begin{aligned} c_0 &= \uparrow\uparrow\uparrow & c_1 &= \uparrow\uparrow\downarrow & c_2 &= \uparrow\downarrow\downarrow & c_3 &= \downarrow\downarrow\downarrow \\ W_{1L} &= \uparrow\uparrow & W_{2L} &= \uparrow\downarrow & W_{1R} &= \uparrow\uparrow & W_{2R} &= \uparrow\downarrow \end{aligned}$$

Each of the 5 subkomas in a composite fermion is attached to a specific "site" i.e. the ordering of the subkomas is significant. The first two sites refer to the W , the last 3 to the c . The charges of the $\uparrow$ subkomas are $(1/2, 0, -1/6, -1/6, -1/6)$; those for the $\downarrow$ subkomas are opposite.

The symmetry of this model is $SO(10)$. The symmetries of the W and c are $SO(4)$ and $SO(6)$ respectively; they are derived from the $SU(2)^n$ symmetries of the n subkomas from which they are constituted. The subkomas are bound into fermions by an $O(5)$ hypercolour force; $SU(2)$ and $SO(3)$ forces are also required to produce W and c preons.

Since the W and c are 2 and 3 subkoma composites, they could have spins of 0 or 1 and $1/2$ or $3/2$ respectively. Yasue speculates that the different spin combinations of W and c could combine to give 5 spin $\frac{1}{2}$ generations.

Yasue also discusses the masses of quarks and leptons, in a model where he chooses a Lagrangian at the W and c level, both of which are assumed to have mass M . This results in the Weinberg angle θ_w and the strong coupling constant α_c being given by

$$\begin{aligned} \sin^2 \theta_w &= 3N_g / 2(4+3N_g) \\ \text{and} \quad \alpha_c &= \alpha(4+3N_g) / 6 \end{aligned}$$

where N_g is the number of generations; for $N_g=2$, θ_w and α_c agree with the predictions of $SU(5)$. The model possesses approximate chiral symmetry, with the composite quarks and leptons acquiring mass from the composite Higgs scalars. The upper limit on the Higgs mass translates into M being below ~ 5 TeV. On the other hand, the experimental value of the anomalous magnetic moment of the muon requires M to be above 30 GeV.

The spontaneously generated composite fermion masses are expected to be less than about 5 GeV. One problem is that the quarks and leptons are degenerate; another is that there is no mechanism for the different generations to acquire different masses.

4.4 The Harari-Seiberg Rishon Model

We saw earlier (section 3.4) how the Shupe-Harari model provided an economical description of the first generation quarks and leptons, but left open many dynamical questions. Harari and Seiberg⁽⁸⁶⁾ have ambitiously attempted to remedy this defect, and we shall now see the way in which this has changed the original picture.

The Shupe-Harari idea of generating quark colour from order permutations of the different rishons has been replaced by giving colour directly to the rishons themselves^{*}; the T and V are assigned as colour 3 and $\bar{3}$ respectively. Furthermore it is assumed that the rishons also carry hypercolour, and it is the hypercolour interactions which are responsible for binding the rishons R into quark and lepton composites. The T and V are hypercolour triplets, while the "observed" quarks and leptons are hyperwhite; this then forbids composites such as RR, RR $\bar{R}$, etc. Thus the 8 first generation fermions are now built out of 18 (rather than the previous 2) rishons. Other suggestions concerning colour in the rishon model have been made by Sogami⁽²⁷⁶⁾ and by Jarvis⁽²⁸²⁾.

Higher generations were first assumed to be due to an extra RR combination, which could give up to 9 generations. More recently, Harari and Seiberg assume that it is the rather inelegant $\bar{T}\bar{T}\bar{V}$ combinations which produce the heavier fermions[†]. Since an axial charge

* Thus the colour TV model has replaced the earlier black and white picture.

† Kobayashi⁽²⁴⁸⁾ has criticised this mechanism on the grounds that if a similar effect occurred in colour SU(3), many exotic quarks would result.

X=1 is associated with each of these rishons, and X is conserved modulo 12, such a scheme could produce 3 generations in all. Thus no new rishons are needed in order to explain the higher generations. It will be interesting to explore further the consequences of this procedure for producing generations. (Does an isolated $\bar{T}\bar{T}\bar{V}$ system have low mass? Will generation exchange processes be discovered? Can mixing matrices be calculated? Must generations have distinct X values? Is generation number defined only modulo 3?). Other approaches to generations in the rishon model have been discussed by Gelmini⁽²³⁵⁾, by Achiman⁽²⁷⁵⁾ and by Sogami⁽²⁷⁶⁾.

The fundamental Lagrangian describing the rishons is assumed to be locally gauge invariant under the group $SU(3)_C \times SU(3)_H \times U(1)_{EM}$, where $SU(3)_C$ and $SU(3)_H$ refer to colour and to hypercolour respectively. These interactions have characteristic energies Λ_C and Λ_H respectively, with $\Lambda_H \gg \Lambda_C$ defining the scale of the composite structure. The gauge bosons (gluons, hypergluons and the photon) are assumed to be massless and elementary^{*}. However the intermediate vector bosons can be composite, and the weak interactions of quarks and leptons are viewed as Van der Waals type residual effects of the short range hypercolour interactions (cf Abbott and Farhi, Fritzsch and Mandelbaum, Greenberg and Sucher, and Squires), rather as the strong interactions between composite hadrons are the residual effects of QCD interactions among the quarks. At the composite level, the effective Lagrangian acquires a $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ symmetry; this is the left-right extension

* The graviton is massless too, but Harari and Seiberg do not include gravity in their model (see, however, ref.(166) which considers a graviton made of rishons, with gravitation existing only at the composite level).

of the Standard Model of Weinberg and Salam. Thus at some stage, the effect of the right handed currents should make themselves apparent in weak interactions; for example, neutrinos should have a mass of order m^2/M where m and M are the masses of the corresponding charged fermion and of the right handed weak boson respectively. Furthermore since the intermediate weak bosons are composite, there could be more than one of each type.

The structure of the rishon model is such that the Weinberg angle is predicted as $\sin^2 \theta_w = 1/4$. This applies at an energy Λ_H which need not be in the range of 10^{15} GeV required by Grand Unified Theories. Indeed Harari and Seiberg claim that such theories are a mirage beyond a non-existent desert, in that the fundamental electromagnetic interaction cannot be unified with the Van der Waals type weak interaction, which appears only at the composite level; at energies $> \Lambda_H$, weak interactions do not exist. If Λ_H were of the order of 10^2 TeV, $\sin^2 \theta_w$ would be modestly renormalised to 0.23 at present energies, and be consistent with experiment.

An attractive idea is that scalar condensates of quark or lepton pairs may form, and these could play the role of Higgs particles: they could provide masses for the fermions (and for the weak bosons too) via dynamic symmetry breaking effects. [The rishons themselves are assumed to be massless, and chiral symmetry is invoked in order to protect them from acquiring masses of the order of the composite scale Λ_H]. Thus it is not necessary to introduce any fundamental scalars, with all the associated arbitrary parameters, into the model.

Interesting effects arise in considering the fermion wave functions in terms of the rishons. In order to satisfy Fermi statistics, the leptons cannot have $J=3/2^+$. Then the right handed positron is

$$e_R^+ = (T_L^+ T_L^+) T_R$$

where the combination in brackets is spinless. The masslessness of the rishons is an essential ingredient in this argument. If the u_L is chosen by analogy as

$$u_L = (T_L^+ T_L^+) V_L,$$

then the $\pi^0 e^+$ decay mode of the proton is forbidden. The proton can then decay only by higher order processes. This is desirable in that the measured limit on the proton lifetime is consistent with a value of Λ_H lower than $\sim 10^{15}$ GeV (and hence keeps alive the hope that substructure effects will actually be observed). The model then predicts that $\Delta(B-L) \neq 0$ processes could be the dominant nucleon decay modes, and the proton lifetime need not be as predicted by Grand Unified Theories**.

A drawback of the model is that it allows composite fermions in colour representations other than singlets and triplets***. This

* This in fact motivated the colour and hypercolour assignments of T and V , and so is a constraint on the model, rather than a prediction from it.

** The fact that direct observation of substructure may become possible soon, while the proton lifetime could be too long to be measured, simply demonstrates that it is difficult for a single theory to encourage all experimentalists simultaneously.

*** Quarks can be colour 3 , $\bar{6}$ or 15 , and leptons 1 , 8 or $\bar{10}$. Gelmini(235) utilises these as being the valence rishon content for the 3 generations; one or more colour gluons or rishon pairs are also included in the higher generation composites in order to reduce the net colour of these quarks and leptons to 3 and 1 respectively.

problem is swept aside for the time being by assuming that for any set of quantum numbers, the simplest colour representation has the lowest mass. The discovery of colour sextets would provide support for the model (as well as having a fundamental influence on particle physics in general).

The Harari Seiberg choice of Lagrangian for the rishons possesses two extra global $U(1)$ symmetries associated with an axial current Y and with the V rishon number. The breaking of these symmetries at the composite level requires the existence of two Goldstone bosons x and y , which are massless if the rishons are. The x is expected to couple only to neutrinos and is effectively unobservable, but the y could contribute to energy losses in stars*.

The model leaves open some fundamental questions. These include the origin of the $SU(3)_C \times SU(3)_H \times U(1)_{EM}$ symmetry, with its 3 independent coupling constants; and many problems associated with the masses of the composites. Some criticisms of the model are mentioned at the end of this section.

The model does have some testable consequences, which are mostly not particularly specific to the rishon picture. Thus

- a) Quarks and leptons should exhibit substructure at energies approaching Λ_H , whose value is unspecified but could be $10^{2 \pm 2}$ TeV.
- b) More than one composite weak boson of each type could exist, and right handed currents should be observable at some level.

* Very few of my colleagues saw the joke in this paragraph, so the published version has the two blanks replaced by 's'.

- c) Neutrinos should have non zero masses.
- d) The proton lifetime need not be 10^{31} years.
- e) Integer charged quarks and fractional charged leptons must not exist, but colour exotics could. Quarks must exist in flavour pairs; the world cannot appear topless.

There are further predictions, which Harari and Seiberg regard as dependent on their specific choice of options within the rishon model, and hence more amenable to modification if they prove incorrect. These include the proton decaying via $(B-L)$ violating modes, the properties of the Goldstone boson x , and the consequences of the mechanism for producing generations.

It thus appears that, as with other substructure models, it will be difficult to find a definitive experimental test of the rishon approach.

We conclude that the attempt to incorporate dynamics into the rishon scheme has resulted in a considerable complication of the original version. Even including the higher generations, the 21 known fermions are composed out of 18 rishons; there are also 17 elementary bosons (gluons, hypergluons and the photon). Thus the original motivation of explaining the large number of known particles in terms of a few fundamental ones has been given up.

What then has been achieved? Some of the phenomenology of quarks and leptons has been replaced by assumptions concerning the rishons and their interactions. This includes the weak interactions (entailing the compositeness of the intermediate vector bosons, and the existence of those coupling to right handed fermions), and the absence of spin $3/2$

and other exotic composites. A pleasing feature of the model is that it has the potential to replace Higgs bosons with internally generated scalar condensates which could produce the right sort of hierarchy of fermion and boson masses. In common with other substructure models, it has also raised a large number of interesting questions concerning mass generation in composite systems. The model has in fact become an exercise in self-consistency: is it possible to build a composite model for fermions without becoming involved in contradictions? It is to the credit of Harari and Seiberg that as yet no insuperable problems have arisen, even if some of their solutions appear to be inelegant*.

Finally we mention some approaches to the rishon model used by other authors. The strongest criticism is Okun's, who draws attention to the following(187):

a) It is curious that the chiral symmetry of colour $SU(3)$ is broken, while that of hypercolour $SU(3)$ is maintained (i.e. quarks and leptons are approximately massless on the relevant mass scale, whereas hadrons are not). More precisely, in the limit that the colour coupling constant α_c can be ignored** at the substructure scale Λ , the rishon model does not satisfy the 't Hooft conditions, and hence hypercolour chiral symmetry is presumably broken.

b) The experimental equality of the axial couplings of the charged and neutral weak currents appears as an accident in the rishon model if

* We have, however, previously mentioned that Nature's view of elegance may differ from ours.

** It has already been remarked that Harari considers that this is not possible.

the Z^0 is $\bar{u}u + \bar{v}v$, while the W is a six rishon state.

c) Perhaps the coloured fractionally charged bosons $\bar{u}v$ and $\bar{v}u$, which can mediate proton decay, should have similar masses to the Z^0 . In that case, the proton lifetime would be many orders of magnitude too small.

d) The colour sextet quarks should, according to Okun, be not much heavier than ordinary quarks. They would have very characteristic signatures, and certainly do not exist at masses below ~ 17 GeV.

A partial answer to the problems of the 't Hooft conditions mentioned in a) above has been provided. Squires(115) investigates the possibility of satisfying the Appelquist-Carrazone constraint, and King(154) looks at the anomaly restrictions. Both, however, assume that the $SU(6)_L \times SU(6)_R$ symmetry of the model in the $\alpha_c=0$ limit is somehow broken to $SU(3)_L \times SU(3)_R$; a plausibility argument for this has been given by King(234). These questions have also been studied by Chou and Xuan-ben(284).

King(154,234) points out that the Harari-Seiberg-Mohapatra approach(87) has difficulties with proton decay when more than one generation of fermions is considered. Bars(80) criticises the rishon model on the grounds that it does not satisfy his 10 constraints.

Squires has considered neutral vector bosons(184) and Heuson gravitons(166) in terms of rishons. Elbaz(236) and Gelmini(277) have provided pictorial approaches to the model. The questions of the possible unification of hypercolour with other interactions(280) and the magnitude of the Cabibbo angle(283) have also been investigated.

It is clear that the rishon model is sufficiently interesting for its difficulties to be considered in detail.

5. The Future

5.1 Models

The number of known quarks, leptons and gauge bosons has increased in recent years. This proliferation has been overtaken by the explosion in the variety of models used to interpret their possible compositeness. While there is evidence that some of the models possess a common substructure, as yet all the experimental data on quarks and leptons is consistent with them being pointlike. Deducing limits on the substructure scale is often model dependent; at present it seems that $\Lambda > 100-1000$ GeV. Models have Λ in the range from several hundred up to 10^{19} GeV.

In the absence of any other experimental indication of substructure, theoretical speculation appears to be unrestricted. It is premature to attempt to choose from among all the current models which (if any) may eventually prove to be correct. The only criteria available at present are aesthetics and consistency; the latter involves both internal self-consistency, and consistency with the known limits from the non observation of possible reactions and decays. Models which do not attempt to make dynamical predictions, however, appear to be untestable.

It turns out that the requirements of consistency do impose severe constraints on models. In particular the problem of constructing

composite fermions which are almost (but, except possibly for neutrinos, not quite) massless has opened up a whole new field of theoretical activity. The unfortunate outcome is that models of substructure become rather complicated. This usually results in the necessity for a large number of preons⁽²⁷⁾. The motivation for suggesting fermion substructure (that their number was uncomfortably large) has thus been discarded; many models currently have more preons than composites.

At least those models that have low values of Λ have, however, added an air of respectability to experimental searches for quark and lepton substructure.

5.2 Experiment

With increasing energies now or soon to be available in e^+e^- , $p\bar{p}$, $p\bar{p}$ and perhaps e^-p collisions, we can hope in the near future for experimental data that would encourage or rule out ideas relevant to substructure.

Data that would exclude certain models

Several models predict that the number of fermion generations is 3. While this agrees with the currently known number, the discovery of a fourth generation would exclude these models, at least in their present form.

The value of the substructure scale Λ , according to some models, is as low as a few hundred GeV. If this is so, direct effects of substructure should become apparent in the near future. Failure to

observe these would imply that these models should be rejected, or at least would need to revise their estimates of Λ . A similar remark applies to specific models with higher values of Λ , but which predict rates for unobserved processes (e.g. $K^0 \rightarrow \mu e$ or $\mu \rightarrow e \gamma$) not far below the currently observed limits; unfortunately most of these models contain arbitrary suppression factors which can be adjusted to explain continued non observation of a reaction.

The actual observation of substructure would inevitably result in many models being rejected. Null results, however, will in contrast have but little effect in restricting the variety of speculation.

Observations that would be indicative of substructure

The most convincing evidence would be the observation of free (or even confined) preons. The experimental signatures of such events are worthy of more detailed consideration.

The other strong indication could come from evidence for fermion form factors. The simplest reactions to study are probably $e^+e^- \rightarrow q\bar{q}$ or $\mu\mu$. We can hope for these experiments to explore the region in Λ up to about 1 TeV at the end of this decade.

One of the major aims of composite models is to find a convincing mass generation mechanism which yields a mass formula for quarks and leptons. The future discovery of new quarks and leptons in agreement with such predictions would also be encouraging. The mere discovery of one or more further generations would increase the historical and psychological arguments in favour of compositeness.

Other predictions common to many composite models, and suggestive of compositeness, include excited quarks and leptons, exotic fermions, a spectrum of intermediate weak bosons and a breakdown of $e-\mu-\tau$ universality.

There are other features which, while being predicted by and encouraging for composite models, are not specific to them. These include generation interchange processes (like $K \rightarrow \mu e$, or $\tau \rightarrow \mu e$), right handed weak currents, non-zero neutrino masses and prolific lepton production in hadronic interactions.

5.3 Conclusion

In the last few years, the field of fermion substructure has been one of great theoretical activity, relatively unhampered by experimental data. We can hope that the future will bring some experimental evidence for substructure. This would then transform the motivation for the subject from Psychology, History and Sociology to Physics.

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TABLE 1 Comparison of Different Composite Models of Basic Structure

Composite	Matter	Atoms	Nuclei	"Elementary" Particles	Quarks and Leptons
Substructure	Atoms	e ⁺ Nucleus	Nucleons	Quarks	Preons
When	1860	1910	1920	1965	1990
Substructure observed	Atoms manifest in kinetic theory	Electrons universal	p known, n subsequently discovered	Partons apparent in hard scattering processes	Not yet
Classification of Composites	None	Mendele'ev	(A,Z) plot	SU(3) singlets, octets and decuplets only	Generation structure?
Mass formula	Gay-Lussac	Integral masses	Integral masses	-Excitation spectrum	None yet
Structure of composites	6.10 ²³ atoms per gm mole	e=1.....100	N~P, P=1.....100	3q or q $\bar{q}$ only	3 fermions or fermion + boson?
Excited states of composites	None	Many known; explained by Bohr	Many known. Played no role in development of substructure	Important for revealing SU(3) structure.	Generations? No orbital or radial excitations yet observed.
No of substructure elements initially	~20	Electron + nuclei	2 (p+e ⁻)	3	2? (T+V)
No of substructure elements to-day	~100	Electron + nuclei	>>100 elementary particles	15 quarks + 6 leptons + 8 gluons + vector bosons +	18 (T+V) + γ + gluons + hypergluons??
Early problems		Why don't atoms radiate?	e ⁻ cannot be in nucleus	1) Wrong statistics of quarks 2) Quarks not observed	1) Massless composites 2) Generations
Resolution of problems		Quantum Mechanics	Replace e ⁻ by neutron	1) Colour 2) Confinement?	?
Energy scale	1 eV	10 eV	10 MeV	1 GeV	> or >> 1 TeV
Binding Force	Van der Waals (residual E.M)	E.M	Strong (residual colour)	Colour	Hypercolour?
Motivation for substructure	Variety of known substances. Chemical combination mass law	Electrons universal Excited states of atomic spectroscopy	Mass formula	Too many "elementary" particles	Too many quarks
"Proof" of substructure	Kinetic theory Measurement of atomic sizes	Rutherford expt. implies point-like sub-structure	Radioactive transmutations and nuclear reactions	Spectroscopy. Scattering expts. indicate point-like sub-structure	None yet

Table 2

Quarks, Leptons, Etc.

Fermions

	Quarks	Leptons
1st Generation	$u_R, u_B, u_G, d_R, d_B, d_G$	e^-, ν_e
2nd Generation	$c_R, c_B, c_G, s_R, s_B, s_G$	μ^-, ν_μ
3rd Generation	$(t_R, t_B, t_G), b_R, b_B, b_G$	τ^-, ν_τ

The subscripts RGB refer to the 3 colours of quarks.

Bosons

Name	Number	Star Rating	Mediates
Photon	1	****	Electromagnetism
Graviton	1	**	Gravitation
Gluon	8	***	QCD (qq strong binding)
$W^\pm$	2	**	Charged Current Weak Interactions
Z^0	1	**	Neutral current weak interactions
Higgs	>2	*	Mass generation
X, Y	Several	*	Baryon decay

Star rating **** = observed as free particles

*** = probably observed as confined particle

** = believed responsible for known interaction

* = hypothesised

Table 3

The Past, Present and Future of Quark-Lepton Parallelism

Past	Discoveries of quarks and leptons
Present	Spin $\frac{1}{2}$ $e_e = 3e_d$ Triangle anomaly cancellation Universality in electro-weak interactions
Future	Quarks and Leptons in Same Multiplet Grand Unification of Strong and Electroweak Interactions Baryon & Lepton Number Conservation violated together Masses of Quarks and Leptons Related Common Substructure

Table 4

Early Papers Relating Quarks and Leptons

Reference	Model	Consequences
Y.Hara (15)	$e^- \mu^- \nu_e$ and ν_μ analogues of 4 fundamental baryonic fields responsible for 8-fold way	
J.C.Pati (18)	q and λ in same multiplet $SU(4)_L \times SU(4)_R \times SU(4)'$ Lepton number is 4th colour	Composite model of basic fermions Multibody proton decays $K^0 \rightarrow \mu e$
G.R.Kalbfleisch (16)	Variety of Han-Nambu model with leptonic and hadronic quarks $(\Delta^{++} = \bar{u}^0 u^+ e^+)$	ν from K decay and from π decay are different
E.Nowak (17)	Leptons bind to universal hadronic core b (Proton = $b \nu_e \bar{\nu}_e$)	Proton stable $R_{ee} = 4+n$ (n = no. of generations) $K^0 \rightarrow \mu e$
H.Georgi (19)	q and λ in same multiplet of $SU(5)$	$\sin^2 \theta_W = 3/8$ $K^0 \rightarrow \mu e$ $p \rightarrow \pi^0 e^+$

Table 5 Limits on Substructure (in TeV)

Limits from the non observation of the specified processes on the substructure scale of the various fermions, or to the masses M_B of the possible bosons which could mediate the reactions. (The bosons required are different for the different processes). These limits should be treated with caution; the assumptions involved in their derivation are discussed in the text.

	Magnetic Moments	$e^+e^- \rightarrow \ell^+\ell^-$, $\gamma\gamma$	R_{ee}	Structure fns	$\mu \rightarrow 3e, e\gamma$, etc	$K \rightarrow \mu e$	$K \rightarrow \bar{K}$	Proton decay
e	.02 or 10^3	0.17	0.2	0.01	10^2 or 10^8			
μ	.6 or $4 \cdot 10^3$	0.12		0.08	10^2 or 10^8			
τ		0.10			1 or $2 \cdot 10^3$			
ν_e				0.07				
ν_μ				0.07				
u	$\sim 10^{-3}$	} 0.2						
d	$\sim 10^{-3}$							
s	$\sim 10^{-3}$							
c								
b								
M_B					10 or 100	20	~ 400	$\sim 10^2$ or 10^4 or 10^{12}

Table 6

(a) Values of MR for different levels of substructure

Particle	M (GeV)	R (cms)	MR
Quarks and leptons	~ 1	$< 10^{-16}$	$< 10^{-2}$
Proton	1	10^{-13}	5
Nucleus A	A	$A^{1/3} 10^{-13}$	$5A^{4/3}$
Hydrogen atom	1	10^{-8}	10^5
Positronium	10^{-3}	10^{-8}	10^3

(b) Upper limits on MR for quarks and leptons

Particle	M (GeV)	Lower limit on R^{-1} (TeV)	MR_1^*	MR_2^*
e	$0.5 \cdot 10^{-3}$	0.2^{**}	$2 \cdot 10^{-6}$	10^{-6}
ν_e	$< 0.5 \cdot 10^{-7}$	0.07^+	10^{-9}	10^{-10}
μ	10^{-1}	0.6^{++}	$2 \cdot 10^{-4}$	$2 \cdot 10^{-4}$
ν_μ	$< 0.6 \cdot 10^{-3}$	0.07^+	10^{-5}	10^{-6}
τ	1.8	0.1^{**}	$2 \cdot 10^{-2}$	$3 \cdot 10^{-3}$
ν_τ	< 0.3	-	-	$5 \cdot 10^{-4}$
u	0.3	0.2^{**}	10^{-3}	$5 \cdot 10^{-4}$
d	0.3	0.2^{**}	10^{-3}	$5 \cdot 10^{-4}$
s	0.5	0.2^{**}	10^{-3}	10^{-3}
c	1.5	0.2^{**}	10^{-2}	$3 \cdot 10^{-3}$
b	5	0.06^{**}	10^{-1}	10^{-2}

* MR_1 is for individual limits on R; MR_2 for a common $R^{-1} > 0.6$ TeV

** From e^+e^- reactions

+ From νN reactions, interpreted in terms of a ν charged radius or a form factor

++ From $g-2$, interpreted as $O(M/\Lambda)^2$

Table 7 Number of Generations

Type	Source	Ref	N_g	Comments
General	Cosmology	194	3-4	Number of ν with $m < 1$ MeV
	Asymptotic Freedom	195	< 8	
	C-P violation	196	> 3	
	Anthropic Principle	197	> 3	
	$m_b - m_t$ relation	142	3	
	Family recurrence relation	198	3, 4 or 1000	
	Terazawa	227	6	From G-u relation
Specific Models	Harari-Seiberg	86	3-9	Extra $\bar{R}\bar{R}$ or $\bar{R}\bar{R}\bar{R}$ combinations
	Gelmini	235	3	Colour structure of rishon model
	Phillips	155	5, 8, 11,	
	Barbieri	64	> 5	
	Ellis	139	3	From N=8 supergravity
	Derendinger	140	Even	From N=8 supergravity
	Mansouri	221	1, 4, 9, 16,	
	Sogami	276	4	Modified Dirac eqn.
Experiment	Currently observed		3	Assuming t quark exists
	$K \rightarrow \pi \nu \nu$	180	$< 2 \cdot 10^4$	
	$e^+ e^- \rightarrow Z^0$	200	± 1	Needs $\Gamma(Z)$ measured to $\pm 6\%$
	$e^+ e^- \rightarrow Z^0 \gamma; Z^0 \rightarrow \nu \bar{\nu}$	250	$\pm \sqrt{N_g}/10$	Needs ~ 1 month's run

TABLE 8

Choice of generation number for antiparticles

Reaction	$G(e^+) = +1$	$G(e^+) = -1$	Experiment
$e^+e^- \rightarrow \mu^+\mu^-$	Forbidden	Allowed	Copious. Similar to $e^+e^- \rightarrow e^+e^-$
$e^-e^- \rightarrow \mu^-\mu^-$	Allowed	Forbidden	Not seen
$d\bar{d} \rightarrow s\bar{s}^*$	Forbidden	Allowed	Copious. Similar to $d\bar{d} \rightarrow u\bar{u}$
$d\bar{d} \rightarrow s\bar{s}^{**}$	Allowed	Forbidden	Not seen

* For example, associated production of strange particle pairs in hadronic collisions.

** For example, $\pi^- p \rightarrow \Sigma^+ K^-$, $pp \rightarrow \Sigma^+ \Sigma^+$, $\Xi^- \rightarrow n \pi^-$

TABLE 9

Unusual Reactions Conserving Generation Number

The table lists reactions which conserve baryon and lepton numbers. Reactions which are allowed by conventional flavour selection rules are not included.

A) Reactions in which each generation number is separately conserved.

Allowed	Experimental Limit	Forbidden
$\mu^- d \rightarrow e^- s$	$e^- c/\mu^- X < 0.6\% (209, 210)$	$\mu^+ d \rightarrow e^+ s$
$e^+ d \rightarrow \mu^+ s$		$e^- d \rightarrow \mu^- s$
$\nu_\mu d \rightarrow e^- c$		$\bar{\nu}_\mu u \rightarrow e^+ s$
$\bar{\nu}_e u \rightarrow \mu^+ s$		$\nu_e d \rightarrow \mu^- s$
$K_L^0 \rightarrow \mu^\pm e^\mp$	$\mu e/\mu\mu < 0.2$ or $700 (76, 77)$	
$K^+ \rightarrow \mu^+ \nu_e$		$K^+ \rightarrow e^+ \nu_\mu$
$K^+ \rightarrow \pi^+ \mu^+ e^-$	$\pi^+ \mu^+ e^-/\pi^+ e^+ e^- < 2\% (74)$	$K^+ \rightarrow \pi^+ \mu^- e^+$
$\Sigma^+ \rightarrow p e^+ \mu^-$		$\Sigma^+ \rightarrow p \mu^+ e^-$
$b \rightarrow d \tau^- e^+$		$b \rightarrow d \tau^+ e^-$

B) Reactions in which net generation number is conserved, assuming that generation number assignments satisfy $G_3 - G_2 = G_2 - G_1$

Allowed	Forbidden
$\tau^+ \rightarrow K^0 \mu^+$	$\tau^+ \rightarrow K^0 \mu^+/\text{all} < 10^{-3} (65)$
$\tau^+ \rightarrow \mu^+ \mu^+ e^-$	
$\tau^+ \rightarrow \pi^- K^+ \mu^+$	
$b \rightarrow c \mu^- \bar{\nu}_e$	
$b \rightarrow s s \bar{d}$ (e.g. $B^0 \rightarrow \bar{K}^0 \bar{K}^{0*}$)	$b \rightarrow s s \bar{d}$ (e.g. $B^0 \rightarrow K^+ K^{-*}$)
$b \rightarrow c s \bar{u}$ (e.g. $B^- \rightarrow K^{*-} \bar{D}^0$)	$b \rightarrow c s \bar{u}$ (e.g. $B^- \rightarrow K^{*-} \bar{D}^0$)
$b \rightarrow c o d \bar{u} \bar{u}$ (e.g. $B^0 \rightarrow D^0 \bar{D}^{0*}$)	$b \rightarrow c \bar{c} d$ (e.g. $B^- \rightarrow D^0 D^{-*}$)

C) Reactions in which net generation number is conserved modulo 3

Allowed	Forbidden
$e^- e^- \rightarrow \mu^- \tau^-$	$e^+ e^- \rightarrow \mu^\pm \tau^\mp$
$\tau^- \rightarrow e^- e^- \mu^+$	$\tau^- \rightarrow e^- e^+ \mu^-$
$e^- d \rightarrow \tau^- s$	$e^+ d \rightarrow \tau^+ s$
$\bar{\nu}_\mu u \rightarrow e^+ b$	$\nu_\mu d \rightarrow e^- t$

TABLE 10 Summary of some recent models

First Author	Ref.	Preons	u, d, e^-, ν_e	Generations	Λ (TeV)	Features	Predictions
Abbott	123, 213	Scalar ϕ IH fermions ψ	$\psi_1\phi, \psi_2\phi,$ $\psi_3\phi, \psi_4\phi$	New ψ for each flavour	0.5	Only LH fermions composite. Weak ints residual $W=\phi\phi$ composite	Substructure visible soon. $M_W > 160$ GeV W^* exist Parity violation. Proton decay suppressed.
Albright	214	W, S, C fermions	$(CW_2)^+, (CW_1)^+$ {or SW_1, SW_2 } $(SSW_1)^+, (SSW_2)^+$ {or WWW_2, WWW_1 }	$N_g=4$		Impose 't Hooft	2 abnormal generations Proton decay with generation flip. $\tau \rightarrow \gamma, K^+ \nu_e, \nu^+ e \gamma$ Fractional charges Exotics at $M \sim M_W$ $L(\mu) = -L(e)$
Ansel'm	124	Q_{ai}	$Q_1/3Q_1/3Q_0, L/3Q_1/3Q^{-1},$ e^-, ν_e	Excitations $N_g=8$ (hypercolours)	10^{12}	Only $SU(5)$ 10 composite $Higgs=QQ$	$\nu^+ e \gamma$ $\mu^+ 3e$ suppressed Extra $q=2/3$ quarks and exotics
Barbieri	129	$P=F$ fermion $\phi=C$ coloured boson $\phi^L=$ leptonic boson	$F\phi^C, F\phi^S,$ $F\phi^L, F\phi^R$	Not considered	0.5	$W=F\bar{F}$ Weak ints residual	Neutrinoless double β decay. Deviations from Standard Model. Substructure visible soon.
Bars	80	3 fermion (ϕ =sterile)	$Upf_1, Dpf_1,$ $Epfl, Npf_1$	Different fs $N_g=4-8$		Satisfies Bars' constraints. Different hypercolour representations.	Parity violation Exotics may exist B, L conserved
Casalbuoni	150, 186	Various				Proton required to be long-lived	
Derman Veltman	130 147 }	U, D, E, N	UH, EH, EH, NE	Higgs	1		$K \rightarrow \mu e$ $M_W \neq 0$ Light HH composite Substructure visible soon
Ellis	139	$SO(8)$ supermultiplet		$N_g=3$	Planck mass	$N=8$ supergravity	Fermions, gauge bosons + Higgs composite. $GUT=SU(5)$
Fritzsche	128	Fermions α, β Bosons x, y	$\alpha x, \beta x, \alpha y, \beta y$	hyperglue	0.5	Weak ints residual $W=\alpha\beta$ $\sin^2\theta_W$ related to size of W .	Colour sextets + octets Excited bosons. Substructure visible soon
Gonzalez-Mestres	169	Fermions ψ_1, ψ_2 (charge $+2/3, +1/3$)	$\bar{\psi}_1\bar{\psi}_2, \bar{\psi}_2\bar{\psi}_1$ $\bar{\psi}_1\bar{\psi}_2, \bar{\psi}_2\bar{\psi}_1$	Extra $\bar{\psi}\bar{\psi}$			Exotics

TABLE 10 continued

First Author	Ref.	Preons	u, d, e^-, ν_e	Generations	Λ (TeV)	Features	Predictions
Greenberg	63	Fermion doublet F Scalars C, S	$F_1 \bar{C}, F_2 \bar{C}$ $F_2 S, F_1 S$	Extra $\bar{C}, \bar{S}$ or radial excitation		Weak ints residual.	
Harari	86	T, V	$\overline{TV}, \overline{TV},$ $\overline{TV}, \overline{VV}$	$\overline{TV}, \overline{TV}$ $N_g=3$		Weak ints residual	$\sin^2 \alpha_w = 1/4$ Proton decays with $\Delta(B-L) \neq 0$ Goldstone bosons Colour exotics $m_\nu \neq 0$ Spectrum of weak bosons + RH currents.
Kakazu	205	Fermions W, C	$W_1 \bar{C}, W_2 \bar{C},$ $\bar{W}_1 \bar{W}_2, \bar{W}_1 \bar{W}_2$	Independent chiral configurations		Only W have electroweak ints	
Kim	242	Fermions	Only SU(5) $\bar{5}$ composite		1-10	Unified preon model SU(5) decuplet elementary	No top quark Anom mag moms small $\mu\tau\gamma$ suppressed Proton decays to LH leptons
Krolkowski	145, 146	Fermion f Boson b (Both charge -1/3)	$\bar{f}b, \bar{f}bb,$ fbb, fbb			QCD binding of preons Weak ints residual Composite W, Z, Higgs	$p \rightarrow e^+ \bar{\nu}_e \bar{\nu}_e$ Exotics
Maki	157	Fermion A Boson e (Both charge 1/6)	Rishons composite	Extra $u\bar{u}$	2 scales	Dicolour binds sub-preons	4 generations? Low mass exotics
Mansouri	221	Fermions $b_1, \dots, b_5$	$[b_1 b_2 b_3] b_4 b_5$ $[b_1 b_2 b_3] b_4 b_5$ $b_1 b_2 b_3 b_4 b_5$ $b_1 b_2 b_3 b_4 b_5$	b_6 and b_7 give $N_g=4$		SO(10) grand unified approach. Gauge bosons + Higgs composite.	
Montvay	153	Fermions	m preons		$> 10^{14}$	Grand unification of colour and hypercolour. Hypercolour SU(m)	
Pati	144, 152, 156	Fermions C, f, s	cf, s, cf, s cf, s, cf, s	Core pair, or different s		Analogous E, M charges Composite γ, W, Z, g + graviton	$e^+ e^- \rightarrow \mu^+ \mu^-, q\bar{q}$ asymmetry
Raitio	138	Fermionic maxons	Like Harari	Gravitational excitation	Planck mass		$\mu \neq e\gamma$ Doubly charged bosons

TABLE 10 continued

First Author	Ref.	Preons	u, d, e^-, ν_e	Generations	Λ (TeV)	Features	Predictions
Shaw	222, 223, 245	$f=E6$ 27 $b=E6$ 78	Elementary	fb		Unifies SU(10) with U(1) ^t	4th generation + exotics.
Squires	115, 184	Fermions	Like Raitio	Radial excitation		Weak ints residual Removes need for Higgs	Exotics Z^0 = doublet
Tanikawa	224	Fermion f Bosons b_0, b_c	$f_1 b_c, f_2 b_c$ $f_2 b_0, f_1 b_0$	Different bs		Duality diagrams for weak ints	$\sigma_v = \sigma_v^-$ p stable, $K^0 \rightarrow \mu e$ Regge type weak ints
Terazawa	110, 207, 225-231	Fermions w, c, h	$w_1 c_1, w_2 c_1, w_2 c_0 b_1, w_1 c_0 b_1$	Different h $N_g=6$ from G-u relation		Weak bosons, Higgs, gravitons + γ composite	$\sin^2 \theta_w$ Free preon prodn in e^+e^- $\sin^2 \theta_c$ decreases with Q^2
Tosa	88	Fermions	fff	$N_g=3$	10-10 ³	Weak bosons not composite Anomaly + exotic free model Pauli Principle incorporated	p stable; $n\bar{n}$ oscillations
Visnjic	202	Boson + fermion	fb	Radial excitation		Heavy preons	No neutral current flavour changes Preons not confined
Visnjic	148	Supersymmetric boson + fermion	fb			Composites=Goldstone fermions Heavy preons	Preons not confined Rise in σ for e^+e^- Anomalous e^+e^- prodn in hadronic reactions.
Wetterich	170	Fermions p1p2 (charge 1/3, -2/3)	$\bar{p}_2 \bar{p}_1, \bar{p}_1 \bar{p}_2, p_1 p_2, p_1 p_1, p_2 p_2$	Spin and isospin recouplings		Maybe $p=\bar{q}$	$\sin^2 \theta_w = 9/20$ $\mu\tau\tau$ suppressed 4 normal generations + exotics
Yanawaki	254	Fermions c, w, t	$w_1 c c, w_2 c c, w_2 t t, w_1 t t$	Different chiral combinations		Composites massless from discrete U(1) symmetry	Proton could be stable
Yasue	158, 261	Fermion c Boson w	$w_1 c i, w_2 c i, w_2 c_0, w_1 c_0$	Spin recouplings	2 scales	w and c composed of sub-preons	$\sin^2 \theta_w$ α_c Mass scale of composites.

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Fig. 2

Fig. 4

Fig. 3

Fig. 5