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Quark Antisymmetrization Effects in Nuclear Physics

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We analyze the observability of quark phenomena in nuclei by studying the effects of the antisymmetrization principle at the quark level in nuclear observables. We discuss the physics associated with one body quark observables and in particular pay special attention to the so called maximal Pauli blocking scenarios. We comment about the calculation of two body quark observables showing results of the Coulomb energy for a two nucleon system with deuteron quantum numbers.

§1. Introduction

Nucleons, deltas and other baryonic excitations appearing in nuclear physics are large objects (rms radius ≃ 0.8 fm). Light nuclei, as for example ^{3}He and ^{3}H are not much larger (rms radius ≃ 1.9 fm). Thus some overlap between the internal structures of the hadrons involved in physical processes of light nuclei seems inevitable. In order to determine the magnitude of the effect the knowledge of hadron structure is necessary. However it is as of yet not uniquely determined, since the underlying fundamental theory Quantum Chromodynamics (QCD) is highly non perturbative and thus unknown in the domain of conventional nuclear physics. We will therefore assume in what follows that the hadron structure is well represented by a naive quark model and will analyze how the composite nature of hadrons contributes to some observed phenomena of nuclear systems. Our point of view [1], together with that of other authors [2], has not been to interpret nuclear physics fully in terms of subnucleonic degrees of freedom or effective QCD based theories, but to search for new physics in the low and intermediate energy regime, hopefully related to those subnucleonic degrees of freedom.

In order to do so, we have proposed the use of many body effects as an alternative tool for unveiling the quark structure in nuclei [1,3]. This effort should lead to complementary information to that obtained by the conventional well developed use of short distance probes. Since the dynamics of quarks at low energies is not well determined we have looked for effects associated with fundamental principles. In this respect characteristic many body phenomena arise due to the Symmetrization Principle and the Spin Statistics Connection Theorem. These phenomena are qualitatively independent of the dynamics involved. Moreover if we look at overlapping systems (or non local operators) we obtain observable effects due to the Pauli principle whose magnitude depends on the degree of overlap (or non locality).

Our aim has been to look for observables and physical systems where the extreme circumstance named maximal Pauli blocking, which we later on describe, takes place. We have for this purpose studied observables related to one body (at the quark level) operators, in particular charge densities, for both conventional light nuclei [1,3] and non conventional or exotic nuclear systems [4]. We review some of this work here in Section 2. In Section 3 we incorporate two body (at the quark level) observables by discussing results of a calculation for the Coulomb energy of a two nucleon system [5]. We end this presentation by elaborating some concluding remarks which state our opinion about these developments . We have omitted technical details throughout the discussion but have intended to guide the reader to the appropriate references, where these can be found.

§2. One Body Observables and Maximal Pauli Effects

In order to study quark effects in nuclear systems a convenient mathematical tool is the Hadronic Quark Cluster Decomposition (HQCD) [6]. The natural implementation of the dynamics in this scheme is by considering that the center of the cluster is subject to a certain force, the remnants of the nuclear force, and the motion of the quarks is governed by some intracluster potential whose origin is confinement. For simplicity we have taken everywhere harmonic forces.

If 3N quarks occupy the available levels of an harmonic oscillator potential of parameter A (quark shell model limit), there is no contribution from antisymmetrization at the quark level to the expectation value of one body observables. But, if we have N clusters of 3 quarks each, the dynamics of the clusters governed by an harmonic oscillator parameter B and that of the quarks within each cluster by one of parameter A, in general, expectation values of one body operators do show effects due to the Pauli principle at the quark level. This last statement represents the scenario we have chosen to develop the contributions due to quark exchange effects. There exist a relation between A and B for which one reaches the quark shell model limit where the effects due to antisymmetrization vanish [5,7].

We have performed the study of one body observables in a simplified model of nature [1,3]. Nevermind the dramatic simplifications involved in our toy model all the possible different scenarios arise. Two types of nuclear systems, with completely opposite behavior appear in our analysis. One in which all the quarks have different internal quantum numbers. For this system, even for large radial overlaps, there is almost no effect associated with the exchange of quarks. Another in which many quarks have the same internal quantum numbers. For this one, even for small radial overlaps, spectacular effects appear due to the Pauli principle at the quark level. These systems we have called maximal Pauli blocked nuclei. Unluckily conventional light nuclear systems, the ones which have been most closely scrutinezed are of the former type.

Several quasi realistic calculations for light nuclei have been performed [1,2,8]. In this case one body observables do not show large non dynamical effects at low momenta ($q < 3\ fm^{-1}$) associated with the exchange of quarks. They become larger at higher momenta. In particular for $3\ fm^{-1} < q < 6\ fm^{-1}$ they are comparable to meson exchange current contributions. However one would need a more fundamental approach to disentangle quark Pauli effects from this more conventional contributions.

The search for maximal Pauli blocked nuclear systems in order to avoid the kind of problems just mentioned has been launched. Several non traditional nuclear systems have been proposed: dibaryons [9], light hypernuclei [10] and delta-nuclei [4]. In this last proposal, we have analyzed delta production mechanisms on light nuclei. Quark Pauli effects are sizeable only for large momenta ($q > 4\ \mathrm{fm}^{-1}$). But several features appear which might lead to a clear experimental determination of these effects at lower q's. One very suggestive result is that electric type transitions are allowed in nuclei due to the exchange terms and forbidden for free baryons. Thus the comparison of data obtained from nuclei and free baryons may lead to disentangle the quark substructure. Moreover different delta channels have different Pauli blocking behavior. Therefore comparison of various channels might also shed some light into the discovery of substructure effects at low energies.

§3. The Two Nucleon Coulomb Energy

We have developed the formalism to calculate the contribution to the expectation value of two body operators from the exchange of quarks. In particular we have performed a quasi realistic calculation of the Coulomb energy for a two nucleon system with deuteron quantum numbers [5]. The dynamical dependence in this calculation enters in the chosen radial forms of the wave functions [1,3]. Different models imply different radial functions and therefore the exchange contribution changes from one model to another. However we can try to exctract some dynamical dependence by changing arbitrarily the parameters of our gaussian wave functions , which implies in turn modifying the overlap between the nucleons.

Table I. Coulomb energy of a two nucleon system as a function of the different parameters which determine the nucleus wave function (The mean square radius of the nucleon is kept fixed at 0.8 fm). R represents the rms of the nucleus and C the average mean distance between the centers of the two nucleons (soft repulsive core).

R (fm)	C (fm)	Total (KeV)	Exchange (KeV)
2.116	0.	-475	-31
	0.25	-504	-60
	0.75	-504	-60
	1.20	-446	- 2
1.5	0.	-535	- 91
	0.25	-624	-180
	0.5	-625	-181
	0.85	-475	- 31
1.0	0.	-753	-309
	0.25	-1100	-656
	0.47	-676	-232

Some numerical results are shown in Table I where we have separated out the nucleon self energies from the total Coulomb energy in order to emphasize the contribution due strictly to quark antisymmetrization. It is apparent from the table that the exchange contribution to the Coulomb energy is related to the nucleon overlap. If the overlap is small, like in the deuteron (rms radius $\simeq$ 2.116 fm) the exchange effect is small ($\simeq$ 50 KeV). In denser systems (rms radius $\simeq$ 1 fm) it can be as high as 600 KeV. The order of magnitude is within the experimental result ($\simeq$ 300 KeV for the difference between the Coulomb energy of ^{3}He and that of ^{3}H). Many indeterminancies remain still in the calculation of this quantity which have to be removed before a more quantitative statement can be advanced [11].

§4. Concluding Remarks

We have developed in this presentation a line of thought whose ultimate goal is the understanding of the effects associated with the structure of hadrons for observables of light nuclei. Under the perspective of an atomistic description of hadrons, we have been motivated to look for explicit quark effects in traditional nuclear systems. We have been led to interpret disagreements of the data with hadronic theories as signals of the Pauli principle at the level of quarks. Such analyses have shown that convolution models are too naive to incorporate properly the many body effects associated with the structure of hadrons. Moreover quark effects and meson exchange currents contribute in the same energy domain. The lack of effective theories derivables from QCD make quantitative estimates not trustworthy.

We have also described searches for new observables and non traditional nuclear systems. From the point of view of the latter aspect we have analyzed in some detail the so called delta-nuclei, in which the exchange effects may play an observable role. From the point of view of the former one we have shown, without dwelling in the details of the complexity of the calculation, that the exchange effects contribute to the Coulomb energy of light nuclei. This contribution is strongly dependent on the overlap integrals and therefore on the precise dynamical model used.

The situation after many analyses is not as of yet clear. From the experimental point of view, low energy theories derived from QCD with known assumptions are needed to perform more quantitative calculations. From the experimental point of view conventional systems, where a wealth of data is available, are at this moment too complex and one would like to go into non traditional systems where some pertinent signatures might be easier to envisage. Certainly the experimental discovery of multihadron resonances would clarify and illuminate our understanding of the structure of systems of hadrons.

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