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NUCLEAR SPIN RESPONSE STUDIES IN INELASTIC POLARIZED PROTON SCATTERING

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ABSTRACT

Spin-flip probabilities S_{nn} have been measured for inelastic proton scattering at incident proton energies around 300 MeV from a number of nuclei. At low excitation energies S_{nn} is below the free value. For excitation energies above about 30 MeV for momentum transfers between about 0.35 fm^{-1} and 0.65 fm^{-1} S_{nn} exceeds free values significantly. These results suggest that the relative $\Delta S = 1/(\Delta S = 0 + \Delta S = 1)$ nuclear spin response approaches about 90% in the region of the enhancement. Comparison of the data with slab response calculations are presented. Decomposition of the measured cross sections into $\sigma(\Delta S = 0)$ and $\sigma(\Delta S = 1)$ permit extraction of nonspin-flip and spin-flip dipole and quadrupole strengths.

INTRODUCTION

Spin excitations in nuclei have been the subject of considerable theoretical and experimental work during the past six years. Indeed, much of the work presented here originated in the study of $M1$ transitions in nuclei, a subject addressed in detail in the 1982 Telluride Conference and in subsequent publications.¹⁻⁷ The initially strong focus on the distribution of $M1$ strength excited by proton inelastic scattering has evolved into a more general study of the distribution of spin excitations in nuclei excited with this probe. The program begun at the high resolution proton spectrometer facility (HRS) at LAMPF has been facilitated by the development of a polarimeter facility associated with the medium resolution spectrometer (MRS) at TRIUMF.^{8,9} The combination of data available from the HRS facility at LAMPF and the MRS at TRIUMF forms a substantial contribution to the study of continuum excitations by inelastic proton scattering up to about 50 MeV in a variety of nuclei from ^{12}C to ^{90}Zr .

The proton is a complex but desirable probe of the nucleus, roughly equally scalar and vector in nature. As such it can be used to excite the full complexity of the nuclear continuum. By contrast, the charge-exchange reaction (p,n) is a probe of purely isovector character; consequently the excitation of the nucleus is selective. The complementarity of these and other probes should result in a detailed understanding of the isospin and spin response of the nucleus. Recent advances in charge-exchange studies addressing the distribution of Gamow-Teller and other isovector strength in nuclei are discussed by other contributors at this conference.

EXPERIMENTAL DETAILS

Experiments have been carried out at both the HRS at LAMPF and the MRS at TRIUMF. Measurements at the HRS were made with a beam of 319-MeV protons polarized perpendicular to the reaction plane. Scattered particles were detected in the standard HRS focal-plane polarimeter¹⁰ modified to minimize backgrounds inherent in small-angle inelastic scattering. The choice of 319 MeV was dictated by precession considerations in the spectrometer and the relative strength of spin-flip to nonspin-flip components of the effective nucleon-nucleon interaction. Measurements at the MRS were made with a beam of 290-MeV protons polarized perpendicular to the reaction plane. Scattered particles were detected in the standard MRS focal plane polarimeter. Beam polarizations at both facilities were monitored continuously with in-beam polarimeters, as well as with the quench-ratio technique at the HRS. Absolute normalization of measured cross sections was made by comparison of measured cross sections for proton scattering from hydrogen with extant data and phase shift analyses.¹¹ Data were taken for scattering from ^{12}C , ^{40}Ca , ^{48}Ca , ^{51}V , and ^{90}Zr at the HRS, and from ^{44}Ca and ^{54}Fe at the MRS.

Typical cross-section spectra for inelastic proton scattering around an incident energy of 300 MeV are shown in Fig. 1.

Fig. 1. Differential cross section spectra for the $^{54}\text{Fe}(p,p')^{54}\text{Fe}^*$ reaction at $T_p = 290$ MeV. The data were taken using the MRS facility at TRIUMF at laboratory scattering angles of 3.1° and 15° .

Preliminary spectra are shown for scattering from ^{54}Fe at laboratory scattering angles of 3.1° and 15° . The strongly quenched $M1$ resonances around 10 MeV are clearly seen at 3.1° , together with discrete states at low excitation and the strong natural parity $\Delta S = 0$ giant resonances around 15-20 MeV, dominated by the Giant Dipole Resonance (GDR) at this angle. A continuum with little structure extends out to 45 MeV and beyond. The 15° spectrum shows more discrete states, no pronounced giant resonance structures, and the feature that the onset of the continuum is at a significantly lower excitation energy than at 3.1° . The continuum has generally been treated as background in the studies of giant resonances. Several authors have assumed the background to be due to single-step quasi-free scattering and have modeled it as such,^{12,13} while other approaches emphasized the drawing of smooth, empirical lines to represent this background.^{14,15}

The principal thrust of this work, then, is to determine the relative distribution of $\Delta S = 1$ and $\Delta S = 0$ excitations in the nuclear continuum up to about 50 MeV of excitation.

SPIN FLIP MEASUREMENTS

An experimental observable well suited for the study of the nuclear spin response is the transverse spin-flip probability, S_{nn} , of the inelastically scattered protons. This is simply the probability that an incoming proton with, for example, spin up (normal to the scattering plane), will interact with the target nucleus and leave with spin down. S_{nn} is related to the Wolfenstein parameter D by

$$S_{nn} = \frac{1}{2}(1 - D) . \quad (1)$$

This observable may be directly related to $\Delta S = 1$ strength and will be shown to be relatively insensitive to structure effects, reaction mechanisms, and the like.

Some comments about typical values for S_{nn} will be helpful in interpreting the data to be presented. Natural parity $\Delta S = 0$ excitations have values of $S_{nn} \simeq 0$ at these incident energies.¹⁶ For discrete unnatural parity transitions such as 1^+ states, excited mostly by the $\sigma_1 \cdot \sigma_2$ term in the nucleon-nucleon (NN) potential, values of S_{nn} around 0.5 or higher are observed.^{16,17} In general, $\Delta S = 1$ transitions exhibit values for S_{nn} which are large but essentially never unity. For free NN scattering around 300 MeV and over the momentum transfers of interest, the isospin-averaged value of S_{nn} for $p-p$ and $p-n$ scattering ranges from ~ 0.2 to ~ 0.35 (Ref. 11). From these values of S_{nn} , it can be determined that the (p, p') probe is roughly equally scalar and vector,

$$\frac{\sigma^f(\Delta S = 1)}{\sigma^f(\Delta S = 0) + \sigma^f(\Delta S = 1)} \simeq 0.5 , \quad (2)$$

where σ^f is the differential cross section for free scattering at a particular momentum transfer q .

Typical spectra of S_{nn} and σS_{nn} are shown in Fig. 2. The data are for scattering from ^{90}Zr at 3.0° in the laboratory; data up to 25 MeV of excitation with somewhat larger error bars have been published previously.⁴

The spectra show large amounts of spin excitation strength in the $M1$ region around 10 MeV and also up to at least 40 MeV of excitation. The giant resonance region is by no means exclusively $\Delta S = 0$, for example, and the spin-flip cross section falls off more slowly at high excitation energies than does the cross section itself.

Fig. 2. Spin-flip probability S_{nn} and spin-flip cross section σS_{nn} data for 319-MeV proton scattering from ^{90}Zr at a center-of-mass scattering angle of 3.0°.

Fig. 3. Spin-flip probability S_{nn} for the $^{40}\text{Ca}(p,p')^{40}\text{Ca}^*$ reaction at $T_p = 319$ MeV as a function of excitation energy at 3.6° , 5.0° , 7.0° , 9.0° and 12.0° . The solid line is the prediction of the Esbensen-Bertsch slab model described in the text. The dashed line corresponds to isospin-averaged free values for S_{nn} .

Fig. 4. Spin-flip probability S_{nn} for the $^{90}\text{Zr}(p,p')^{90}\text{Zr}^*$ reaction at $T_p = 319$ MeV as a function of excitation energy at 3.0° , 4.5° , 6.5° , and 8.5° . The solid line is the prediction of the Esbensen-Bertsch slab model described in the text. The dashed line corresponds to isospin-averaged free values for S_{nn} .

Roughly similar behavior has been observed in all the nuclei we have studied, from ^{12}C to ^{90}Zr . Lower excitation regions (≤ 20 MeV) tend to be dominated by specific excitations — the $M1$ excitations in ^{48}Ca , ^{51}V , and ^{54}Fe , are particularly prominent, as are a variety of resonances in ^{12}C in the 20 – 30 MeV range. Structures are observed at 7° laboratory in the 15 MeV range for all targets. In general, though, σS_{nn} tends to increase relative to σ as excitation energy increases, the ratio becoming roughly constant at an angle-dependent excitation energy.

The shapes of S_{nn} as a function of excitation energy for ^{40}Ca and ^{90}Zr shown in Figs. 3 and 4 are therefore not surprising. What is remarkable are the magnitudes of S_{nn} , particularly at laboratory angles of about 5° and 7° and for the higher excitation energies. The value of S_{nn} attained is about 0.4, and this is consistent for all nuclei studied thus far. Comparison with the free NN isospin-averaged values shown by the dashed lines indicates a significant enhancement. Also noteworthy is the fact that even in the giant-resonance region, where the only well-known structures correspond to $\Delta S = 0$ excitations, the value of S_{nn} is not much different from the free values. At low excitations, where discrete states dominate, S_{nn} is indeed much smaller than the free values, indicative of the strong attractive nature of the $\Delta S = 0$ components of the effective NN interaction.

Fig. 5. Spin-flip probability S_{nn} for the $^{44}\text{Ca}(p,p')^{44}\text{Ca}^*$ reaction at $T_p = 290$ MeV as a function of excitation energy at 7.0° .

Preliminary data for S_{nn} at 7° from ^{44}Ca , measured at TRIUMF, are shown in Fig. 5. The excitation energy here extends to about 80 MeV, and S_{nn} is seen to remain at a roughly constant value of about 0.4 over the entire range of excitation energy. At the largest angles measured (15° for ^{54}Fe and 18° for ^{12}C) values of S_{nn} are found to be similar to the free values at about 40 MeV; a similar observation can be made for the data at 3° .

THE RELATIVE NUCLEAR SPIN RESPONSE

Given the extensive S_{nn} data discussed above, what may we deduce about the nuclear spin response to the proton? As we shall see, S_{nn} is relatively insensitive to such effects as Fermi averaging, distortions, multi-step processes, and so on. We may therefore consider S_{nn} to be a robust variable. Given this understanding, we may write:

$$S_{nn} = \frac{\alpha \sigma_1}{(\sigma_0 + \sigma_1)} \quad (3)$$

where σ_i is the differential cross section for spin transfer $\Delta S = i$ scattering, and α is the spin-flip probability for a pure $\Delta S = 1$ scattering. Adopting a factorized approximation,¹⁸⁻²⁰ the partial cross sections may be written as

$$\sigma_i^A = N_{eff} f_i \sigma_i^f \quad (4)$$

Fig. 6. The value of α for quasifree scattering as a function of angle and excitation energy for an incident energy $T_p = 300$ MeV.

Here N_{eff} is the effective number of target nucleons participating in the reaction, and f_i is the modification of the free cross section σ_i^f in the channel i by the nucleus. f_i is then the nuclear response for the spin channel i . From Eqs. (3) and (4) we may deduce

$$\frac{f_1}{f_0} = \frac{\sigma_1^A / \sigma_0^A}{\sigma_1^f / \sigma_0^f} = \frac{S_{nn}}{\alpha - S_{nn}} / \frac{\sigma_1^f}{\sigma_0^f} . \quad (5)$$

We may now define the relative nuclear spin response R_s as

$$R_s = \frac{f_1}{f_0 + f_1} . \quad (6)$$

R_s is then the fraction of the nuclear response that corresponds to $\Delta S = 1$ excitations. If the nuclear medium were a non-interacting Fermi gas, then R_s would be 0.5. Since the free cross sections are known, measurement of S_{nn} enables calculation of R_s , provided α is known. The quantity α is then a single model-dependent parameter required to determine R_s . Except in regions of the nuclear excitation dominated by resonances of particular structure, spin, and parity, α is determined mostly by the nature of the effective NN interaction.

The simplest determination of α may be made from free scattering using Eq. (3). Essentially identical values may be obtained from surface-response calculations described in the next section. The behaviour of α as a function of laboratory scattering angle and excitation energy is shown in Fig. 6. The trend of R_s as a function of excitation energy computed from the data for ^{40}Ca and ^{90}Zr is shown by the solid lines in Figs. 7 and 8. The solid lines have been drawn to guide the eye through the actual values shown by the data points. Because both theoretical and experimental uncertainties contribute to the data points shown, it is likely that only the general shape of the line is significant.

These figures dramatically illustrate our answer to the question posed previously: they show our measurement of the distribution of the relative spin-excitation strength in nuclei. These data present the first general picture of the nuclear spin response in this nuclear regime of q and E_x . Of particular interest is that R_s approaches 90% at the highest excitation energies for some angles, and that since $\sigma_1^f / \sigma_0^f \simeq 1$, the ratio of the cross sections actually excited in 300-MeV nuclear scattering also approaches about 90% at these excitation energies.

The conclusions drawn from the data thus far rest on two assumptions: S_{nn} is a robust variable, and $\alpha^A \simeq \alpha^f$. Calculations have been performed by Esbensen²¹ in the framework of the surface-response model developed by Bertsch, Esbensen, and Scholten. In this model the nucleus is considered as a semi-infinite slab with RPA correlations and an absorbing surface; the absorption is treated via an approximate form of Glauber theory. Single hard scattering described by the free NN amplitudes is assumed, and Pauli blocking is included. Values of α determined from this model are very similar to those computed directly from free NN values. Predicted values of S_{nn} as calculated by Esbensen are shown as solid lines in Figs. 3 and 4. The general form of S_{nn} is described well, and an enhancement relative to the free values is predicted at the higher excitation energies. This enhancement is not sufficient, however, to account for the large values seen in the data. The relative response R_s determined from these calculations is shown as the solid line in Figs. 7 and 8. The calculations clearly do not predict the large fraction of $\Delta S = 1$ strength seen at the higher excitations around 7° .

Fig. 7. The nuclear spin response R_s determined from the S_{nn} data for $^{40}\text{Ca}(p,p')^{40}\text{Ca}^*$ as shown in Fig. 3. The lines have been drawn to guide the eye.

Fig. 8. The nuclear spin response R_s determined from the S_{nn} data for $^{90}\text{Zr}(p,p')^{90}\text{Zr}^*$ as shown in Fig. 4. The lines have been drawn to guide the eye.

What then of corrections to this model? Several have been considered, and the effects of all appear to be small. Smith has considered the possibility of a second hard collision within the framework of the surface-response model.²² The effect of this process is negligible for small E_x , increasing roughly linearly as E_x increases. Corrections to the cross section are about 5% at $E_x = 40$ MeV and are expected to increase at higher excitation energies. The results of these calculations are shown in Fig. 9 for scattering at 7° from ^{40}Ca . Note that the cross sections themselves are roughly described, but the simple model of the nucleus used precludes the description of resonances. S_{nn} itself is minimally affected by the inclusion of two-step processes. Smith has also calculated the effect of spin-orbit distortions on the values of S_{nn} ; such distortions increase the calculated values of S_{nn} uniformly by about 0.03 (Ref. 22). Smith has also included 2p-2h correlations in the excited states to the RPA correlations existing in the surface response model.²² These correlations spread spin strength to higher excitation energies, but the results of preliminary calculations indicate that this spreading is only significant above about 40 MeV of excitation. Horowitz and Murdock have studied the effects of Fermi averaging and changes in the effective nucleon mass in the nucleus that arise from a treatment of quasifree knockout within a Dirac equation framework.²³ The predicted changes in S_{nn} are very small, while predicted changes in other observables are quite large. Rees has also shown that Fermi averaging effects are small at about 300 MeV.²⁴

Fig. 9. Differential cross sections σ and spin-flip cross sections σS_{nn} for elastic scattering at 7° from ^{40}Ca at 319 MeV as a function of excitation energy. The solid and dashed lines are the results of one- and two-step calculations by Smith.

The net effect of all these possible corrections is small. The response R_s should then be a very good estimate of the actual relative nuclear spin response. Since all these calculations contain approximations, it is still conceivable that what is observed at high excitation energies is an artifact of the choice of the incident energy of the probe. The relative spin dependence of the free scattering is maximized at this energy. Given the assumption that the simple model presented here is valid, it is possible to predict a value for S_{nn} at a different incident energy. At 800 MeV, the free value of S_{nn} is about 0.05. If R_s is taken to be about 0.85, then a value of around 0.20 is predicted for S_{nn} at this energy, a much larger enhancement than at 300 MeV. Preliminary data taken at the HRS at 800 MeV and 4° from ^{40}Ca give an average value of $S_{nn} = 0.23 \pm 0.03$ over the excitation energy range 33 to 44 MeV in very good agreement with the prediction. The nuclear response appears energy independent, as it should.

GIANT RESONANCE STUDIES

As has been mentioned previously, analysis of backgrounds under giant resonances excited by inelastic proton scattering has been problematical.¹²⁻¹⁵ The measurement of S_{nn} has revealed that much of the background underlying the giant dipole and quadrupole resonances at these small angles is from $\Delta S = 1$ transitions. The decomposition of the cross section into partial terms σ_1 ($\Delta S = 1$) and σ_0 ($\Delta S = 0$) holds the promise of allowing a much better estimate of this background than has previously been possible. As outlined above, only the one model-dependent parameter α is necessary.

Once the decomposition into σ_1 and σ_0 has been accomplished, contributions from various multipoles may be determined. Baker et al.²⁵ have performed such an analysis of the ^{40}Ca data shown above. Nonspin-flip dipole strength is found to be concentrated in the GDR at 20 MeV of excitation but persists to higher E_x , in agreement with the results of photon absorption experiments. The summed strength relative to the energy-weighted sum rule (EWSR) in the 10-35 MeV region in this analysis is $148 \pm 21\%$, compared with 130% for the photon absorption data.²⁶ Significant monopole strength is not seen. Nonspin-flip quadrupole strength is concentrated in a broad resonance between 10 and 30 MeV; above 27 MeV the quadrupole strength is consistent with zero. It is found that $76 \pm 12\%$ of the EWSR is exhausted in the excitation energy range of 10-27 MeV. These measurements should not be considered definitive because of the limited angular range of the data; further measurements at the HRS have been approved to extend the angular range. Strong evidence has been provided that quantitative subtraction of spin-flip background under giant resonances is a sound approach to extraction reliable strengths.

A preliminary multipole analysis of the σ_1 spectra has been performed; simple particle-hole transitions have been assumed. A giant spin-flip dipole excitation is observed to extend from about 12 to 28 MeV with a centroid at approximately 18-20 MeV, as shown in Fig. 10. Roughly similar observations have been made at 334 MeV incident proton energy using a different approach.²⁷ Spin dipole strength above 30 MeV of excitation is consistent with zero. Evidence for a spin quadrupole excitation is seen above about 25 MeV, with an apparent centroid at 33-34 MeV of excitation. Definitive analysis of the spin quadrupole requires extension of the data to both larger angles and higher excitation energies.

CONCLUSIONS

Measurements of S_{nn} have been shown to yield a general picture of the relative spin response of the nucleus to intermediate energy protons. This is fundamental data about nuclei that would be interesting even if no unexpected behavior was revealed.

Fig. 10. Preliminary analysis of spin-dipole strength in $^{40}\text{Ca}(p, p')^{40}\text{Ca}^*$ inelastic scattering at 319 MeV incident proton energy.

Fig. 11. Spin-flip probability S_{nn} for for inelastic scattering at 7° from ^{40}Ca at 319 MeV incident proton energy. The curves are schematic-model calculations by Boucher, et al.

The large enhancement of S_{nn} at high excitations in the 0.5 fm^{-1} momentum transfer region is not yet definitively explained. The ^{44}Ca data of Fig. 5 suggest that a relatively narrow spin resonance is not responsible. The preliminary 800-MeV data show it is not an artifact of 300-MeV scattering. The suggestion was made in Ref. 28 that exhaustion of $\Delta S = 0$ strength at lower excitation energies would imply an enhancement of relative $\Delta S = 1$ strength at high E_x above the free ratio. The slab model calculations indicated, however, that this was only a partial explanation. However, new RPA calculations of S_{nn} published recently by Boucher et al.²⁹ lend support to this hypothesis (Fig. 11). The localization of $\Delta S = 0$ strength present in these RPA calculations but missing in the slab calculations may be the crucial ingredient. It will be important to determine whether improved versions of these RPA calculations can explain the lack of A dependence in the S_{nn} spectra, as well as the absolute cross sections for both $\Delta S = 0$ and $\Delta S = 1$ transfer. The separation of the longitudinal and transverse response will also be a useful experimental test of this theory. A consistent picture of $\Delta S = 0$ and $\Delta S = 1$ collectivity in nuclei seems to be emerging.

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