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Spin-flip probabilities in ^{208}Pb measured with 200 MeV protons

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Measurements using 200 MeV protons of the spin-flip probability parameter $S_{NN'}$ have been made on ^{208}Pb covering an excitation energy range of 2 to 24 MeV for momentum transfers from 0.45 to 0.84 fm^{-1}. These data have been compared to calculations that use random-phase-approximation wave functions in an impulse approximation model. Distortions are shown to have a large effect in the calculation of $S_{NN'}$. The calculations describe the data well and suggest that natural-parity transitions contribute significantly to the spin-flip response. A broad structure is observed near 7 MeV; calculations suggest that this structure is composed of a superposition of a number of spins and parities.

The study of the spin-isospin response of nuclear matter from quasifree scattering to the multipole decomposition of resonances induced by hadronic scattering has been an area of intense interest in nuclear physics. The availability of polarized proton beams, coupled with scattered proton detection by magnetic spectrometers and polarization analysis with focal plane polarimeters, has resulted in the measurement of the normal-component, spin-transfer coefficient $D_{NN'}$ over a large range of excitation energies and on a variety of targets. These data yield the normal spin-flip probability, $S_{NN'}$ [$S_{NN'} \equiv (1-D_{NN'})/2$], for these nuclei. The targets studied so far range from ^{12}C to ^{90}Zr [1]. Only lighter nuclei have been studied because their structure is generally simpler and better known. They are also easier to investigate, since their various multipole transition cross sections peak at larger scattering angles, making it easier to observe them, due to experimental difficulties associated with cleanly detecting small angle scattering.

This new body of data has stimulated theoretical interest in studying the spin dependence of the nuclear response. One of the earliest models used for the continuum was the semi-infinite slab model (SISM) of Bertsch and co-workers [2]. Their model qualitatively describes both cross section [3] and spin-flip data [1,4,5]. The SISM calculations were extended by Smith and Wambach [6] in the analysis of ^{54}Fe data obtained from (n,p) and (p,p') reactions. This work identified the importance of 2p-2h damping in random-phase-approximation (RPA) calculations. Boucher *et al.* [7] have also made nuclear response calculations using a schematic model that includes π and ρ exchange and is based on energy weighted sum rules with coupling to 2p-2h states. They have also performed calculations using an RPA model for the nuclear structure [8]. In both cases their calculations also qualitatively describe the data. Ichimura *et al.* [9] have performed distorted-wave-impulse approximation (DWIA) calculations of the nuclear response using an RPA model. In this study of the effects of distortions on spin observables they observed significant effects. Smith [10] has also included distorted waves in the eikonal approximation for continuum calculations. It was observed that distortions effect various observables with the largest differences occurring at the smaller scattering angles.

In this paper, we present new distorted and plane wave calculations by Unkelbach and Wambach using RPA wave functions for ^{208}Pb. These are compared to new spin-flip probability measurements using 200 MeV protons. The choice of ^{208}Pb for this comparison benefits from narrower giant-resonance widths, a property of heavier targets, and a lack of resonance splitting from nuclear deformation. However, this heavier target mass moves the spin-dipole cross sections to smaller angles, making them more difficult to observe. The experiment reported here is the first attempt to study the spin response of ^{208}Pb. Our smallest scattering angle corresponds to the peak for an $L=2$ transfer, making us sensitive to spin quadrupole strength. The efficiency of the focal plane polarimeter provides the high statistics data needed to search for possible new resonances. Spin-flip data on ^{208}Pb could also elucidate the spin and isospin response of nuclear matter.

The experiment was performed at the Indiana University Cyclotron Facility (IUCF) utilizing 200 MeV protons polarized normal to the horizontal scattering plane. The scattered protons were detected by the K600 magnetic spectrometer [11] and their polarization deduced by a second scattering in the associated focal plane polarimeter [12]. The momentum acceptance of the focal plane and polarimeter is approximately $\delta p/p = \pm 7\%$, making measurements for excitation energies up to 24 MeV possible with one magnetic-field setting. The energy resolution was 40 keV (full width at half maximum) in the region of the giant resonances (near 12 MeV), and increased to 50 keV near the ends of the energy acceptance. The dependence of the detector efficiency on position along the focal plane was determined by measuring the elastic cross section from a gold target at several points across the focal plane. The efficiency was determined to be uniform to $\pm 2\%$.

Data were taken at laboratory scattering angles of 8°, 10°, 12°, and 15°, corresponding to momentum transfers between 0.45 and 0.84 fm^{-1}. At these angles, the elastic-scattering cross section is large enough to dominate the data acquisition rate. For this reason elastically scattered protons were blocked from the focal plane by a movable copper stop located in front of the focal plane detectors. Beam currents were varied from 2.5 to 7.5 nA, with a ^{208}Pb target thickness of 5.85 mg/cm^2 and a solid angle of 1.21 msr. The beam polarization was measured periodically using proton—^{4}He elastic scattering in a polarimeter [11] located between the injector and main cyclotrons. The magnitude of the polarization varied during the course of the experiment between 0.72 and 0.76. The polarization direction was reversed every 20 sec to cancel systematic effects.

As a check of possible systematic errors in the focal plane polarimeter, we simultaneously measured the 3^- state at 2.614 MeV, for which $D_{NN'}$ is expected to be near unity. The observed $D_{NN'}$ values (0.959 ± 0.035 at 8°, 0.947 ± 0.031 at 10°, 0.993 ± 0.037 at 12°, and 0.971 ± 0.141 at 15°) are consistent with collective, deformed potential model calculations using ECIS79 [13] and optical model parameters from Ref. [14], indicating little systematic error.

In Fig. 1 we present the new spin-flip probability results. The data bins are approximately 200 keV wide at

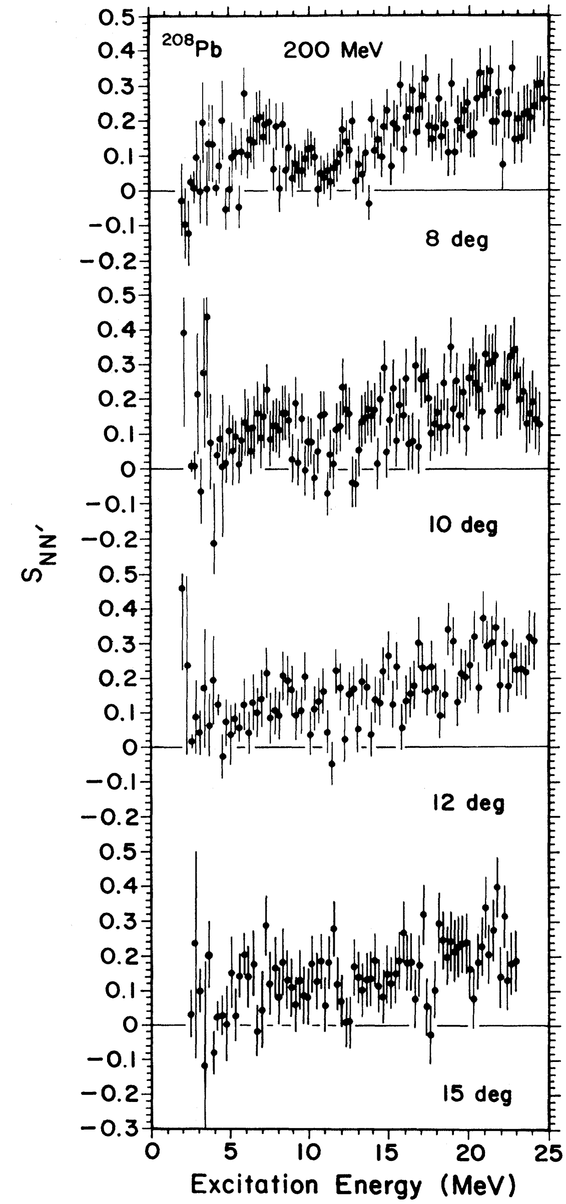

FIG. 1. Spin-flip probability $S_{NN'}$ for ^{208}Pb as a function of excitation energy, measured with 200 MeV polarized proton scattering.

8° and 10°, and approximately 280 keV wide at 12° and 15°. We have chosen this energy width as a compromise between our search for possible structure and the need to maintain good statistics in each bin. The uncertainties for the $S_{NN'}$ values in the continuum range from 0.05 to 0.1. To obtain comparable uncertainties, previous $S_{NN'}$ results have used bins 1–2 MeV wide.

The data at 8° and 10° exhibit a broad structure centered near 7 MeV with a width of 2.5–3 MeV. This excitation energy is known to have a high-level density of low angular momentum states [15] whose cross sections are largest in this angle range. Thus, the observed broad structure may result from a superposition of the spin-flip strength for these states. The data at these angles also suggest a structure near 12 MeV with a width of about 1 MeV. The 8° data also suggest a peak near 10 MeV with a width of about 1 MeV. The isoscalar giant quadrupole resonance is located at 10.6 MeV [14]; the isovector giant dipole and isoscalar giant monopole resonances are located near 13.6 MeV [14]. At larger scattering angles the isoscalar giant hexadecapole resonance is located at 12 MeV [14,16], but it does not contribute significantly to the 8° and 10° response. Therefore, the spin and parity of these structures cannot be assigned to any known resonance. The magnitude of the spin-flip cross section ($\sigma \times S_{NN'}$) integrated over the 11–13-MeV excitation energy range is 3.5 mb/sr MeV at 8° and 2.2 mb/sr MeV at 10°, with uncertainties of 10% and 20%, respectively.

In Fig. 2 we compare calculations by Unkelbach and Wambach to our data rebinned with a 1 MeV width to improve statistical precision. This theory is based on 1p-1h RPA including 2p-2h damping in the continuum [6]. The same single-particle basis and residual interaction as in Ref. [17] have been used. This interaction is a zero-range Landau-Migdal force. To look for finite-range effects, a calculation with a $\pi+\rho$ exchange force has been performed. The ρ coupling constant was increased by a factor 1.25 in order to properly describe the energy of the Gamow-Teller and the M1 resonances. An additional δ force in the electric channels had to be added to describe the electric resonances. The reaction model is based on the impulse approximation using either plane or distorted waves. The Love-Franey effective interaction [18] is used for the residual projectile-target interaction. No Coulomb excitation is included. The distortions are described by phenomenological optical potentials of Woods-Saxon type from Ref. [14]. In Fig. 2 the solid (dashed) curves are the distorted-wave calculations using the finite-range (zero-range) residual interaction. The dotted curves correspond to the plane-wave calculations with the zero-range force.

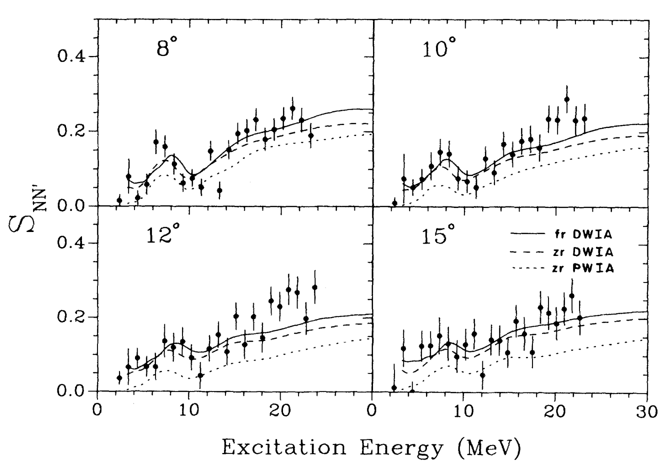

FIG. 2. The same data as Fig. 1 rebinned with a 1 MeV width. The solid (dashed) curves are the result of distorted-wave-impulse approximation calculations using the finite-range (zero-range) residual interaction. The dotted curves correspond to plane-wave calculations with the zero-range force.

The first result apparent from Fig. 2 is the sensitivity to distortions illustrated by the difference between the plane-wave-impulse approximation (PWIA) and the DWIA calculations. This effect is mainly due to the spin-orbit terms in the nuclear distortions. The PWIA results are always lower in magnitude than the DWIA. This difference increases with angle until at 15° the PWIA is approximately $\frac{2}{3}$ of the DWIA results. At higher-momentum transfers the LS-distortions become more important. This distortion dependence can lead to problems extracting spin-flip strength for the various multipoles if the distortions are not included. In order to search for a dependence on the type of distortion employed, $S_{NN'}$ was calculated using two different optical-model parameter sets from Ref. [14] (both of which equally well described the elastic-scattering data). One set was based on a best fit to only 200 MeV elastic cross section and analyzing power data on ^{208}Pb [19]; the other set was obtained from a global fit of 200–500-MeV cross section and analyzing power data on ^{208}Pb [19]. The difference between the two distorted wave $S_{NN'}$ calculations was about 5%, much less than the errors in the present set of measurements.

The difference between the finite- and zero-range distorted-wave calculations in Fig. 2 is a measure of the dependence of $S_{NN'}$ on the residual interaction. This difference arises from the tensor-exchange part of the interaction, which acts strongly in the isoscalar $\Delta S=1$ channel.

Overall, the DWIA calculations describe the $S_{NN'}$ data well, particularly in the vicinity of the structure near 7

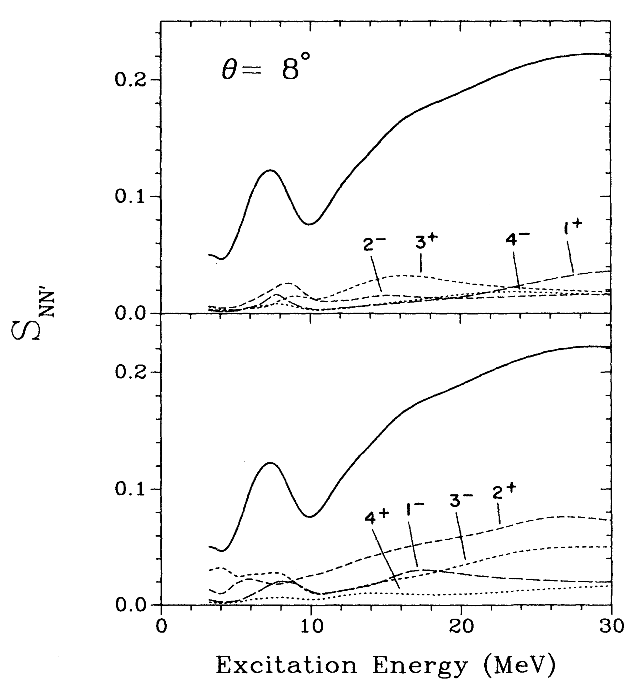

FIG. 3. Multipole decomposition of the 8° DWIA calculation (finite-range) for $S_{NN'}$. The top portion is for unnatural-parity transitions while the bottom portion is for natural-parity transitions.

MeV. However, the calculations do not describe the structures observed near 10 and 12 MeV. At the higher excitation energies the calculations are somewhat smaller than the data, especially at 10° and 12°.

Figure 3 presents the DWIA calculations for $S_{NN'}$ at 8° (solid line) along with the predictions of various multipoles that contribute to $S_{NN'}$. The upper portion of the figure presents the contributions for the unnatural-parity excitations, while the lower portion presents those for the natural-parity excitations. The largest contribution to $S_{NN'}$ is from the spin-flip strength of the natural-parity excitations, with the 2^+ contributing the most followed by the 3^-. The strongest unnatural-parity excitation is the 3^+ spin quadrupole between 10 and 20 MeV. Except for the region around 7 MeV there are no observed localizations of strength. In general, the spin-flip probability rises at higher excitation energies as has been observed in other experiments [1,4,5]. This trend has been attributed to the depletion of most of the $\Delta S=0$ strength at the lower excitation energies, so that only $\Delta S=1$ strength remains at the higher excitation energies.

As is observed in Fig. 3, the broad structure centered around 7 MeV is a superposition of many spins and parities, as would be suggested from the levels reported in the Nuclear Data Tables [15]. One of the largest contributors to this structure is 3^- strength. This may possibly be further evidence for the low-energy octupole resonance in ^{208}Pb as observed by Fujita *et al.* [20] with 65-MeV proton inelastic scattering and as calculated by Unkelbach, Speth, and Wambach [21]. We will further study this structure with our cross-section data.

In summary, we have obtained high statistics measurements of $D_{NN'}$ for ^{208}Pb, covering an excitation energy range from 2 to 24 MeV and a momentum-transfer range from 0.45 to 0.84 fm^{-1}. This is the heaviest nucleus in which the continuum spin-flip probability $S_{NN'}$ has been measured to date. Our data are described well by a recent DWIA, RPA calculation. This calculation, when compared to PWIA results, shows the importance of including distortions on the shape and magnitude of the calculations of $S_{NN'}$. At a momentum transfer of 0.84 fm^{-1} the PWIA calculations are $\frac{2}{3}$ of the DWIA results. We observe a structure centered near 7 MeV with a width of 2.5–3 MeV. The RPA calculations suggest this structure contains a large variety of spins and parities. We also observe a structure at 8° and 10° and centered near 12 MeV with a width around 1 MeV, the 8° data also suggest a peak of similar width located at 10 MeV. The RPA calculations do not describe these structures. In the continuum region the major contributors to the observed spin-flip strength are the natural-parity excitations with no localization of strength for any spin and parity.

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