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Using the $(\vec{p},\vec{p}')$ reaction to study $\Delta S=0$ giant resonances

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Measurements of spin-flip probabilities for inelastic scattering of 318 MeV protons from ^{40}Ca reveal that much of the background underlying the giant dipole and quadrupole resonances at small angles is from $\Delta S=1$ transitions. This holds the promise of allowing a much better estimate of this background than has previously been possible; one model-dependent parameter is necessary. Subsequent analysis with a first estimate of this parameter is presented.

Investigation of non-spin-transfer ($\Delta S=0$) giant resonances (GR) using inelastic hadron scattering is plagued with two experimental difficulties. (1) The resonances usually appear as small peaks on a large "background" which is then subtracted to obtain the resonance strength. However, it is never clear how much subtracted cross section has the same multipolarity as the GR being studied. Sometimes a phenomenological shape is calculated to represent quasi-free scattering "background."[1] (2) GR of different multipolarities frequently overlap causing additional uncertainties in the individual strengths. In this note we suggest a different approach to the problem of estimating the "background" in (p,p′) spectra so that analysis of the background-subtracted spectra will yield cross sections appropriate for comparison with $\Delta S=0$ sum rule strengths. Using a simple estimate of the one model-dependent parameter involved, we make a first application of this technique to data for ^{40}Ca up to 40 MeV excitation energy (E_x). We then carry out a multipole decomposition of the angular distribution of the resulting background-subtracted cross sections in 1.8 MeV bins to obtain the distribution in E_x of $\Delta S=0$ dipole and quadrupole strengths.

Our approach is similar in spirit to the consistent treatment of peaks and "background" suggested by Osterfeld *et al.*[2] to determine the strength of Gamow-Teller resonances in the (p,n) reaction. It relies on the assumption that the entire (p,p′) spectrum at intermediate energy arises from one-step nucleon-nucleon (NN) collisions via the free scattering amplitude. This is consistent with recent analyses by Bertsch, Esbensen, Scholten, and Smith.[3-5] In these models, the spectrum is composed of incoherent contributions from spin transfer ($\Delta S=1$) and $\Delta S=0$ transitions. The strength of interest here, the cross section σ_0 for $\Delta S=0$ excitations, can then be obtained if the cross section σ_1 for $\Delta S=1$ excitations is known.

The determination of σ_1 is based on measuring the spin-flip probability S_{nn} as well as the differential cross section σ. It is then possible to separate the spectrum into the spin-flip cross section σ_{SF},

$$\sigma_{SF}=\sigma S_{nn} \tag{1}$$

and the non-spin-flip cross section σ_{NSF},

$$\sigma_{NSF}=\sigma(1-S_{nn}) \ . \tag{2}$$

Since $\Delta S=0$ transitions at intermediate energy are known to have $S_{nn}\approx 0$, σ_{SF} is almost entirely due to $\Delta S=1$ transitions. However, σ_{SF} is not equivalent to σ_1 since S_{nn} is not unity even for pure $\Delta S=1$ transitions; for the same reason, σ_{NSF} contains both $\Delta S=0$ and $\Delta S=1$ contributions. In order to obtain σ_0 and σ_1, one must know the spin-flip probability a for σ_1 alone:

$$\sigma_0=\sigma-(\sigma_{SF}/a) \ . \tag{3}$$

This introduces some model dependence into the determination of σ_0 and σ_1 since a depends on the wave functions of the nuclear states and the strengths of the spin-dependent terms in the NN interaction.

Our group has recently been studying $\Delta S=1$ transitions in the continuum for nuclei between ^{12}C and ^{90}Zr. At incident energies around 300 MeV, we have measured[6,7] values of S_{nn} up to about 0.50 at 40 MeV for small angles ($\theta\leq 15°$). These values are significantly larger than the free NN values; they indicate that the nuclear response is sometimes dominated by $\Delta S=1$ excitations.[7]

Figure 1(a) shows typical data, obtained at the Clinton P. Anderson Meson Physics Facility, for the 318 MeV ^{40}Ca (p,p′) reaction at 7° (lab). Absolute normalization of the data, judged to be accurate to approximately $\pm 10\%$, was achieved by normalizing the ^{40}Ca yields to yields for p-p elastic scattering for which cross sections are accurately known; the deduced cross sections for excitation of the 6.91 MeV 2^+ and the 8.42 MeV 2^- states agree very well with previous measurements[8] at 334 MeV. The giant dipole resonance (GDR) at about 20 MeV and the giant quadrupole resonance (GQR) at about 18 MeV can be seen, unresolved, in the σ_{NSF} spectrum. The σ_{SF}

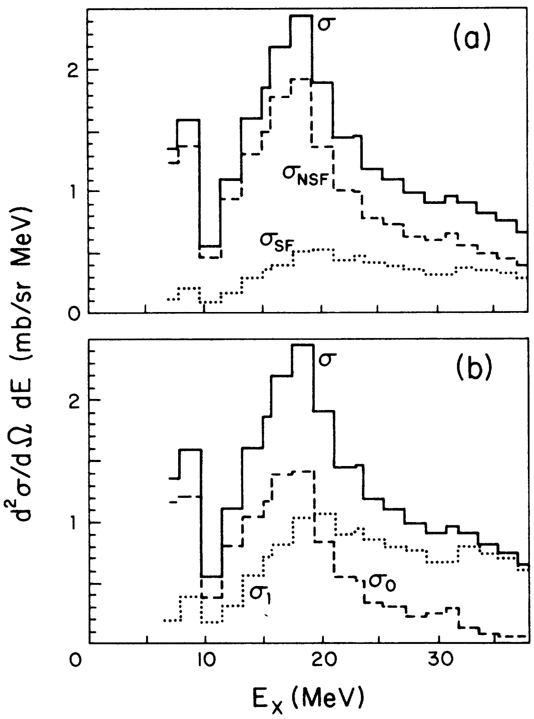

FIG. 1. Spectra for the double differential cross section for 318 MeV ^{40}Ca (p,p′) at a center of mass scattering angle of 7.24°. (a) The measured spectra for σ, σ_{SF}, and σ_{NSF}. (b) The model-dependent spectra σ_0 and σ_1 compared with the spectrum for σ.

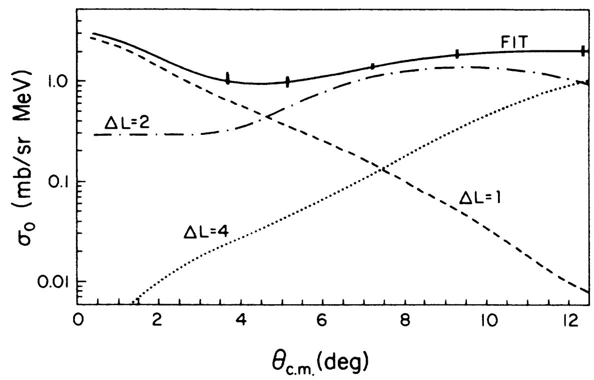

FIG. 2. The angular distribution of σ_0 and the multipole decomposition for the 1.8 MeV bin centered at $E_x=18.4$ MeV.

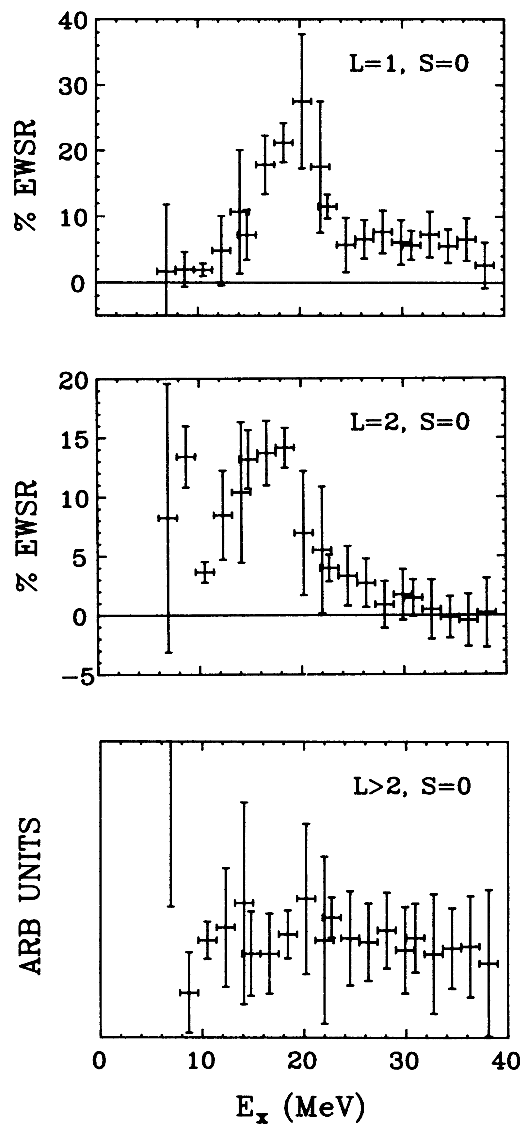

FIG. 3. The distribution of $\Delta S=0$ multipole strength as a function of excitation energy as determined from the present analysis.

spectrum is clearly not featureless in the GR region; preliminary multipole analysis of σ_{SF} indicates that the broad peak near 20 MeV is mainly due to a spin dipole resonance ($\Delta L=1, \Delta S=1$).

In this first exploratory application of the ideas outlined above, α has been approximated to be that for the free nucleon-nucleon (NN) interaction. It decreases smoothly with angle from about 0.6 near 3° to 0.36 near 12° and is almost independent of excitation energy. An example of the deduced σ_0 and σ_1 is shown in Fig. 1(b). The slab model of Bertsch *et al.*,[3,4] which has had considerable success in describing σ and S_{nn} for proton scattering to the continuum, predicts α to be essentially the same as these free NN values. More reliable estimates of α must await either elaborate RPA+DWIA calculations or a more detailed understanding of the multipole content of σ_1.

Having obtained an estimate for σ_0 via Eq. (3), we next must separate the contributions from various multipoles. To achieve this we have performed χ^2 minimization searches for the angular distribution of each 1.8 MeV bin of our data; these data were fitted by sums of predicted angular distributions described below. Since our data are at small angles, the main contributions to the cross section are from low multipolarity transitions. We have omitted contributions from a giant monopole resonance since previous searches using alpha-particle[9] and proton[10] inelastic scattering have failed to detect this resonance. The GDR angular distribution was calculated using the transition potential of Satchler[11,12] (Goldhaber-Teller model). The

TABLE I. Percentage (P) of the energy-weighted sum rule (EWSR) for the giant quadrupole (GQR) and giant dipole resonances (GDR) in ^{40}Ca measured in various experiments. Uncertainties, where known, are shown in parentheses. Also shown, where known, are the integration ranges (IR) used in the summation of strengths.

			GQR		GDR	
Reaction	E (MeV)	Reference	P (%EWSR)	IR (MeV)	P (%EWSR)	IR (MeV)
$(\vec{p},p')$	318	this work	76(12)	9.6–27.2	148(21)	9.6–35.4
					112(20)	9.6–25.4
$(\pi^-, \pi^{-\prime})$	130	16	30	15.2–22	100	15.2–22
$(\pi^+, \pi^{+\prime})$	130	16	27	15.2–22	130	15.2–22
$(\pi^+, \pi^{+\prime})$	241	17	77	...	...	...
(p,p')	60	10	40(10)[a]	...	100	...
(α, α')	117	9	48(8)	16.3–20.5	...	...
			61	13.2–20.5	...	...
(α, α')	99	9	43(9)	16.3–20.5	...	...
			56	13.2–20.5	...	...
(e,e')	150–250	18	$66(^{+10}_{-15})$	10–25	...	...
(^{3}He, ^{3}He)	109	19	34[a]	...	...	...
Photon absorption		15	...	...	130	10–35

[a] Gaussian shapes, which may exclude some quadrupole strength, were assumed.

optical potential used was determined[8] by fitting 334 MeV ^{40}Ca $(\vec{p},p')$ elastic scattering data. The isovector potential (U_1) was obtained by scaling the optical potential (U_0)

$$U_1 = (J_1/J_0)U_0 \ ,$$

where J_1 and J_0 are the volume integrals of the two-body interaction in the isovector and isoscalar channels respectively (obtained from the 325 MeV Love-Franey t matrix[13]). Similarly, the full Thomas spin-orbit term was used; again, the two-body interaction was used to scale the optical potential. The $L \geq 2$ angular distributions were calculated in the usual first-order collective model with equal deformation lengths for all potentials. All calculations were done using the code ECIS79,[14] included Coulomb excitation, and used relativistic kinematics.

The searches included $L = 1$, 2, and 4 angular distributions. Because the data described here have $\theta \leq 12°$, the data are insufficient to allow a clear separation between $L = 2$ and $L = 3$ strengths since the $L = 3$ angular distribution peaks at approximately 15°, beyond our data. Lack of a datum between 9 and 12° also contributes to the difficulty of separating $L = 2$ and $L = 3$ strengths. Contributions from higher multipoles are certainly not negligible, particularly at 12°, so an $L = 4$ angular distribution has been included in the searches. The $L = 4$ strength deduced will include contributions from all multipoles with $L \geq 3$. A typical fit, at $E_x = 18.4$ MeV where both the GDR and the GQR are strong, is shown in Fig. 2. The results of the searches, distributions of strengths for the various multipoles, are shown in Fig. 3. Errors shown include contributions due to correlations among the three parameters.

The dipole strength is concentrated in the GDR at 20 MeV but persists to higher excitation. This is in agreement with the results of photon absorption measurements.[15] Quantitatively, the photon-absorption cross section for 10–35 MeV excitation is about 130% of the classical dipole sum. The summed strength relative to the energy-weighted sum rule (EWSR) in this region of the spectrum for the present analysis is 148(21)%. If we take 10–25 MeV to be the region of the GDR, then this becomes 112(20)% of the EWSR. Results from other inelastic scattering experiments, shown in Table I, are all in the range of 100–130% for the GDR. The present values are thus in quite good agreement with previous values. These results also support the results of experiments[9,10] which have failed to find significant monopole strength; a monopole angular distribution would, like the dipole, peak at forward angles and therefore lead to apparently larger deduced dipole strength in our analysis.

The quadrupole strength is found to have considerable concentration in a broad resonance between 10 and 30 MeV. Some $E2$ strength at lower energies arises from previously observed[8] discrete states. Above 27 MeV, the quadrupole strength is consistent with zero. The summed strength determined in the present analysis, 76(12)% of the EWSR in the energy range of 10–27 MeV, is compared with results from other experiments in Table I. As can be seen, the present measurement is in agreement with the largest previously determined strengths. Detailed comparisons, however, are difficult because of different integration ranges and different assumptions used in the data reductions.

In conclusion, the results of the present analysis, while not a definitive measurement because of the limited angular range of the data, provide strong evidence that the ideas presented here for quantitatively removing the background under giant resonances are sound. Experiments with a larger angular range should be able to provide measurements of strength distributions for multipolarities $L \geq 2$. More sophisticated calculations of the spin-flip probability of the $\Delta S = 1$ continuum are also needed.

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