WHERE IS THE ATOMIC NUCLEUS GOING?

D.N. Wilkinson

Nuclear Physics Laboratory, Oxford University, England.

Research into the structure and behaviour of the atomic nucleus has so far been severely limited by the availability of bombarding particles, in respect of both type and energy, and by the availability of techniques. As a result our thinking about the nucleus tends to be dominated by those considerations that have been so successful for describing what we have been able to get at to date: chiefly the low-lying excitations of nuclei not too far from the floor of the stability valley. But we for something as simple as the emission of a single particle from a "single particle" state it is the properties of the nuclear surface that determine, in a critical way, the relationship between the theoretically-interesting quantity, viz. the spectroscopic factor, and the observable, viz. the actual lifetime or width of the state. Energetic "head on" collisions of heavy ions obviously involve most of the nucleons of the nucleus because the nuclei come apart into many pieces; ultimately we may hope that such collisions will bring us word of the details of inner nuclear structure but for the present we are merely struggling to approach an understanding of how the kinetic energy is transformed into energy of internal excitation in the grosser terms and for that purpose are using the language of classical hydrodynamics - concepts such as bulk compressibility and viscosity which obviously remove the structural details rather than reveal them. The weak and electromagnetic interactions are better off and truly bring us word of the depths of the nucleus but there the information is usually superficial in the second sense:

(ii) The surface of the Fermi sea. Detailed accounts of nuclear structure involve our describing the relative motions and interactions of various interactions of a chosen number of nucleons or quasi-nucleons that are thought to be of especial importance. Computer power, if nothing else, limits the number of nucleons to which we can accord this special role; if we want to stick to exact diagonalisation the most that can be coped with at present is 6 nucleons even in so simple a shell as the $2s,1d$ although this limit can be relaxed somewhat if we are prepared to use approximate, although still accurate, methods (Whitehead-Lanczos tri-diagonalization) and also forgo the luxury of having an actual wavefunction to show for it. For most purposes we take as the chosen few the unsaturated valence nucleons at the top of the Fermi seas. If we can manage the reason allowing for the "un-saturated" meaning all nucleons outside the nominally closed shells which themselves we take as major e.g. $^{24}$Mg we take as $(2s,1d)^5$; falling this we pretend that we can truncate to the minor shells e.g. take $^{24}$Mg as $(2s,1d)^3$; falling this we invoke pairing to saturate the lower-lying nucleons and cope with the rest in a seniority scheme. But whatever we do, not many nucleons are involved: those nearest to the top of the Fermi sea which, in the best calculations, we imagine to be whirled into a modest foam by the effective residual nucleon-nucleon interaction via. we allow our valence nucleons to wander through all the subshells of the uppermost unfilled major shell; in terms of energy this means an excitation comparable with the strength of the effective residual interaction which is a few MeV. Given the total depth of the Fermi sea, namely several tens of MeV, we see how superficial, in this sense also, is our best account of nuclear structure. Of course, for special purposes, such as attempting to assess the magnitude of core polarization in microscopic terms, we calculate the effects of the N-N interaction in digging deeper holes in the Fermi sea, raising particles, either singly or in pairs, from the "closed shells" either into the company of the valence nucleons or into higher states. However, such limited exercises have as their objective the setting up of effective operators and so on, that can be used in conjunction with the conventional valence nucleon picture; they do not constitute any genuine broadening of the vision of the nucleus as a vast quasi Fermi sea with a very few active particles at its surface.

This tranquil vision is not essentially disturbed by the repulsive core that seems to operate in the N-N interaction at small distances, whether due to the effect of the exclusion principle operating between the quarks of the individual nucleons, or whatever. This core, whether technically "hard" or "soft" does not matter, excites a few nucleons massively from the depths of the Fermi sea to far above its endpoint and can be thought of as making a few deep holes in the sea; because they are made by strong short-range forces these deep holes are difficult to refill; the holes tend to persist and the Fermi sea and its holes are therefore rather "stiff" - and one of the effects of the residual (long-range and rather weak) N-N effective interaction that whips the most valence nucleons of the sea into the foam of which we have already spoken i.e. excites a large fraction of the valence nucleons into associated minor shells closely above the nominal Fermi surface; the holes of the foam, made by relatively feeble forces, are easily fillable for example by a
(d,p) reaction so the foam is soft. The two effects together, the strong short-range part of the N-N force giving the Emmerthaler excitations and the gentler longer range part the foam, result in the beer-and-swiss-cheese model of the nucleus. Of course, the transition from the foam to the cheese is not sharp except in two cases of the basis (often arbitrarily) adopted for the full shell model treatment.

However, as has been known since the early days of Brueckner theory, the high-lying Emmerthaler excitations may be mathematically and magically recombined with the orbitals from which they arose, the deep holes, in a way that effectively replaces the original tranquil particle orbitals by equally tranquil low-lying particles with the same quantum numbers as before but now interacting with each other through effective (and shell-dependent) forces that we can use to describe the generation of the foam at the top of the Fermi seas, effective forces now most genially lacking the short range repulsive core that would otherwise have made impossible any perturbative description of the generation of the foam.

It may be argued that certain phenomena, and our understanding of these, are not superficial in this present sense. One may cite the famous electric dipole giant resonance that exhausts the nuclear equivalent of the Thomas-Reiche-Kuhn sum rule that contains the factor $N/A$ and that therefore obviously involves all the nucleons of the nucleus. Closer examination, however, shows the example to be false because the only role, in the shell model scheme, of the shells below 1% of the Fermi surface is to prevent, by the Pauli principle, the downward transitions, into those shells, of the higher-lying nucleons that would, but for that prohibition, have counted negatively in the dipole sum. The contribution of the lower-lying nucleons to the dipole sum is therefore effectively passed upwards, shell by shell, until it emerges at the Fermi surface to be ostensibly enjoyed by the valence nucleons and those within 1% of them.

Our quantitative shell model account remains superficial.

(iii) The superficiality of the shell model.
The fullest microscopic calculations of nuclear structure, and the nucleons concerned in the description of the foam at the top of the Fermi sea, specify forces between those nucleons such as are given by a C-matrix procedure, via the quantitative consequence of the Brueckner quantization referred to earlier and than make small adjustments to those C-matrix elements to secure best fit with the low-lying states (usually below 5–10 MeV) of the nuclei in question. What fraction of the shell model spectrum that is generated by the mutual rearrangement of the valence nucleons among themselves is covered by these fits between shell model theory and experiment? If that fraction is large we shall call the agreement deep but if it is small we must call it superficial. For the very lightest nuclei for which the shell model deserves the name, e.g., at the beginning of the 1p-shell, agreement is deep but only for $A=6$, via just 2 active nucleons, and even there not complete; already for 3 valence nucleons, $A=7$, the bulk of the theoretical states is missing experimentally. Jump now to nuclei under active realistic study through the shell model. What about the $J^p=3^+$, $T=1$ states of $^{28}$Al (obviously interesting because experimentally the ground state is of this character)? The shell model, via $\delta$$_k$ (2s,1d)$^2$ predicts 6,706 such states spread over an excitation of some tens of MeV.

Experimentally we know 2 of them. It is evidently unlikely that we shall ever check more than a tiny fraction of the shell model's predictions about $^{28}$Al: but note that our satisfaction with the shell model account must then derive from those spurious and favoured states that lie low in excitation; we have no means of knowing whether or not the empirical adjustments that we make to the C-matrix elements to optimize agreement on these low-lying states improve or worsen agreement on those more highly excited states that must forever remain without association with the states of the model (if only because long before we reach excitations of many MeV, let alone many tens of MeV, we reach states of more elaborate configuration such as those involving pair excitation from the "closed shells"). To make the situation even more ludicrous, consider the same number of valence nucleons: $12 = 2$ beyond the next closed shell and ask for the $(2p,1f)^{12}$ states of $^{52}$Cr, specifically those of $J^p=4^+$, $T=2$ which again include the ground state; there are 3,327,065 of which 3 are known (these illustrations are due to Malcolm Harvey). We conclude that not only do our most detailed microscopic calculations involve only a superficiality of the nucleons of the nucleus but that we can be concerned with no more than a superficiality of the resultant predictions. In these circumstances it is no longer surprising in mind that to some degree agreement between shell-model theory and experiment is the result of the ad hoc adjustment of the "honest" C-matrix elements, we can be proud of the achievements of the shell model while recognizing that we have no clue as to whether it still works for those states for which the valence nucleon interaction is weak or repulsive, particularly those of highest isospin where the nucleons try to avoid each other rather than coming as close together as possible.

Beyond Neutrons and Protons

We have begun our discussion of the nucleus in traditional manner by speaking of neutrons and protons organized in shell model schemes of greater or less detail. This has been done in order to emphasize, even if we do not quite agree on the neutron/proton starting point, how superficial must be our claim to an understanding of nuclear behaviour. But if we are to be radical we must question that starting point itself and see whether, even if it is justified, it is, or will remain, adequate.

Since the discovery of the neutron in 1932 we have said that the atomic nucleus contains neutrons and protons. More cautiously we should have said that when neutrons and protons are brought together they coalesce to form atomic nuclei. The two statements are not necessarily the same: the nucleons, on coalescing, might lose their identity and form some sort of undifferentiated nuclear "black hole" matter, without granular structure, characterized just by a few overall quantum numbers such as electrical charge, baryon number and angular momentum. The fact that when nuclei are struck violently together nucleons come out does not prove that nucleons were there inside in the first place: barks come out of dogs but that does not prove that dogs are made of barks.

It is, indeed, very difficult to get anything like direct evidence that there are nucleons inside nuclei. Perhaps the nearest approach to direct evidence comes from bombarding heavy nuclei such as lead with very energetic protons, of about 25 GeV in the best
(CERN) experiments, measuring the energy distribution of the outgoing protons closely in the forward direction and comparing that distribution with what would be expected if the nucleus were indeed composed of 2 protons and 2-3 neutrons that interacted with each other. The theory, put like that, sounds easy but is extremely complicated to work out in full numerical detail because you have to allow for the possibility that the bombarding proton makes not just one but many successive collisions as it struggles through the nucleus and also for the possibility that it creates secondary particles (mesons) as it goes. However, when theory (the Glashower method as worked out by O. Kofoed-Hansen) and experiment are compared they agree very well (better than 30%) over the whole investigated energy range; this is about as good as could be expected in view of the inaccuracies in our knowledge of the input data themselves. Nuclear-nucleon collision probabilities. We are therefore convinced that nuclei, even heavy ones, are basically made of neutrons and protons through and through. But is this all?

The literal truth of the shell model.

We know that the picture of a nucleus as nucleons in orbits in independent non-interacting orbitals - the zero-order nuclear shell model - is reasonably correct because we can knock, say, protons out of a nucleus by bombardment with, say, energetic electrons (500 MeV or so in the best (Saccley) experiments) - an (e,p) reaction - and thereby - through the e vs e'p energy imbalance - map out the energy distribution of the protons within their Fermi sea and also - through the e vs e'p momentum imbalance - map out the associated momentum distribution of the protons which is linked by general laws of quantum mechanics, having nothing in particular to do with the nucleus, to the angular momentum distribution of the protons, this latter being itself specified by our independence. Shell model, hypothetically. Energy and angular momentum distributions tally most impressively with expectation in light nuclei such as $^{12}$C. So not only is the neutron-proton model of the nucleus correct but the shell model, at least for light nuclei, is also literally correct: but we must return later to the question of the heavier nuclei, here just noticing in passing that in light nuclei the shell model is virtually indistinguishable from a variety of explicit cluster models.

The simplicity of the atom occasions no surprise because the electron-electron interaction, that perturbs the simple orbital motions of the individual electrons, is feeble compared with the interaction of each electron with the central nucleus that produces the simple orbital motions. But in the nucleus the nucleon-nucleon forces that tend to break down the simple orbital motions (nucleons "bumping into each other") are the very same that must give rise to the overall field of force that somehow generates those simple orbital motions. So how can the motions be so simple? The answer to the conundrum lies in the Pauli exclusion principle that gives rise to the exclusion of the nucleon-nucleon interaction is zero and that the nucleon orbital motions are established by some external field of force so that every quantum state up to some maximum is occupied by a single nucleon. Now switch on the nucleon-nucleon interaction that will try to make nucleons bump into each other and so break down the simple motions of the Fermi sea; the "bump", however, will not be effective unless it is sufficiently violent to lift both participant nucleons right out of the Fermi sea into unoccupied quantum states above its surface since smaller excitations would put the bumping nucleons into already-occupied states and this is forbidden - one state, one nucleon. So whether or not the simple Fermi-sea motions survive in a real nucleus is a question of the depth of the Fermi sea (several tens of MeV as we have seen) in relation to the interaction energy between two nucleons at their usual spacing inside the nucleus. It is not too easy to give a simple answer for this interaction energy because it depends on the details of the nucleon motions and on the effective spectroscopic states in which the "bump" takes place but it is certainly only of the order of 10 MeV. It is therefore not surprising that the Fermi sea survives except in the immediate vicinity of its surface where excitations into a few higher states may take place: the "configuration mixing", the generation of the form of the previous shell model from its primitive forbear of 1950.

Detailed calculations: the conventional approach.

Turning to the quantification of these ideas, we find that detailed shell-model calculations of nuclear structure, starting from nucleons whose orbits are adjusted in size to fit actual nuclear dimensions, but including the experimentally determined nucleon-nucleon interactions operating between the nucleons, give quite good agreement with experiment not only in the level schemes but in static properties such as magnetic moments and in dynamical properties such as radiative transition probabilities although this agreement is superficial in the sense discussed above. Technically much more elaborate unrestricted self-consistent calculations, similar in principle to Hartree-Fock calculations of atomic structure, in which the nucleons are left to work out their own salvation on the basis of their mutual interactions, without the presupposition of any particular dimensions for the resulting orbitals, yield a theoretical nuclear structure - dimensions, surface thickness and binding energies that agree quite well with Nature. An additional feature of these Hartree-Fock calculations is that they predict that many nuclei should not be roughly spherical but rather strongly deformed - have as long as they are wide in some cases - and this is in striking accord with experiment.

Many nuclear properties can be simply represented by speaking in classical-bounding terms of bulk properties of the nucleus: it rotates as a whole or vibrates as a whole. Such collective descriptions of nuclear behaviour are completely consistent with the microscopic shell model that we have just sketched and may be directly derived from it in full quantitative detail in sufficiently simple cases and in convincing outline in more complicated ones where we believe we are held back from a full description only by lack of adequate computer power. For regions where we cannot do that we can make use of semi-classical crutches: the Nilsson model through its evaluation of single particle motion in non-spherical potentials is brilliantly successful in redefining and realistically limiting the number of modes that matter from closed shells in circumstances where the high deformations of the nucleus could certainly not be described in conventional shell model terms within conceivable limits of computer power; both near to and remote from closed shells. New concepts of phonon excitation, themselves susceptible of direct shell-model description in sufficiently simple circumstances and therefore a priori acceptable elsewhere, permit,
by themselves or in association with rotations, an impressive account of nuclei that the shell-model cannot at present realistically touch. But we must beware of too easy seduction: there is no clear-cut line between the rotational and vibrational regimes; where hand-waving draws a sharp distinction Nature seems to make a smooth passage. So bridge models arise: the tri-axial rotator (Davydov), the variable moment of inertia or WME model (Scharff-Goldhaber) the more-radial boson model in the SU(6) scheme (Arima-Iachello) that we shall mention later and so on. Useful concepts are borrowed from other parts of science, superconductivity being a prime example. But we tend to believe that none of these crutches would be essential but for practical limitations on the shell model itself: for example there is no pairing force as such to lie behind superconductivity in nuclei any more than there is to lie behind superconductivity in metals; the nuclear force in nuclei and the Coulomb force in metals ally with the Pauli principle to give extraordinary properties to certain coherent superpositions of otherwise unremarkable quantum states.

All the foregoing, whether rigorous within the shell model scheme or supported by the crutches, we shall call the "conventional" approach to nuclear structure. It makes it sound as though nuclear structure is a closed book — we measure empirical forces between nucleons, we calculate, aided or unaided by a bit of classical imagination, the properties of complex nuclei and the answer comes out right. This is true, but only up to a point.

There are two problems. The first is that our detailed accounts of nuclear structure, as already mentioned, really involve only a few "valence" nucleons near the top of the Fermi sea — just a few per cent of the total nuclear contents.

The second problem is that the "conventional" approach is pressed really quantitatively in a place where it should be able to withstand that pressure, i.e. in a place where, in its own terms, its predictions are unambiguous and not qualified by uncertainties in its own formulation or its own relevant parameters, it fails.

Failure of the conventional approach.

A single example: the intrinsic magnetic moment of the proton, the simplest illustration of this quantitative failure of the "conventional" approach will suffice. The simplest nuclear reaction is the radiative capture of slow neutrons by protons to form deuterons: \( n + p \rightarrow d + \gamma \). The known nucleon-nucleon forces permit an accurate and unequivocal prediction of the cross-section for this process:

\[ \sigma = 0.303 \pm 0.004 \times 10^{-24} \text{ cm}^2 \]

The experimental number is also accurately known:

\[ \sigma = 0.332 \pm 0.002 \times 10^{-24} \text{ cm}^2 \]

The discrepancy between theory and experiment is therefore 

\[ (10 \pm 1.5\%) \]

We find similar discrepancies between theory and experiment wherever we look in systems of the type where the "conventional" approach has no escape: the \( \beta \)-decay of \( ^{3}H \) and other light nuclei; magnetic moments of nuclei of supposedly well-known structure; the density of nuclear matter; the binding energy of nuclear matter. Sometimes almost always goes wrong at the few per cent level: what is it and can we put it right?

To see what is wrong in the "conventional" approach we go back to the beginning: we have spoken of empirically-determined forces acting between nucleons as the basis of our theories of complex nuclear structure; but where do these forces come from and should we not regard to their origins in working out the consequences of their actions? In other words the properties of nuclei may depend not only on the forces between the constituent nucleons but also on the means by which those forces are engendered.

The essential point is that the meson cloud around a nucleon must be pictured as dense rather than tenous, with several virtual mesons around at any moment, so that the meson cloud dressing a nucleon is to be thought of as part of the normal essential substance of the nucleon and not, as in the case of the virtual photon dressing of an electric charge, an insubstantial frill that may be disregarded to a first approximation.

Indeed, when the internal charge distribution of a proton is probed by the scattering of energetic electrons from it, it is found that the proton, unlike the electron, is not a point charge but an extended structure \( r = 2\times10^{-14} \text{ cm} \).

So nucleons may be thought of as fuzzy balls of size about \( 10^{-13} \text{ cm} \); when two nucleons approach, each has no means, apart from the relatively weak electric force that we disregard at this stage, of knowing that the other is there until their mesonic clouds begin to interpenetrate; when this happens we can imagine that occasionally a meson that has emerged from one nucleon will not go back in again but will rather pass across to the second nucleon and thereby carry word of the first one's presence i.e. establish an interaction, a force.

It is therefore this exchange of mesons, pions at the greater distances, heavier mesons, pairs of pions and so on at smaller distances, that constitutes the force between nucleons that we can empirically measure and that, then forgetting the mesonic origins of the force, we use as the starting point of our "conventional" theories of nuclear structure — that typically get things wrong by about 10%. However, the overall properties of a complex nucleus must depend on the totality of what is going on inside it and not just on what its nucleons are doing; for example the flow of charged pions between the nucleons, helping to establish the force between them, constitutes an electric current in addition to the currents due to the motions of the protons themselves and so will contribute to all current-linked phenomena, for example the magnetic moment. Another possibility is that a pion "in the air" between two nucleons may disappear to give an electron-neutrino pair, \( \pi \rightarrow e + \nu \), thereby contributing to the weak (\( \beta \)-decay) properties of the nucleus. Such mesonic effects must show up everywhere to some degree and when we calculate that degree to the best of our present ability, it turns out to be typically a few percent. We must obviously "mesonize" our "conventional" nucleons-only approach and let in the mesons explicitly.

Consequences of "mesonization".

"Mesonization" has further consequences; when real pions bombard nucleons in the laboratory we find that the nucleons can be thereby raised into a multitude of excited states: the resonances or isobars; just as the quanta of the electromagnetic field, photons, can raise systems held together by that force, e.g. atoms or molecules, into excited states, so when nucleons interact, which they do by bombarding each other with the quanta of the nuclear force field, viz. pions and other mesons, in
the virtual state to be sure but that makes little essential difference, there must be a certain chance that the bombardment will result in the excitation of isobars.

It is worth pausing to notice that these isobars, excited states of the nucleon, bear very direct relationships to the familiar excitations of complex nuclei: the nucleon and its excited states represent the internal consequences of the primitive strong force that may, or may not, be described as the exchange of coloured vector gluons between coloured quarks to preserve the baryon as an overall colour singlet, at least to the excitations so far investigated in detail; the external consequences of the strong force that holds nucleons together into complex nuclei are not due to the direct exchange of gluons between nucleons but are described as the exchange, between nucleons, of mesons, themselves quark plus anti-quark held together through a colour field. The external and internal strong forces are therefore distinct but generically related and may bear much the same relationship to each other as the Coulomb force, which is the internal force that holds together atoms and molecules, bears to the external van der Waals force that operates between discrete molecules.

The "external" van der Waals force is the almost-screened-out tail of the "internal" Coulomb force whereas the "external" N-N force is the similar tail of the primitive "internal" strong gluon force, almost screened out by its pre-occupation with holding together the quark and anti-quark of the exchange meson. Another way of expressing the awkwardness, and so the weakness, of the N-N force in quark terms is to see it as due to the simultaneous exchange of two quarks between the nucleons, one quark from each nucleon going to the other; since the two quarks are "going in opposite directions" one appears as an anti-quark and their combination as a meson. Alternatively, as one quark leaves one nucleon for the second nucleon, a quark-anti-quark pair is produced in the first nucleon; the quark of the pair carried off by the departing quark while the anti-quark accompanies the departing quark, the two forming a meson; on arrival at the second nucleon the antiquark annihilates with a quark of the second nucleon and the quark from the first nucleon joins the remaining two of the second nucleon. But the consequences of the internal and external strong forces have the close parallels that this digression draws to attention: excited states of the nucleon can be pictured in just the same way as excited states of the nucleus:

(i) the first excited state of the nucleon is the isobar $J^P = 3/2^-$, $T = 3/2$ at about 1232 MeV (total energy). It is made simply by flipping the spin of the quark whose spin opposes the other two from the anti-parallel to the parallel position just as in a nucleus one makes an excited state by reversing a nucleon's spin direction relative to the rest. The difference with the quarks is that because of the colour degree of freedom three quarks with parallel spins can be in a mutual s-state giving $J^P = 3/2^+$ and $T = 3/2$, ranging from 3 "up" quarks (charge +2) to 3 "down" quarks (charge -1);

(ii) the $J^P = 1/2^+$, $T = 1/2$ N$^\pi$-isobar at 1470 MeV, sometimes called the Roper resonance, is thought to be the radial excitation, "breathing mode", of the quarks of the ordinary nucleon, directly analogous to the giant E0 resonances of nuclei;

(iii) the $J^P = 3/2^-$, $T = 1/2$ N$^\pi$-isobar at 1520 MeV is thought to be formed by raising one of the quarks of the nucleon into an $l = 1$ state and is therefore the direct analogue of the E1 giant resonance of nuclei;

(iv) the $J^P = 3/2^+$, $T = 1/2$ N$^\pi$-isobar at 1668 MeV, the first Regge recurrence of the nucleon, is the nucleon's first "bulk" rotational state, analogous to the famous rotational states of ordinary nuclei.

The intervention of the isobars has two important consequences for our discussion of complex nuclei:

(i) If an isobar is formed in a free nucleon-nucleon ($N-N$) low energy collision it cannot persist because it is more massive than the free proton and so, by the Heisenberg uncertainty relation, must disembarass itself of its excitation energy $A\delta$ within a time $\delta t$ given by $A\delta t = h$; the lightest isobar is the $\Delta$ for which $A \Delta$ = 290 MeV so the longest $\delta t$ is about $2 \times 10^{-24}$sec; this de-excitation must be effected by, for example, the re-emission of a pion such as gave rise to the excitation and its reabsorption by the other nucleon; this merely constitutes part of the $N-N$ force such as we use in the "conventional" shell model computation. If, however, the two nucleons in question are part of a complex nucleus another option is open: the pion that de-excites the isobar may be absorbed by a third nucleon thereby constituting a force of an essentially 3-body nature that comes into play only when the two nucleons are close enough together and that is distinct from the sum of the various possible 2-body forces that operate between the three. This 3-body $N-N$ force may therefore be introduced into our computation of nuclear structure additionally to the 2-body $N-N$ forces of the "conventional" approach. (Such genuine $N-N$ forces can arise in other ways: for example the exchange of a p-meson between two nucleons is part of the $N-N$ force; but the p-meson, after emission by one nucleon of a complex nucleus, may decay, $\rho \rightarrow \pi + \gamma$, and not be absorbed as a p-meson by a second nucleon at all; if both decay pions are then in fact absorbed by the second nucleon this is again just a piece of the $N-N$ force but if one decay pion is absorbed by the second nucleon and the other by a third we have an $N-N-N$ force.)

(ii) The isobar, having been formed, may de-excite to a nucleon not by emission of a pion but by emission of, for example, a photon, real or virtual, or an electron-neutrino pair, which will therefore constitute an electromagnetic or weak interaction of the nuclear system additional to that involving.
nucleons alone (or nucleons plus mesons only).

A further possibility is that a pion, in flight between two nucleons A and B, may dissociate into a nucleon and an anti-nucleon; the anti-nucleon then annihilates with nucleon B giving a pion that is absorbed by nucleon A so that the final state, as the initial one, consists of two nucleons and this process is just part of the N-N force. However, if nucleons A and B are part of a complex nucleus, the pion coming from the annihilation of the anti-nucleon with nucleon B could be absorbed not by nucleon A but by a third nucleon of the initial system thereby constituting another component of the N-N force. Similarly, the annihilation could yield a photon or an electron-neutrino pair rather than a pion so that this pion-dissociation mechanism contributes also to the electromagnetic and weak properties of the nucleus.

What is the quantitative importance of these processes whose qualitative rôle is undeniable? We examine the example of radiative neutron-proton capture that we saw above to have a (10 ± 1.5)% discrepancy with "conventional" nucleons-only theory. We now see that the "conventional" theory in which the gamma-ray "comes out of the nucleons" must be supplemented by at least three additional mechanisms:

(i) A pion is emitted by one nucleon but, while it is "in the air", before being absorbed by the other nucleon, emits the gamma-ray;

(ii) A pion is emitted by one nucleon and on absorption by the other raises it into an isobaric state that de-excites emitting the gamma-ray;

(iii) A pion is emitted by one nucleon and dissociates "in the air" into a nucleon and an anti-nucleon; the anti-nucleon annihilates with the second initial nucleon giving the gamma-ray.

The sum of these three mechanisms in fact completely removes the 10% discrepancy. (Rh-\textit{Cheung-Hiski-Brown}). Other discrepancies among the properties of the lightest nuclei, for which we think have quantitatively-reliable "conventional" predictions, are similarly removed, or significantly reduced, by similar mesonic interventions.

The rôle of mesons and isobars in the structure of more complex nuclei and of nuclear matter similarly remains at the 10% level and we must now work out reliable ways of bringing the effects to account in specific calculations.

It is therefore quite wrong just to think of the mesons as the generators of the N-N force then to use that force for nuclear structure computations and forget about the mesons that gave rise to it: they must be brought in explicitly if we want to get the right answer.

So far we have spoken chiefly of pion-exchange because the pion is the lightest meson and so has the longest "reach": \( \pi/\hbar c = 1.4 \text{ fm} \). But the heavier mesons can also be exchanged and give important contributions to the N-N force at smaller distances; for example the \( \rho \)-meson's coupling to nucleons is very strong and although its reach is only about 0.3 fm it is an important contributor to the N-N force. However, the fact that a meson is heavy does not exclude it from certain long-range effects. For example a \( \rho \)-meson could emerge from a nucleon, quickly convert to a \( \tau \)-meson by emission of a photon or interaction with the electromagnetic field, \( \rho \rightarrow \pi + \gamma \), giving a "long-reach" pion to be absorbed by another nucleon. This process contributes to certain nuclear properties, specifically to the isoscalar magnetic moments of nuclei to which the process \( \pi + n \rightarrow \gamma \) does not, and so it can in principle be picked out and identified.

Complex nuclei must similarly contain "strange" mesons and hyperons by virtue of processes such as \( s \rightarrow \Xi + \bar{\Xi} \) and \( N + \Xi + \bar{\Xi} + N \) but it is more difficult to put their undoubted presence into evidence.

The ambiguities of mesonization.

Although it is now clear that explicitly mesonic effects are important at least at the 10% level this does not mean that the procedures by which we have introduced them are adequate or even right. We have taken the line that we start from an empirical N-N force that is presumably generated by meson exchange in a manner that we do not understand in detail; the mesons are then forgotten for the time being, the empirical N-N force being used to calculate the structure of the "conventional" system of nucleons only, moving under the influence of that N-N force; such mesons as we know how to treat adequately are then let back into that nucleonic structure without changing it and their explicit additional effects such as their electromagnetic and weak properties and their generation of isobars and N-N forces are essentially treated as perturbations that do not fundamentally change either the initial structure or the nucleons that constitute it. We will now look at a few difficulties.

The first difficulty is that this "mesonated conventional" approach is essentially ambiguous, for example we quickly find that we are running the danger of double counting: when long-lived nucleon states, such as the zero-order shell model orbitals of the Fermi sea, are involved it is fairly clear that the mesonic exchanges between them, of time order \( \hbar/\pi c^2 = 5 \times 10^{-24} \text{ sec} \) for a pion and shorter for other mesons, are relatively fleeting additions that can be explicitly separated out and discussed; when considering more complicated nucleon motions such as are associated with the successful N-N "bumps" that do occasionally lift nucleons out of the otherwise tranquil Fermi sea and that may involve excitations of \( \Delta E = 100 \text{ MeV} \) or much more, we see that such nucleonic excitations are themselves fleeting (\( \Delta t = \hbar/\Delta E = 7 \times 10^{-24} \text{ sec} \) when \( \Delta E = 100 \text{ MeV} \)) and are comparable in time scale with the exchange times of the mesons themselves that gave rise to the "bump". The meson exchange and the associated nucleon motion can no longer be cleanly separated from each other and we clearly must not simply add their separately-computed effects because they must to some degree just be different representations of each other.

The need for a many-body field theory.

In principle the way out of this first difficulty is to abandon the "mesonated conventional" approach, in which we take the empirical N-N interaction as the starting point and add explicit mesons and isobars later, in favour of a true many-body relativistic field theory in which nucleons, mesons and isobars partake with equal right in an overall description of the resultant system whose properties, such as its interaction with the
electromagnetic field, would then be given un-
ambiguously; there would be no forces as such in
the input data but only the identity of the
various nucleons and the associated coupling
constants appropriate to the various particle
combinations.

This counsel of perfection cannot yet be
followed but we might hope for progress along the
following lines: take a very simple model,
soluble in relativistic many-body field theory, a
system containing perhaps one species each of
nucleon, isobar and meson then: (i) compute the
N-N force that would arise from the meson exchanges,
use this force in the "conventional" way to
calculate "meson-only" wavefunctions, "mesonate"
this "conventional" structure by adding the mesons
and isobars perturbatively as sketched above and
then compute whatever properties you are interested
in using various recipes for resolving such
ambiguities as you can spot; (ii) compute the same
properties from the proper full solution.

In this way we should get a feel for the right
way to handle the ambiguities and for the degree to
which the "mesonated conventional" approach can be
relied upon as a stand-in for the real thing.
Although it may not be possible to treat field
theoretically a realistic assembly of mesons,
nucleons and isobars it may be possible to treat
separately several sub-sets, viz. different limited
selections of mesons and isobars, and so get a feel
for whether the ambiguities can be systematically
resolved. Whether such different limited recipes are going to
be necessary for different meson exchanges etc.

New modes of nuclear behaviour; condensation;
clustering.

The second difficulty of the "mesonated
conventional" approach is related to the first and
is that it may miss entire new degrees of freedom,
new modes of nuclear behaviour, essentially
because it closes its eyes to the possibilities.
For example, our "mesonation" considers only meson
exchanges between pairs of nucleons, or threes
when isobar excitation is included. But it is
entirely possible that meson circuits involving
more than two nucleons may get excited with the
very strong $\pi + N - N$ (N=O) interaction, involving the $\Delta$-isobar, as a kind of catalyst for the
generation of pions. Indeed, so strong is the
N=O interaction that it is quite on the cards that
the entire nucleus may participate in such pionic
circuits with the pions then pursuing orbits
referred to the nucleus as a whole like those of
the nucleons themselves. The total energy of the
system could then minimise at a very high pion
density: the "pion condensation" phenomenon,
associated particularly with A.B. Migdal, that
has been much discussed recently. Although it seems
unlikely that nucleon of normal density already
contain such condensed pions (a point made
especially by C.E. Brown) it also seems likely
that this phenomenon might set in at densities
elevated by only a factor of two or three above
normal, so that real nuclei may already contain
the beginnings of such condensations, on a short
time scale associated with density fluctuations;
these mini-condensations or multi-nucleon pion
circuits may already have some importance for the
overall energy balance and, specifically, might
lower the energy of certain types of nuclear
cluster structure, promoting clustering into possibly well-defined nuclear sub-structures;
these sub-structures would not necessarily be
long-lived but might be numerous and even fairly
well defined if seen in a snapshot.

If quasi-stationary sub-nuclear many-N=O
clusters exist then the $\pi$ themselves in such
clusters will be modified free-space properties just as the properties of a coupled
system of identical resonators of any kind differ
from the properties of the individual identical
resonators: the effective energy and width of the
$\Delta$ will depend on the type of cluster of which
it is part. This we might hope to see by exciting
such clusters through the bombardment of nuclei
by real pions: in principle the $\Delta$-resonance might
shift or split and we should probably stand our
best chance of seeing this by looking specifically
in final-state channels that might be preferentially
fed in the ultimate decay of such clusters via
involving high energy complex fragments such as
$\pi$-particles etc. as has been emphasized by E. Vogt.

Even more radical "whole-nucleus" consequences of
mesonic exchanges might be envisaged. Although
the N=O interaction that may make pion condensation possible is very strong it is a $\pi$-wave interaction that
peaks for free pions bombarding stationary
free nucleons at $E_\pi = 200$ MeV so that the indivi-
dual condensed pions tend to be "energetic" and this
tends to raise the energy of the condensate. How-
ever, consider the case of the hypothetical
$\pi + \sigma$-meson that would have a strong $\sigma$-wave
interaction with nucleons; this could promote condensation for "zero-energy" $\sigma$-mesons and it has been
suggested by T.D. Lee and G.C. Wick, on the
basis of a very many body field-theory, that the
associated nucleon density could be very high —
perhaps ten times normal — and the system more
stable than the normal nuclear ground state. It is
therefore conceivable that there are some such
collapsed nuclei, "abnormal nuclear states", already around in nature but if so they are very
few. Recent work by M. Eho suggests that although
such abnormal states of high density can probably
be made they are probably also high in
excitation above the normal ground state and so
will be difficult to identify. However, their
transitory role, rising upon density fluctuations
in ordinary nuclei as discussed above for pions, may
not necessarily be totally negligible. Note
that even if an identifiable $\sigma$-meson does not exist
such (and a broad correct quantum numbers has been seen in the $\pi$ system at
a total energy of about 1200 MeV) states of
appropriate properties could be synthesized out
of pairs of pions, $\pi\pi$ etc.

The time scale of condensation phenomena.

An interesting question of practical
importance is raised by these field-theoretical
and other discussions of the density of mesonic
fields as a function of density of nucleons: the
time scale. If the nucleon density is suddenly
changed say in a shock-wave generated by the
collisions of two fast heavy ions or in a sponta-
naneous nuclear fluctuation how long does it take,
say, the pion field to establish its equilibrium
value, how long does the phase change to the
condensed state, if there is to be one, take to come about? The calculations of, say, the pion field
density are equal time calculations in which,
as a function of nuclear density, pions have
themselves a right to a certain equilibrium density
by virtue of the magnitudes of the various
coupling constants; but these equilibrium
calculations do not tell us how the pions get there:
obviously, in a sense they must
"come out of the nucleons" but the calculations do
not tell us how and so they do not tell us how long
equilibrium will take to reach. The situation is analogous to that of the Planck spectrum of black-body radiation. If I suddenly ask how long does it take for the Planck spectrum to establish itself? The spectrum is an equilibrium spectrum to which the cavity has a right determined only by its temperature and not dependent on the material out of which its walls are made and yet the photons must "come out of the walls" and take a time to do it that will be determined by the nature of the walls. This question of time scale is obviously of importance in the nuclear case because the only means we have available, at least on earth, for changing the nuclear density are themselves of short time scale; it is quite possible that critical densities for condensation might be exceeded in a heavy ion collision but the nucleus pull itself apart before condensation has time to establish and manifest itself; that would be a pity.

Nucleon structure in the nucleus.

Returning to the difficulties of the "mesonated conventional" approach we find a third substantial problem that takes us right back to our discussion of nucleon structure. The free nucleon is a dynamical structure containing pion and omegaonic currents. We must interact with each other only by virtue of the exchange of the same mesons such as contribute to the build-up of their individual structures; in saying this we must additionally bear in mind that mesons are not conserved so that the exchange of mesons between nucleons will affect the flow of mesons within the individual nucleons but not in any simple way. The situation is very much like that of the near-zone of a radio antenna; energy flows out of the antenna again (circulation of virtual photons); when a second, identical, antenna is brought near the first, energy now flows out of one and into the other but the original flow of energy out of each and back into the same antenna again is also changed. Thus those properties of the individual nucleons that are affected by their internal mesonic constitution (the \(i\)nter-nucleonic meson currents) such as their magnetic moments and intrinsic \(\beta\)-decay rate will be changed when they are brought into each other's vicinity, in a manner additional to the contribution to the overall nuclear property in question that is due to the \(i\)nter-nucleonic meson currents. Indeed, just as in the analogy of the antennas one cannot separate the "intra" from the "inter" effects in any unambiguous way; we find ourselves, at this deeper level, facing the same kind of problem as arose in our discussion of the exchange-current/configuration-mixing ambiguity; in the present case we clearly need a model of nucleon structure before the resolution can be effected and this is one stage beyond the relativistic many-body field theory that constituted our in-principle hope for resolving the earlier problem. It is impossible to guess how important such "nucleon modification" effects might be but they will clearly be greater for processes that require nucleons to be in strong interaction and we might hope to get some indication from, for example, high energy photodisintegration that will depend on, among other things, the magnetic dipole moments of the "individual nucleons".

Nuclei in Unusual Conditions.

This wide digression into the mesonic workings of the nucleus has shown both that "mesonation" is necessary if we are to improve the answers that come from the "conventional" approaches and that we must in addition be ready for major surprises. It is clear that both explicit "mesonation" and the move towards a many-body field theoretical view of the nucleus are going to be major directions of development of nuclear structure physics over the next many years. But let us now return to more conventional matters if only to realize how little we may take for granted even if we restrict our view of the nucleus to nucleons only.

Is the shell model all right inside?

As we have noticed, all we really think we know is some aspects of the foam on top of the Fermi sea; the behaviour of the very few effective valence nucleons. What in fact is happening in the depths of the Fermi sea? Are the underpinning "closed shell" nucleons that hold up the foam really pursuing the shell model orbitals as they are supposed, apart from the Emmenthaler effect, filling up the quantum states in orderly fashion from the bottom of the effective potential wall or are they perhaps doing something significantly different? Is it possible, for example, that the "A-minus-foam" Emmenthaler nucleons are not on shell model orbitals at all but are a mass of \(p\)-particles? Or a crystal lattice? Nice? Not nice. One might be tempted to reject such radical notions arguing that when I carry out the reaction \(^{209}\text{Pb}(d,p)^{209}\text{Pb}\) to the ground state of \(^{209}\text{Pb}\) I find that a good \(l = 4\) stripping pattern results with a single-particle spectroscopic factor that combines with the known \(J^\pi = 9/2^+\) of \(^{209}\text{Pb}\) to confirm that, as expected, \(^{209}\text{Pb}\) is a doubly-closed shell with single particles sitting on all the lower orbitals and the single valence nucleon of \(^{209}\text{Pb}\) in its \(2g_9/2\) state. Let us see how far we may have to retreat from this naiveté:

(i) The facts just recited do not imply that \(^{208}\text{Pb}\) is a doubly-closed shell; the top of the \(^{208}\text{Pb}\) Fermi sea could be covered with foam representing excitation from shells just below the surface to those just above and then, provided that that foam remained unchanged on adding the extra neutron (weak coupling) the facts could remain as stated;

Retreat further:

(ii) We cannot really say that the \(2g_9/2\) neutron width is a single particle width with great precision. Such statements always have some elements of the hocus-pocus about them in the sense that optical model potentials such as are essential to interpret the stripping cross sections are always checked against "known single-particle states" and there is no indication that we can significantly relax the weak coupling assumption of (i) and say that the stripping reaction merely transforms the \(J^\pi = 0^+\) foam at the top of \(^{209}\text{Pb}\) into a \(J^\pi = 9/2^+\) foam at the top of \(^{209}\text{Pb}\) the two being related through a rather large fractional parentage coefficient but one that may be significantly less than unity;

Retreat further:

(iii) The nucleons below the foam may not be totally filling the nominal shell model levels; each level may be significantly
occupied to the degree that the associated quantum number is pre-empted in the manner that would indeed make the $2g_9/2$ level the next available to the $169$ neutron of $209\text{Pb}$ but at the same time each level may have an occupation number significantly less than unity with "the rest of the nucleons" spread over states above the Fermi surface.

This is probably as far as we can responsibly re-treat from priority: the properties of $209\text{Pb}$ make it seem unlikely that the depths of $209\text{Pb}$ can be entirely $\alpha$-particles or a crystalline nucleon lattice because that would make "$2g_9/2$" for the last nucleon of $209\text{Pb}$ difficult to understand. However, it must be stressed that all that is demanded by the experimental data is that the shell model quantum numbers be pre-empted in turn and this does not demand anything like occupation numbers of unity. It is clear that this situation of pre-emption can arise only if the excitations that partly empty the low-lying levels are rather massive: the effect would not arise unless the excitations were typically of many tens or hundreds of MeV and we may here indeed by speaking of the difference between particles and quasi-particles in the Brueckner sense. Unless the average excitation in question were high we could anticipate a situation in which, although for light nuclei the effective filling of shells would follow the normal sequence, beyond a certain point in the shell sequence new nucleons would begin to accommodate themselves chiefly by dividing themselves among the unoccupied fractions of the "already filled" lower orbitals with only a small amplitude for the nominally next vacant shell model orbital which they would therefore not effectively pre-empt. Obviously this effect of division of a new nucleon, part going down into the stiff low-lying holes, part going up into shells above the Fermi surface, part into the soft fat at the top of the Fermi sea including part into the nominal shell model orbital, must almost certainly result in a less than optimal weight of the nucleons at the top" tends to squash out the resistant low-lying holes in the Emsenenthaler. All that we can say is that for the heaviest nuclei of which we have knowledge a significant, and probably major fraction, of the new nucleon is still going into the nominal orbital although we have no idea as to how long this will persist and it must remain as an uncertainty in, for example, our arguments about the possible structure of super-heavy elements.

So we cannot rule out the possibility that the nominal shell model description of the insides of heavy elements is far from the whole story and that we have significant amounts of excited orbitals to speculate with. What is most likely to happen?

Nucleon clustering in the nuclear depths?

The first thing to notice is that the nucleus contains a lot of empty space. The r.m.s. size of the electromagnetic structure of the proton is about 0.8 fm, which distance we may then crudely take as the "radius" of a nucleon. Take an equatorial slice through $209\text{Pb}$ treated as a random gas of spheres of radius 0.8 fm distributed so as to reproduce the known radius and surface diffuseness of lead; bring any nucleon so sliced into the equational plane; a typical result would be as in the figure where neutrons are open circles and protons are solid. We see that $209\text{Pb}$ is chiefly empty space, it is "full of air", with plenty of opportunity for the nucleons to get closer together should that prove to be energetically profitable.

One immediately thinks of the possibility of $\alpha$-particle clustering. The size of clusters into which nucleons will tend to accrete is determined by the binding energy of the last particle: about 20 MeV for the $\alpha$-particle as against 8 MeV or so for a heavy nucleus; there is therefore strong encouragement for nucleons, left to their own devices, to form $\alpha$-particle-like clusters. It must be remarked in this context that $\alpha$-particles are indeed significantly different from ordinary nuclei; a corollary of the difference of last-nucleon binding energy just remarked upon is that the central density of the $\alpha$-particle approaches twice that for a heavy nucleus so that it is indeed a relatively compact object that could well group itself in significant numbers taking advantage of the empty spaces seen in the figure. Presumably such $\alpha$-particle groupings would be pretty transitory affairs with a rapid dissolving of the $\alpha$-particles into the rest of the nucleus followed by new formations elsewhere but it would only take a persistence of some 10 MeV or so, viz. $10^{-22}$ sec. or so, to establish an $\alpha$-particle adequately for the purposes of present discussion.

In the past one has tended to discount the possibility of more-or-less literal $\alpha$-particle groupings within the nuclear depths on the grounds that they would be inhibited by the Pauli principle: if all shell model states are fully occupied this means that nucleons are moving on large orbitals centred on the nucleus as a whole and so cannot simultaneously be running around each other in small circles. One has been prepared to admit that in the nuclear surface, where the nucleon density is getting low and so the local effect of the Pauli principle is not so strong, $\alpha$-particle clustering may be more likely. Indeed, "knock-out" experiments, in which pre-equilibrium emission of $\alpha$-particles takes place under neutron or proton bombardment, have for long demonstrated that the probability that the initial
(largely surface) Interaction of the incident nucleon with the nucleus should be with an effective $\alpha$-particle is high - typically 0.4 or so (recent systematic work by the CISE, Milan group) - so that the surface of a heavy nucleus must be thought of as exhibiting several $\alpha$-particles (say 2 - 6) if seen in a snap-shot; the nucleus begins to look like a raspberry. (Note that this notion does not imply that the fractional percentage coefficient, with respect to an $\alpha$-particle, between the ground state of a particular nucleus and low-lying states of its daughter gained by $\alpha$-particle emission should be high or similar from one nucleus to the next; these are matters for determination by the local shell structure. Thus all nuclei might look similar, in a snap-shot, in respect of $\alpha$-particle clustering on their surfaces but some might display that clustering in respect of low-lying states of the $A-\alpha$, $A-2\alpha$, $A-3\alpha$ ... nuclei and others in respect of more highly excited states; off-hand we should expect the $\alpha$ and multi-$\alpha$ parentage to be higher for low-lying states of the single-nucleon shell model orbitals is significantly less than unity which would be equivalent to saying that nucleons can run round each other in small circles for short times. It has been known for many years (Narada 1961) that quite small amounts of configuration mixing into low-lying shells just above the surface of the Fermi sea can dramatically enhance the probability of surface $\alpha$-particle formation; no systematic study has been made of the efficiency in this respect of excitation into significantly higher configurations such as we are now hypothesizing - indeed have to hypothesize to preserve the correct pre-empting of the low-lying shell model orbitals - but we can well imagine that on account of the higher momentum states involved and the associated richer modulations of the radial wavefunctions, such high excitations may be very efficient in promoting $\alpha$-particle clustering also in the depths of the nucleus.

It therefore seems possible that the insides of large nuclei look quite $\alpha$-particle like and it will be tremendously exciting to get an experimental handle on this by appropriate modes of excitation. What these appropriate modes are to be is not clear although we should remember that 20 years or more ago it began to appear from cosmic ray studies of relativistic heavy ion collisions that $\alpha$-particles are very abundant among the products of the fragmented incident nuclei; this does not prove that alpha-particles were there in the first place - cf. the above cautionary remark about dogs and barks - but is at least consistent with it. (See later for a comment on a related but distinct possibility for generating $\alpha$-particles in such collisions through "continuum isomers").

When we come to consider lighter nuclei, $\alpha$-particle sub-structures emerge as merely alternative representations of the simplest shell model itself, as being due just to the Pauli principle acting on symmetrically-filled neutron and proton shells and without any explicit $N=Z$ forces at all; this has been known for many years (Perring and Smythe 1956). These purely shell model $\alpha$-particles have the same angular wavefunctions as real $\alpha$-particles, referred to their own centres of mass, but a somewhat looser radial structure. There is, however, no doubt that the $N\alpha$-interaction will tighten the clusters into something much more like "real" $\alpha$-particles although the degree to which this happens in practice is still unknown.

Returning to the more general and interesting problem of the heavy nuclei, with this remark about light nuclei in mind, we see that $\alpha$-particle formation will be most likely between neutrons and protons that occupy the same shell model orbitals so that the phenomenon may become significantly more striking as we move away from the stability valley in the proton-rich direction.

Continuum isomers.

We turn now to the "related but distinct" matter referred to above. Ask what happens when a heavy nucleus becomes highly excited (say by 10A MeV or so) in a fairly uniform manner throughout the nucleus, if that is possible. As the nucleus expands there will be competition between evaporation of its contents and their recondensation under the attractive nuclear forces. As evaporation proceeds the nucleus cools and condensation of what is left becomes more likely. Initial condensation into $\alpha$-particles is most likely and, conversely, in the course of expansion $\alpha$-particles are the clusters least likely to have been broken up following the initial heating process. So it seems quite probable that a stage composed of a mix chiefly of $\alpha$-particles and neutrons, the free protons having been the more likely to have been evaporated because of the entraining effect of the Coulomb force, will be reached. The number of $\alpha$-particles in relation to the original nucleus and the $A/N$ ratio will obviously depend on the circumstances. The intriguing question is the time scale of the final stages. The expanded cloud of separate $\alpha$-particles will be tending to condense itself under the mutual Coulomb repulsion but the neutron gas in which the $\alpha$-particles are dispersed will tend to produce positive binding. It is conceivable that some temporary balance may be struck between these competing effects resulting in what might be termed a "continuum isomer". Whether or not such a state, long-lived on the nuclear time scale, is formed, it seems very likely that the debris of the initial nucleus will pass through an $\alpha$-particle-rich phase whose breakeven point $E_b$ finally carries it that way, may contain many $\alpha$-particles. This effect could then be a source of the many $\alpha$-particles seen in cosmic ray events referred to above in some of which an incident nucleus is seen to dissociate entirely or almost entirely into $\alpha$-particles.

Meson condensation and clustering.

We earlier noticed that if nuclei are not too far from the conditions of phase change to meson condensation of some type then certain sorts of excited state may show up at unexpectedly low energies of excitation because they resemble nucleonic configurations, possibly into certain types of cluster structure, in which meson condensation is easiest: there will be a boot-
strapping between configuration and incipient condensation. Although this effect may well be present in nuclei at modest excitation, or even in ground states, induced via ordinary density fluctuations, it could be much stronger when nuclei are highly compressed as they might become in energetic heavy ion collisions. This might detect through the products of energetic heavy ion collisions differing significantly from the shower of α-particle and related "ordinary" fragments that our reflections on "continuum isomers" lead us to expect: if the "isomeric" stage is passed through than by definition the time scale is long and we expect few nuclear products but if the whole time scale is short then meson condensation or incipient condensation could well lead to very unexpected modes of fragmentation.

α-particle clustering.

It will clearly be very difficult to pin down the degree of α-particle clustering, particularly in the heavier nuclei and particularly from the point of view of α-particle formation through the reaction mechanism; we have examined one example of this problem under "continuum isomers". There are, however, some strands in the wind, apart from direct measurements of spectroscopic factors. We look now at two, both pointed out by G.E. Brown.

The Nolen-Schiffer anomaly is the persistent failure, by some 102 throughout the periodic table, of the mass differences between isotopic analogue states to be explained in terms of the computed Coulomb energy based on "realistic" wavefunctions and the known nuclear sizes ős. The sense of the discrepancy is that the measured mass differences are bigger than the computed e.g. if we consider the well-studied pair ⁴¹°Ca - ⁴¹°Sc. ⁴¹°Sc is some 0.7 MeV heavier than it should be on the basis of its extra Coulomb energy. The obvious way out of the problem is to involve a breakdown of charge symmetry: if the pτ bond in ⁴¹°Sc is weaker by several tenths of a percent than the pτ bond in ⁴¹°Ca, that it replaces, the effect would be produced. However, so strong a departure from charge symmetry is not an attractive proposition: like-nucleon forces are due to symmetry of exchange, whether single or multiple, so no charge symmetry is expected on the grounds of the mass differences between charged and neutral nucleons such as give a ready explanation for the breakdown of charge independence. Only if isospin mixing in the exchange mesons themselves, e.g. ²⁻⁻ and ⁰⁺⁻ mixing, or by virtue of mass differences among intermediate-state isobars for multiple pion exchange, could one understand a breakdown of charge symmetry and then the required magnitude seems to be surprising large although not perhaps out of all reason. All conventional nuclear structure approaches have so far failed to resolve the anomaly; but consider what we should expect if nuclei had a strong tendency to develop an α-particle-rich surface. Consider ⁴¹°Ca and ⁴¹°Sc, to continue our present illustration, to be ⁴⁰Ca plus an odd ²⁻⁻ neutron and proton respectively. Now Hartree-Fock models of the high nuclei show the surface to be slightly proton-rich essentially because of the Coulomb repulsion suffered by the protons and not by the neutrons. The odd ²⁻⁻ neutron and proton, which tend to be towards the surface because of the peaking of their ²⁻⁻ wavefunctions, therefore find themselves in a slightly proton-rich environment, which will make it easier for the odd neutron of ⁴¹°Ca to find partners to form an α-particle than for the odd proton of ⁴¹°Sc. ⁴¹°Ca is then depressed slightly relative to ⁴¹°Sc because of its greater richness in the strongly-bound surface α-particles: the sense of the observed anomaly.

The second persistent problem that may be resolved by α-particle clustering is the energy of the electric dipole giant resonance. This is found at energies from about 20 MeV for light nuclei to 13 - 14 MeV for heavy nuclei. The origin of the resonance as a coherent superposition of single- particle excitations between successive major shells is well understood and has its classical visualization as a collective swinging backwards and forwards of all the protons relative to all the neutrons. If, now, the neutron and proton distributions were not free to swing backwards and forwards relative to each other without change of their individual sizes and shapes but were constrained to do so within an enclosure that did not change its overall size and shape, e.g. if the neutron and proton motions were tied down at their edges so that all could change was the relative n/p density within a fixed boundary, then the resonant frequency would obviously be higher than if there were no such boundary condition and the swinging were free. In fact, in the heavy nuclei, the shell model, which contains no such boundary condition, persistently gets the resonance energy too low by 1 - 2 MeV. If, now, we tied the nuclear surface down by an α-particle crust, the resonance energy would go up. Alternatively, if we consider a more generalized α-particle-rich description of the nucleus such as hinted at above, we would naturally expect the resonance energy to be higher than for a more traditional shell model nucleus because the giant resonance in the α-particle itself is at over 20 MeV.

Boson models.

Mention has been made of the observation, by Arima and Iachello, that a very impressive unification of "vibrational" and "rotational" states of nuclei can be achieved by pretending that nuclei are made of spinless bosons individually able to occupy states of l = 0 and l = 2. The level schemes, which are representations of the SU(6) group, display vibrational or rotational characteristics as limiting forms depending on the relative importance of the interaction between the bosons and the potential chosen by the n = 0/l = 2 splitting; in between there is the smooth transition of which, as we have already noted, Nature seems to approve. The scheme is a compelling one and one naturally seeks a physical identification for the bosons. The α-particles for which nīhil obstat case has been made out as being generated from the partly-filled deep-lying shell model states plus admixture of high-lying excitation, e.g. of the neutron and proton states, may seem to offer themselves; but what, then, is the essential l = 2 excitation? Configurationaly one can take two "deuterons" and put them together to make the ground state of the α-particles or, alternatively, using the [2,2] particle, to make the ³²°F° free ³⁴°T = 0 l = 2 state that may be seen experimentally at about 33 MeV but this would not seem to be relevant for those purposes of the model where the ³⁴°T = 0/l = 2 splitting has to be taken as quite small; here the l = 2 excitation could perhaps result from some orbital motion of the α-particle within the nucleus.

More-radical possibilities.

If we move into unexplored regions of the N,Z
diagram and into new regions of excitation there is a rich field for speculation. Our thinking about nuclear structure has been dominated by the one-centre shell model, within conventional potentials, whether spherical or deformed in its basis. But it is clear that Nature is not confined in this way. Even if we stay with one-centre models we must recognize the possibility that the effective shell model potential may change significantly as we move far away from the stability valley so that, for example, nuclei of very large neutron excess may be possible in which neutrons form an expanded cloud enwrapping a "conventional" nucleus at their centre, a cloud that would then permit a significant expansion of the conventional nuclear core with a stability gain coming from the loss of Coulomb energy. Such "2-component" nuclei have simply not been investigated. A corollary of this is the possibility, still not explored, of the stability or near-stability, of poly-neutron clusters such as \( {}^6 \text{n} \). There will certainly be a tendency towards such clustering and this may evidence itself in the neutron cloud of the above 2-component nucleus so that the cloud would tend to condense into many poly-neutron clusters.

Here we begin to move away from one-centre models and begin to think of highly-differentiated nuclei which are essentially non-centred or many-centred. Thus a natural extension of the 2-component model is one which we picture as the bringing together of several "conventional" nuclei, each at its neutron drip line and immerse the collection in a bath of neutrons. The neutrons do not then bind to the individual conventional nuclei but may bind to the ensemble as well as exhibiting their own tendencies towards mutual clustering. We cannot at present answer in either direction the question as to whether the binding effects will or will not outweigh the mutual Coulomb repulsion of the conventional nuclei which will certainly be able themselves to reduce their individual Coulomb energies by a measure of expansion. It will be seen that this picture is essentially an extension of the "continuum isomers" mentioned above in which the conventional nuclei at their neutron drip lines were \( \alpha \)-particles.

Nor is it clear that if such differentiated nuclei exist what their optimum form would be. To reduce the mutual Coulomb repulsion it may turn out to be more advantageous to arrange the conventional nuclei on the surface of a sphere filled with and surrounded by the partially-condensed neutron gas. Or perhaps a ring of conventional nuclei would be nice ...

If we retreat from such highly-radical notions we must still admit that non-spherical and non-centred shapes for nuclear matter of more-or-less the normal n/p mix have been by no means fully explored. It is becoming more generally recognized that, in the light nuclei at least, states that resemble strings of \( \alpha \)-particles, either straight strings or crooked strings, such as have been advocated by Morinaga for many years, very probably exist. It is also clear that the shell model which attempts to describe them simply as many-particle-many-hole states within an essentially conventional basis fails massively to get the excitation energy sufficiently low: Nature is doing something cleverer. May such strong-nuclei not extend much further? If \( \text{\textsuperscript{24}Mg} \) can exist as 6 \( \alpha \)-particles in a row there seems little reason why \( \text{\textsuperscript{48}Cr} \) cannot exist as 12 in a row and so on. It may be profitable to increase the nuclear binding without too much increase of Coulomb energy by bending the ends round to make a ring as Morinaga has also long advocated. A few neutrons running along the rows or round the rings would certainly enhance the stability.

We must similarly take very seriously the possibility of bubble nuclei of various kinds ranging from the "conventional" sort already widely discussed within the ordinary shell model framework (Wong), in which the central depression of density is not very large or marked, through genuinely hollow nuclei perhaps to be thought of as spheres covered with \( \alpha \)-particles plus a few cementing neutrons running on the surface of the sphere to the more general hollow agglomerations of drip-line nuclei already mentioned.

Of course, and it is a big "of course", behind all these speculations lies the question as to how we are going to put nuclear matter into such configurations and how we are going to know that we have done it when we have done it. But that is what new machines and techniques are for.