Enhancement of the Relative $(\Delta S=1)/(\Delta S=0)$ Response of ^{40}Ca at High Excitation Energies

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Spin-flip probabilities have been measured for inelastic proton scattering from ^{40}Ca at 319 MeV at angles between 3° and 12° and excitation energies up to about 40 MeV. These data can be directly related to the relative [(spin transfer)/(no spin transfer)] nuclear response via one model-dependent variable. Nuclear spin excitations appear relatively suppressed at low excitation energies but surprisingly enhanced at the highest excitation energies at intermediate angles. Many features of the data can be explained with a slab nuclear response with random-phase-approximation correlations.

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Inelastic-scattering spectra at low excitation energies (ω) are known to be dominated by collective states arising from the strongly attractive scalar-isoscalar component of the nuclear force. In the 10–20-MeV region of ω a similar situation seems to prevail; the obvious structure in the spectra comes from natural-parity giant resonances which are excited without spin transfer $(\Delta S=0)$. Spin-transfer $(\Delta S=1)$ resonances are weak; when the continuum beneath these resonances is subtracted, the $\Delta S=1$ strength remaining in the peaks is found to be strongly quenched compared to sum rules or the best theoretical calculations.[1-3] The spin response of the continuum itself has hardly been investigated, but initial studies of ^{90}Zr and ^{51}V, for ω below 25 MeV and three-momentum transfers q smaller than about 75 MeV/c, indicated that it contains substantial spin excitation strength.[4,5] Here we present the results of measurements of the spin-flip probability S_{nn} for inelastic proton scattering from ^{40}Ca at 319 MeV; ω extends up to about 40 MeV for scattering angles out to 12° (about 175 MeV/c). Because S_{nn} is directly related to the relative strength of $\Delta S=1$ and $\Delta S=0$ transitions, these measurements yield the first comprehensive picture of the relative spin response of a nucleus in this most interesting (q,ω) regime.

The measurements were carried out with a 319-MeV transversely polarized beam at the Clinton P. Anderson Meson Physics Facility (LAMPF) with the focal-plane polarimeter[6] at the high-resolution spectrometer. The beam polarization, typically about 0.8, was monitored continuously with a CH_2 beam-line polarimeter upstream of the target. The calibration of the focal-plane polarimeter was checked by direct measurement of the polarization of the beam transported through the spectrometer at 0°. Measurements of S_{nn} for elastic scattering at large angles where systematic errors are amplified yielded values of S_{nn} of 0.00 ± 0.02. The ^{40}Ca target was 76.7 mg/cm^2 thick. In addition to the S_{nn} data of primary interest here, differential cross sections σ, analyzing powers A_y, and spin-flip cross sections σS_{nn} were also measured during the same experiments.

Examples of σ and σS_{nn} spectra at 7° are shown in Fig. 1. The σ spectra at all angles show the standard features of individual nuclear states up to roughly 8 MeV excitation energy (when binned more finely than shown in Fig. 1), then giant resonances up to about 20 MeV, and a featureless spectrum beyond. The resonance around 17 MeV in Fig. 1 includes $\Delta L=0$, 1, and 2 contributions. The σS_{nn} spectra reveal little strength below about 8 MeV, large cross sections with noticeable gross structure up to about 25 MeV, and then, at small angles, gradually decreasing strength or, at large angles, gradually rising strength. The 7° σS_{nn} spectrum shows clearly what preliminary analysis indicates is the spin dipole resonance at about 20 MeV. Note that such structure in the σS_{nn} spectra in the giant-resonance region would make it difficult to estimate accurately the continuum "background" beneath these resonances from the σ spectra alone.

The S_{nn} spectra are of most concern to us here $[S_{nn}\equiv\frac{1}{2}(1-D_{nn})$, where D_{nn} is the Wolfenstein D parameter]. This is a robust variable; as we shall see below, it is insensitive to most effects which would cloud its direct relationship with the relative strength of $\Delta S=1$ transitions. We can then write

$$S_{nn}=\alpha\sigma^A(\Delta S=1)/[\sigma^A(\Delta S=0)+\sigma^A(\Delta S=1)]. \quad (1)$$

Here σ^A is the proton-nucleus differential cross section in the appropriate spin-transfer state and α is the spin-flip probability for pure $\Delta S=1$ excitations. Spectra of

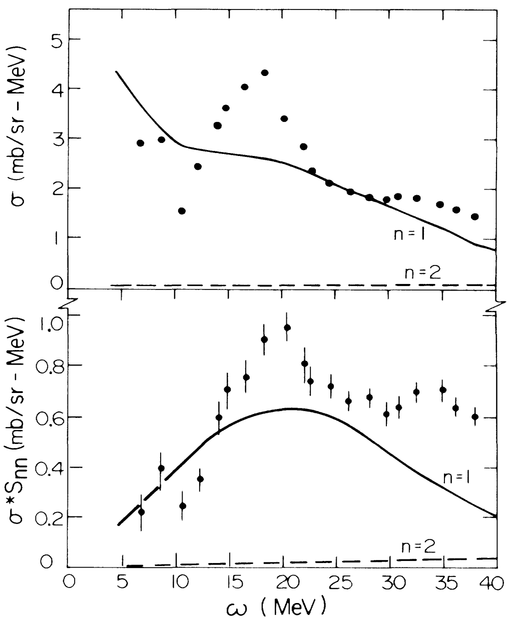

FIG. 1. Differential cross sections σ and spin-flip cross sections σS_{nn} for inelastic scattering at 7° from ^{40}Ca at 319 MeV as a function of excitation energy ω. The solid and dashed lines are the results of one-step and two-step calculations described in the text.

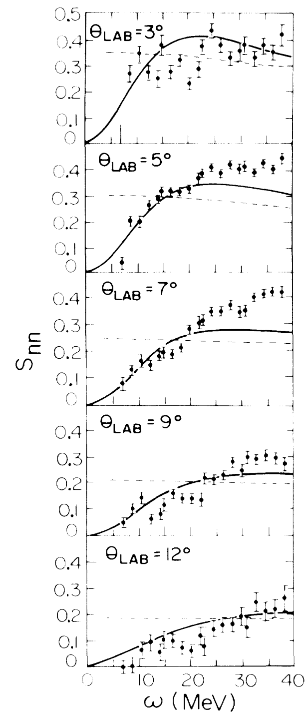

FIG. 2. Spin-flip probabilities S_{nn} for inelastic scattering from ^{40}Ca at 319 MeV as a function of excitation energy ω. The solid line is the prediction of the Esbensen-Bertsch slab-response model described in the text. The dashed lines correspond to the free NN values of S_{nn}.

S_{nn} at all angles are plotted in Fig. 2. The dashed lines in Fig. 2 correspond to the isospin-averaged free NN values of S_{nn} at the appropriate q, taken from the Arndt phase-shift solution.[7] (At 3° the Coulomb amplitude has been removed.) At the lower ω, the measured values of S_{nn} for scattering from ^{40}Ca are mostly much smaller than the free NN values. On the other hand, at large ω, particularly at 5° and 7°, the nuclear-scattering values can rise to more than 50% above the NN values. At 12°, the maximum values of S_{nn} are consistent with the free NN values.

The modification of the free values of S_{nn} by the nuclear medium is not surprising at low ω because of the strong $\Delta S=0$ collectivity. In the $\Delta S=0$ giant-resonance region, our work shows that the continuum background in inclusive (p,p') spectra is largely $\Delta S=1$ and S_{nn} is close to the free value. At larger ω the nucleus is often assumed to have the properties of a free Fermi gas. In this model, S_{nn} for proton-nucleus scattering is predicted to be essentially the same as the free NN value, provided effects of distortion, multistep processes, Fermi averaging, and the like are negligible. The clear discrepancies between such a model and the data suggest that the effects of both the repulsive $\Delta S=1$ correlations and the attractive $\Delta S=0$ correlations are important, even at ω of 40 MeV. We follow Esbensen and Bertsch[8] and treat the nucleus as a semi-infinite slab of interacting particles, with correlations determined by the random-phase approximation (RPA). An incoming proton transfers energy and momentum to a target nucleon in one quasifree interaction. Absorption is treated via an approximate form of Glauber theory and Pauli blocking is included. While this surface-scattering model cannot yield the detailed structure of a microscopic RPA calculation of a finite nucleus, it does describe well the main features of intermediate-energy scattering from nuclei over a wide (q,ω) range.[8] Calculations with this model are shown by the solid curves in Figs. 1 and 2; a separable interaction was used with a strength fixed as in Ref. 8. These calculations are in good agreement with the S_{nn} data at the smallest and largest angles over the entire range of ω. (Coulomb NN amplitudes have been omitted.) At the intermediate angles also, the dominance of $\Delta S=0$ transitions at low ω is well explained, as is the increasing importance of $\Delta S=1$ as ω increases. The only serious discrepancies occur at the highest ω for 5° and 7° where S_{nn} is predicted to be somewhat above the free NN values, but still noticeably below the measured values. The typical calculations of cross sections in Fig. 1 show that the model roughly accounts for the magnitude of σ, particularly at high ω where there is little structure. As expected, the resonance at about 17 MeV is not predicted. The σS_{nn} is generally underestimated, partly because of the structure around 20 MeV and partly because of the underestimation of S_{nn} at high ω. Calculations of σ and σS_{nn} are much more sensitive than calculations of S_{nn} to distortions and other effects.

The main effect of the distortion is the absorption due to the imaginary part of the central optical potential. This causes the scattering to be localized in the surface region, and determines the effective number of participating nucleons $N_{\rm eff}$.[9] In this simple model,[9] the spin observables, which are ratios of cross sections, do not depend on $N_{\rm eff}$. However, they may be influenced by the real optical potential and by the spin-orbit potential. Both of these effects, as well as contributions from two-step processes, have been included in a new computer code which is based on the formalism developed by Smith and Wallace[10] and extended to include a Lorentzian parametrization of the slab response.[8] These calculations are based on a short-range approximation for the NN amplitudes which gives rise to an expansion of the cross section in gradients of the nuclear density. Here only the two leading terms have been retained; the effect of higher orders is currently under investigation. The real and spin-orbit potentials turn out to influence some spin observables but they have almost no effect on S_{nn}. Contributions from two-step processes (dashed lines in Fig. 1) become noticeable at the largest energy loss but they still contribute only about (10–20)% of the calculated cross section at 40 MeV. Because these processes yield values for S_{nn} close to those predicted for one-step processes, they change the calculated values shown in Fig. 2 hardly at all. We also expect off-shell modifications of the NN amplitudes to be small below 40 MeV excitation. Fermi averaging of the NN amplitudes and possible relativistic effects have not been included in our calculations, but both are included in new quasielastic knockout calculations by Horowitz and Iqbal[11]; the predicted change in S_{nn} is very small. Additional calculations of the effects of Fermi averaging have been carried out by Rees[12] who finds that the effects can be significant but that they always tend to decrease the values of S_{nn}; this is opposite to what we observe.

The measured values of S_{nn} can thus be used to give an estimate of the relative nuclear spin response R_s. This can be defined as follows:

$$R_s = f_1/(f_0+f_1), \qquad (2)$$

where $f_i = \sigma^A(\Delta S=i)/\sigma^f(\Delta S=i)$ and σ^f is the differential cross section for free NN scattering. Because of the normalization by σ^f, R_s is the fraction of the nuclear response which corresponds to $\Delta S=1$ strength; if the nucleus were a noninteracting Fermi gas, R_s would be 0.5 everywhere. We can use Eq. (1) to give us the ratio f_1/f_0 and thus R_s:

$$\frac{f_1}{f_0} = \frac{S_{nn}/(\alpha - S_{nn})}{\sigma^f(\Delta S=1)/\sigma^f(\Delta S=0)}. \qquad (3)$$

The ratio of the free cross sections in the denominator is about 1:1 at 319 MeV at low q. Now α is model dependent; it depends both on the NN interaction and on the wave functions of the states excited. A precise determination of R_s thus requires a careful microscopic calculation. The slab response discussed above should, however, give a reasonable estimate of α particularly at high ω, and it is almost identical to the free value. These values vary with angle in the range from about 0.65 to 0.40. An example of the qualitative shape of the R_s determined this way at 7° is shown by the solid line drawn to guide the eye in Fig. 3 (the measured values of S_{nn} actually translate into the R_s values shown by the points in the figure). At the highest ω (where the results are most sensitive to the value of α), the response at the intermediate angles seems almost entirely $\Delta S=1$. Even in the giant-resonance region, the nuclear $\Delta S=1$ response is not much smaller than the $\Delta S=0$ response.

In summary, we have determined for the first time the spin-flip probability for proton scattering from ^{40}Ca over a wide range of q and ω. Via Eq. (3), these data provide the first estimate of the relative $(\Delta S=1)/(\Delta S=0)$ response of a nucleus. (It should be noted also that we have now obtained similar results for ^{54}Fe in collaboration with O. Häusser *et al.* at TRIUMF.) These data confirm the previously observed dominance of $\Delta S=0$ modes at low ω; they show an unexpectedly large relative $\Delta S=1$ response at high ω for intermediate momentum transfers. A careful theoretical investigation will be necessary to consider the absolute strengths of $\Delta S=0$ and $\Delta S=1$ strengths separately, and to determine the multipole distribution of the enhanced strength. It will then be possible to consider the relationship between the presently observed relative enhancement of $\Delta S=1$ modes at high ω and the previously observed absolute quenching of these modes at lower ω. (For example, the enhancement observed at intermediate q may be a reflection of spin resonances at high ω where $\Delta S=0$ strength is depleted because it has already been exhausted in strong resonances at lower ω.) Analysis of comple-

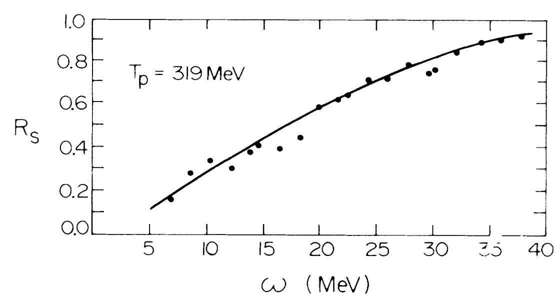

FIG. 3. The estimated shape at 7° of the relative nuclear spin response R_s defined in the text. The solid line has been drawn to guide the eye through the points which have been determined from the measured S_{nn} values using Eqs. (2) and (3).

mentary measurements of S_{nn} in the (p_{pol},n_{pol}) reaction may be useful in the separation of $\Delta T=0$ and $\Delta T=1$ contributions.[13,14] The slab-model response functions discussed here show the validity of the single-step reaction mechanism and qualitatively account for much of the data. It will be particularly interesting to include a strong tensor force in future microscopic calculations, as suggested by Bertsch and Hamamoto[15] to spread spin excitation strength to high ω.

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