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Proton scattering at intermediate energies on ^{58}Ni: How well is it understood?

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The excitation-energy region up to 23 MeV in ^{58}Ni has been investigated with the $(\vec{p}, \vec{p}')$ reaction at an incident energy of 172 MeV and forward angles favoring the excitation of the spin-dipole mode in the continuum. The measured cross sections, spin-flip cross sections, and spin-flip probabilities are compared to microscopic reaction-model calculations using various effective projectile-target interactions. The nuclear structure input, which takes into account one-particle one-hole (1p1h) as well as two-particle-two hole (2p2h) excitations, allows for a reasonable description of the continuum region well above the particle-decay thresholds. However, considerable problems remain in the description of spin-flip resonances at lower excitation energies, which cannot be explained by a quenching of the spin-isospin interaction.

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The description of cross sections and spin-flip observables in hadron scattering through microscopic nuclear structure models is a long-standing problem. Such models are needed on the one hand to extract the relevant effective degrees of freedom from the basic nucleon-nucleon (NN) interaction [1], on the other hand intermediate energy (100–400 MeV/nucleon) scattering is an important tool for the study of collective modes in nuclei [2]. As an example, α particle scattering, because of its selectivity to isoscalar electric modes, is the primary source of experimental information on the compressional monopole and dipole resonances [3]. Proton scattering has been less utilized to investigate collective electric nuclear modes [4], because of the complexity of the effective projectile-target interaction, where contributions from the isovector and spin-flip parts are non-negligible.

Recently, experimental and theoretical efforts have focused on a systematic understanding of isovector spin-flip modes ($\Delta S = 1$, $\Delta T = 1$) such as the Gamow-Teller (GT) resonance, characterized by a transferred angular momentum $\Delta L = 0$, and the spin-dipole (SD) resonance with $\Delta L = 1$. This interest is partly driven by new experimental developments permitting the study of charge-exchange reactions with high resolution [5,6], thus providing access to different isospin components of these resonances. The extraction of the corresponding modes from proton scattering provides a complete isospin set, which in turn serves as a unique testing ground for microscopic calculations, as, e.g., put forward recently in light nuclei [7]. Furthermore, understanding the properties of the GT and SD resonances has important astrophysical implications because of the direct relation to the analogous weak-decay modes [8]. For example, the SD response is important for neutral-current neutrino scattering on nuclei during a supernova explosion and the accompanying nucleosynthesis [9].

This raises the question of how well spin-flip resonances in nuclei can be extracted experimentally from inelastic proton scattering and what predictive power can be achieved by a comparison with state-of-the-art reaction-model calculations. In proton scattering a separation of spin-flip and non-spin-flip cross sections is possible by a measurement of the transverse spin-flip probability $S_{nn'}$. Our test case in the present work has been the reaction ^{58}Ni$(\vec{p}, \vec{p}')$ because a unique set of high-resolution data on the GT and SD modes from charge-exchange and electron scattering experiments is available [10–13].

Rather than trying to extract the properties of the spin-flip resonances from a model-dependent multipole decomposition, theoretical predictions are given for the experimental observables permitting a direct comparison between both. A similar approach has been attempted for lighter nuclei [14], but with experimental limitations in the measurement of $S_{nn'}$ (typical resolution of 1 MeV) and the restriction of the microscopic description of the nuclear structure part to the mean-field level, i.e., 1p1h excitation. Significant deviations were observed for cross sections and spin-flip observables in the giant resonance region and it remained unclear whether these were caused by an insufficient description of the effective NN interaction (based on a t-matrix approach [15]) or on the limitations of the structure approach. Therefore, in the present work different parametrizations of the projectile-target interaction [15–17] are tested within microscopic calculations, and the nuclear structure input takes into account for the first time a more realistic treatment of the fragmentation of giant resonances by the inclusion of 2p2h configurations. Due to the advent of a new generation of polarimeters with very fast data readout [18], a resolution of 200 keV even at forward angles is reached in the present measurement of the spin-flip probability, which allows us to study details of the structure of spin-flip modes important at lower excitation energies.

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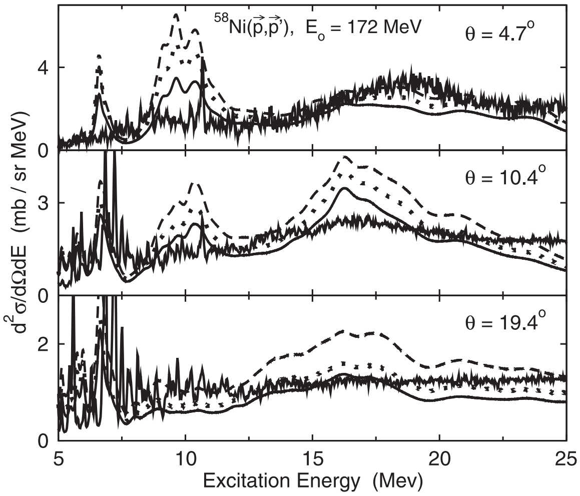

FIG. 1. Experimental cross sections for the ^{58}Ni($\vec{p}$, $\vec{p}'$) reaction at $E_0 = 172$ MeV and theoretical predictions using QPM wave functions and models I (dotted lines), II (dashed lines), and III (solid lines) for the effective target-nucleon interaction explained in the text.

The experiment was carried out at KVI, Groningen. Unpolarized and polarized protons with an energy of 172 MeV and currents of 1–4 nA were delivered by the superconducting cyclotron AGOR. The beam polarization (typically about 65%) was measured in regular time intervals using an in-beam polarimeter [19]. Scattered protons were momentum analyzed with the Big-Bite magnetic Spectrometer (BBS) [20] and detected with a focal plane system consisting of vertical drift chambers [18]. The polarimeter for the determination of the spin-flip probability is described in [18].

Data were taken at center-of-mass scattering angles $\theta = 4.7°, 6.3°, 10.4°$ with a polarized beam and additionally at $\theta = 16.4°, 19.4°$ with an unpolarized beam. A self-supporting, 99% enriched ^{58}Ni foil with a thickness of 17.6 mg/cm^2 was used as the target. The acceptance of the BBS allowed for a measurement of the spectra up to an excitation energy of about 23 MeV with a single setting of the spectrometer magnets. The energy resolution was $\Delta E \simeq 70$–100 keV full width at half maximum. The data analysis methods are described in [21].

Figure 1 displays the resulting double-differential cross sections as a function of excitation energy in ^{58}Ni. For the measurements with the polarized beam these were obtained from the sum of non-spin-flip and spin-flip cross sections. Elastically scattered events were suppressed by means of a veto scintillator. Transitions at low energy (up to $E_x \simeq 5$ MeV) are discussed in Ref. [22]. The experimental cross sections are in good agreement with earlier proton scattering experiments [23,24]. For higher excitation energies no comparable data exist. A resonance-like structure is visible in the spectra at forward angles between 15 and 20 MeV excitation energy. One recognizes a shift of the maximum from $E_x \approx 18$ MeV to about 16 MeV with increasing scattering angle θ indicating that different multipolarities contribute with comparable strength.

The lines in Fig. 1 are predictions of the cross sections obtained in the distorted wave Born approximation (DWBA) [25]. For the effective projectile-target interaction three different models were tested: G-matrix parameterizations [16,17] based on the Paris (model I) or the BonnB NN potential (model II) and the widely used t-matrix parametrization [15] of Love and Franey (model III). The relevant nuclear structure input was taken from a quasiparticle-phonon model (QPM) calculation. Excitation energies and wave functions for excited states were obtained from a diagonalization of a model Hamiltonian in a space of one- and two-phonon configurations. The typical size of the model space was 1000–2000 configurations for each spin-parity value $J^\pi = 0^\pm$ to $6^\pm$. The one-phonon components in the wave functions of the excited states were used as microscopic input for the DWBA program to calculate the corresponding transition densities and observables of each state. It is known that the two-phonon components give marginal contributions to the excitation probability in a one-step process while they are important for a description of the damping of the giant resonances [26]. The QPM has been shown to account very well for the gross properties of collective modes and their fine structure (see, e.g., [13,26–28]). Note that above the particle-emission threshold an empirical smoothing with an energy-dependent width has been performed in order to facilitate the comparison between experiment and theory [29].

In Ref. [22] it was pointed out that elastic scattering observables exhibit significant differences for the three effective interactions. On the other hand, low-lying collective transitions were described with similar quality except for an 30% overall variation in the absolute magnitudes. The same is true for the calculations in the continuum region above $E_x \approx 10$ MeV, where differences up to 40% are observed. The results for all three interactions are shown in Fig. 1. At larger angles, model II overestimates the experimental cross sections, while the models I and III provide a reasonable description. The strong peaks predicted around 6.5 and 10 MeV without experimental counterparts are discussed below.

Next, the spin-flip part of the cross sections is considered, i.e., the quantity $S_{nn'} \cdot d^2\sigma/d\Omega dE_x$. In Fig. 2 this quantity is shown at a scattering angle of 6.3°, at the expected maximum of the SD angular distribution. In the experimental spectra a sharp resonance-like structure is visible at an excitation energy $E_x \simeq 11$ MeV. Otherwise the spin-flip cross sections are more broadly distributed but show some structure around 17 and 20 MeV. The three different models for the effective projectile-target interaction predict a very similar energy dependence determined by the nuclear structure input, again with up to

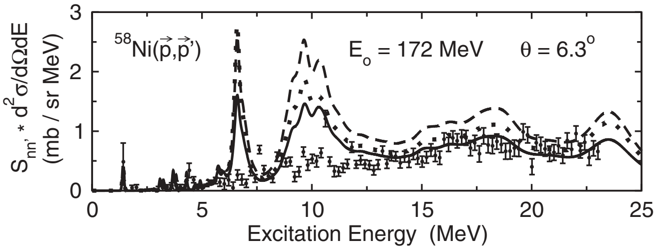

FIG. 2. Spin-flip cross sections of the ^{58}Ni($\vec{p}$, $\vec{p}'$) reaction at $E_0 = 172$ MeV and $\theta = 6.3°$ in comparison to theoretical predictions using QPM wave functions and models I (dotted lines), II (dashed lines), and III (solid lines) for the effective target-nucleon interaction.

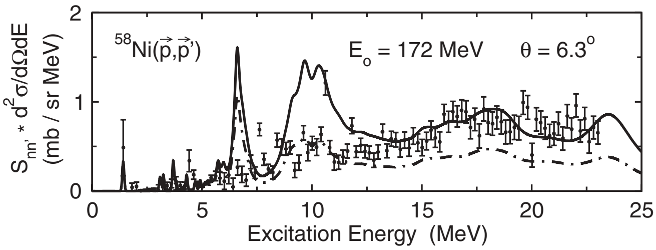

FIG. 3. Same as Fig. 2 for model III of the effective projectile-target interaction without (solid line) and with (dashed-dotted line) a quenching of the spin-isospin channel.

40% interaction dependence for absolute values. The energy dependence is well described at higher excitation energies but all calculations predict strong resonances around $E_x \simeq 7$ and 10 MeV not observed experimentally.

It is well known that the nuclear spin-isospin response is quenched at low energies because of higher-order configuration mixing and/or coupling to Δ-hole configurations (see, e.g., Ref. [30]). In fp-shell nuclei this quenching factor is well established for the weak GT decay [31] and for spin-flip $M1$ [32] and $M2$ transitions [33]. This effect can be taken into account by a quenching of the spin-isospin part of the NN interaction which should be interpreted as a renormalization of the axial charge in the nuclear medium [34]. For the strong interaction the latter is not conserved. The effect of taking into account a quenching factor $q = 0.8$ for the t-matrix interaction is demonstrated in Fig. 3. The model results (dashed-dotted line) now reproduce the excitation-energy region around 10 MeV but at the expense of a significant underestimate at higher energies.

These calculations must be viewed as two extreme cases. A large part of the quenching observed in the resonance region is predicted to result from the coupling to high-lying states via the tensor force [35,36] redistributing the strength to higher excitation energies. The dominance of this quenching mechanism has been experimentally demonstrated [30]. However, the tensor interaction is not included in the QPM approach which therefore cannot be expected to provide results consistent in the GT resonance as well as in the highly-excited region. This requires calculations including 2p2h degrees of freedom based on a realistic interactions [37].

While quenching of the spin-isospin interaction can explain the reduction of the spin-flip cross section around 10 MeV, the bump around 7 MeV which has no experimental counterpart remains. A decomposition of the QPM results shows that the peak around 7 MeV is generated by transitions to $J^{\pi} = 1^+$ states with dominant GT character and the broad bump around 10 MeV is shared between GT and SD excitations, the latter mostly populating $J^{\pi} = 2^-$ levels with some contributions from transitions to 1^- states. The absence of pronounced spin-flip cross sections at lower excitation energies in the data in contrast to the QPM predictions might partly result from an extreme experimental fragmentation of the GT and SD strengths [12,13]. It cannot be fully reproduced by the inclusion of 2p2h states but requires many-particle many-hole degrees of freedom as provided, e.g., by large-scale shell-model calculations of the GT strength in fp-shell nuclei [38]. However, shell-model calculations in this mass region are presently restricted to transitions within one major shell which precludes calculations of the cross-shell SD mode.

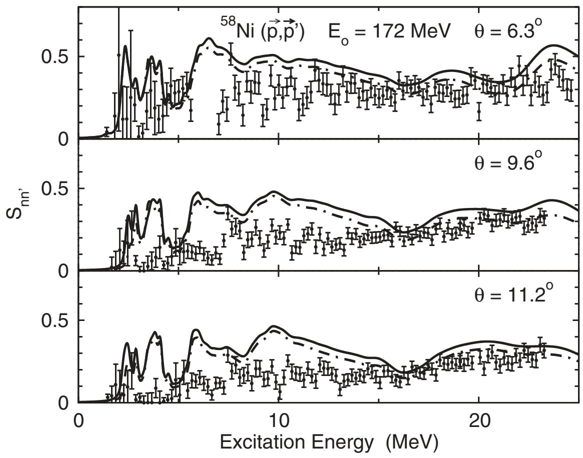

FIG. 4. Comparison of measured and calculated spin-flip probabilities of the ^{58}Ni($\vec{p}$, $\vec{p}'$) reaction at $E_0 = 172$ MeV at $\theta = 6.3°, 9.6°$, and 11.2°, using model III for the effective projectile-target interaction without (solid line) and with (dashed-dotted line) a quenching of the spin-isospin channel.

Finally, results for the spin-flip probability $S_{nn'}$ are presented. This observable turns out to be less dependent on the reaction dynamics than the cross sections. In Fig. 4 the experimental results for three different scattering angles are given as a function of excitation energy in bins of 200 keV. The calculations presented in Fig. 4 were performed using model III for the projectile-target interaction but the results do not depend much on the particular choice, since all results typically agree within 10%. An overshoot of $S_{nn'}$ is visible for $E_x \leqslant 12$ MeV, similar to results obtained for lighter nuclei [14]. Somewhat unexpectedly, this finding exhibits little sensitivity to a quenching of the spin-isospin interaction part, as shown by the dashed-dotted lines in Fig. 4. However, the continuum region is well described contrary to [14], where $S_{nn'}$ was strongly underestimated. The progress made here is clearly due to the inclusion of a structure model allowing for a more realistic degree of complexity.

To summarize, cross sections, spin-flip cross sections, and spin-flip probabilities have been measured in the ^{58}Ni($\vec{p}$, $\vec{p}'$) reaction with medium-energy protons and for kinematics favorable to observe the spin-dipole mode. The spin-flip variables could be determined with a resolution of 200 keV providing details of their excitation-energy dependence. The experimental data were directly compared to DWBA calculations based on a nuclear-structure model generally providing realistic strength distributions, especially in the giant resonance region. Various parameterizations of the effective projectile-target interaction were explored. With respect to RPA models [14] for the structure part the description of the response in the giant resonance region is considerably improved by the inclusion of two-particle two-hole configurations. However, ^{58}Ni is still a rather light nucleus and the neglect of the continuum leads to an underestimation of the damping, which is only partly compensated by the empirical smoothing procedure described above. This requires further theoretical development. The spin-flip cross sections and spin-flip probabilities are strongly overestimated below $E_x \approx 12$ MeV (as also observed in [14]). This calls for calculations based on realistic nucleon-nucleon interactions including both tensor correlations and the coupling to complex configurations. Work along these lines is under way [37].

At present the quantitative differences observed between the effective projectile-target interactions and the need to empirically introduce a quenching of the spin-isospin response, whose magnitude is not well determined (cf. the differences between Figs. 3 and 4), constitute a serious limitation for attempts to extract the properties of spin-isospin modes from the wealth of recent high-resolution hadronic scattering and charge-exchange reaction data. This calls for a combined experimental and theoretical effort to improve the reaction models, in particular in the light of current programs at all major rare-isotope beam facilities for studies of giant resonances with light-ion induced reactions in inverse kinematics [39].

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