THE NEXT GENERATION OF ACCELERATORS AND THEIR CHALLENGE FOR INSTRUMENTATION

Erich Vogt, Director, TRIUMF

4004 Wesbrook Mall, Vancouver, B.C., Canada V6T 2A3

1. Introduction

These are heroic times for subatomic physics. In the last decade new ideas about quarks and leptons, and about their interactions, have led to the Standard Model. This is a remarkable synthesis which describes the multitude of short-lived particles in terms of a few basic building blocks - the three pairs of quarks and the three pairs of leptons - and which uses local gauge symmetry to combine the electromagnetic interactions with the weak interactions and also with the strong.

This remarkable leap forward has raised many questions, both theoretical and experimental. Theoretically one would like to do everything: combine the fourth force, gravity, with the other three in a common framework and then to leap beyond toward a single theory whose content includes both forces and basic building blocks. The wave of theoretical euphoria which is now driving this attempt at an ultimate theory of nature now uses the word "superstrings" as a mantra and the early universe as a playground for the remarkable mathematics which it has chosen for a framework. Its contact with our real world lies in the future.

In spite of the current optimism about such theoretical speculations it should be expected and hoped for that nature is both more subtle and surprising in this, our world. It seems likely to me that the unravelling of subatomic physics will continue to be an experimental and not a theoretical science, that what we can measure will continue to determine what we know, that the role of theory will be to stimulate experimental searches and provide appropriate frameworks for the description of experimental discoveries.

It is my purpose in this paper to employ broad brush strokes to paint a picture of the extraordinary challenges which the Standard Model now poses for those who are designing new experiments in particle physics and nuclear physics. The new physics questions are extraordinarily important. The corresponding experiments required are correspondingly difficult. The times are heroic indeed - more than any since the 1920s when quantum mechanics burst on the scene and when every scientist could address world-shaking issues. Now that is true again except that the technical challenge in our heroic era is unprecedented. The community of scientists represented by the participants at this conference carries with it the responsibility of being able to respond to the new challenges. In short, I want to begin this conference by giving some glimpses of where we are heading and what is the force of ideas currently driving technical ingenuity for accelerators and detectors. The challenge is so great, the required response so important, the required resources so large and the international cooperation so requisite that the task at hand might form an attractive alternative to putting more weapons into space.

I would like to begin my description of the new ideas and the proposed responses by a simple allegory. In our quest for the particles which occur in our world we are led to look for ever more massive and short-lived particles and to use ever more energetic accelerator beams to create them. Figure 1 shows the Livingston plot¹ about how the maximum energy achieved with accelerator beams has increased with time since the earliest accelerators of 1930.

There are many different accelerator concepts.

Each accelerator concept "frets and struts its hour upon the stage and then is heard no more". But the envelope of all the accelerator activities has, over five and a half decades, pushed the maximum energy forward by an order of magnitude every six years. This inexorable law seems to be one of the best we have. It carries forward to the mid-nineties with the superconducting super collider (SSC). Extrapolating toward the discovery of the X-particles - intended to accomplish the ultimate unification of the strong interactions with the electroweak (the X-particles are anticipated to have a mass of about 10^{15} GeV, a mass which roughly equals the kinetic energy of a human jumping from the roof of this hotel) - we can now say with reasonable certainty that the X-particle will be created in the year 2135. The question is, with what accelerators and what detectors?

The main technical challenge appears to reside now in the detectors. As I shall mention briefly below there are a number of accelerator concepts in view which will provide fantastic energies within short distances. We must focus now on how we shall handle the resultant beams.

This is a turnabout. In the final year of his life, 1954, Fermi looked ahead 30 years to the prophetic year of 1984 and envisaged an accelerator of such energy and size that it encircled the world.² That 30-year prognostication has been overtaken by our ingenuity with colliding beams although, even here, the size of each ring of the proposed SSC is approaching Fermi's prediction. We have also achieved magnificent ingenuity in the luminosity, or event rate, of colliding beams. With the tremendous energies of the colliding beams of the CERN SPPS and of the Fermilab Tevatron the future challenge now lies in detectors which can unfold the complicated events which occur at energies of the SSC and other accelerators.

Fig. 1

Fig. 2

The Livingston plot for detectors would show - as I shall illustrate below - an even more rapid increase than a factor of ten every six years. Some decades ago detectors were minor add-ons to an accelerator facility. They are gaining. They will win in the future. Turning around Fermi's vision, thirty years later, we might now again look thirty years ahead from the present and forecast that our whole world will be turned into a single detector, Fig. 2. The very efficient colliders which produce the collisions are, along with the human race, placed in appropriate orbits around our planet. The whole earth is one vast detector and calorimeter, capable of coping with the trillions of ultrarelativistic reaction products from a single collision. For what other reason does our earth contain primarily the appropriate raw materials: iron for use as a converter, silicon for solid-state drift chambers and hydrocarbons for liquid ionization chambers. Or do we live in the remnants of a large detector for which the TMS exploded? Extending the whimsy further we might look for intelligent life elsewhere through bursts of high-energy particles - such as those which some observers may have seen recently from Cygnus X3 - indicative of other civilizations driven inexorably toward the same fundamental questions about our universe that now impel us.

2. The Standard Model

It is the important questions posed by the Standard Model - and the ideas go leap beyond it - which are now driving the development of new accelerators and detectors. The responses to these questions are so difficult because our world is so very interesting.

In describing here briefly the basic building blocks (the quarks and leptons) and the unification of forces of the Standard Model, we want to contrast the systematic development of the Model with the much less systematic and more theoretical new ideas about supergravity described below.

The basic properties of the quarks and leptons are given in Table I. How do we know that each baryon (the relatives of the proton and neutron) is made of quarks with just those properties or that all mesons are made of quark-antiquark pairs? The answer is that the quarks emerged from a very systematic classification of the very many different baryons and mesons which resulted from experiments in the 1950s and 1960s.

Table 1. Quarks and leptons - the basic building blocks of the Standard Model. Each quark or lepton is a fermion of spin 1/2 and each has an antiparticle. The quarks each come in three different colours.

Some quantum numbers			
	Spin	Charge	Baryon number
<u>Quarks</u>			
$\begin{pmatrix} u \\ d \end{pmatrix}, \begin{pmatrix} c \\ s \end{pmatrix}, \begin{pmatrix} t \\ b \end{pmatrix} \dots$	1/2	+2/3	1/3
	1/2	-1/3	1/3
Names: u = up, d = down, c = charmed, s = strange, t = top, b = bottom			
Masses (GeV): $m_u \approx 0.35$, $m_d \approx 0.35$, $m_c \approx 1.8$, $m_s \approx 0.55$, $m_t \approx 35??$, $m_b \approx 4.5$			

Leptons

$\begin{pmatrix} e \\ \nu_e \end{pmatrix}, \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}, \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix} \dots$	1/2	-1	0
	1/2	0	0
Names: e = electron, ν_e = electron's neutrino, μ = muon, ν_μ = muon's neutrino, τ = taon, ν_τ = taon's neutrino			
Masses (MeV): $m_e = 0.511$, $m_{\nu_e} < 0.0003$, $m_\mu = 105.6$, $m_{\nu_\mu} < 0.5$, $m_\tau = 178.4$, $m_{\nu_\tau} < 250$			

Take, for example, the baryons. As baryons heavier than the neutron and proton were discovered reaction studies assigned a spin and parity, J^π , to each, as well as an electric charge, a mass and a further property of unknown origin called "strangeness" which clearly could be assigned to each particle from the selection rules for observed reaction products. Without any reference to substructure each baryon could be grouped with others of the same J^π but spanning a range of charge and strangeness values. The octet ($J^\pi = 1/2^+$) and the decuplet ($J^\pi = 3/2^+$) of Table II are two examples of many such baryon charge-strangeness tables.

Table 2. Two charge-strangeness tables for baryons.

	C=-1	C=0	C=+1	C=+2	Mass (MeV)
<u>The octet ($J^\pi = 1/2^+$)</u>					
S=-2	Ξ^-	Ξ^0			1315
S=-1	Σ^-	Σ^0, Λ	Σ^+		1190, 1115
S=0		N	P		940
<u>The decuplet ($J^\pi = 3/2^+$)</u>					
S=-3	Ω^-				1672
S=-2	Ξ^-	Ξ^0			1535
S=-1	Σ^-	Σ^0	Σ^+		1385
S=0	Δ^-	Δ^0	Δ^+	Δ^{++}	1232

If we begin to ask what basic subunits might form these baryons, and all the other baryons and mesons, we clearly would like the number of such building blocks or "quarks" to be minimal. For either the octet or decuplet one can rapidly show that two quarks is not enough.

Our next try, with only three quarks, is successful. Since the octet and decuplet have fractional spin it clearly makes sense to assume that the three quarks are fermions of spin $1/2$. We assign names "s", "u" and "d" to the three. Then a very simple exercise - which can be carried out by any elementary schoolchild without any training in group theory, but adept at solving puzzles - yields the basic quantum numbers of s, u and d. Taking three fermions in the same energy level with their spins all aligned yields a state $J^\pi = 3/2^+$, $M_J = +3/2$. We note at once that there are only ten different possible combinations of our three quarks (sss, ssd, ssu, sdd, sdu, suu, ddd, ddu, duu, uuu). Can these ten be the ten particles of our decuplet which are then each made of three quarks? This intriguing question when confronted with the charge-strangeness combinations of the decuplet (Table II) leads at once to the quark quantum numbers of Table I for s, u and d. It turns out that Ω^- is sss, Δ^{++} is uuu, Σ^0 is sdu, etc.

But what about the octet with $J^\pi = 1/2^+$? If we take s, u and d in the same orbit but with two spins up and one down we now get eighteen different combinations (ssts+, sstsd+, sstdd+, etc.). Ten of these are the $M_J = 1/2^+$ states of the decuplet. The remaining eight are exactly those of the octet.

But there is much more. All of the many baryon tables existing before 1974 now fit with the same s, u and d. All of the similar meson tables (qq) also fit.

Following the dramatic discovery of the charmed quark (c) in 1974, and then the b quark and recent hints of the t quark, the spectroscopy of baryons and mesons became richer but the building blocks worked.

However, we can see at once that each quark must occur in three different kinds distinguished by a property called colour. In the picture above we required (for example, for the Ω^- state which is sss) that three identical quarks occupy the same orbit. But the quarks are fermions and forbidden to do this. To escape from this it was necessary to assume that each baryon was made of a "colour-neutral" combination of three differently coloured quarks. The strong interaction of the coloured quarks is called quantum chromodynamics (QCD).

The remarkable step forward in the understanding of the basic building blocks (quarks and leptons) is surpassed by the dramatic unification of three of nature's forces within the Standard Model. Electromagnetic interactions, weak interactions and strong interactions have been unified as "renormalizable local gauge theories".

The unification began, in about 1865, with Maxwell's unification of electricity and magnetism into the theory of classical electromagnetism. This theory possessed a remarkable symmetry. One can transform the potentials of the electric and magnetic fields, but the physics remains invariant. One must then make a choice or "gauge" for the description. Moreover, the gauge choice is local - it can be made independently at each point in space. Maxwell's classical electromagnetism is then a local gauge theory.

The advent (1905-1928) of quantum mechanics brought forward the photon (γ) as the quantum of the force field. The quantum description was initially

plagued by infinities. It took twenty years (1928-1948) of hard work for physicists to discover how, through the use of the powerful local gauge symmetry, the infinities could be removed. The process was called renormalization. What emerged was our modern quantum electrodynamics (QED) - a renormalizable local gauge theory of great power and accuracy.

With this success the question was whether QED could be used as a template for the description of the other forces. Attention turned first to the weak interactions responsible for radioactive decay. According to Fermi's β -decay theory (1935) the weak interaction was very short range and varied with the quantity called isospin which was needed to describe hadrons - such as the neutron and proton - which appeared to exist in several different charge states. Where was the powerful local gauge symmetry? Yang and Mills³ first showed (1957) that because of the short range and isospin any local gauge theory of the weak interaction would require field quanta carrying mass and charge, unlike the massless, chargeless photon.

Through the 1960s Weinberg⁴ and Salam⁵ and others uncovered the local gauge symmetry of the weak interaction and combined it with electromagnetism into a single force - the electroweak force. In a remarkable insight it turned out that the inherent gauge symmetry was hidden by an auxiliary force field, called the Higgs field. The Higgs field spontaneously broke the symmetry and provided mass to the new quanta of the electroweak theory. It required that the electroweak theory have four quanta, γ , $W^\pm$ and Z^0 and predicted the mass of the latter three. The discovery of $W^\pm$ and Z^0 at CERN in 1983 - by Carlo Rubbia and his many colleagues - confirmed the electroweak unification.

En route to this triumph the electroweak theory encountered those same terrible quantum infinities. Again it was the powerful gauge symmetry which led to renormalization. The proof of this by 't Hooft (1972) required high speed computers. What emerged was electroweak theory as a renormalizable local gauge theory.

On toward the strong interactions. Here the traditional viewpoint has been Yukawa's meson theory (1935) in which nucleons interact through meson exchange. Yukawa's theory marks the beginning of modern particle physics and has been the cornerstone of nuclear physics. More recently we know that nucleons and mesons are made of coloured quarks and that the strong force is that between the quarks (QCD). Is QCD a gauge theory which can be unified with electroweak theory?

Superficially QCD is very different from electroweak theory. When the quarks are very close together (compared to the size of a nucleon $\approx 10^{-15}$ m) their interaction is weak. One says the quarks are "asymptotically free". As one separates the quarks their force of attraction grows - and grows and grows. The quarks are confined in colour neutral combinations. Moreover, at the separations important for nuclear physics the force is so strong that it is nearly intractable - QCD is then said to be "nonperturbative" and one now resorts to cumbersome lattice gauge calculations to dimly understand the physics of systems of quarks. Yet QCD is a gauge theory.

The field quanta of QCD carry colour and the gauge theory then requires at least eight different such quanta which are called gluons. This picture of quarks and gluons rests on a solid foundation. In high energy electron scattering from nucleons the quark constituents with their fractional charges are seen. Similarly gluons are detected in reactions initiated by very high energy electrons.

In seeking a unification of QCD with the electro-weak theory one needs to search for some grand symmetry which encompasses the electric-magnetic symmetry of electromagnetism, the further isospin symmetry of the weak interactions and now the further colour symmetry of QCD. Beginning with the work of Glashow and Georgi⁶ several candidate theories (called grand unification theories or GUT) have been brought forward. They would bring in at least twelve additional field quanta (beyond γ , $W^\pm$, Z^0 , the Higgs particles and the gluons) which are collectively called X. The mass of X - which corresponds to the energy at which the grand unification is accomplished - is about 10^{15} GeV! Creating these particles and measuring their properties would be a real challenge for future builders of accelerators and detectors. With GUT the unification of the three forces in a single normalizable local gauge theory is realised and the edifice of the Standard Model is complete.

The Standard Model poses a host of vital questions for particle physics and for nuclear physics. Some of the questions currently driving the interest in large new accelerator facilities are:

- Are there extra pairs or "generations" of quarks and leptons beyond the three presently known?
- Where are the Higgs bosons through which the $W^\pm$, Z^0 , charged leptons and quarks acquire mass?
- Are neutrinos massless? Are there neutrino oscillations?
- Are the couplings of the gauge bosons to quarks and leptons only left-handed, as presently observed, or even-handed like the photon?
- Is the proton unstable as predicted by GUT?
- What is the origin of CP-noninvariance (time-reversal) as observed in kaon decay?
- Do gluons combine into objects called glueballs?
- How does the long-range Yukawa force - formerly the cornerstone of nuclear physics - arise from QCD?
- What are the appropriate constituents for the description of the nucleus - neutrons and protons interacting through meson exchange or quarks interacting through gluon exchange?
- How does one describe the physics of quark confinement, for example, in terms of cumbersome lattice gauge calculations or phenomenological bag models?
- Are the quarks partially deconfined at the centre of a nucleus?
- Can one find new multiquark states (e.g. six-quark bags) or new phases of nuclear matter (e.g. "strange matter", a possible stable large system including strange quarks, or a "quark-gluon plasma", a new phase of nuclear matter possibly attained at high density or temperature)?

Then there are other equally vital questions probing beyond the Standard Model.

3. Beyond the Standard Model

The Standard Model constitutes such a remarkable step forward in our understanding and such a remarkable challenge for experiment that one might ask what more do we want? There are deficiencies in the picture.

First of all, there are far too many basic building blocks: three pairs of quarks in three colours each ($6 \times 3 = 18$), three pairs of leptons (6), multiple Higgs bosons (2 or more), the gauge bosons γ , $W^\pm$ and Z^0 (4), many gluons (8) plus at least a dozen X particles (12). Anyone who wishes to regard this whole agglomeration as basic must feel that some humour was used in the creation of our universe. Are all of these particles composites of more basic subunits? Is there a more fundamental theory?

Next, gravity is not included among the unified forces. The reconciliation of gravity with quantum mechanics has remained a very deep problem for physics. Perhaps the reconciliation should accompany unification. Einstein's general theory of relativity views gravity as geometry - mass is curvature of space. Perhaps any unification including gravity needs a geometric theory.

Further, there is a lack of symmetry in the theory between fields and particles, between fermions and bosons. All the field quanta are bosons (integral spin) and all the building blocks are fermions (half-integral spin). How does spin enter into a more basic theory?

The present attempts to solve these problems with supersymmetry and supergravity and superstrings involve a style in science distinct from that which pertains to the development of the Standard Model. As described above the building blocks and force unification were accomplished with an analytical approach common to most scientific disciplines. When experiment provided more particles one classified them and used the analysis to determine the constituents. The next generation of experiments then found the constituents, etc. In unifying the forces one patiently followed the template of electromagnetism. For additional forces one followed the same mathematics but added new field quanta with each addition. In contradistinction to this analytical approach the supertheories belong to a style unique to physics.⁷ One discovers some elegant mathematics and one postulates that this mathematics must somehow pertain to our universe. That style is the one to which Dirac's theory of the magnetic monopole belongs and which underlies superstring theory.

In the approach of supersymmetry one searches for a higher symmetry which includes spin and which combines in one theory both bosons and fermions, both forces and particles. It is intended as a theory of everything in our universe. Some of the most interesting mathematical groups for this purpose produce hundreds of particles - both building blocks and field quanta. The theory requires the existence of new supersymmetric particles, of boson partners for each presently known fermion and vice versa. The experimental discovery of such partners would be a real boost for supersymmetry. The symmetry operations of the mathematical groups appear to have geometrical aspects. In such theories there is some indication that the powerful symmetries insist on renormalizability rather than allowing it reluctantly as in the gauge theories of the Standard Model.

Superstrings focuses on the beautiful mathematics of vibrating strings which can only be consistently formulated in multidimensional space. One first extends Einstein's compelling view of gravity as curvature of four-dimensional space time. Sixty years ago Kaluza and Klein extended Einstein's mathematics to include also electromagnetism. Kaluza found that if one dealt with a five-dimensional world then electromagnetism (charge) could also be assigned to curvature, and Klein showed that the extra dimension was "rolled up" in such a way that it would only be revealed at fantastically small distances. The fifth dimension seemed far-fetched and in any event quantum mechanics and the Yukawa force and Fermi's β -decay theory took centre stage.

With the current need to unify gravity with the other gauge interactions interest has centred on a geometrical interpretation of all the forces. Including isospin and colour enlarges the dimensions beyond the five of Kaluza and Klein. The need to quantize the whole theory and to remove the very bothersome anomaly

lies which plagued the reconciliation of gravity with quantum mechanics may enlarge the dimensions further. Present work focuses on a world of ten or twenty-six dimensions, most of which are "rolled up" or "compactified" to our relevant four.

The mathematics of superstrings drives the quantization. The theory involves a Planck mass ($\sim 10^{20}$ GeV) at which energy gravity joins the other three interactions. At present the theory has many beautiful aspects at such ultrahigh energies, but it remains to be seen if any physics of our everyday particles and forces can be extracted from the theory. It represents a promising start toward the description of an interesting universe. Is it ours?

Speculations about the early universe fuel the flights of fancy of the supertheories. Is our own universe a "mini-universe" arising from a quantum fluctuation in some cosmic foam? Did our own laws of physics and our dimensionality originate in the earliest moments? Are there other universes with different laws and different dimensions? Are the special laws and dimensions of our universe among the very few which produce interesting physics and chemistry and life? When do such speculations depart from valid science? The questions posed by the supertheories, however fervently presented, should perhaps be regarded as providing hope for future surprises rather than concrete guidance for present experiments. The questions of the Standard Model must now be confronted.

4. The World Network of Large New Accelerators

In response to the important new questions raised by the Standard Model much of the future action in nuclear physics and particle physics will take place at a network of very large new accelerator facilities now planned or under construction around the world. These magnificent new edifices are an expression of the spirit of our age in a way analogous to the network of gothic cathedrals which straddled western Europe eight hundred years ago or the network of stone circles which girdled the northern hemisphere thirty-five hundred years ago. I outline briefly, and with some personal biases, the nature and purpose of the new accelerator laboratories.

The Tevatron now approaching initial operation at Fermilab near Chicago is a proton-antiproton collider to operate at $1 \text{ TeV} \times 1 \text{ TeV}$ with a luminosity exceeding $10^{30}/\text{cm}^2/\text{s}$. Building on the success of the SPPS collider at CERN (which operated at $0.27 \text{ TeV} \times 0.27 \text{ TeV}$ for the discovery of $W^\pm$ and Z^0 but is now increasing its energy) the Tevatron will explore the physics lying well above the threshold for the production of the gauge bosons.

The SLC at Stanford and LEP at CERN will both provide electron-positron collisions at $50 \text{ GeV} \times 50 \text{ GeV}$. LEP is scheduled for operation in late 1988. Its 28 km tunnel under towns and people and cows is well along. For electrons it is bremsstrahlung losses which make the accelerator circumference so large at even modest energies. At SLC, scheduled for operation in early 1987, one avoids this problem by having a linear collider in which the two beams collide only once. There are four massive detectors being built at LEP (ALEPH, OPAL, DELPHI and L3) and two at SLC (Mark II and SLD). These two colliders should be veritable factories for the production of the gauge bosons. They will allow detailed studies of the mass and width and branching ratio of the Z^0 providing crucial information for the parameters of the electroweak theory. The high Z^0 event rate (thousands per day instead of one or two) should make it possible to study the cascade decay of heavy quarks, to search for the top quark and for $t\bar{t}$ (toponi-

um), the simple meson consisting of a quark-antiquark pair. One will be able to search for neutral and charged Higgs bosons and for other heavy long-lived particles. In spite of their modest energies compared to hadron-hadron colliders these lepton-lepton colliders are essential because of the cleanliness of the events they produce. Also they are in an energy regime where the coupling strengths of the weak and electromagnetic interactions become comparable and one can carry out many model-independent studies of electroweak interactions. At somewhat more modest energies there are electron-positron colliders nearing completion at Beijing (BEPC) and in Japan (TRISTAN), and there remains an important facility at Cornell (CESR).

The HERA-collider at DESY in Hamburg is the only new lepton-hadron accelerator. It is scheduled to begin operation in 1990 with electron-proton collisions at $30 \text{ GeV} \times 820 \text{ GeV}$. HERA will provide very clean QCD tests in studies of the proton structure function $f(x, Q^2)$ at very high momentum transfers ($Q^2 \approx 10^4 \text{ GeV}^2$). It will provide data for high energy photon physics, for example the QCD Compton effect, and possibilities for new phenomena on both the quark and lepton sides.

The superconducting super collider (SSC) is a multiTeV hadron-hadron collider which carries with it the greatest hopes for new discoveries in particle physics. The major development plans for it now exist in the USA, but at CERN there are also hopes for such a collider in the LEP tunnel. As envisaged in the USA the SSC would be a proton-proton collider (the distinction between pp and $p\bar{p}$ becomes less important at these high energies) to operate at $20 \text{ TeV} \times 20 \text{ TeV}$. It would have 6 T magnets but even so a circumference of 90 km. Above all the SSC is a facility which carries with it the hope of discovering the particles responsible for the mass of the basic fermions. There are general arguments, based on the strength of the Fermi coupling constant, that such particles should lie in the TeV regime. This is much too high an energy to attain now with lepton probes so that one must perforce resort to hadrons. We must remember that a proton-proton collision is really a messy system of three quarks colliding with another such system. Each quark-quark collision has only one-third of the total collision energy. Besides the wanted events each collision is likely to produce hundreds or thousands of other unnecessary particles, scores of mesons and muon-antimuon pairs with energies which will be daunting even for designers of gargantuan detectors. In spite of its messy collisions the SSC is not only a large edifice but physics on a grand scale - a huge quantum step upward in energy which, in the past, has always produced exciting new physics.

The new questions for nuclear physics have brought forward three very different new facilities. The first of these, the continuous electron beam accelerator facility (CEBAF), to be built in Newport News, Virginia, is very close to full funding approval. It will provide 4 GeV cw electron beams at $150 \mu\text{A}$. This facility uses the cleanest probe, the electron, to study multihadron systems, especially the lightest nuclei. No previous cw electron beams have existed in its energy regime. It is intended to study the physics of quark confinement and hadronic physics - the excitations of nucleons in the nucleus.

The proposal for a relativistic heavy-ion collider (RHIC) at Brookhaven would build a synchrotron to accelerate very heavy nuclei (e.g. ^{197}Au or ^{238}U) to energies of up to 100 GeV per nucleon and then to collide two beams of such relativistic ions. As an accelerator project RHIC is particularly cost effective because it uses the existing CBA tunnel - one of the few man-made structures clearly visible by the naked eye from outer

space. The main purpose of such ultrarelativistic collisions is to compress and/or heat nuclear matter in order to attain a new state of matter, a quark gluon plasma. As the nuclei retreat after a central collision the hot plasma might exist very briefly in the space between them. It would be a spectacular recreation of conditions which existed in the earliest moments of the big bang. The total energy (tens of TeV) of the colliding system has very high multiplicity, producing up to tens of thousands of emerging pions.

The final new facility I shall mention is the KAON factory for which proposals now exist at both LAMPF and at TRIUMF. These proposals would use the present meson factory accelerators as injectors into a system of accumulator rings and synchrotrons to boost the proton beam energy sixtyfold up to the present energy of the Brookhaven AGS or above. With very intense beams (~ 100 μ A) one would produce a variety of secondary beams, each with an intensity about two orders of magnitude above those presently available. The word "KAON" can be considered as an acronym for these secondary beams of kaons, antinucleons, other strongly interacting particles and neutrinos. With these beams one intends to address many of the important questions in both particle physics and nuclear physics. The very rich spectroscopy of light hadrons relates directly to the distances associated with quark confinement. Inserting strange quarks into nuclei confronts the question of quark mobility in nuclei. The fixed-target particle physics offers attractive alternatives to the collider work at the high energy frontier and addresses some of the same physics. For example, the multitude of kaon rare decay modes can set limits on the existence of Higgs scalars and leptoquarks in the TeV regime or, indeed, provide direct evidence for them. Already the meson factories have added greatly to the new particle physics: a recent TRIUMF experiment by Mark Strovink and his colleagues⁸ has set much the best lower limit (400 GeV) on the mass of any right-handed W^+ . Important as those limits are the KAON factory would bring the science of these rare decays within reach. One always learns more from an observed rate than from a lower limit! To illustrate the science within reach Fig. 3 shows the history of one rare decay mode $K^+ \rightarrow \pi^+ \nu \bar{\nu}$. The figure shows how improvements in detector technology are now allowing experimentalists to approach the region in which the Standard Model predicts that this reaction will be discovered. With the added kaon flux of a KAON factory one will cover the region and reveal its physics. [Incidentally the figure also illustrates how detectors are winning over

accelerators. The dashed line in the figure corresponds to an improvement of a factor of six every ten years which pertains to accelerators (Fig. 1). The detector improvement is greater.] The kaon is one of nature's richest laboratories and it is particularly important to have more kaons to study the physics of time-reversal noninvariance.

5. The Challenge for Accelerators and Detectors

The accelerators required for the next generation of new facilities just described are based on existing technology and do not appear to present any insurmountable obstacles. If one looks beyond the SSC and toward the distant X particles at 10^{15} GeV one will require new accelerator concepts or alternatives to colliders.

There are new ideas about achieving much higher energies in short distance using laser accelerators.⁹ Lasers have electric fields up to 10^{12} V/cm! The new concepts include laser-driven microstructures, plasma beat-wave accelerators, inverse free-electron laser accelerators, etc. Although we are not about to build the accelerators whimsically depicted on Fig. 2, there are interesting beginnings to the physics of the laser accelerator concepts. Clearly as one increases the energy one will get less intense beams and require greater luminosity in the colliding beams of such accelerators. Can one approach the ideal of a direct hit each time - at least to the extent that Heisenberg's uncertainty principle allows?

Alternatives to colliders will have their inevitable place. They include fixed-target facilities such as the KAON factory, large underground detectors for proton decay or solar neutrinos, and even possibly the "poor man's alternative" to an accelerator - the study of the early universe.

The challenge for detectors is already very great, or overwhelming, for the next generation of facilities. The problem lies in the messiness or multiplicity of the collisions and in the extraordinary event rate. The very high energy of the reaction products leads to very large detector size and cost. The high multiplicity of hadrons and lepton pairs leads to the need for very good track definition - good spatial resolution. The need to use hadrons at the highest energies makes the collisions much more complicated. As one pushes toward higher energy the total cross sections remain at nucleon dimensions but the cross sections for individual channels fall off drastically. This channel proliferation means that the sought-for events are buried in ever more background noise and implies very high energy resolution for the huge calorimeters. With the drop-off of individual channels one increases the luminosities to higher levels - to the value of $L = 10^{33}$ cm²/s for the SSC. The resultant high event rate ($L\sigma$) puts almost impossible demands on read-out times, data analysis, etc. It is not clear to me that we presently know how to handle this problem for the SSC.

At this meeting the participants will address many of the urgent problems now facing detector development. Some of these are¹⁰: the large electronic overhead of strip detectors; the requirement of greater speed for CCDs; the improvement of resolution for gaseous drift chambers; the accuracy of visual detectors; improved particle identification, for example with ring-imaging Cerenkov detectors (RICH); and, above all, the improved performance of calorimeters both in the converters which should treat electrons and hadrons democratically and in the ionization chambers where one has present choices between doped liquid argon, some infelicitous hydrocarbons and cheap silicon. It is a daunting challenge.

Fig. 3. History of the branching ratio limit for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay showing the level achievable with a KAON factory compared with the predictions of the Standard Model.

6. Conclusions

This paper was intended to describe the heroic times for subatomic physics in which we now work. The experiments are as difficult as the rewards are great. The important questions raised by the Standard Model remain as the main driving force for experiment for the next decade or two. The super theories and superstrings promise to keep theorists frivolously occupied and to remove them as obstacles to progress for a long time. Subatomic physics remains an experimental science with many possibilities for surprises. One should not take seriously the possibility of a physics desert in the energy regime between the gauge bosons (100 GeV) and the X particle (10^{15} GeV). For the immediate future the greatest need for ingenuity lies in a broad front of detector technology. Especially we must give far greater attention to coping with the high event rate of the new colliders. For the long-term future - beyond the SSC - the development of new accelerator technologies is essential and the consideration of noncollider alternatives attractive.

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