Spin excitations in light nuclei: Effect of projectile energy

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We present a microscopic analysis of the nuclear spin response to proton excitation by examining the specific case of the ^{40}Ca($\vec{p},\vec{p}\,'$) reaction. Recent results indicate that the spin-flip probability decreases with an increase in the incident proton energy from $E_p=319$ to 800 MeV but otherwise maintains the essential features of an enhancement at high excitation and a quenching at low excitation. We show that this feature is consistent with nuclear structure effects and is not likely to depend on the particular choice of proton beam energy. We also suggest that the decrease in spin-flip cross section with increasing E_p is directly linked to the energy dependence of the t-matrix coefficients and conclude by presenting predictions for cross sections at lower incident proton energy.

The study of the nuclear spin response continues to attract a great deal of attention in both experimental and theoretical contexts. From the experimental point of view, several recent results of proton inelastic scattering have provided new insight on the problem.[1–3] In particular, the results of experiments performed by Glashausser *et al.* at 319 MeV and more recently at 800 MeV (Ref. 4) have shown that spin-flip states in ^{40}Ca are strongly excited at energies above 10 MeV; moreover, excitations at higher energy, in the neighborhood of 35 MeV, *appear surprisingly enhanced.* At this projectile energy, isospin-dependent excitations are known to be excited strongly in the case of spin-dependent resonances.[5] Simple shell-model considerations suggest that the states at lower energy, in the 10–20 MeV region, are of $\Delta N=1$, *spin-dipole* nature while those at higher energy (30–35 MeV) are of $\Delta N=2$, *spin-quadrupole type.* Both categories of states are pushed toward higher energy by the repulsive spin-isospin interaction. Since many 1p-1h configurations can contribute to build the spin-dipole and -quadrupole resonances, one can expect to learn something about the properties of the residual interaction by studying the behavior of spin-flip collective states. This is what has been investigated in this paper by studying the response of spin-flip resonances in ^{40}Ca to a hadronic probe using the random phase approximation (RPA) method. In particular, the experimental results at both 319 and 800 MeV are used to suggest that the spin-flip cross sections are definitely of nuclear structure origin and are not the results of reaction dynamics at particular proton beam energies.

Our approach will be to first describe the reaction and then the nuclear structure formalisms before discussing the results and comparing them with experiment. The first step is to write the nucleon-nucleon t matrix for nucleon-nucleon scattering as

$$\begin{aligned} t(q)=t_A(q)&+t_B(q)(\boldsymbol{\sigma}^i\cdot\hat{\mathbf{n}})(\boldsymbol{\sigma}^p\cdot\hat{\mathbf{n}}) \\ &+t_C(q)(\boldsymbol{\sigma}^i+\boldsymbol{\sigma}^p)\hat{\mathbf{n}}+t_E(q)(\boldsymbol{\sigma}^i\cdot\hat{\mathbf{q}})(\boldsymbol{\sigma}^p\cdot\hat{\mathbf{q}}) \\ &+t_F(q)(\boldsymbol{\sigma}^i\cdot\hat{\mathbf{p}})(\boldsymbol{\sigma}^p\cdot\hat{\mathbf{p}})\ , \end{aligned} \quad (1)$$

where the superscripts p and i denote the projectile and target nucleons, respectively. In Eq. (1), $t_A(q)$ is used to denote

$$t_A(q)=t_A^0(q)+t_A^1(q)\boldsymbol{\tau}^i\cdot\boldsymbol{\tau}^p,\ \text{etc}\ . \quad (2)$$

The choice of coordinate system is as follows:

$$\hat{\mathbf{q}}=\frac{\mathbf{k}_i-\mathbf{k}_f}{|\mathbf{k}_i-\mathbf{k}_f|},\quad \hat{\mathbf{n}}=\frac{\mathbf{k}_i\times\mathbf{k}_f}{|\mathbf{k}_i\times\mathbf{k}_f|},\quad \hat{\mathbf{p}}=\hat{\mathbf{q}}\times\hat{\mathbf{n}}\ . \quad (3)$$

The coefficients of Eq. (1) are derived from the nucleon-nucleon t matrix of Love and Franey at the appropriate projectile energy.[5] At the momentum transfer of the experiments, $q=0.5\ \text{fm}^{-1}$, the isospin-dependent part of the coefficients in the spin channel is much larger than the isospin-independent part. We have also neglected, because it is small under the experimental conditions and for simplicity, the spin-orbit interaction term. Thus, only the spin-isospin-dependent term of the t matrix is necessary for our calculation. In the plane-wave Born approximation, the spin-flip cross section can be written as

$$\sigma_{SF}=\frac{m^2}{4\pi^2\hbar^2}\frac{k_f}{k_i}\sum_n\left[|t_E^1(q)|^2\left|\left\langle n\left|\sum_k\boldsymbol{\sigma}^k\cdot\mathbf{q}e^{i\mathbf{q}\cdot\mathbf{r}_k}\tau_z^k\right|0\right\rangle\right|^2+|t_F^1(q)|^2\left|\left\langle n\left|\sum_k\boldsymbol{\sigma}^k\cdot\hat{\mathbf{p}}e^{i\mathbf{q}\cdot\mathbf{r}_k}\tau_z^k\right|0\right\rangle\right|^2\delta(\omega-\omega_n)\right]\ , \quad (4)$$

where $\mathbf{q}$ denotes the momentum transfer and ω and ω_n denote the energy transfer and excitation energy of the nuclear state $|n\rangle$, respectively.

We now briefly describe the calculation for the nuclear states. The spin-isospin response function, $\hat{R}_J(q,q';\omega)$, was calculated in the RPA formalism using a particle-hole interaction composed of π- and ρ-meson exchange components and the Landau parameter g_0' (Refs. 6 and 7).

Only ring diagrams were included in the calculation. The RPA response function, $\hat{R}_J$, and the unperturbed response function, $\hat{\Pi}_J$, are 2×2 matrices in $[L,L']$ (equal to $[J,1]$ in the case of unnatural parity states). The following integral equation has been solved in momentum space by inverting the matrices

$$\begin{aligned}\hat{R}_J(q,q';\omega)=&\hat{\Pi}_J(q,q';\omega)\\&+\int_0^\infty \frac{k^2dk}{(2\pi)^3}\hat{\Pi}_J(q,k;\omega)\\&\times\hat{W}(k;\omega)\hat{R}_J(k,q';\omega)\ .\end{aligned} \tag{5}$$

The unperturbed response function can be written as follows:

$$\begin{aligned}[\hat{\Pi}_J(q,q';\omega)]_{L'L}=\sum_{ph}F_{ph}^{JL'}(q)&\left[\frac{1}{E-E_{ph}+i\delta}\right.\\&\left.-\frac{1}{E+E_{ph}-i\delta}\right]F_{ph}^{*JL}(q)\ ,\end{aligned} \tag{6}$$

where

$$F_{ph}^{JL}(q)=\langle (ph^{-1})J||i^L j_L(qr)(Y_L\otimes\sigma)_J\tau_z||0\rangle\ . \tag{7}$$

Finally, the p-h interaction in momentum space is written as

$$\begin{aligned}W_{ph}=[&V_\pi(\omega,q)(\sigma(1)\cdot\hat{\mathbf{q}})(\sigma(2)\cdot\hat{\mathbf{q}})\\&+V_\rho(\omega,q)(\sigma(1)\times\hat{\mathbf{q}})\cdot(\sigma(2)\times\hat{\mathbf{q}})\tau_1\cdot\tau_2]\ ,\end{aligned} \tag{8}$$

where the π- and ρ-dependent potentials are given by

$$\begin{aligned}V_\pi&\equiv\frac{f_\pi^2(q)}{m_\pi^2}\left[g_0'+\frac{q^2}{E^2-m_\pi^2-q^2}\right]\ ,\\V_\rho&\equiv\frac{f_\pi^2(q)}{m_\pi^2}g_0'+\frac{f_\rho^2(q)}{m_\rho^2}\frac{q^2}{E^2-m_\rho^2-q^2}\ .\end{aligned} \tag{9}$$

The particle and hole wave functions used for the unperturbed response function were calculated self-consistently using the Hartree-Fock method[8] with the Skyrme interaction SGII.[9] The unbound particle states were determined by diagonalizing the Hartree-Fock Hamiltonian in a large harmonic oscillator space. Once the RPA response function was obtained, we considered the spreading width resulting from the coupling of the RPA states to the 2p-2h states. The spreading width in our calculation was determined by the model introduced by Smith and Wambach[10] which relates the coupling to 2p-2h states with the imaginary part of an optical potential using empirical information from the decay widths of particle and hole excitation.

We now turn to a discussion of the results and comparison with experiment. In Figs. 1 and 2, we present the spin-flip probability $S_{\rm nn}$ at the two projectile energies that have been studied experimentally and at two different values of momentum transfer. Here, $S_{\rm nn}$ is defined as the ratio of the spin-flip cross section to the total cross section. In each case the solid curve which

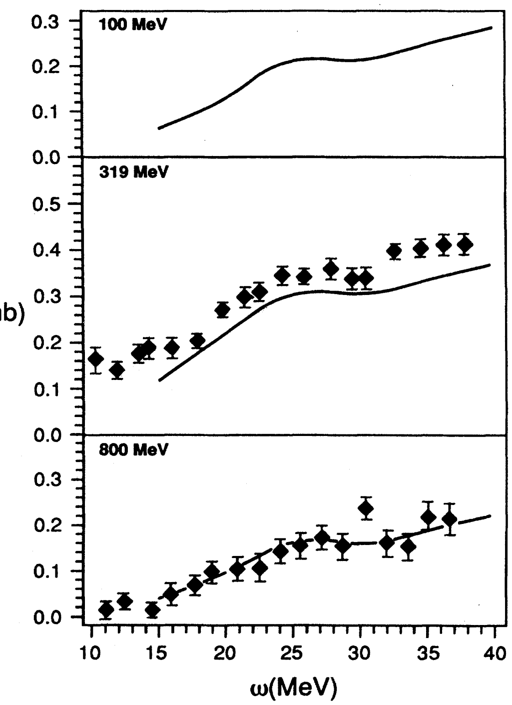

FIG. 1. The influence of projectile energy on the spin-flip probability at momentum transfer $q=0.5$ fm^{-1}. The curves are identified by the three different values for proton beam energies.

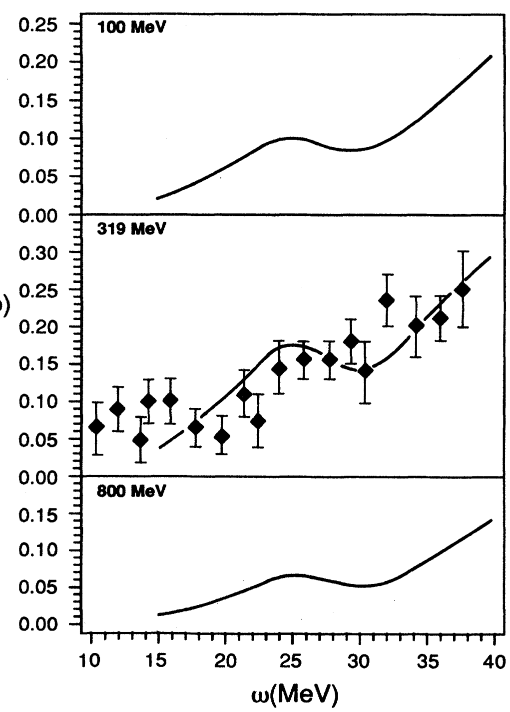

FIG. 2. The influence of projectile energy on the spin-flip probability at momentum transfer $q=0.82$ fm^{-1}. The curves are identified by the three different values for proton beam energies.

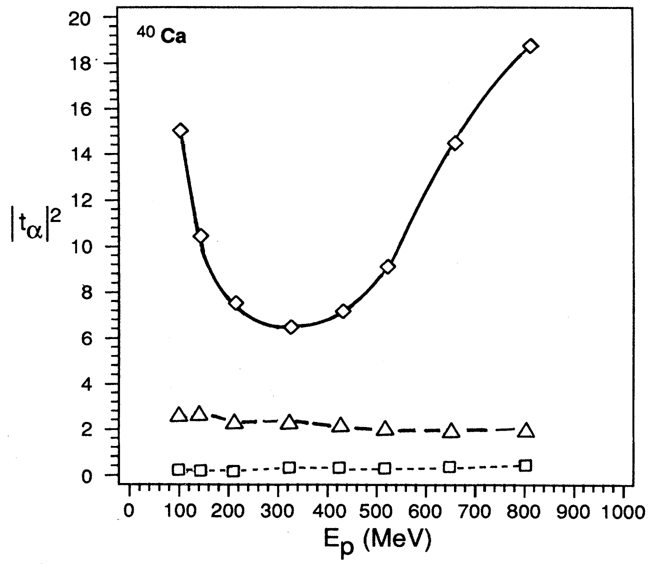

FIG. 3. The dependence of t-matrix coefficients on projectile energy at $q=0.5$ fm^{-1}. The solid curve shows the marked dependence of the $|t_A^0|^2$ coefficient, the broken line the $|t_F^1|^2$ coefficient, and the dashed line the $|t_E^1|^2$ coefficient. Note that only the non-spin-flip channel shows any strong energy dependence. The general behavior of the t-matrix coefficients is very similar at $q=0.82$ fm^{-1}.

displays the result of our calculation can be seen to be in good agreement with experiment, although the agreement is improved at higher momentum transfer for the $E_p=319$ MeV results. The similarity between the S_{nn} curves at 319 and 800 MeV reflects the fact that the nuclear structure calculation is the same in both cases. As to the change in scale, it can, in our opinion, be easily traced back to the t-matrix coefficients pertaining to the two calculations. To understand this, we have plotted in Fig. 3 the t-matrix coefficients of interest at the momentum transfer of $q=0.5$ fm^{-1}. The most notable result is that while the spin-isospin coefficients $|t_E^1|^2$ and $|t_F^1|^2$ are roughly independent of energy, the spin-independent coefficient $|t_A^0|^2$ shows a strong energy dependence. The increase in $|t_A^0|^2$ at high projectile energy results in an increase in the overall strength of the spin-independent channel, while the contributions from spin-flip channels remain constant. As a result, the spin-flip probability, which is calculated as a ratio of the spin-flip cross section to the *total* cross section, is correspondingly reduced.

In summary, we would like to emphasize that the spin-flip probability measured in proton inelastic scattering on ^{40}Ca can be well understood from the results of a realistic RPA calculation. The comparison of the results at two different projectile energies, and their consistency with what is essentially a *single* structure calculation, indicates that the spin distribution as a function of energy is indeed a *structure effect* and not a result of the reaction dynamics associated with a particular projectile energy. In addition, we found that the relative scale of the spin-flip probability can be well understood by invoking the energy dependence of the relevant t-matrix coefficients. In that context, we should note that we predict the cross section at lower proton energy to show a decrease compared with the $E_p=319$ MeV data. The Indiana University Cyclotron Facility is able to produce $E_p=100$ MeV beams and could test our prediction for S_{nn} at this proton energy, which is displayed in Figs. 1 and 2. In general, experiments in the low proton energy range would be most welcome to test our hypothesis regarding the dependence of S_{nn} on t-matrix coefficients.

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