MODIFICATIONS OF MESON MASSES AND THE THREE-NUCLEON PROBLEM

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Motivated in part by recent experimental determinations of the ρ-meson mass in the nuclear medium, we apply the Brown–Rho scaling hypothesis in the three-nucleon system. We pay particular attention to two open problems, namely, the binding energy and the analyzing power in neutron-deuteron elastic scattering ("A_y puzzle"). We show that both issues can be successfully addressed by a scaling of meson masses corresponding to an average density of the three-nucleon system.

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1. Introduction

One goal of modern nuclear physics is to describe the properties of hot and dense nuclear matter near the chiral phase transition density. These extreme conditions govern the behavior of systems such as neutron stars and supernovae, and can be probed via relativistic heavy-ion collisions at facilities such as RHIC. However, QCD-based theories predict that a signature of such transition could already be observable in normal nuclear matter (for a review, see Ref. [1]). This hypothesis can be tested, for instance, in heavy-ion experiments or in electro/photonuclear reactions at beam energies of a few GeV, and the sought-after signature should manifest itself through modifications of the meson spectral properties.

The CERES dilepton measurements [2] do indeed provide strong evidence that the properties of the ρ meson are nontrivially modified in the nuclear medium. The experiments report an excess of dilepton production at low invariant mass, as well as strength missing from the region of the free ρ mass, although these determinations are not yet very quantitative. The simplest explanation for these findings can be given in terms of hadron masses dropping as a function of density. This has become known as Brown–Rho (B/R) scaling [3], and establishes an appealing link to the chiral structure of the hadronic vacuum.

Recent experiments of ρ^0 photoproduction on ^{3}He [4], in which the ρ^0 mass was directly accessed in the measurements, have revealed substantial reduction of its mass from the vacuum value. In view of this observation, which indicates in a rather indisputable way that meson masses are indeed modified in a nucleus as light as ^{3}He, we want to explore the possible impact of B/R scaling on some well-known issues concerning the three-body problem. In this note, we will present an exploratory calculation of the triton binding energy which incorporates B/R scaling of meson masses. We will then show how this reflects on the most problematic observable in low-energy nd elastic scattering, namely the analyzing power below ~25 MeV.

From the results shown here, it can be concluded that this less conventional approach appears promising and worthwhile further consideration.

2. Three-body calculation with dropping meson masses

It is well known that all modern high-precision nucleon-nucleon (NN) potentials used in a charge-dependent Faddeev calculation consistently underestimate the triton binding energy by approximately 0.5 MeV or more [5–10]. The conventional wisdom is to interpret the missing energy as evidence for the existence of three-nucleon forces (3NF). The inclusion of phenomenological attractive 3NF, however, does not resolve what has become known as the "A_y puzzle": a drastic discrepancy between the predictions by NN forces and both nd and pd data for the low energy elastic scattering vector analyzing power A_y [11, 12]. Present day 3NF models have insignificant effects [11–15] and thus do not remove the discrepancy. Because A_y depends very sensitively on the triplet P components of the NN force, a trivial explanation might be that the ^3P NN phase-shift parameters from modern phase-shift analyses have not yet been settled to the true ones [16]. In Ref. [17] arguments are given to show that changes in the NN forces, with the exception of drastic modifications of the well established properties of the one-pion exchange, are not capable of reproducing A_y. On the other hand, there are still doubts whether the ^3P NN force components have been constrained sufficiently well by the NN data basis, which might leave some room to modify ^3P NN force components [18]. If the reason does not lie in the NN phases, a 3NF of still unknown properties would be responsible. One possibility for such 3N forces is discussed in Ref. [19].

For our present purpose, the choice of the particular NN potential is not a crucial issue, since we are just exploring certain mechanisms and their qualitative effect. We take the well-known Bonn B potential [20] (which is a one-boson-exchange potential) as our starting force, which produces a triton binding energy of 7.82 MeV (using the *pp* version and ignoring charge-dependence for simplicity). Typically, high-precision local potentials yield between 7.6 and 7.7 MeV for the triton binding energy in a proper charge-dependent calculation, while a result of 8.0 MeV is obtained with the non-local CD-Bonn interaction [9, 10]. Thus our starting value can be seen as simulating an average of the most widely accepted theoretical results for the triton binding energy.

According to the B/R scaling prescription [3], meson masses (except for the pion, which is protected by its Goldstone boson nature), scale with density as

$$\frac{m^*}{m} = 1 - C\frac{\rho}{\rho_0}\,, \tag{1}$$

where m^* denotes the (scaled) meson mass in the nuclear medium and m the mass in free space. The constant C is approximately 0.15 and ρ/ρ_0 is the density in units of nuclear matter density. In choosing the proper level of scaling to be applied here, we are guided by previous calculations [21] of average meson masses in light nuclei, and reduce vector and scalar meson masses, as well as the corresponding cutoff masses, to approximately 95% of their free-space value.

The simultaneous scaling of masses and cutoff masses is motivated by consistency arguments. A cutoff mass (by preventing short-distance approach) is essentially equivalent to a repulsive meson contribution, and thus should be treated on the same footing as meson masses and subjected to the same change of scale prescribed by Brown–Rho. In fact, when Brown *et al.* have implemented the scaling scenario within the nuclear many-body problem (such as, for instance, in Ref. [22]), scaling of cutoff masses has been included as well. Thus, the modified values of masses and cutoff masses are closely connected components of the physical model we propose.

The resulting modifications to the dynamical input are reported in Table I. Any parameter not shown in the Table is left to its standard Bonn B value [20].

With the above modifications applied in the Bonn B potential, we then proceed to a Faddeev calculation of the triton bound state which includes

TABLE I

Standard and modified meson masses and corresponding cutoff masses. The σ parameters given in brackets apply to the $T = 0$ NN potential [20].

Parameter	Standard value (MeV)	Modified value (MeV)
m_ρ	769	729
m_ω	782.6	742
m_σ	550(720)	521(683)
m_δ	983	932
Λ_ρ	1850	1754
Λ_ω	1850	1754
Λ_σ	1900(2000)	1801(1896)
Λ_δ	2000	1896

partial waves up to a total two-nucleon subsystem angular momentum of $J = 4$ (all of which are modified), and obtain a triton binding energy of 8.49 MeV. This increase in binding energy can be understood as follows. First, notice that the strenght of a one-boson exchange diagram depends inversely on the square of the boson mass, since the meson propagator has the structure

$$P = \frac{1}{m^2 + \boldsymbol{k}^2} \tag{2}$$

with $\boldsymbol{k}$ the three-momentum transfer. Applying B/R scaling, the mass in the above equation is replaced by the mass in the medium, m^*. Therefore, the dropping of a meson mass always enhances the contribution from that meson. The central forces created by σ- and ω-exchange carry opposite sign and so do the corresponding enhancements due to B/R scaling. Thus, there are large cancelations. However, since the enhancement of the σ is more effective than the one from the ω (due to the smaller mass of the σ), the net effect is an increase in the attraction.

The next step of our exploratory study is to check whether this prescription also helps with the problematic issue of the analyzing power in nd elastic scattering below ~25 MeV. We will apply to the two-body input the same modifications as used for the bound state, (namely, the modifications as in Table I). However, *only* the triplet P-waves will now be subject to those modifications. The reason is the following: in nd scattering calculations, one needs the deuteron wave function in order to keep the appropriate pole structure. Now, the modifications in Table I are appropriate for an average density corresponding to the three-nucleon system, and thus should not be applied to the deuteron (which is essentially free-space). Therefore, in order to preserve the deuteron properties and pole structure, we do not modify S- and D-waves in the scattering calculation. This limitation, however, is not likely to affect our conclusions in a substantial way, as we explain next. The major effect from Brown–Rho scaling originates from the contributions of σ and ω acting coherently in the spin-orbit force (this will be discussed in more details later). In the central force, large cancelations occur between the σ and the ω contributions, as pointed out above when discussing the binding energy result. As far as the tensor force is concerned, a 5% scaling of the ρ meson mass would have a negligible effect (in fact, systematic work by Sammarruca, Stephenson, and collaborators [23] with proton-nucleus scattering has shown that effects from scaling *only* the ρ mass are very small, even at a 10-20% level, which is much more than what applied in the present context). Therefore, *at this level of scaling*, B/R effects are essentially σ-ω effects on the spin-orbit component, which is of course the chief mechanism behind the P-waves. It is then reasonable to expect that even this selective application of the modified interaction (entirely due to technical reasons), will give us a realistic insight of Brown–Rho scaling effects on the scattering observables.

The results are shown in Fig. 1 at various incident laboratory energies. All scattering calculations include two-nucleon angular momenta up to J=3, which give converged results for the low energies of interest here. In all cases, the solid curve is a calculation based on the original Bonn B potential, while the dashed curve contains the modifications as in Table I, but applied *only* to the triplet P-waves (to which A_y is mostly sensitive), for the reasons explained above. Clearly the predictions which include B/R scaling move in the right direction, indicating enhancement of the spin-orbit force. The spin-orbit forces generated by σ- and ω-exchange add up coherently and so do the enhancements caused by B/R scaling. Thus the effect is quite large. Notice that this is in contrast to the case of the central force discussed above. The effect is most dramatic at the lower energies, where the contribution of the P-waves to A_y is largest, and decreases with increasing incident energy. The differential cross section is dominated by the S-waves,and because these are not modified at the present stage of the calculation, no significant differences exist, see Fig. 2.

Concerning other spin observables, the general pattern we have observed is very well represented by the observables displayed in Figs. 3–7, where the original Bonn B predictions (solid line) as well as the predictions including B/R scaling (dashed) are shown. Besides the dramatic improvement in A_y, the deuteron vector analyzing power iT_{11} also shows improvement as a consequence of B/R scaling. This is not surprising, given its sensitivity to the P-waves. Overall, the quality of the predictions for the other observables remains essentially unaltered.

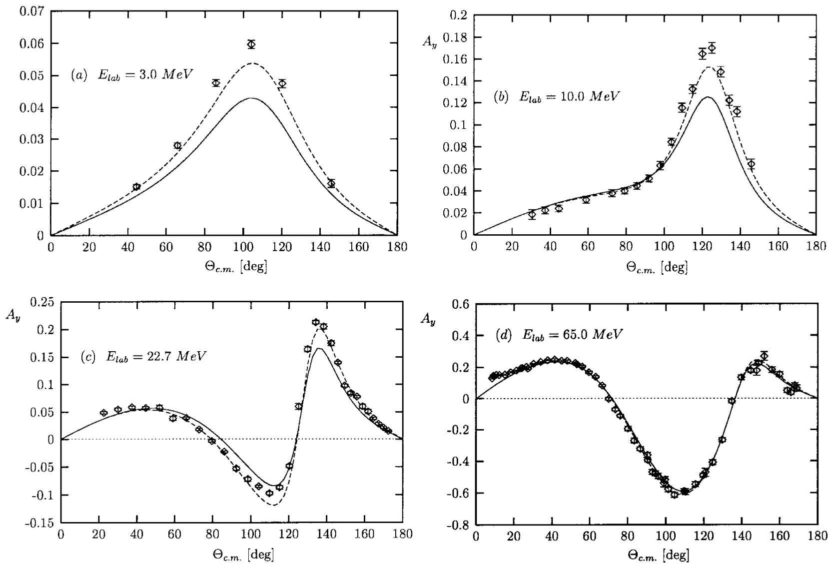

Fig. 1. The analyzing power for nd elastic scattering at various energies. In each case, the solid curve uses the Bonn B potential as the input two-body force; the dashed curve is obtained with triplet P-waves modified by the B/R prescription as explained in the text. The experimental data shown at 3, 10, 22.7, and 65 MeV were taken from Ref. [24–26] and [27], respectively.

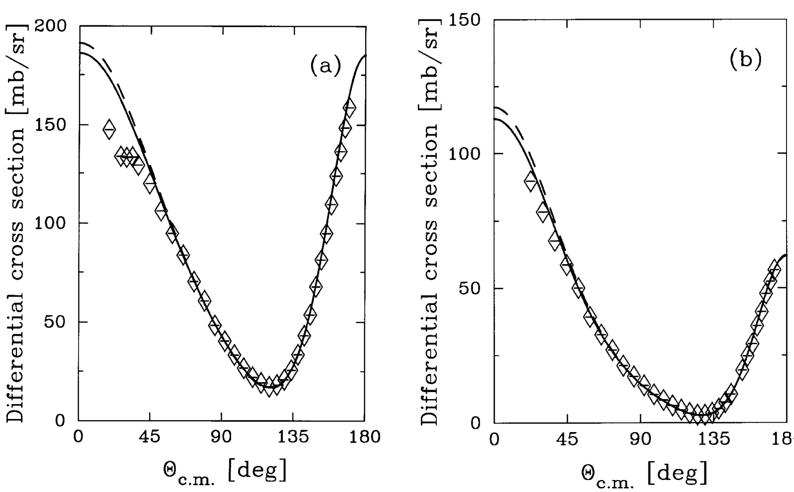

Fig. 2. Angular distributions for nd elastic scattering at 10 MeV (a) and 22.7 MeV (b). The definition of the curves is as in Fig. 1. Data from Ref. [26].

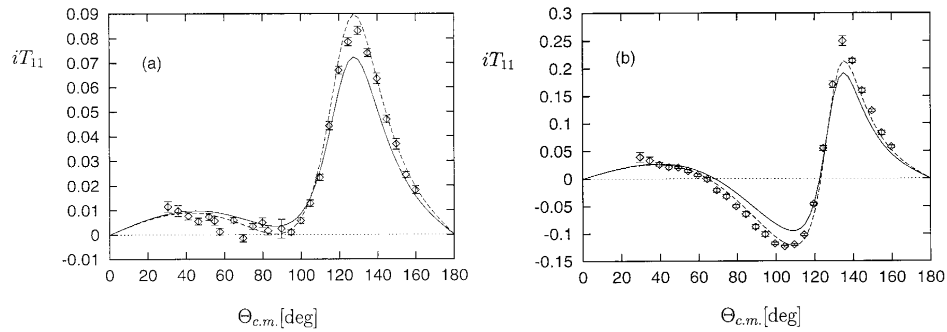

Fig. 3. The deuteron vector analyzing power iT_{11} for nd elastic scattering at 10 MeV (a) and 22.7 MeV (b). The definition of the curves is as in Fig. 1. Data from Ref. [26].

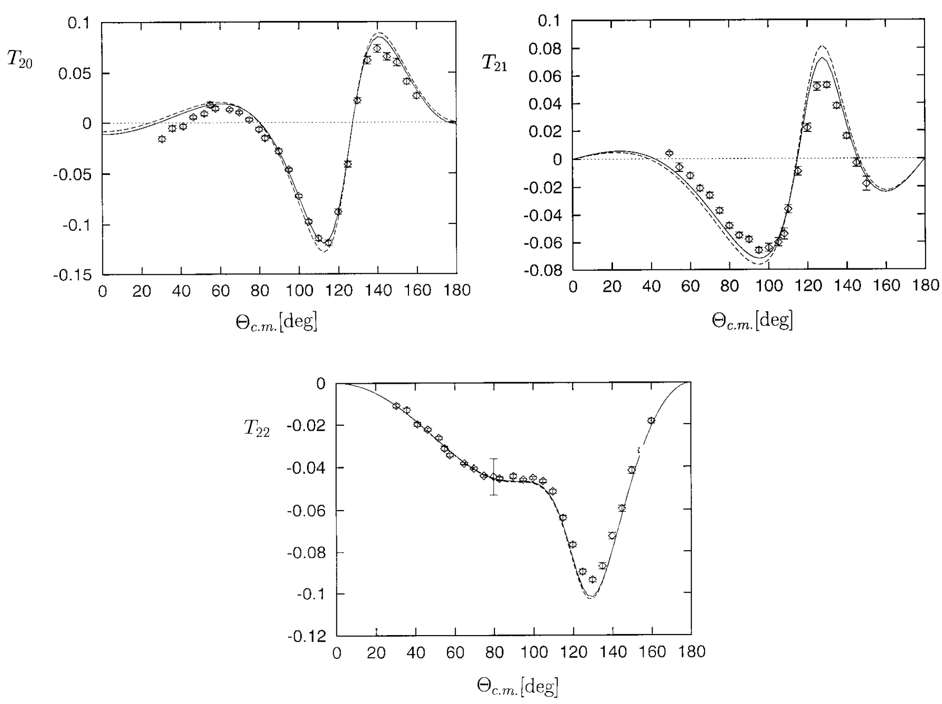

Fig. 4. The deuteron tensor analyzing powers T_{20}, T_{21}, and T_{22} in nd elastic scattering at 10 MeV. The definition of the curves is as in Fig. 1. Data from Ref. [26].

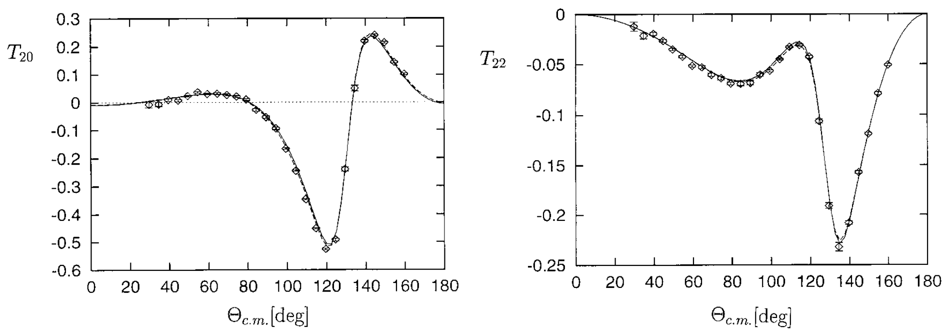

Fig. 5. The deuteron tensor analyzing powers T_{20} and T_{22} in nd elastic scattering at 22.7 MeV. The definition of the curves is as in Fig. 1. Data from Ref. [26].

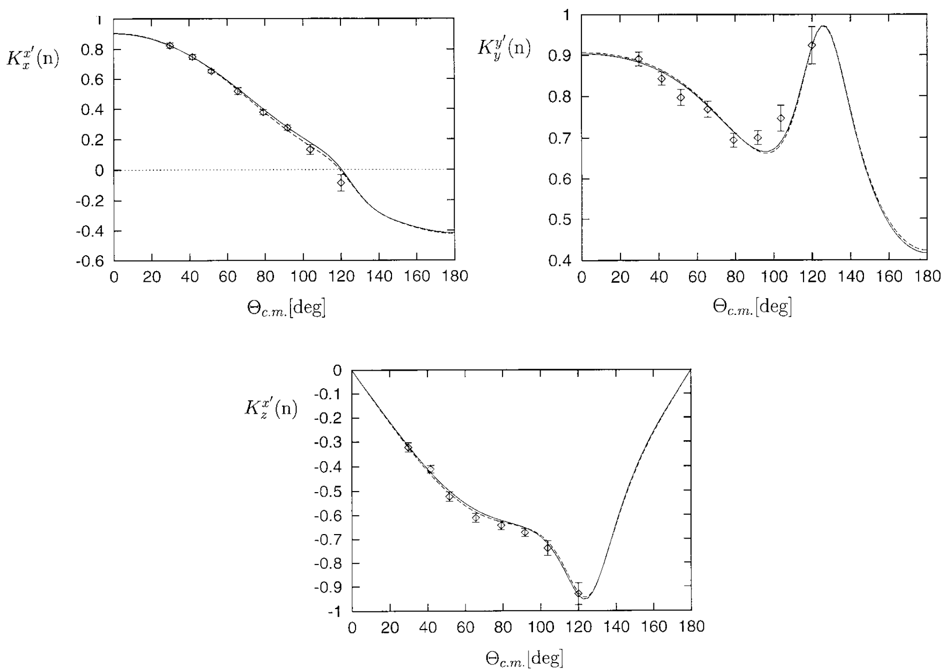

Fig. 6. Some nucleon to nucleon spin-transfer coefficients in nd elastic scattering at 10 MeV. Definition of curves as in Fig. 1. Data from Ref. [26].

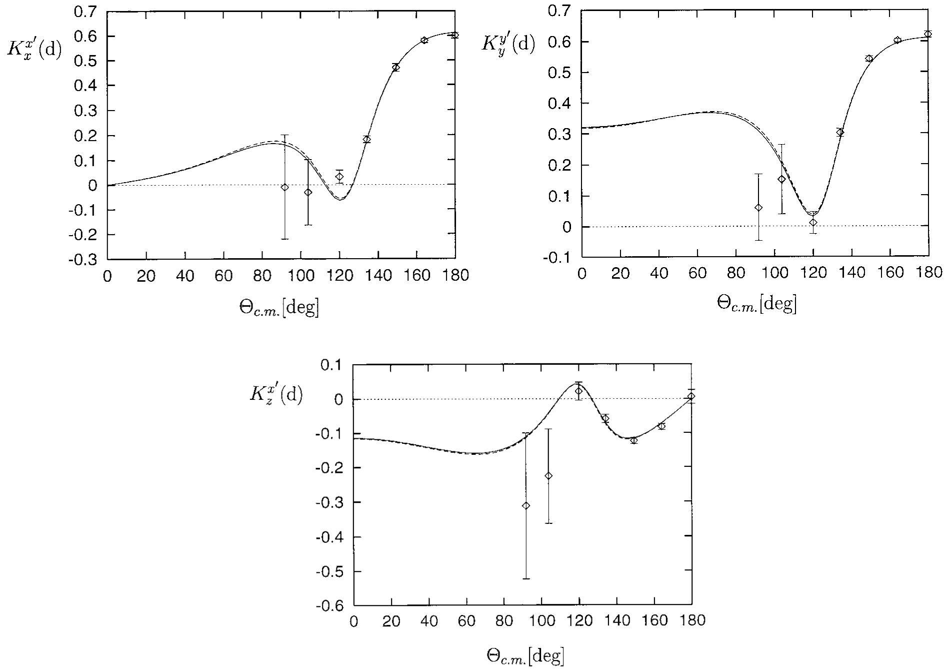

Fig. 7. Some nucleon to deuteron polarization transfer coefficients in nd elastic scattering at 10 MeV. Definition of curves as in Fig. 1. Data from Ref. [26].

3. Conclusions

We have applied the B/R model for density-dependent meson masses to calculate the triton binding energy and various observables of nd elastic scattering at several incident energies. Concerning the continuum, we have paid particular attention to the analyzing power A_y, which has been, for over ten years, one of the most elusive problems in low-energy few-body physics.

For both the bound state energy and the nd analyzing power, the effect due to B/R scaling goes in the desired direction, diminishing the discrepancy between data and 3N predictions obtained with modern free NN forces. Notice that this is not a trivial result. The two main open problems concerning the three-nucleon system are of very different nature. The triton binding energy is typically underpredicted by 0.7$\pm$0.2 MeV. This figure must be compared with the total potential energy of the triton, which is approximately -50 MeV. Thus, only about 2% of the potential energy is missing, which is very little. On the other hand, in the case of the A_y puzzle the disagreement with the data is as large as 30% in the region of the maximum, which is a large discrepancy. Because of the different nature of the two observables, and because of the very different sizes of the discrepancies in the two cases, it is by no means trivial that a single mechanism can fix both problems simultaneously. For the binding energy the central force plays the main role, while for the analyzing power the spin-orbit force is crucial. The central forces created by σ and ω are opposite in sign, which results in a small net effect, while the corresponding spin-orbit forces add up coherently giving rise to a large effect. Thus, the B/R scaling mechanism is exactly of the nature needed to address both problems successfully. Thus we conclude that this approach is promising and deserves further consideration.

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