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Structure of Finite Nuclei Starting at the Quark level

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We briefly review the motivation for building a theory of nuclear structure based at the fundamental level of quarks and gluons. This is followed by a discussion of recent progress in the area and possible experimental tests of the approach.

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1. Motivation

Given that QCD is the fundamental theory of the strong force and that quarks and gluons are the corresponding degrees of freedom it seems worthwhile to seriously investigate how this is reflected in the properties of finite nuclei and dense matter. Traditional nuclear theory typically assumes that apart from producing nucleons and pions QCD is more or less irrelevant to nuclear structure. Modern effective field theory builds in the chiral symmetry of QCD but otherwise works under the same hypothesis. Yet there are hints that there might be more to this story. The EMC effect, discovered at CERN more than 30 years ago [1], has a natural interpretation in terms of a change of the structure of a bound nucleon [2, 3]. Early investigations of the longitudinal response of a nucleus in inelastic electron scattering suggested a change in the electric form factor of the bound proton [4]. Yet the interpretation of these experiments has proven controversial with the community reticent to accept the possibilty of a change in nucleon structure in-medium.

On the other hand, as first recognised by Guichon [5], the model independent fact that there is a strong scalar mean field in a nuclear medium, often parametrised in terms of σ exchange, means that the quarks confined in a nucleon inside a nucleus will behave as though their mass is significantly modified. This implies a reduction in the coupling of the "nucleon" to the mean scalar field with density (often parametrised in terms of a "scalar polarisability"), which in turn is a powerful mechanism for the saturation of nuclear matter. It also leads to important changes in the properties of the bound nucleon, including a substantial reduction in its axial charge and a softening of its electric form factor [6].

The model, known as the quark-meson coupling model (QMC), was substantially developed in 1996 to provide a fundamental theory of finite nuclei, including a very natural derivation of the spin-orbit force [7]. Because the model was built from the quark level, under the very natural assumption (motivated by the Zweig rule) that the mean σ, ω and ρ fields do not couple to strange quarks, it was able to predict the in-medium properties of a variety of hadrons, including a succesful description of Λ-hypernuclei [8, 9], including a natural understanding of the very small spin-orbit force there. There are suggestions that the predictions for the binding of cascade hypernuclei given almost 20 years ago are also correct in recent results [10] from J-PARC, also reported at this conference. For a thorough review of the consequences of the model in a wide variety of systems we refer to Ref. [11].

2. Application to Finite Nuclei

Just over a decade ago, Guichon and Thomas [12] were able to establish the connection between the scalar polarisability, which appears naturally in the QMC model as a consequence of the change in the confined quark wave functions in a mean scalar field, and the appearance of three-body forces in traditional Skyrme interactions. With the more modern focus on density dependent Skyrme forces, the derivation was later improved [13] to produce a density functional, equivalent to the underlying QMC theory, which yielded a new effective NN interaction with a novel, non-linear density dependence. The coefficient of the novel non-linear density dependence (equivalent to the appearance of many-body forces) explicitly involved the scalar polarisability, thus providing a clear physical demonstration of the key role played by the self-consistent modification of the structure of the nucleon in the QMC model.

It is this new, density dependent energy functional which offers the opportunity to make use of sophisticated modern nuclear structure codes to investigate the consequences of the QMC model for finite nuclei. In a recent study of 106 nuclei across the periodic table, Stone *et al.* [14] showed that the derived effective NN force, with just three fitting parameters (constrained to reproduce the properties of nuclear matter as well) was able to describe the binding of these 106 nuclei with an error of just 0.35%. This is comparable to the quality of fit obtained with purely phenomenological Skyrme forces with 3 times the number of free parameters. It is especially exciting that the binding energies of superheavy nuclei, which were not included in the fit, were reproduced with an accuracy of 0.1%. This suggests a number of lines of investigation for the near future.

It is also fascinating that the *derived* spin-orbit force in this model [7] agrees remarkably well with that found in the best modern phenomenological Skyrme force, UNEDF1 [15]. That is, it has both isoscalar and an isovector components and their magnitudes agree with UNEDF1 within a few percent. We are in the process of exploring the practical importance of this observation.

3. Experimental Tests of the Underlying Concepts

From the point of view of utility and appeal to the nuclear structure community it is important that it has been possible to derive a non-relativistic density functional from the underlying quark level. For spectroscopic applications one can then forget that the nucleons being used do not have the same internal structure as a free nucleon. Yet that structure *is* different and, because this picture really constitutes a new paradigm for nuclear theory, it is crucial find ways to test experimentally whether it is indeed so.

As we already mentioned, early application of the QMC model to deep inelastic scattering suggested that it was indeed compatible with the EMC effect. However, there are serious difficulties in calculating quantitative structure functions in the MIT bag model, which is the quark model upon which QMC is built. More modern treatments of nuclear deep inelastic scattering use the covariant generalisation of QMC constructed by Bentz and Thomas [16]. Once again the structure of the nucleon, this time in the NJL model, is modified by the mean scalar field generated self-consistently in a nuclear medium. The resulting nuclear structure functions describe the EMC effect very well indeed [17, 18]. Even more interesting from the point of view of testing the *predictions* of the model, these calculations suggest that the EMC effect for spin dependent structure functions should be even larger than for the unpolarised case. Of course, polarisation effects in a nucleus are an order $1/A$ effect and therefore challenging to measure but such experiments are a priority at Jefferson Lab following the 12 GeV upgrade there. The polarised EMC effect has the added advantage that in an alternate model for the EMC effect, in which only highly correlated nucleons are modified [19, 20], there is *no* EMC effect predicted in the polarised case, thus providing a clear distinction between these proposed explanations.

A second unexpected consequence of the description of nuclear structure described here is that it also predicts a substantial isovector EMC effect [22], with a difference between the nuclear modification of the u and d quark parton distribution functions in a heavy nucleus with $N \neq Z$ of the order of 10% or more. This too will be the subject of experimental investigation at Jefferson Lab using parity violating deep inelastic scattering [21].

A very different signal of the modification of the structure of a bound nucleon has its roots in the expeirmental work of Meziani *et al.* in the early 80s. As we already remarked, that work was controversial and it is only with the development of Jefferson Lab with its very high luminosity and duty factor that it has been possible to repeat that earlier work in a much more thorough way, with proposed errors at the few percent level [23]. The longitudinal response function is key as it is the one most affected by the predicted change in nucleon structure in-medium [24]. In its integrated form this yields the Coulomb sum rule and it is there that dramatic effects are predicted to arise [25]. We eargerly await the results of the final analysis of this experiment which is expected soon.

4. Concluding Remarks

We have briefly outlined a totally different view of the structure of atomic nuclei in which the nucleons occupying shell model orbits have their internal structure significantly modified by the medium. This modification, which is a consequence of the self-consistent response to the mean scalar field, is the critical ingredient needed for nuclear saturation. From this very different starting point one can nevertheless derive an energy density functional which can be used to make serious calculations of the properties of atomic nuclei. The initial application of the derived density functional produced very promising results. Future applications are under consideration to superheavy and exotic nuclei, shell structure away from stability, fission, fusion and so on.

In parallel with these applications to nuclear structure, significant experimental efforts are underway to test the underlying prediction that the internal structure of the bound ”nucleon” differs from that when it is free. The next few years should prove crucial in deciding whether or not our fundamental view of nuclear structure needs to change.

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