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Proceedings of the 15th International Conference on Hadron Spectroscopy (Hadron 2013), as published in PoS : Proceedings of Science, 2013 / vol.113807, pp.1-6

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28 June 2017

<http://hdl.handle.net/2440/105899>

Modification of Hadron Structure and Properties in Medium

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In the quest to understand QCD there are a number of outstanding challenges. Here we focus on one of these, namely what one expects to happen to the structure of a hadron when it is immersed in a nuclear medium. We argue that the necessary changes in the quark structure are intimately related to nuclear binding and saturation. Some of the potential experimental implications of these ideas are discussed.

*XV International Conference on Hadron Spectroscopy-Hadron 2013
4-8 November 2013
Nara, Japan*

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1. Introduction

Over the past decade our capacity to calculate hadron properties from lattice QCD has improved dramatically. Ground state masses are well under control [1] and there has been substantial progress with respect to electromagnetic form factors [2] and even GPDs [3]. The especially challenging problem of disconnected diagrams, which for example are entirely responsible for the strange quark contributions to nucleon properties [4], have also seen some remarkable success [5, 6, 7]. The relatively accurate determination of the strange sigma commutator [8, 9] has had unexpectedly dramatic consequences for the accuracy with which one can calculate the cross sections for some particularly promising dark matter candidates [10].

The study of hadron properties along the quark mass axis [11], which of course is not available experimentally, has given us important new insights into how hadron structure works. For example, we have discovered that meson cloud effects die fairly rapidly once the current quark masses rise above about 50 MeV (or equivalently the pion mass above 0.4 GeV) [12]. We eagerly await the exploitation of this through the development of constituent quark models in this mass region, where they can be expected to work well; with the connection to data made after chiral extrapolation [13].

Tackling resonance properties is a much trickier proposition, with the work of Luescher [14] providing a critical framework within which one can calculate two-body phase shifts. We are particularly excited by a new approach in which an appropriate Hamiltonian model is tuned to lattice data on a finite volume and then the physical resonance properties deduced from an infinite volume calculation. For an introduction to the method in the simple case of the Δ baryon we refer to Ref. [15].

Many baryon systems present far greater challenges. There have been some surprises in the case of di-baryons, with the infamous H seeming to be still just on the edge of discovery [16, 17, 18] as the lower limit on its mass continues to rise [19]. In retrospect, the insights into the role of the meson cloud that have come from studying baryon properties versus light quark mass provide even stronger support for the physics included in the original study of Mulders and Thomas [20]. There, in contrast with the work of Jaffe [21], meson cloud corrections were included *but* in a way that recognised they would be suppressed strongly as the size of the hadron increased (roughly as one over the cube of the hadron size). This was why Mulders and Thomas found the H to be around the Λ - Λ threshold, rather than deeply bound – the attractive pionic self-energy terms for the H were suppressed with respect to the two Λ 's because of the former's significantly larger radius. This alone may well explain the otherwise surprising absence of most low mass exotic objects. Although we do note that the possible strangeness minus one state reported by the FINUDA Collaboration [22] at Frascati is remarkably close to the corresponding mass calculated in Ref. [20].

When one thinks of atomic nuclei within the framework of QCD it is difficult to imagine how the complex many-body structure of a free nucleon cannot be modified by the presence of other hadrons separated by distances similar to the size of the hadrons themselves. For example, this may lead to the exchange of quarks between neighbouring colorless clusters or even the formation of hidden color configurations. The reliable calculation of such effects presents a formidable theoretical challenge.

A related effect, which is rather more amenable to modelling, is the effect of the strong scalar mean fields that we have known for more than 40 years play a major role in nuclear structure.

In particular, since the development of the Paris potential [23] on the basis of dispersion theory one has known that the attractive intermediate range NN force is an isoscalar, Lorentz scalar force associated with two-pion exchange, often represented through the exchange of a σ meson. In a relativistic mean-field model such as Quantum Hadro-dynamics (QHD) [24] this led to a mean scalar field in a heavy nucleus of order 0.5 GeV – more than half the mass of the nucleon itself. It is inconceivable that the application of such a field would not lead to significant modification of the properties of a bound nucleon.

In Sect. 2 we briefly review the quark-meson coupling (QMC) model which was developed by Guichon and colleagues [25, 26, 27] to tackle this issue. We shall see that this model very naturally explains the saturation of nuclear binding and provides very helpful guidance as to the possible experimental consequences. In Sect. 3 we recall the extension of the QMC model using NJL, rather than the MIT bag model. Because the model is covariant it provides a more reliable framework for discussing changes in the structure functions of bound nucleons. The final section contains some concluding remarks.

2. QMC

Within this model the valence quarks in the bound nucleon interact directly with the scalar and vector mesons that give rise to the mean fields in a nuclear medium. In its most natural form the isoscalar vector meson, the ω , simply redefines energy levels and in uniform matter has no dynamical effect. On the other hand, the scalar field modifies the Dirac equation for the confined quark, enhancing the lower Dirac component of the 1s wave function as the density rises. Since the scalar coupling to the nucleon as a whole depends on the integral over the upper component squared minus the lower component squared, the effective σ -nucleon coupling decreases with increasing density. This in turn constitutes a new saturation mechanism for nuclear matter and leads to considerably lower scalar mean-fields than those appearing in QHD.

Physically we may interpret this tendency for the scalar coupling to decrease as a response of the internal structure of the nucleon to the applied mean scalar field. By analogy with the more familiar electric and magnetic polarizabilities, this is known as the scalar polarizability of the nucleon [25, 28]. An initial attempt to derive this term from lattice QCD proved quite promising [29] but this needs further investigation.

Starting with QMC one can derive an equivalent energy functional and hence extract Skyrme forces equivalent in this sense to the original model. The first investigation of this kind revealed many-body forces that were a direct consequence of the scalar polarizability [30], while a later study led to density dependent Skyrme forces that produced rather good results for closed-shell, finite nuclei [31]. Once again the origin of the density dependence was the scalar polarizability, which modifies the force between two nucleons because of the presence of others. It will be very important to see further applications of these derived forces. It is particularly interesting that in a study of more than 200 phenomenological Skyrme forces, many with 10-20 parameters fitted to various nuclear data, the forces derived from the QMC model with just 3 parameters performed extremely well [32].

Of course, if we were just concerned with nuclear binding energies the model would be of limited interest. However, because of the change of the valence quark structure, we expect that

every property of the nucleon must change with density. Particular attention has been paid to the modification of the elastic form factors of the nucleon for which there has been an ambitious program at JLab [35, 36, 37, 38]. The QMC predictions [33, 34], made more than a decade before the actual measurements, anticipated key features of the data. Unfortunately, a multitude of unknown parameters associated with the more conventional analysis of the data make it difficult to draw a firm conclusion at present.

A modification of the proton electric form factor has long been recognised as a potential correction to the longitudinal response of a nucleus in quasi-elastic electron scattering. There we eagerly await results from the extensive study conducted a few years ago at Jefferson Lab. A complete modern calculation based on a model such as QMC is urgently needed to complement that measurement.

Deep inelastic nuclear scattering from nuclei has been of enormous interest since the discovery of the EMC effect in the early 80's at CERN. Early calculations within QMC showed that, indeed, the modifications of the structure of the bound nucleon predicted within that model were capable of producing just such an effect [39]. However, the static bag model, upon which QMC is based, is not ideal for such calculations and more recent work has focussed on a similar approach within the NJL model.

3. NJL Model for Nuclear Matter

Starting with the NJL model one can construct nucleons and the mesons that bind them, creating a covariant, quark-level description of atomic nuclei where the Faddeev wave function of the bound nucleon is self-consistently modified in-medium [40]. This model not only generates remarkably good structure functions for the free nucleon [41, 42] but also reproduces the EMC data for nuclei across the periodic table [43]. The challenge is how to test the model in ways that have not yet been measured.

In this regard there have been two very important suggestions. The first relates to the importance of the lower Dirac component of the valence quark wave function in spin structure functions. Calculations of the EMC effect on the structure function of a bound nucleon suggest that it should be expected to be as much as twice as large as the unpolarised EMC effect [43]. Such experiments must be pursued at JLab after the 12 GeV upgrade is complete.

The second test of this new paradigm for nuclear structure involves the so-called iso-vector EMC effect [44]. This was discovered in connection with the NuTeV anomaly, where it accounts for more than 1σ of the nominal deviation from the Standard Model. The idea is very simple, namely in a nucleus with more neutrons than protons there is an iso-vector mean-field which modifies the structure function of *every nucleon*. Thus simply subtracting the free structure functions of the extra neutrons does not eliminate their effect. A number of experiments have been proposed which should reveal this effect. These include parity violating DIS [45], again ideally suited to JLab at 12 GeV, and even better charged current DIS on nuclei at a future electron-ion collider [46].

4. Conclusion

Taking seriously QCD as the fundamental theory of the strong interaction, with quarks and

gluons as the fundamental degrees of freedom, leads to a new paradigm for nuclear structure. It implies a new mechanism for nuclear saturation and predicts significant changes in the structure of the clusters of quarks with nucleon quantum numbers that occupy shell model orbits. It is imperative that the predictions of the observable consequences of these ideas be pursued vigorously in the next few years.

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