Screening of the tensor force in the isoscalar $M1$ state in ^{208}Pb

S. Drożdż,*,† J. L. Tain,† and J. Wambach
Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801
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The influence of the residual ph tensor force on the wave function of the 5.846 MeV isoscalar 1^+ state in ^{208}Pb is investigated. While the (e,e′) form factor is well described within a 1p1h random-phase-approximation model and is fairly insensitive to the strength of the tensor force, medium energy proton scattering experimental angular distributions are not reproduced within this model. It is demonstrated that the inclusion of 2p2h excitations yields screening corrections to the effective tensor force which reduce its strength considerably. Thus the apparent failure of the 1p1h random-phase-approximation wave function to describe the inelastic proton scattering data at medium energy can be resolved.

Isoscalar $M1$ modes in nuclei provide important information on the spin stability of symmetric nuclear matter.[1] If the effective tensor force in the spin $S=1$ isospin $T=0$ particle-hole channel is sufficiently strong, the infinite system develops a zero mode which signals an instability of the normal ground state. In Fermi liquid theory the stability condition is obtained by spin dependent deformations of the Fermi sphere, which correspond to 1p1h excitations of the random-phase approximation (RPA) type. After projection onto ph states of total angular momentum J and orbital angular momentum $L=J\pm1$ one derives a stability matrix for the change in the potential energy part δA of the free energy, which in the presence of tensor forces has been given in Ref. 2. It is a straightforward extension of the well-known Pomeranchuck stability criteria[3] for Fermi liquids and involves the isoscalar spin-central and tensor Landau parameters G_L and H_L. For isoscalar 1^+ excitations of nuclear matter, which correspond to $[\sigma Y_0]^1$ and $[\sigma Y_2]^1$ distortions of the Fermi sphere, one derives the following matrix elements of the 2×2 stability matrix $\langle LJ \mid \delta A \mid L'j\rangle^2$:

$$\langle 01 \mid \delta A \mid 01\rangle = 1+G_0 \,, \tag{1a}$$

$$\langle 21 \mid \delta A \mid 01\rangle = \langle 01 \mid \delta A \mid 21\rangle = -\sqrt{2}(H_0-\tfrac{2}{3}H_1+\tfrac{1}{5}H_2) \,, \tag{1b}$$

$$\langle 21 \mid \delta A \mid 21\rangle = 1+\tfrac{1}{5}G_2-\tfrac{7}{15}H_1+\tfrac{2}{5}H_2-\tfrac{2}{35}H_3 \,. \tag{1c}$$

Stability of the normal ground state is guaranteed if the eigenvalues of this 2×2 matrix are positive, which implies that the free energy A has a minimum for a spherical Fermi surface and that the curvature is positive. One easily verifies that for pure one pion exchange, which induces a strong tensor force in the spin isoscalar ph channel via the Pauli exclusion principle, the eigenvalues become negative, i.e., the normal ground state is unstable against isoscalar spin oscillations. More realistic tensor interactions which involve also ρ-meson exchange yield, however, positive eigenvalues.[1]

Checking the stability of symmetric nuclear matter with respect to a given excitation mode frequently provides a useful gauge of the stability of finite nuclei. But not necessarily. In particular, when shell effects bring one or more ph states substantially down in energy, a finite nucleus may be far less stable than nuclear matter. In particular, in spin nonsaturated nuclei like ^{208}Pb, the $[\sigma Y_0]^1$ operator, upon acting on the ground state, generates a very low spin-flip state with the shell model wave function

$$\begin{aligned} \mid 1^+\rangle_1 &= [\sigma Y_0]^1 \mid 0^+\rangle_{\text{g.s.}} \\ &= a \mid \pi h_{9/2} \pi h_{11/2}^{-1}\rangle \\ &\quad + (1-a^2)^{1/2} \mid \nu i_{11/2} \nu i_{13/2}^{-1}\rangle \,, \end{aligned} \tag{2}$$

while the $[\sigma Y_2]^1$ operator excites a collective $2\hbar\omega$-isoscalar $M1$ mode

$$\mid 1^+\rangle_2 = [\sigma Y_2]^1 \mid 0^+\rangle_{\text{g.s.}} \,. \tag{3}$$

The exchange part of the tensor force leads to a coupling of these two modes and thus admixes a $[\sigma Y_2]^1$ component to the low lying spin flip mode. Thus

$$\mid 1^+\rangle_l = \alpha \mid 1^+\rangle_1 + (1-\alpha^2)^{1/2} \mid 1^+\rangle_2 \,. \tag{4}$$

For pure one-pion exchange this mixing is so strong that the 1p1h RPA equations have an imaginary root, i.e., the low energy state is pushed below the ground state. This result is of course expected from nuclear matter. For more realistic interactions, one still observes a sizable $[\sigma Y_2]^1$ component in the low energy state, which signals the proximity of ^{208}Pb to a phase instability. As pointed out in Ref. 1, the excitation of the $[\sigma Y_2]^1$ component of $\mid 1^+\rangle_l$ is probe dependent. Inelastically scattered electrons do not couple to this component. The pure spin flip wave function [Eq. (2)] and the full RPA wave function with tensor force mixing [Eq. (4)] therefore yield essentially the same q dependence in the transverse form factor,[4] as shown in the upper part of Fig. 1. Inelastic proton scattering should, however, strongly excite the $[\sigma Y_2]^1$ part of the wave function via the exchange tensor part of the residual projectile-target nucleon interaction.[1] As is demonstrated in the lower part of Fig. 1, the pure spin flip wave function which results from an RPA calculation without tensor force (full line) and the wave function including a $\pi+\rho$-exchange tensor force (dashed line) yield considerably different angular distributions for 201 MeV incident protons. The curves shown were obtained with the microscopic distorted wave code DWBA70 (Ref. 5) using the Love-Franey parametrization of the two nucleon t matrix.[6] The optical model parameters were taken from Ref. 8. It should be noted that the spin flip wave function, used here, and the wave function of Vergados[7] give almost identical DWBA cross sections. The RPA results with tensor interaction are in sharp contrast to the data,[8] which are much better described by the pure spin flip wave function [Eq. (2)], indicating that the isoscalar tensor force obtained from one boson exchange (π,ρ) is too strong.

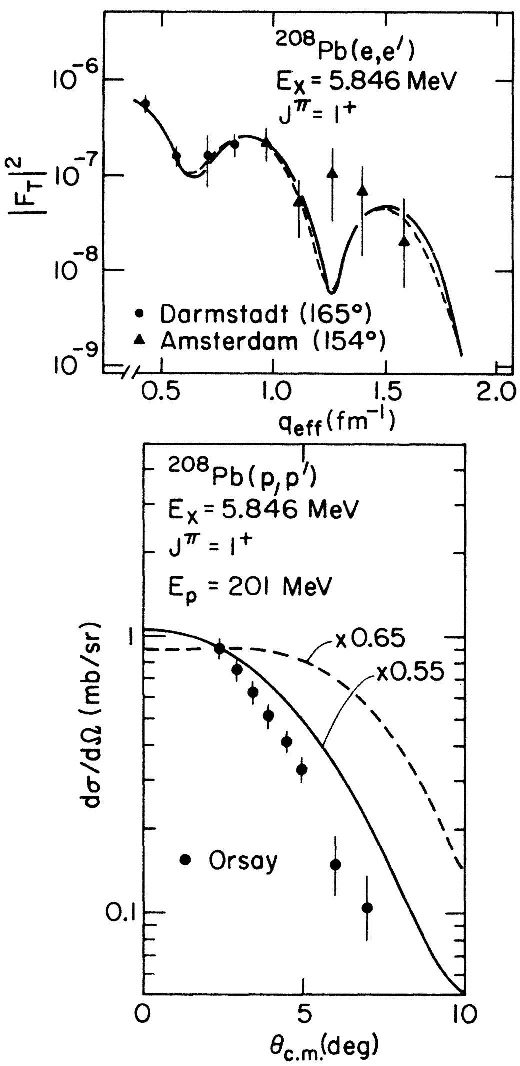

FIG. 1. Upper part: Comparison of the experimental (e,e') form factor (Ref. 4) with 1p1h RPA predictions (taken from Ref. 4). Full line: 1p1h RPA without tensor force; dashed line: 1p1h RPA with $(\pi+\rho)$-tensor force. Lower part: Comparison of the experimental 201 MeV (p,p') angular distribution (Ref. 8) with 1p1h RPA predictions (same wave functions as in Ref. 4). Full line: 1p1h RPA without tensor force; dashed line: 1p1h RPA with $(\pi+\rho)$-tensor force.

To resolve this problem, we argue that a 1p1h RPA description of the low lying isoscalar 1^+ wave function is not sufficient, and 2p2h excitations have to be included. A similar discussion for symmetric nuclear matter has been given recently by Nakayama.[9] The appropriate theory for finite nuclei has been developed in Refs. 10 and 11. After projection of the equations of motion for the creation operator $Q_N^\dagger$ of an excited state $|\psi_N\rangle = Q_N^\dagger|0\rangle$ onto the 1p1h subspace, one obtains modified RPA equations

$$\begin{bmatrix} A(E_N) & B \\ -B^* & -A^*(-E_N) \end{bmatrix} \begin{bmatrix} X(E_N) \\ Y(E_N) \end{bmatrix} = E_N \begin{bmatrix} X(E_N) \\ Y(E_N) \end{bmatrix} , \tag{5}$$

in which the A matrix becomes energy dependent due to the formal elimination of the 2p2h subspace. Separating the nuclear Hamiltonian H into a mean-field part H_0 and a residual interaction V,

$$H = H_0 + V , \tag{6}$$

one obtains explicitly

$$\begin{aligned} A_{mi,nj}(E) = {} & \langle mi^{-1} | H_0 | nj^{-1} \rangle + \langle mi^{-1} | V | nj^{-1} \rangle \\ & + \sum_{pqkl} \langle mi^{-1} | V | pqk^{-1}l^{-1} \rangle \\ & \quad \times \langle pqk^{-1}l^{-1} | (E-H_0)^{-1} | pqk^{-1}l^{-1} \rangle \\ & \quad \times \langle pqk^{-1}l^{-1} | V | nj^{-1} \rangle . \end{aligned} \tag{7}$$

Here we have neglected the residual interaction V in the 2p2h propagator which is justified for high 2p2h-level density and simplifies the numerical calculations in large shell model spaces considerably. Within this extended RPA formalism, long range screening of the tensor force is introduced in a natural way via ph polarization of the medium which is included in the energy dependent term of the A matrix. The corresponding Goldstone diagram is depicted in Fig. 2. Such polarization effects are well known in the electron gas, where they lead to a long range modification of the Coulomb potential and ensure stability of the Fermi surface.

Within the extended RPA formalism we have calculated the screening effects on the isoscalar 1^+ state using a G matrix derived from the HM3A version[12] of the Bonn potential as a residual interaction V. In the relevant channel this interaction is very similar to the $\pi+\rho$-exchange force used in Ref. 1. As discussed above, the tensor force mixes a $[\sigma Y_2]^1$ component to the low lying state wave

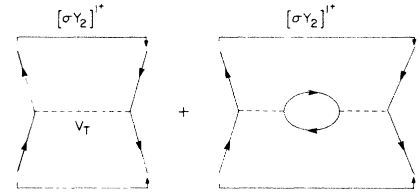

FIG. 2. Diagrammatic representation of the tensor force screening included in the 2p2h RPA theory.

function and leads to an enhancement of the ground state transition strength

$$|_{\mathrm{g.s.}}\langle 0^+ | r^2[\sigma Y_1]^1 | 1^+ \rangle_l |^2 .$$

Table I lists this strength together with the excitation energy E_x for three different cases: (i) 1p1h RPA without tensor force (first line); (ii) 1p1h RPA with inclusion of the tensor force (second line); and (iii) 2p2h RPA with tensor force. As expected, inclusion of the tensor force in the 1p1h RPA leads to a significant enhancement of the transition matrix element and a considerable lowering of the excitation energy. The result is consistent with the findings of Ref. 1 in which the $\pi+\rho$ model was used. Including 2p2h effects, the enhancement of the transition strength is reduced essentially to the 1p1h RPA result omitting the tensor force altogether. Note also that the excitation energy obtained with the 2p2h RPA is in very good agreement with experiment.

From this we conclude that the strong isoscalar tensor force implied by one boson exchange models is largely reduced by 2p2h-screening effects which are well known to be important for the long range parts of the interaction in other Fermi liquids, like the electron gas. This mechanism enhances the stability of symmetric nuclear matter against spin collapse. The reduction of the tensor force also explains the apparent failure of a pure 1p1h RPA description of inelastic (p,p′) form factors once realistic interactions are used.

TABLE I. Excitation energies E_x and ground state $r^2[\sigma Y_2]^1$-transition strength for the low lying isoscalar 1^+ state in ^{208}Pb.

Model	E_x	$r^2[\sigma Y_2]^1$ strength
1p1h RPA (no tensor)	6.1 MeV	516 fm^4
1p1h RPA (with tensor)	4.7 MeV	1226 fm^4
2p2h RPA (with tensor)	5.7 MeV	682 fm^4

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*On leave from Institute of Nuclear Physics, PL-31-342, Krakow, Poland.

†Present address: Institut für Kernphysik, Kernforschungsanlage Jülich, D-5170 Jülich, Federal Republic of Germany.

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