NORMAL AND ABNORMAL NUCLEAR STATES

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1.

The concept of abnormal nuclear states (i.e. Lee-Wick states) [1] has a far reaching implication on Nuclear Physics as well as some fundamental issues of particle Physics. Symmetries spontaneously broken in normal vacuum [2], a mechanism currently believed to be essential in the unification of weak, electromagnetic and perhaps strong interactions, may be restored by means of high temperature or of high matter density. The temperature required to effect the restoration of symmetries is, however, predicted to be much too high for environments other than early universe. On the other hand, it seems feasible with the new generation of heavy-ion machines to produce sufficiently dense nuclear matter so as to induce a phase transition from a symmetry spontaneously broken to its restoration. The relevant symmetry in connection with abnormal nuclear states is chiral symmetry [2].

It is a controversial issue, but some people argue that the existence of abnormal nuclear states is tantamount to the presence of strongly attractive many-body forces in normal nuclei [3,4]. If this turns out to be true, then discovery of abnormal states is bound to drastically modify our notion of the role of many-body forces in normal nuclei and hence the foundation of the present day knowledge of nuclear structure. It is much too early to know whether or not a link between the two drastic forms of nuclear matter materializes in such a simple form. We will need a respectable field theory of nucleus which is unfortunately nowhere in sight.

It is perhaps possible to discuss the controversial issue of abnormal nuclear states in a general framework, but I do not believe that it will be illuminating. Let me instead take the line of argument dictated by the chiral symmetric σ-model Lagrangian [5]. Since we have nothing but a theoretical conjecture, based on as yet untested (though plausible) concept, no unambiguous and simple description of the phenomenon can be given, much less the means to see it. What I will do here is to present in a greatly simplied way which, I am afraid, may offend some purists, the present situation of theoretical arguments for and counter arguments against abnormal states of nuclei, and what one could say on the basis of extrapolation from the normal nuclear matter which we claim we understand reasonably well.

2. Normal nuclei : a lore

To appreciate fully the fascinating nature of abnormal nuclear states, and also the conflicting views taken by the pros and the cons, it is appropriate to review in simplest terms what we know about normal nuclei. Consider the N-N potential in its skeleton form as in fig. 1.

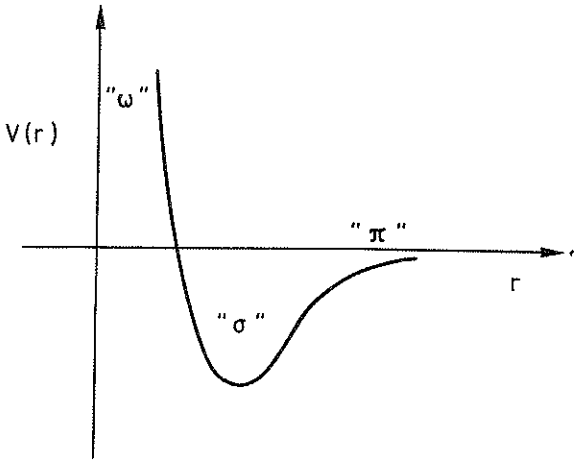


Figure 1 - Skeleton structure of the N-N potential in which mesons responsible for each range of force are indicated roughly by " π ", " σ " and " ω ".

If one is willing to skip the complicated details, the following simple picture of the N-N interaction arises : at large distances, say $> m_\pi^{-1}$, between two nucleons, one-pion exchange is all that matters. As the nucleons get closer, they feel the intermediale-range attraction represented in fig. 1 by the scalar meson σ. The attraction turns to repulsion at shorter distances, this due to the exchange of the vector meson ω (and ρ). The only thing definitely known in this qualitative picture is the role of the pion, the others (their coupling constants etc..) only incompletely known or completely unknown. Now the lore in nuclear physics can be stated as follows :

1 - The bulk of two-body interaction gives rise to an effective average potential in which particles more quasi-independently, subject to weak residual interactions. This is the basis of the shell model.

2 - Intrinsic multi-body (3-body, 4-body..) forces are negligible compared with the two-body force. There is no inconsistency with this statement from ^{3}He to nuclear matter.

To see what these mean for the binding energy of nuclear matter, we recall that :

$$B \equiv -(E - m_N A) = C_{vol}\, A - C_{surf} A^{2/3} + \ldots$$

where .... stands for the symmetry energy, the Coulomb energy etc.. In what follows, we restrict to the volume energy. This consideration puts constaints on the kinds of nuclei the abnormal ones can be : $A^{1/3}$ must be large enough to beat out the surface energy, $N \approx Z$ to minimize the symmetry energy etc.. What is implied by the picture of fig. 1 is best seen in the schematic plot of C_{vol} vs. ρ (density), fig. 2.

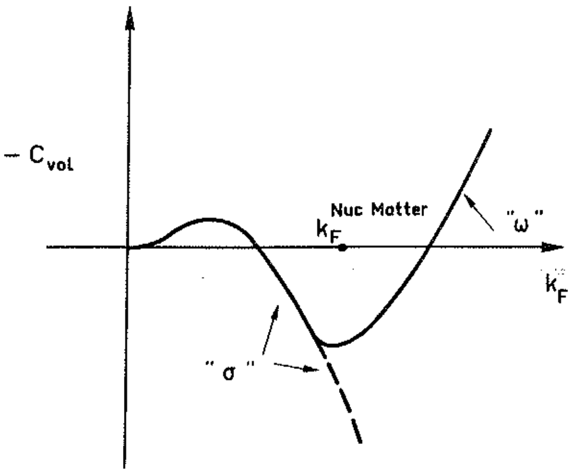


Figure 2 - A schematic structure of the volume energy of nuclei (nuclear matter energy) vs. density ρ *or equivalently Fermi momentum* k_F*. Mesons responsible for each seqments of the curve are indicated.*

If no repulsion due to ω were present, the binding energy would continue to increase and a nucleus would collapse. The " ω " provides the mechanism for saturation. As nucleons are squeezed in closer, the repulsive force would eventually dominate. This is all that one can expect at high density within the conventional framework. It appears that this is not inconsistent with what one finds in neutron stars (the only " observed " dense matter, so far). That this may not be the entire scenario beyond the normal nuclear matter density is what the abnormal nuclear states are all about.

3. Chiral symmetry : another lore

In the σ-model, a scalar meson (σ) and a triplet of pseudoscalar mesons (π^+, π°, π^-) are coupled to nucleons in a chiral symmetric way. In the manifest symmetric state (referred to as the Wigner mode), the nucleon would be massless , and the scalar and pseudoscalar mesons degenerate. In reality, this is not so. It is believed to be manifested in the Goldstone mode in which the nucleon picks up a mass, the σ becomes massive, while the pions are nearly massless, the small mass of 140 MeV being attributed to a small chiral symmetry breaking mechanism. In the world in which we live, there is no way of knowing whether there exists such a symmetry. However there is a signal in the form of the pion known as a Goldstone particle. This is somewhat like the Heisenberg's infinite ferromagnet which defines the direction and where therefore the rotational invariance is (spontaneously) broken. We, occupying a small region of space, would have no way of knowing the existence of the rotational invariance that is the symmetry of the Hamiltonian. The signal for such a symmetry is the long wave-length excitation ($E_k \to 0$ as $k \to 0$) known as the spin waves.

That the chiral symmetry is probably the right and fruitful concept is borne out by the success of the PCAC and the current algebras. So let us take this as a fact, and consider what the σ-model implies in nuclear matter. In what follows, I shall forget about pions, and also the small chiral symmetry breaking mechanism which gives the pion its mass. Then the implication is that, in general, in addition to the usual 2-body terms, there are also a priori non-zero contributions from 3-body, 4-body, etc... forces to the nuclear matter (normal and abnormal unless otherwise specified) energy, as depicted in fig. 3.

The chiral symmetry tells us [4] that:

1. the coefficients a,b,c, have some definite relations among themselves and are functions of " m_σ " alone ;

2. the σ_{NN} coupling is of the same strength as the π_{NN} coupling.

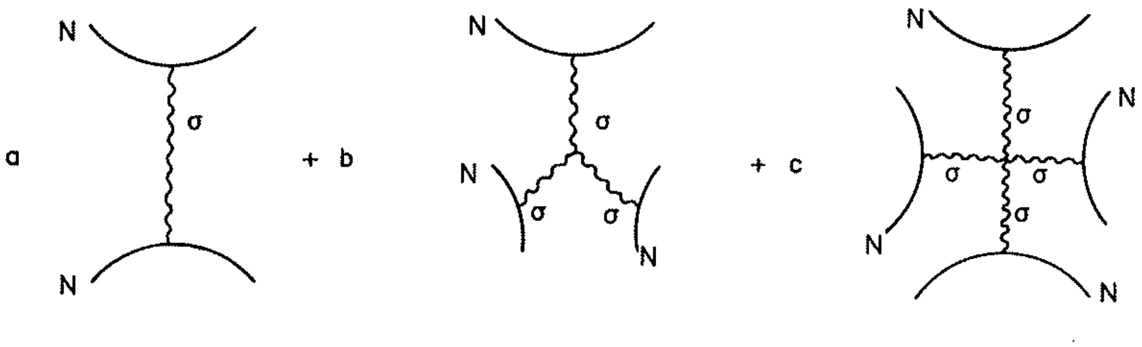


Figure 3 - Two-body, three-body, four-body forces implied by the σ-model Lagrangian. a, b, c are coefficients corresponding to their strength.

but cannot tell us what " m_σ " is. It is not in general the mass of a free scalar meson, but modified by the nuclear medium ; so it is a parameter of the theory, being too complicated to calculate in practice, though in principle well defined. *The crux of the matter is that when quantum corrections including vacuum fluctuations are taken into account, it can be chosen in the normal phase to make the coefficients b and c (hence the many-body forces) arbitrarily small or arbitrarily large* [4,6]. Here is the element wherein prejudices can play a role. Let me for definiteness call those who insist on the negligible role of many-body forces in normal nuclei as pessimists and those who do not as optimists. Depending upon whether one is an optimist or a pessimist, the scenarios on the structure of abnormal states differ. They would imagine the C_{vol} as a function of density in the different ways given in fig. 4.

In this figure, our ignorance on the details of the normal-abnormal phase transition is indicated by the shaded area. Note that I am assuming in both cases a normal state exists. At this moment it is not quite clear how in the optimist case one can assure a normal state to be formed or rather, how to prevent the collapse of the normal state to the abnormal state [7]. In any event, both cases are agreed upon (possibly) a first order phase transition from a normal state ($m_{eff} \approx m_N$) to an abnormal state ($m_{eff} \approx 0$). The rest of the scenarios go follows :

Issues	Optimists	Pessismists
a. Lore	Chiral symmetry (spontaneously broken)	Shell model
b. Many-body forces	large	≈ 0
c. ρ_c	$(2 - 3)\ \rho_o$	$\gtrsim 8\ \rho_o$
d. Binding	strongly bound	unbound by large amount
e. Formed in heavy ion collision ?	yes	perhaps but explode
f. Why not seen so far ?	$A^{1/3}$ not large enough	unbound

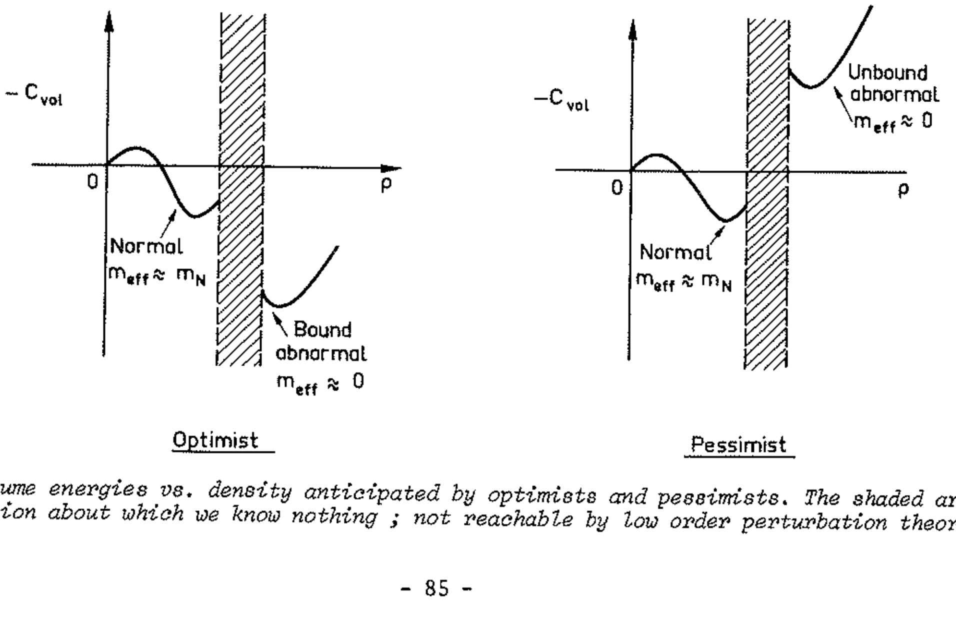
4. Normal nuclear matter

One may take the view (as perhaps does an optimist) that the link between the properties of normal and abnormal states is far too complicated to allow a discussion in terms of many-body forces, the strength of which is constrained only in the normal phase. In particular, one may argue that even if the σ-model were realistic, the renormalization effects would be so large that the chiral symmetry could be completely masked or even badly broken in the normal phase. One may argue that it cannot be ruled out that the non-linearity in meson fields responsible for many-body forces is cancelled in the normal phase by other mechanisms of non-chiral origin, but dominates in the abnormal phase. Thus in this view, abnormal nuclei are well described by the σ-model in its low orders while we simply do not know how to treat the normal nuclei or even whether the σ-model is adequate even if we could do a complete calculation. Much is needed to be done in this direction.

5. Neutron star

Pessimists could perhaps take the presently available data on neutron stars to argue against highly bound abnormal states occuring at relatively low densities. There is an additional repulsion due to the ρ exchange in neutron matter so that the formation of an abnormal neutron matter would be less likely than that of the abnormal nuclear matter. However the theory in which an abnormal state is strongly bound at relatively low densities implies also a bound (albeit less strongly) neutron matter and hence a softer equation of state for neutron stars. A star with softer equation of state has a smaller critical mass (above which the star is unstable against collapse) than one with a stiffer equation of state. If an abnormal neutron matter is bound at a density relevant to neutron stars, the maximum stable mass M_{max} must be less than 0.7 times the solar mass ($M_\odot$), the critical mass for a star with non-interacting neutrons.

The recently determined mass of the compact X-ray source Her X-1[8], M(Her X-1) = $(1.33 \pm 0.13)\ M_\odot$, and that of Vela X - 1[9], M(Vela X - 1) > $1.7\ M_\odot$, would then suggest



Optimist

Pessimist

Figure 4 – The volume energies vs. density anticipated by optimists and pessimists. The shaded area represents the region about which we know nothing ; not reachable by low order perturbation theory.

that a bound abnormal neutron star with the observed properties is unlikely. If, however, abnormal nuclear states are unbound by a large amount, then so would be an abnormal neutron matter. Therefore there would be no conflict with the observed masses. In this version the phase transition is still expected, but at a density much beyond the density relevant to the core of neutron stars. At this high density, the σ-model Langrangian itself may even cease to be of any value. The phase transition to a non-interacting " quark gas state " is more probable and for this, a theory with asymptotic freedom (Viz, gauge theories) must be a lot closer to reality [10].

6. Experimental searches

The search for abnormal nuclear states promises both excitement and frustration : excitement because a discovery of such states would lead to an instant glory, frustation because one has no clear idea of how to go about finding one and of course a search even if one knows how to proceed might bear no results. Nevertheless some works have been done - and are in progress - and I shall describe where we stand at the moment.

1. Relativistic collision of heavy ions

There will be a lot of results from Berkeley in the near future. What has been done so far is somewhat indirectly connected to the issue. ^{40}Ar ions, with 1.1-1.6 GeV per nucleon, were bombarded on Pd target and tracks for large Z signalling something unusual were looked for in Lexan sheets [11]. No tracks corresponding to $Z \gtrsim 21$ were found.

This is an experiment in which many of the requirements for forming abnormal states (high density, large $A^{1/3}$ etc..) are not met and therefore one should not draw any conclusion from it. The failure to see a large Z track in particular implies neither that abnormal states are non-existent nor that the cross section for their formation in other reactions, say, uranium-uranium collision, will be small. What one learns is simply that nothing spectacular happened in this particular reaction. We should await the results on uranium-uranium collision.

2. Shock waves [12]

If the density required is more than 2 ρ_o (ρ_o = nuclear matter density), then one has to resort to something like shock waves to generate the environment. Very rough (and as yet unrealistic) calculations show that one can reach $\sim$ 8 times the nuclear matter density. This is promising, but there are a lot of controversies, such as whether one has actually seen the shock waves, and what the signal for abnormal states would be in shock-wave-generated dense nuclear matter etc.. The field is still too young.

3. Terrestrial concentration

If abnormal states are real things, then they must exist already in the terrestrial environment. So one way of search is to determine the terrestrial concentration of abnormal nuclei [13]. So far, search was made on two fronts ; one, using the assertion that abnormal states favor $N \approx Z$ and two, large binding energy. The first is based on the fact that there is an additional repulsion from the ρ exchange if $N \neq Z$, and the second on the optimist's view of large attractive many-body forces.

a. Mass measurement : the mass of B_i was determined by mass spectrometer and stoichiometric chemical measurements, and the probability for an N = Z nucleus (i.e. $^{166}B_i$) was estimated to be $\lesssim 6 \times 10^{-5}$.

b. Neutron capture : if an abnormal state is strongly bound (say several hundred MeV/particle), a capture of neutron by the nucleus will release an energy corresponding roughly to the binding energy in the form of γ's or π's (if enough energy is available). The measurement of high-energy γ's following thermal neutron capture by radon sample which is presumed to contain abnormal R_n nuclei sets the limit to the present terrestrial concentration at $< 10^{-29}$ per atom of S_i.

The two above results put the range of the concentration of abnormal matter rather generously between 10^{-6} and 10^{-35}. I have not understood very well, but it is claimed that the theoretical range of concentration expected from optimist's estimates is just about the same, from 10^{-8} to 10^{-40}. If this is really so, the idea of abnormal states is very much alive.

7. Conclusion

The argument of both optimists and pessimists are based on incomplete, though compelling, calculation and neither can claim to be more convincing than the other. The basic idea of abnormal nuclear states looks, however, simple and sound and it is very likely that the phase transition of the sort does occur. Where and how depend upon models, and can only be settled by experimentalists. Either way would be interesting. If abnormal nuclear states are not found to be present in nature, we will acquire more confidence in what we know about nuclear structure. If they are, much of our knowledge on nuclei will have to undergo a drastic revision, not to mention the whole new field of the structure of abnormal nuclei, their responses to external field etc.. that will be opened by the discovery.

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