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NUCLEAR-LIKE STATES OF QUARK MATTER

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ABSTRACT

We show that, in a world with only one flavor of light quark, QCD suggests that the low energy states of quark matter are similar to nuclei, but are not well represented as collections of baryons. Except for the existence of open nucleon channels, the same would be true for the actual, two-light-flavor world.

INTRODUCTION

Why does nuclear physics have to be that way? More precisely, is the surprising utility of the point nucleon approximation in nuclear physics due to general properties of QCD, or due to some accident? We cannot really know the range of validity of this approximation until we know its origins in the theory of the strong interactions. We describe here, in the context of a model of QCD, cases in which QCD is virtually unaltered, but in which the point baryon is a poor approximation for describing nuclear-like states.

A ONE FLAVOR WORLD

Suppose only one flavor of quark were light. Then 3 quarks in the same space state would also be symmetric in flavor, since they must be overall antisymmetric, and antisymmetric in color to form a color singlet. Thus, they form a delta as the lowest energy state. (A spin 1/2 state may be formed by radial or orbital excitation of one of the quarks, but this is a higher mass state -- an N.) Note that QCD has suffered only a tiny change in its beta-function, and is virtually unaltered -- it still confines, with almost precisely the same strength and range, according to conventional ideas wherein the gluon self-interaction dominates the theory.

What do nuclei look like in this world? For simplicity, we first consider the analog of the deuteron.

We model QCD with a linear (scalar) confining potential

$$V = 0.9 \text{ GeV/fm} \times (r - 0.57 \text{ fm}) \quad (1)$$

which is consistent with the potential analyses of Buchmuller and Tye¹. A three quark system in this potential has an rms radius of ~0.8 fm. Including the color-magnetic spin-splitting effect of the current-current interaction of these (massless) quarks allows us to fix the effective QCD coupling constant by fitting to the delta

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mass. For massless gluon exchange, we obtain $\alpha_c = 1.0$. Analysis of the gluon field equations as fluctuations about a mean field responsible for the confining potential, however, suggests that these additional exchanged gluons suffer a confinement effect also, which is representable as a mass term. For a Yukawa value of ~ 400 MeV, we find $\alpha_c = 1.5$. Although the reasonable values in (1) and (2) have been chosen to fit the real world spectrum, we expect only very small changes in the one flavor world. In all of these calculations, we have used a Monte Carlo integration technique so that we could apply it to the geometrically more complicated problems below.

Our model for the "deuteron" is then to build a two well potential with a separation R between the minima. The value of the potential at any point is given by (1) where r is the distance to the nearer minimum. (A section through both minima shows a W-shaped potential.) This is similar to what would be found for the two meson case by averaging the model of Lenz *et al.*² Naturally a symmetric wavefunction gives the lowest energy, due to tunnelling, as we have noted before.³ We load this potential with 6 quarks, saturating the color and spin degrees-of-freedom.

We then find a total binding energy from the effective of quark delocalization of 528 MeV at an energy minimum occurring at $R \sim 1.1$ f. However, the color-magnetic spin-spin interaction must also be included. Although some of the pairs of quarks are now in color-6 and spin-zero representations, they still produce the same sign interaction as the color-3, spin-one pairs. The current-current interaction has three times the weight as in one delta (due to the larger number of interacting pairs) but the current-current spatial matrix element is smaller. The net effect of all of this, since the color-magnetic spin interaction is repulsive in the delta, is to reduce the binding energy, to 114 MeV, and to shift the preferred size to $R \sim 1.4$ f. This is still a very strongly bound state. The total energy of the system rises sharply with decreasing R ; all of the binding energy is lost by $R \sim 1$ f. Thus the system shows a strong core repulsion: this is primarily due to the color magnetic interaction.

TWELVE QUARKS

How much does this result depend upon the number of quarks in the system? To study this, we consider a 4-well system, with minima at the corners of a tetrahedron. Again, R is the separation between minima, and the value of the potential is given by (1) referred to the nearest minimum. We restore the second light flavor, and saturate the spatial wavefunction symmetric over all 4 wells with twelve quarks. The color magnetic interaction involves more pair combinations, but produces the same factor of three as above. We find a binding energy of 1060 MeV at R just under 1.6 f.

Once again the system is strongly bound, with respect to 4 deltas. Unlike the previous case, however, we must close the nucleon channel "by hand", as the system is ~ 120 MeV above the energy of 4 nucleons. (It can just barely decay into a pion plus

⁴He; otherwise it must decay by relatively slow gamma emission.) As can be seen from the one flavor case, this need not mean that any drastic change has been implicitly made in the strong interactions. Once again, we also find that the binding energy vanishes if the system is compressed to $R \sim 0.7 f$, showing a strong core repulsion.

We have also tried to examine the effect of spatial correlations in this system. We have done this with a single parameter ϵ . For $\epsilon = 0$, the quark wavefunctions are those for individual deltas centered in each well. For $\epsilon = 1$, we return to the symmetric wavefunction used above. We also kept track of which pairs of quarks came from the same "delta", and which pairs were from different ones. This allowed us to follow the system to four separate deltas at $\epsilon = 0$ and large R . Not surprisingly, the energy of the system was higher at all R and ϵ than at the minimum found above for $\epsilon = 1$; this was due to increases in both localization and color-magnetic energy as ϵ was reduced. Furthermore, it occurred even though no effort was made to include repulsive effects, due to the Pauli principle, from overlapping components of different deltas.

CONCLUSIONS

By closing the nucleon channel in two ways which do not affect the strong interaction, we have shown that nuclear-like states are formed in our model of QCD. There are local density fluctuations such as one would find from localized baryons, and short distance repulsive effects which suggest density and binding energy saturation in the "nuclear matter" limit. However, the minimum energy states are more properly described as quark matter: The quark wavefunctions extend over the entire "nucleus", and there are no local deltas, although the overlap with same is not small. In the $A=4$ case, the large binding energy makes it clear that this system is not an approximate sum of point baryons. It also suggests that there may be a significant 4-delta component of ⁴He. Finally, note that this system has an enormous EMC effect, as the quark wavefunctions are very different from those for 4 incoherently summed baryons.

We conclude that nuclear physics didn't have to be that way, and that the nature of QCD is not the determining factor for the point nucleon approximation. Two light flavors are essential.

We wish to thank Kim Maltman on for stimulating discussions the question of the quark structure of nuclei.

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