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THE NUCLEUS CONSISTS OF MORE THAN JUST NUCLEONS, DELTAS AND MESONS

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ABSTRACT

The possibility that quark degrees of freedom have significant effects in nuclear physics is discussed.

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INTRODUCTION

I would like to use my prerogative as one of the reviewers of this session to mention some ideas that have not been discussed by the speakers, but which are, in my opinion, extremely relevant for debates about constituents of nuclei. The main point is that it may be more accurate to treat nucleon-nucleon wave functions at small separation distances as collections of six quarks instead of two distinct nucleons (or, e.g., two baryon resonances). This results from simple considerations of nucleon sizes 1). If one takes the three quarks in a nucleon to be confined in a spherical region (e.g., bag 2)) of radius about 1 fm, two such bags overlap when their separation distance is 2 fm. This distance is roughly the same as the average spacing (1.8 fm) between nucleons in nuclei, so that the overlapping of nucleons is not so unusual. When two three-quark bags overlap, one six-quark bag is formed 3), and such a system is likely to behave differently than two distinct nucleons 4). A variety of interesting examples already exists; and a partial list is given in Refs. 3), 5)-11). Six-quark bag treatments of the short distance part of the nucleon-nucleon wave function have been made to nucleon-nucleon scattering 3),10), electron nuclear interactions 5)-7), the $pp \rightarrow d\pi^+$ reaction 8), the weak proton-proton force 9), and the ^3H-^3He mass difference 11). Non-bag model quark treatments of nuclear physics have also been made, see, e.g., Ref. 12). In many cases good agreement with experimental data is achieved and evidence for the significance of quark degrees of freedom in the nucleus is beginning to accumulate.

THE DEBATE

It is clear that a crucial element in determining the influence of quarks in nuclear physics is the size of the nucleon bag. Bags of small radius 13), R, do not overlap as much as bags of large 2), or medium values 11),14) of R. Equivalently, one can also discuss the importance of pionic effects in the structure of the nucleon. Small values of R are associated with large pionic effects and conversely 15). This can be understood in several ways. It is well known that the electromagnetic size of a proton is characterized by a root-mean-square radius of about 0.8 fm. A proton made of a bag with R much smaller than that would be required to have a very significant cloud of charged mesons to fill up the volume imposed by experiment. Another way of obtaining an inverse relation between R and the importance of pionic effects is to consider, in lowest order perturbation theory, the nucleon expectation value of the pion number operator, N_π.

This is of second order in the pion-nucleon coupling constant. Thus it goes like $1/f_\pi^2$ (where f_π is the pion decay constant, 93 MeV) since $1/f_\pi$ is proportional, via the Goldberger-Treiman relation, to the pion-nucleon coupling constant. The expectation value of N_π is dimensionless, and the only significant dimensionful parameter, besides f_π, is R. Thus $\langle N_\pi \rangle \propto$ $\propto 1/(f_\pi^2 R^2)$, and it is clear that as R decreases $\langle N_\pi \rangle$ grows. In a similar fashion, one can show that the pointlike pion's contribution to the nucleonic mass goes like $-1/(f_\pi^2 R^3)$; the negative sign is universal for second order contributions to energies.

A previous speaker [16)] has argued forcefully that pionic effects in the nucleon are very significant, so much so that the modification of the energy associated with pions caused by bringing two nucleons together is sufficient to account for 3.4 GeV of repulsion. With such a large barrier to overcome, nucleons would not overlap significantly, and six-quark bag effects would not be relevant in nuclear physics.

The salient evidence for small bags (large pionic effects) is presented in Fig. 1 of Ref. 16). Shown therein is a very deep minimum at small R in the energy of the nucleon, E(R). This is caused by the very strong, negative contributions of the pions to E(R) for small values of R. Should this curve and its interpretation as a potential energy to be used (along with a kinetic energy $-1/(2M_{eff}) \times d^2/(dR^2)$, with M_{eff} about half a nucleon mass) in a Schroedinger equation that determines the probability amplitude for the nucleon having a radius R be correct, the conclusions of Brown and co-workers would result.

However, there are reasons to doubt the accuracy of their Fig. 1, as well as the value of M_{eff}. First, there are some technical worries. In using that curve, it is assumed that as the bag surface vibrates, the only change in the quark wave functions is the alteration of R, and that this occurs instantaneously. Since quarks carry a fairly large constituent mass, it is difficult for me to understand how this instantaneous rearrangement of quark orbitals can occur. Perhaps a simpler way to account for surface oscillations is to use the soliton bag model [17),18)]. In that model, oscillations of the confining sigma field are treated [18)] in a quantum field theoretic fashion, analogous to the Bohr-Mottelson treatment of collective nuclear vibrations. The result of Goldflam and Wilets is that the energy associated with the quantum fluctuation of the bag surface is quite high, about 1 GeV. Thus one would not expect such excitations to play a dominant rôle in determining the properties of baryonic ground states. In the language of Ref. 16), this may mean that M_{eff} is much larger than half a nucleon mass.

Another worry about using Fig. 1 of Ref. 16) is possibly more fundamental. It is natural to expect that the forces that cause confinement of quarks are due to gluonic rather than pionic exchanges. QCD effects rather than old-fashioned field theory cause quarks to be bound with infinite separation energy. Thus quarks and gluons, not pions, determine the size of the confinement region. Indeed, if one neglects pions, and obtains a minimum of $E(R)$ at a radius (R_o) of about 1 fm, one can show 19) that the lowest order pionic contribution to $E(R)$ does not change the value of R_o ! Furthermore, the perturbation theory treatment of pionic effects is very well justified 20) for bag radii of about 1 fm.

The result of these considerations is that I can see no reason to believe that the bag is very small and that pionic effects are dominant. Inclusion of pions in bag models is necessary in order to maintain the chiral symmetry of the Lagrangian. But cloudy bag model calculations 14),21),22) show that pionic effects give significant, but not dominant, corrections to bag model computations of observables. (An exception is the root-mean-square charge radius of the neutron, which would be essentially zero for bag models without pions.) With R in the neighbourhood of 1 fm, the cloudy bag model gives very good results for pion-nucleon scattering 14), charge and magnetic moments of the nucleon 14), magnetic moments of the baryon octet 21), and the strength 14) and momentum dependence 22) of the axial vector form factor. Furthermore, $\langle N_\pi \rangle \approx 0.3$ so the schematic picture of the nucleon as three quarks in a bag radius of about 1 fm is qualitatively valid 23). It is also reasonable to expect that nucleons do overlap (at least sometimes) in nuclei.

HOW DOES THE NUCLEON-NUCLEON REPULSION ARISE ?

There is no definitive answer to the above question at present, in my opinion. There have been a variety of interesting attempts at finding an answer that employs six-quark wave functions and interactions between quarks. To my knowledge, the most recent is that of Ref. 10). A repulsive phase shift characteristic of a hard core of radius ≈ 0.3 fm is obtained from resonating group method computations. A phenomenological quark-quark force constrained by baryonic properties, rather than the single gluon exchange of earlier computations, is used. There is no large potential barrier resulting from these calculations 10). Instead, the repulsion arises from a combination of Pauli principle and interaction effects. Of course, these calculations are not definitive. For example, long-range effects of one and two pion exchanges between nucleons are absent in Ref. 10). The non-relativistic treatment of quark dynamics could also be a problem. Nevertheless, it seems that quarks could indeed give significant repulsive effects.

A PHENOMENOLOGICAL ALTERNATIVE

I would like to mention a simple procedure 8),9),24) which allows one to include six-quark effects along with a correct description of the nucleon-nucleon scattering data. The idea is to use a spatial separation in treating the nucleon-nucleon wave function. For separation distances, r, larger than some fixed value r_0 ($r_0 \approx 0.9$ fm) one employs a conventional nucleon-nucleon potential, V, and wave function $\psi(r)$. In this way use of the experimental phase shifts is guaranteed (to the accuracy at which V describes the data). For $r < r_0$ one instead resorts to a six-quark wave function. The remarkable result 22) is that $\psi(r=r_0)$ and $(\partial/\partial r)\psi(r=r_0)$ determine the probability amplitudes of the six-quark wave functions. This conclusion is obtained by using conservation of probability current across the boundary at $r = r_0$.

CONCLUDING REMARKS

Cloudy bag model calculations, as well as simple estimates based on the nucleon size, suggest that the bag radius is about 1 fm, and that pions do not overwhelm quarks. With such a size for the confinement region, it is reasonable to expect, at least, occasional overlap of nucleons. Thus treatments of the short distance part of the nucleon-nucleon wave function as six quarks in a bag are reasonable. Several results of such calculations 5)-13) exist, and I believe that in the future many interesting and significant properties of nuclei will be explained from this point of view.

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REFERENCES AND FOOTNOTES

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