Medium-Polarization Effects: A Crucial Ingredient in the Δ(1232)-Nucleon Interaction

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The exchange of a virtual nuclear collective mode is shown to have an important effect on the isobar–nucleon-hole interaction. A numerical estimate for the Landau parameter in the isobar-nucleon sector is given by solving the fully coupled Babu-Brown equation in a simple model.

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The Δ(1232) isobar has been suggested to play an important role in the reduction of spin-isospin strength in nuclei,[1-4] especially after the experimental discovery of the Gamow-Teller giant resonance.[5] The magnitude of the reduction of magnetic strength due to isobar-hole admixtures in the nuclear wave function depends strongly on the isobar-hole coupling strength. In this Letter, we present a microscopic derivation of the isobar-hole interaction for vanishing momentum transfer.

In Ref. 3, where only schematic interactions were used, one obtained quenching effects of more than 50%. On the other hand, in Ref. 4 the residual interaction in the spin-isospin channel was constructed from one-pion (V_π) and one-rho (V_ρ) meson exchange, and therefore, antisymmetrization effects were explicitly included. The effects of short-range correlations were included by a central correlation function $g(\vec{q}-\vec{k})$, while the effects of tensor correlations and other renormalizations were summarized by a Landau parameter $\delta g_0'$, which was fitted to several low-lying magnetic states. The particle-hole (ph) interaction in the nucleon-nucleon sector therefore reads

$$F_{\sigma\tau}{}^{\mathrm{ph}}(\vec{q}) = \int \frac{d^3k}{(2\pi)^3} g(\vec{q}-\vec{k})[V_\pi(\vec{k}) + V_\rho(\vec{k})] + \delta g_0' \vec{\sigma}\cdot\vec{\sigma}' \vec{\tau}\cdot\vec{\tau}'. \tag{1}$$

This interaction basically agrees with exact G-matrix calculations[6] performed with meson-exchange interactions. A problem arose, however, when this interaction was extended to the isobar sector. In Ref. 4 it was pointed out that especially the short-range parts of the interaction, such as the rho exchange, involve almost exact cancellations between the direct and exchange isobar-hole interaction. This is because nucleons carry spin and isospin $\frac{1}{2}$, while the isobar has both spin and isospin $\frac{3}{2}$. Therefore the two interacting nucleons must have total isospin $T=1$ and, in the spin-isospin channel, total spin $S=1$. This implies that all even relative angular momenta of the interacting nucleons are suppressed in the spin-isospin channel, while in the isovector tensor channel all even or odd relative momenta are suppressed according to spin S being odd or even, respectively. Because of this argument, Arima *et al.*[7] concluded that the isobar probably plays only a minor role in explaining the reduction of magnetic strength in nuclei.

Now we would like to point out that the G matrix is only a part of the full quasiparticle-quasihole interaction. It is well known that employing the G matrix as a residual particle-hole interaction leads to an instability in nuclear matter.[8] Therefore one has to go beyond a simple Brueckner approach. It has been shown by Babu and Brown[9] and Sjöberg[8] that the inclusion of screening effects in the so-called "crossed channel" reduces strongly the attraction of the G matrix, e.g., the contributions are strongly repulsive. Therefore one expects also an additional repulsion in the spin-isospin channel. A general feature in many-body systems, and one which we shall show applies here, is that when an interaction is strongly repulsive (here, that in the $\vec{\sigma}\cdot\vec{\sigma}' \times\vec{\tau}\cdot\vec{\tau}'$ channel), then the exchange term in the particle-hole interaction is strongly screened, whereas the direct term is unaffected.

The full ph interaction can be written as[9]

$$F^{\mathrm{ph}} = K^{\mathrm{ph}} + F_{\mathrm{induced}}(F^{\mathrm{ph}}). \tag{2}$$

The so-called direct interaction K^{ph} may be approximated by an antisymmetrized G matrix. The induced interaction $F_{\text{induced}}(F^{\text{ph}})$ sums all ph bubbles in the crossed channel and thus makes the equation nonlinear. Note that F^{ph} already includes antisymmetrization. In Fig. 1 we show the graphical representation of Eq. (2). A linearized version of Eq. (2) has been studied by Dickhoff.[10]

The major effects of Eq. (2) can be studied in the Landau limit, where the particle-hole interaction has the form

$$F^{\text{ph}} = C_0(f_0 + f_0'\vec{\tau}\cdot\vec{\tau}' + g_0\vec{\sigma}\cdot\vec{\sigma}' + g_0'\vec{\sigma}\cdot\vec{\sigma}'\vec{\tau}\cdot\vec{\tau}') \qquad (3)$$

with a constant $C_0 = \hbar^2\pi^2/mk_{\text{F}} = 302$ MeV fm^3. Neglecting in a first step also all possible momentum dependences in the exchange channel, one obtains the following simple model:

$$\begin{aligned} f_0 &= f_0^G + \tfrac{1}{4}(f_0^I + 3f_0'^I + 3g_0^I + 9g_0'^I), \\ f_0' &= f_0'^G + \tfrac{1}{4}(f_0^I - f_0'^I + 3g_0^I - 3g_0'^I), \\ g_0 &= g_0^G + \tfrac{1}{4}(f_0^I + 3f_0'^I - g_0^I - 3g_0'^I), \\ g_0' &= g_0'^G + \tfrac{1}{4}(f_0^I - f_0'^I - g_0^I + g_0'^I). \end{aligned} \qquad (4)$$

Here, within our approximation, f_0^G, etc., denote the Landau parameters derived from the G matrix, while the terms arising from the induced interaction are given by

$$f_0^I = 2f_0^2 U(q=0)/[1 + 2f_0U(q=0)] \qquad (5)$$

with $U(q=0) = +\frac{1}{2}$ denoting only the forward-going contribution of the Lindhard function at zero momentum transfer in nuclear matter. In finite nuclei, the shell model introduces a gap between the energies of the occupied and the unoccupied levels. Consequently the backward-going contribution of the Lindhard function is reduced with respect to the forward-going one. In order to obtain an estimate as realistic as possible for the Landau parameters in finite nuclei, we decided to omit the backward-going contribution in nuclear matter entirely.

The major effect of the induced interaction is to stabilize the parameter f_0, since all induced contributions add coherently to compensate the attractive f_0^G. In all other channels, however, the induced pieces cancel to a large extent. It introduces, e.g., in the spin-isospin strength g_0' a correction of about 20%.[10]

In the isobar sector, however, the situation is different for two reasons: (i) The isobar has to be excited via the spin-isospin channel. Therefore the cancellation in Eq. (4) does no longer appear. (ii) The factor $\frac{1}{4}$ (due to the exchange term) which reduces the induced pieces in Eq. (4) does not occur, since $\vec{S}\cdot\vec{\sigma}'P_\sigma = \vec{S}\cdot\vec{\sigma}'$.

In the Landau limit, the force in the isobar sector is given by

$$(F^{\text{ph}})_{\Delta N} = C_0(g_0')_{\Delta N}\vec{S}\cdot\vec{\sigma}'\vec{T}\cdot\vec{\tau}'. \qquad (6)$$

An estimate of the coupling strength $(g_0')_{\Delta N}$ can be obtained in the same approximation as before by summing only nucleon-nucleon ring diagrams in the crossed channel:

$$(g_0')_{\Delta N} = (g_0')_{\Delta N}{}^G + \frac{2(g_0')_{\Delta N}g_0'U(q=0)}{1 + 2g_0'U(q=0)}. \qquad (7)$$

Using the Landau parameters from a G-matrix calculation based on Holinde, Erkelenz, and Alzetta[11] (see Table I) one gets from Eq. (4) $g_0' = 0.76$ in the nucleon sector, while in the isobar sector [Eq. (7)] $(g_0')_{\Delta N} = 1.60$ is obtained, which means a change by a factor of 1.8. This rough estimate shows that the virtual collective excitation in the nucleon sector has an important effect on the

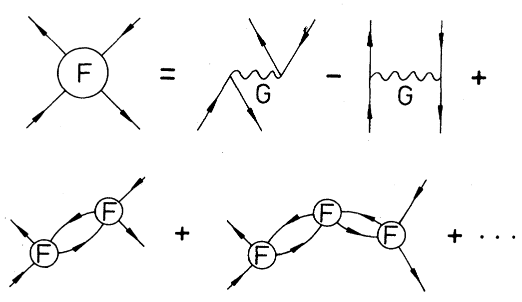

FIG. 1. Graphical representation of the effective particle-hole interaction. The first two terms are the direct and exchange contributions from the direct interaction (Brueckner G matrix), while the remaining graphs together are the induced interaction.

TABLE I. Landau parameter (in units of $C_0 = 302$ MeV fm^3) in both nucleon (g_0') and isobar $(g_0')_{\Delta N}$ sector based on Holinde-Erkelenz-Alzetta potential. The experimental value $(f^*/f) = 2$ was used. The row G denotes the results derived from a G matrix, while $F^{\text{ph}}(N+\Delta)$ includes a self-consistent coupling between isobars and nucleons using $(g_0')_{\Delta\Delta}{}^G = 0$. In the row $F^{\text{ph}*}(N+\Delta)$ a value of $(g_0')_{\Delta\Delta}{}^G = 1.82$ was used.

	g_0'	$(g_0')_{\Delta N}$
G	0.63	0.91
$F^{\text{ph}}(N+\Delta)$	0.75	1.45
$F^{\text{ph}*}(N+\Delta)$	0.75	1.63

isobar–nucleon-hole interaction. A more reliable calculation should, however, take care of the momentum dependence of F^{ph} and consider the self-consistent coupling between isobars and nucleons.

Since the induced interaction contributes only to the exchange term of F^{ph}, one has to average over the momentum in order to get Landau parameters. This averaging process is not done explicitly in Eq. (5). Therefore one might argue that this dependence modifies considerably the above estimate. In fact, the spin-isospin channel contains the one-pion- and one-rho-exchange interaction, which makes this channel strongly momentum dependent. However, one has to remember that with increasing momentum the isovector tensor force becomes important. A calculation[10] shows that, as far as the spin-isospin channel is concerned, the induced interaction has essentially no momentum dependence (or even increases) when the tensor force is taken into account.

In Eqs. (4) and (7) the influence of the isobar on the nucleon sector has been neglected. It is straightforward, however, to generalize the simplified model given by Eqs. (4) and (7) to include a self-consistent coupling between isobars and nucleons. Details will be given in Ref. 6. Here we discuss the results of the fully coupled self-consistent equations, which are displayed in Table I.

As we saw already from the simplified model, the induced interaction causes a dramatic enhancement of the isobar-hole coupling strength $(g_0')_{\Delta N}$. In our improved model taking into account the full coupling we obtain an additional repulsion of about 59% of the G-matrix result for $(g_0')_{\Delta N}{}^G$, while the nucleon-nucleon strength g_0' is increased by only 19% (compare first and second lines), the chief difference being the factor of 4 in the different ratios of exchange to direct term. Here it is also worthwhile to mention that the self-consistent coupling between isobars and nucleons reduces the contribution of the induced interaction to $(g_0')_{\Delta N}$ by ~22% with respect to the corresponding contribution given by Eq. (7). In the nucleon-nucleon sector this reduction is ~8%.

The results discussed above were obtained by setting the isobar-nucleon-nucleon-isobar interaction $(g_0')_{\Delta\Delta}{}^G$ equal to zero because the short-range correlation in this channel is unknown. In order to get some feeling about the influence of this channel, we simply scaled the value $(g_0')_{\Delta\Delta}{}^G = (f^*/f)(g_0')_{\Delta N}{}^G$. Although g_0' is almost insensitive to this value, $(g_0')_{\Delta N}$ slightly increases when $(g_0')_{\Delta\Delta}{}^G$ is switched on (see the last line of Table I).

The above considerations pertain to other versions of the one-boson-exchange potential.[12]

In conclusion, we have pointed out that the induced interaction enhances drastically the isobar-hole coupling by screening out the exchange term in the interaction. Our calculation justifies the force *Ansatz* made by Suzuki, Krewald, and Speth.[4]

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