Energy and density dependence of the isovector tensor interaction

K. Nakayama, S. Krewald, and J. Speth
Institut für Kernphysik, Kernforschungsanlage Jülich, D-5170 Jülich, West Germany

W. G. Love
Department of Physics and Astronomy, University of Georgia, Athens, Georgia 30602

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The energy and density dependences of the effective t- and G-matrix tensor interactions have been analyzed. An apparent contradiction between experimental evidences on the effective isovector tensor force observed in nuclear structure and that observed in nuclear reactions has been explained.

A unified understanding of the magnitude and shape of the isovector tensor force is a long standing problem of extreme importance in both nuclear structure and nuclear reaction physics. The experimental evidence which has been obtained on the isovector tensor force in the past few years seems to contradict itself. In particular, Nakayama *et al.*[1] have recently shown that the tensor component of the effective nuclear matter G-matrix interaction between two nucleons below the Fermi level in the initial state is practically unaffected by correlations. On the other hand, the real and dominant part of the isovector tensor component of the t-matrix interaction, extracted from the recent nucleon-nucleon amplitudes of Arndt and Roper[2] using the methods of Ref. 3, shows a strong energy dependence. This means that the isovector tensor component of the t-matrix interaction is strongly affected by short-range correlations. The aim of the present Brief Report is to explain the behavior of the t- and the G-matrix tensor interactions. All our numerical results are based on the one-boson exchange potential of Holinde *et al.*[4] The discussion following Eq. (2) makes obvious that our conclusions do not depend on the details of the particular bare interaction used.

The scattering of two nucleons in nuclear matter is described by Brueckner's G matrix which may be obtained by solving the Bethe-Goldstone equation, which in a partial wave representation[5] may be written as

$$G^{JST}_{L_f,L_i}(K;k_f,k_0)=V^{JST}_{L_f,L_i}(k_f,k_0)+\frac{2}{\pi}\sum_{L'}\sum\int_0^\infty dk'k'\,V^{JST}_{L_f,L'}(k_f,k')F^{JST}_{L_i,L'}(K;k',k_0). \qquad (1)$$

Here, the bare interaction is denoted by V. The relative momenta in the initial and final states are k_0 and k_f; K refers to the center-of-mass momentum. The effects of short-range correlations and Pauli blocking are contained in the defect function F given by

$$F^{JST}_{L_i,L'}(K;k',k_0)=k'\frac{\bar{Q}(K,k')G^{JST}_{L',L_i}(K;k';k_0)}{E(K,k_0)-E(K,k')+i\epsilon}. \qquad (2)$$

The sums of the Brueckner-Hartree-Fock energies in the initial and intermediate states are denoted by $E(K,k_0)$ and $E(K,k')$, respectively. The angle-averaged Pauli operator is denoted by $\bar{Q}(K,k')$. In the limit of vanishing density, the Pauli operator reduces to unity and the G matrix should converge to the matrix which describes the scattering of two nucleons in the vacuum. In the present investigation the so-called "continuous choice"[5] for the self-consistent Brueckner-Hartree-Fock potential has been used.

For the tensor interaction, the effects of correlations are largely restricted to the $^3S_1$-$^3D_1$ states, even at incident energies up to 250 MeV. Here we discuss the partial wave contribution to the tensor force which causes a transition from a D to an S state via an intermediate D state. A similar discussion holds for other partial waves. In the upper part of Fig. 1, the product $k'V_{02}(k_0,k')F_{22}(k_0;k',k_0)$, which describes the correlated contribution in Eq. (1) in the vacuum, is shown as a function of the intermediate momentum k'. We consider two different incident energies of $E_p=50$ (curve a) and 210 MeV (curve b) to illustrate the points. The position of the pole is determined by the energy denominator of the defect function [Eq. (2)]. At $E_p=50$ MeV, the correlated contribution to the D-to-S t-matrix element is positive, since the pole occurs at a relatively small value of k'. As the bombarding energy increases, three qualitative changes occur. (i) The energy denominator increases in the region of k' where the numerator of the defect function is significant, which implies a reduction of the absolute magnitude of the defect function. (ii) The magnitude of $V_{02}(k_0,k')$ decreases, as k_0 increases, in the region of k' where the defect function $F_{22}(k_0;k',k_0)$ is significant. Therefore, the absolute magnitude of the product $k'V_{02}(k_0,k')F_{22}(k_0;k',k_0)$ is further reduced. (iii) The pole of the principal part integral moves to a larger value of k' and thus produces a larger cancellation in the principal part integral. The contribution via an intermediate S state, $k'V_{00}(k_0,k')F_{20}(k_0;k',k_0)$, even becomes attractive due to this pole structure and tends to cancel the repulsive contribution via an intermediate D state. These effects combine coherently and reduce the influence of correlations with increasing energy. As a result, the influence of correlations on the t-matrix tensor interaction decreases with increasing bombarding energy.

The middle part of Fig. 1 shows the product $k'V_{02}(k_0,k')F_{22}(k_0;k',k_0)$ as a function of k' at $E_p=50$ MeV for several values of the density ρ. The decrease of the correlated part with increasing density is due mainly to

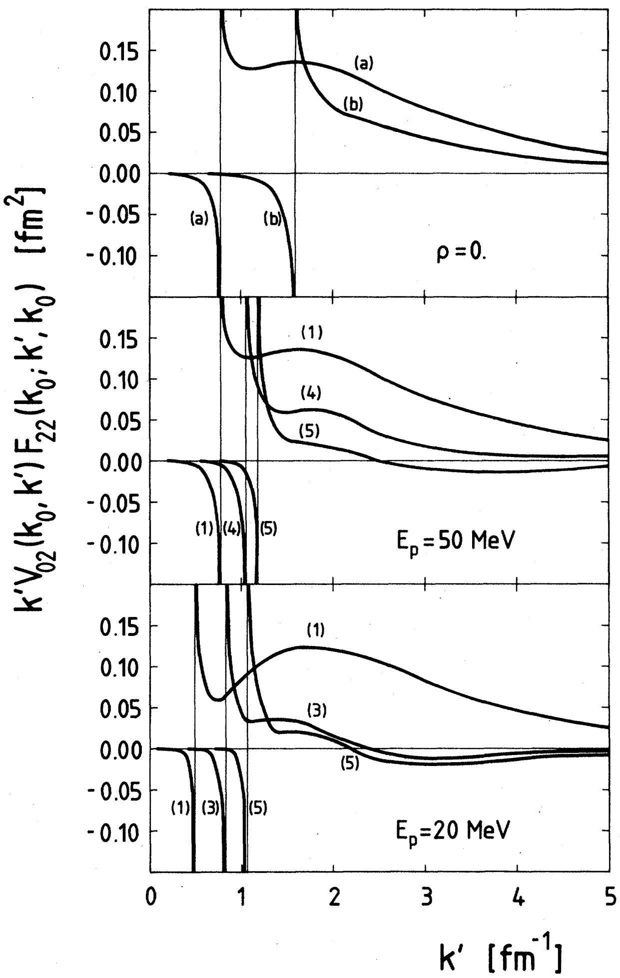

FIG. 1. Upper part: The product of the intermediate momentum k', the bare interaction $V_{02}(k_0,k')$ and the D-state defect function $F_{22}(k_0;k',k_0)$ describing the correlated contribution [Eq. (1)] of the transition from a D to an S state via a D state is shown as a function of k'. Two different incident energies of $E_p=50$ MeV [curve (a)] and $E_p=210$ MeV [curve (b)], which correspond to the initial relative momentum of $k_0=0.78$ and 1.59 fm^{-1}, respectively, are displayed. The final relative momentum k_f has been chosen to be equal to k_0. Middle part: The same quantity as in the upper part is shown now for three different densities ρ: $\rho=0$ (curve 1), $\rho=0.53\rho_0$ (curve 4), and $\rho=\rho_0$ (curve 5), where ρ_0 stands for the normal density of nuclear matter. Here, the values of k_0, as well as the center-of-mass momentum K, have been determined from the local momentum of a particle with an asymptotic energy of $E_p=50$ MeV that interacts with a nucleon having momentum $\frac{3}{4}k_F$ inside the nucleus at a density corresponding to the Fermi momentum $k_F=(3\pi^2/2\rho)^{1/3}$. Lower part: The same quantity as in the middle part is shown for densities $\rho=0$ (curve 1), $\rho=0.34\rho_0$ (curve 3), and $\rho=\rho_0$ (curve 5) at the incident energy $E_p=20$ MeV.

the Pauli operator and the energy denominator. For small incident energies, the defect function for momenta less than $k'=(k_F^2-k_0^2)^{1/2}$ is entirely suppressed due to the Pauli blocking and is reduced for momenta $k'\leq k_0+k_F$. Furthermore, the energy denominator increases with increasing density, since in the nuclear medium the energy of a nucleon consists of the sum of the kinetic energy and of the potential energy due to the self-consistent Brueckner-Hartree-Fock potential, which increases in absolute magnitude with increasing density. In addition, the defect function $F_{22}(k_0;k',k_0)$ starts to oscillate around zero as the density increases and produces a large cancellation of the product $k'V_{02}(k_0,k')F_{22}(k_0;k',k_0)$ as curve (3), corresponding to normal nuclear matter density ρ_0 ($\rho_0=0.17$ particles per fm^3), illustrates. The position of the pole, on the other hand, changes very smoothly with density. {Note that the effect of the energy denominator on the defect function [Eq. (2)] is not linear.} Therefore, at low incident energies, a strong density dependence of the effective tensor force should be expected. Moreover, at high densities the influence of correlations on the tensor force is strongly reduced.

In the lower part of Fig. 1 the same quantity as in the middle part is shown, now at a very low incident energy of $E_p=20$ MeV. At this energy the product $k'V_{02}(k_0,k')F_{22}(k_0;k',k_0)$ decreases rapidly with density in the very low density region ($\rho\leq 0.3\ \rho_0$). For larger values of the density, k_F is practically density independent, showing characteristics similar to the case of $E_p=50$ MeV at high densities. The change in its behavior at small ρ compared to the case of $E_p=50$ MeV is mainly caused by the energy denominator, which becomes larger as the incident energy decreases for a fixed density. For instance, at $\rho=0.5\ \rho_0$, the energy denominator increases by a factor ~ 2 in the region of $1.0<k'$ $(\text{fm}^{-1})<2.0$ in going from $E_p=50$–20 MeV.

At high incident energies, the density dependence of the effective tensor force is weak and the G matrix approaches the t matrix. This occurs for two reasons: (i) as the energy of the incident nucleon increases beyond the Fermi momentum, the influence of Pauli blocking is reduced since intermediate states become available at momenta up to $k'=k_0-k_F$, and (ii) the energy denominator becomes similar to that of the t matrix as the bombarding energy increases.

In Fig. 2, the real part of the isovector tensor t-matrix interaction, obtained by the methods of Ref. 1, is shown as a function of momentum transfer q for different bombarding

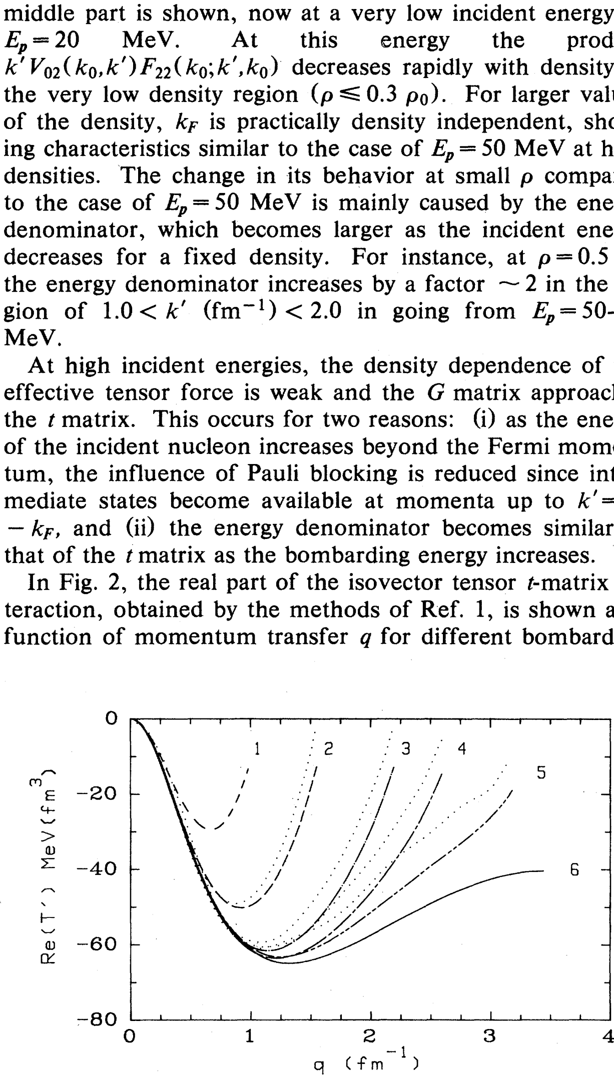

FIG. 2. The real part of the isovector t-matrix tensor interaction is shown as a function of momentum transfer q. The incident energies are $E_p=20$ MeV (1), 50 MeV (2), 100 MeV (3), 140 MeV (4), and 210 MeV (5). The isovector t-matrix tensor interaction extracted from the SP 84 nucleon-nucleon amplitudes of Arndt and Roper[3] corresponding to these last four energies are given by the dotted curves. The isovector tensor interaction arising from the bare one-pion and one-rho exchange processes is represented by the solid line (6).

energies. The results are compared with the isovector tensor interaction (dotted curves) extracted directly from SP84 amplitudes,[3] which shows a similar energy dependence. The magnitude of the interaction is seen to increase with increasing bombarding energy. This behavior follows from the energy dependence of the correlated part of the effective interaction (see upper part of Fig. 1), as discussed before. With increasing energy, the repulsive correlated contributions are reduced and as a consequence, the isovector tensor t-matrix interaction becomes close to the attractive one-pion plus one-rho exchange potential (solid curve) for high energies of the incident nucleon.

The density dependence of the isovector tensor interaction is shown in Fig. 3. At low energies ($E_p = 20, 50$ MeV), a strong density dependence of the isovector tensor interaction is found, as one expects from the behavior of the correlated part (see lower part of Fig. 1) of the effective G-matrix tensor interaction. At very low energies ($E_p = 20$ MeV) the isovector tensor force shows a rapid variation with density in the very low density region up to $\rho \sim 0.3\ \rho_0$. At higher densities it remains practically unchanged, showing no correlation effects. In the lower part of Fig. 3 we show the density dependence of the isovector tensor force for high energies ($E_p = 210$ MeV). The density dependence is weak because in this case the G matrix approaches the t matrix, as discussed before.

In summary, for the case in which one of the two nucleons in the initial state is above the Fermi level, the real (and dominant) part of the effective isovector tensor interaction has an energy dependence which becomes weaker as the density increases. Its absolute magnitude increases with increasing bombarding energy. It also exhibits a strong density dependence at low incident energies and its magnitude increases with increasing density. Either at high densities or at high bombarding energies, the effective isovector tensor interaction approaches closely the bare one-pion plus one-rho exchange interaction.

The isovector tensor G-matrix interaction between two nucleons below the Fermi level shows a very weak density dependence, at least up to $q \sim 2\ \text{fm}^{-1}$, for values of the density ranging between $0.35\ \rho_0 \leq \rho \leq \rho_0$, as was pointed out in Ref. 1. However, it is extremely dangerous to extrapolate this finding to lower densities. In fact, our present results for the case in which one nucleon is above the Fermi surface shows a very similar behavior for $0.35\ \rho_0 \leq \rho \leq \rho_0$ at very low incident energies and, therefore, strongly suggests a rapid reduction of the isovector tensor force at lower densities when both nucleons are below the Fermi level.

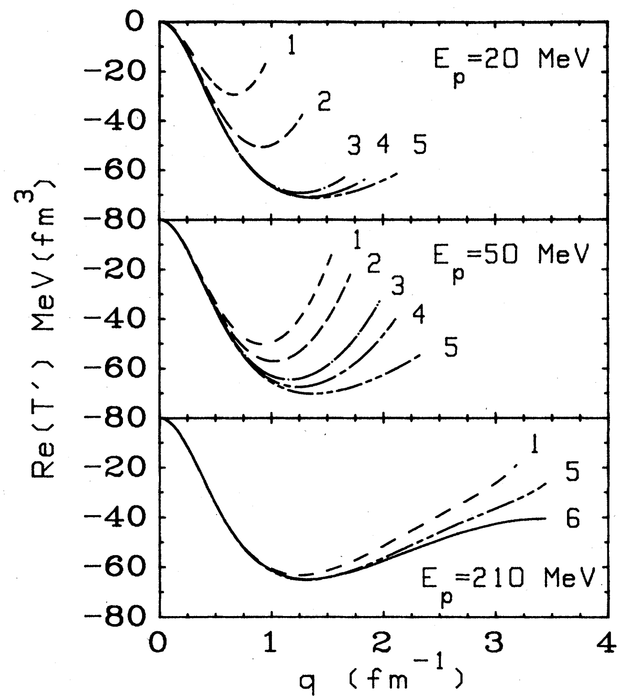

FIG. 3. Upper part: The real part of the isovector tensor interaction in the medium is shown as a function of the momentum transfer for five different densities. The densities are $\rho = 0$ (1), $0.11\ \rho_0$(2), $0.34\rho_0$(3), $0.53\rho_0$(4), and ρ_0(5). The energy of the incident nucleon is $E_p = 20$ MeV. Middle part: Same quantity as in the upper part for incident energy of $E_p = 50$ MeV. Lower part: Same quantity as in the upper part for an incident nucleon energy of 210 MeV. The densities are $\rho = 0(1)$ and $\rho = \rho_0(5)$. For comparison, the isovector tensor interaction arising from bare one-pion and one-rho exchange is displayed by the solid line (6).

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[1]K. Nakayama, S. Krewald, J. Speth, and W. G. Love, Nucl. Phys. **A431**, 419 (1984).
[2]R. A. Arndt and L. D. Roper, Virginia Polytechnic Institute Scattering Analysis Interactive Dial-In Program, solution SP84.
[3]W. G. Love and M. A. Franey, Phys. Rev. C **24**, 1073 (1981); W. G. Love, M. A. Franey, and F. Petrovich, in *Proceedings of the International Conference on Spin Excitations, Telluride, Colorado, 1982*, edited by F. Petrovich *et al.* (Plenum, New York, 1984), p. 205.
[4]K. Holinde, K. Erkelenz, and R. Alzetta, Nucl. Phys. **A194**, 161 (1972).
[5]J. P. Jeukenne, A. Lejeune, and C. Mahaux, Phys. Rep. **25C**, 83 (1976).