Investigation of Compound Elastic Scattering Near Isobaric Analog Resonances with Polarized Protons*

W. Kretschmer and G. Graw
University Erlangen–Nürnberg, Erlangen, Germany
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A rather model-independent separation of direct and compound elastic cross sections has been obtained from the analysis of elastic scattering of polarized protons near the lowest $d_{5/2}$ isobaric analog resonances in ^{89}Y and ^{91}Nb.

In energy-averaged nuclear scattering experiments, compound elastic scattering may be important if there are only few channels open. The measured differential cross section $\langle\sigma\rangle$ may be described as a sum of the direct cross section $\sigma^{\rm DI}$, calculated from energy-averaged scattering matrix elements, and a Hauser-Feshbach cross section for the compound elastic contribution, $\sigma^{\rm CE}$. In a polarized-beam experiment $\sigma^{\rm CE}$ does not contribute to the measured left-right difference of the differential cross section $\langle\sigma A\rangle$,[7] where σ is the differential cross section, A is the analyzing power, and the angular brackets denote an appropriate energy average. Hence, a model-independent separation of $\sigma^{\rm DI}$ and $\sigma^{\rm CE}$ will be obtained, if it is possible to determine the energy-averaged S-matrix elements $\langle S_c^{lj}\rangle$ from $\langle\sigma A\rangle$ only, as then $\sigma^{\rm CE}$ is obtained by $\sigma^{\rm CE} = \langle\sigma\rangle - \sigma^{\rm DI}$.

In this Letter we report on the separation of $\sigma^{\rm DI}$ and $\sigma^{\rm CE}$ in the reactions ^{90}Zr(p,p_0) and ^{88}Sr(p,p_0) near the lowest $d_{5/2}$ isobaric analog resonance (IAR), performed with polarized protons. Since both $\sigma^{\rm DI}$ and $\sigma^{\rm CE}$ show resonance behavior, a good determination of resonance parameters is of interest.

For a quantitative analysis of the extracted $\sigma^{\rm CE}$ in terms of Hauser-Feshbach theory, it is important that the elastic channel be the only important direct channel and all other channels are of Hauser-Feshbach type. Then the transmission coefficients T_c are obtained from the energy-averaged scattering matrix elements[2]:

$$T_c^{lj} = 1 - |\langle S_c^{lj}\rangle|^2. \quad (1)$$

For these scattering experiments near 5 MeV proton energy, the Coulomb barrier is very important, and thus possible direct inelastic proton scattering is strongly suppressed. Possible neutron decay is assumed to be of pure Hauser-Feshbach type. In the case of ^{90}Zr all neutron channels are closed, whereas in the case of ^{88}Sr there are two neutron channels open. For the analysis of the extracted $\sigma^{\rm CE}$ in the framework of Hauser-Feshbach theory[2] in the first case, $\sigma^{\rm CE}$ is completely determined by the parameters obtained from elastic scattering, whereas in the second case, the transmission coefficients of the two neutron channels also contribute.

For the $d_{5/2}$ IAR in ^{90}Zr(p,p_0), the compound elastic cross section has been determined by Scott, Swann, and Rauch[3] from the analysis of differential cross section only and using $\sigma^{\rm DI}$ and $\sigma^{\rm CE}$ as independent magnitudes. For the $d_{3/2}$ IAR near $E_p = 6.8$ MeV, the influence of $\sigma^{\rm CE}$ on polarization data has been discussed by Thompson, Adams, and Robson.[4]

The experiment was performed with the polarized proton beam of the Erlangen 12-MeV tandem accelerator.[5] At six lab scattering angles, $\theta = 40°$, 60°, 90°, 120°, 140°, and 160°, protons were detected with symmetric pairs of counters. To obtain reliable cross-section and analyzing-power data, each measurement was performed twice with reversed sign of beam polarization. The absolute value of the cross section should be correct within 5%. Isotopically enriched targets of metallic Zr (0.5 mg/cm^2) and evaporated SrO (0.2 and 0.6 mg/cm^2) on thin carbon backings were used. The experimental energy resolution was 22 keV; in the experiment with the thin Sr target, 10 keV.

Figures 1 and 2 show measured data of $\langle\sigma\rangle$ and $\langle\sigma A\rangle$ for three angles—160°, 140°, and 120°—and their fitted curves. The curves have been obtained by the use of the optical model[6,7] and Hauser-Feshbach[8] programs which also perform the energy average over the experimental energy resolution.

For the resonant channel the following expressions for the direct S-matrix element $\langle S_c^{lj}\rangle$ and the transmission coefficient T_c^{lj} have been

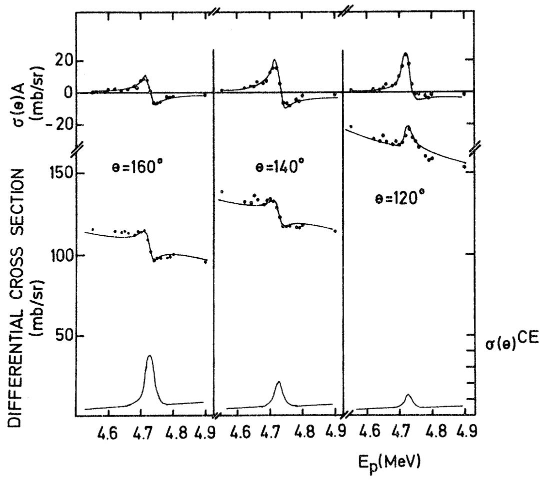

FIG. 1. $\langle\sigma(\theta)\rangle$ and $\langle\sigma(\theta)A(\theta)\rangle$ for ^{90}Zr(p,p_0)^{90}Zr near the $d_{5/2}$ g.s. IAR. The solid curves are calculated from optical-model potentials with the resonance parameters of Table I. At the bottom of the figure $\sigma^{CE}(\theta)$ is shown.

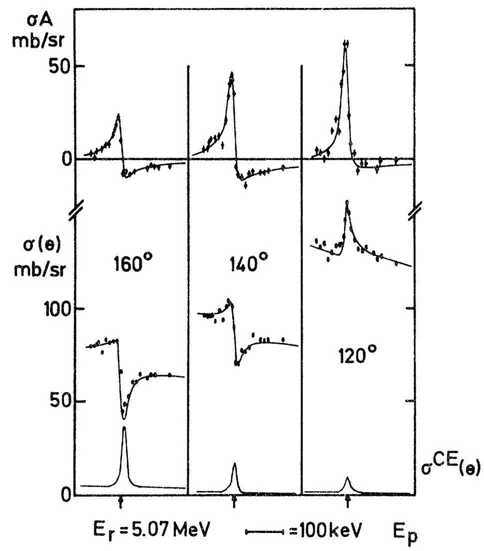

FIG. 2. $\langle\sigma(\theta)\rangle$ and $\langle\sigma(\theta)A(\theta)\rangle$ for ^{88}Sr(p,p_0)^{88}Sr near the $d_{5/2}$ g.s. IAR.

used[9]:

$$\langle S_c^{lj}\rangle = \exp[2i\,\mathrm{Re}(\delta_{lj})]\left[\exp[-2\,\mathrm{Im}(\delta_{lj})] + i\frac{\exp(2i\varphi_R)\Gamma_p}{E_R - E - \frac{1}{2}i\Gamma}\right], \tag{2}$$

$$T_c^{lj} = \{1 - \exp[-4\,\mathrm{Im}(\delta_{lj})]\}\frac{(E - E_R + \Delta)^2 + B^2}{(E - E_R)^2 + \frac{1}{4}\Gamma^2}, \tag{3}$$

where the δ_{lj} are the optical-model phase shifts; E and E_R the incident proton and the resonance energy, respectively; Γ and Γ_p the total and elastic partial width, respectively; and φ_R the resonance mixing phase. The magnitudes Δ and B are obtained by trivial calculation from parameters of formula (2) using formula (1) (compare Ref. 2).

Since proton scattering in this energy region is dominated by Rutherford scattering, all optical-model phase shifts are small and hence not very sensitive to the choice of the optical-model parameters. For both proton and neutron channels we used the optical-model parameters of Becchetti and Greenless.[10] To obtain good background fits and good reproduction of the (p,n) cross section,[11] we used the absorption potential for both proton and neutron channels, $W_D = 4$ MeV instead of 12 MeV, which corresponds to the well-known weakness of the strength function in the $A = 90$ region.[12]

The curves in Figs. 1 and 2 have been obtained with a set of resonance parameters given in Table I. They reproduce very well the experimental values of both $\langle\sigma A\rangle$ and $\langle\sigma\rangle$. The compound elastic cross section is shown separately in the lower part of the figures. Since this determination of σ^{CE} is rather model-independent and the analysis is consistent with Hauser-Feshbach calculations, we think that the resonance parameters are determined rather reliably.

Interesting features of these parameters are that the resonance mixing phases are small,

TABLE I. Resonance parameters for ^{88}Sr(p,p_0)^{88}Sr and ^{90}Zr(p,p_0)^{90}Zr.

	J^π	E_R(lab) (MeV)	Γ (keV)	Γ_p (keV)	φ_R
^{88}Sr(p,p_0)^{88}Sr	$\frac{5}{2}^+$	5.07	19.0	6.3	0.01 ± 0.05
^{90}Zr(p,p_0)^{90}Zr	$\frac{5}{2}^+$	4.727	17.0	3.1	0.05 ± 0.05

which is in good agreement with recent theoretical results from Auerbach *et al.*,[13] and the spreading width $\Gamma^+ = \Gamma - \Gamma_p$ is in both cases nearly the same, whereas the partial widths differ by a factor of 2. The derived quantities Δ have very small values near 10 keV, whereas the symmetric term of the enhancement, indicated by $B \approx 40$ keV, cannot be neglected.

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$^{12}C(^{13}C, \alpha)$ Transitions to Possible Eight-Particle, Three-Hole States in ^{21}Ne†

R. Middleton, J. D. Garrett,* H. T. Fortune, and R. R. Betts
Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania 19104
(Received 30 August 1971)

Excitation functions and energy-averaged angular distributions have been measured for the $^{12}C(^{13}C,\alpha)$ transitions to the 3.66- and 3.89-MeV states in ^{21}Ne. The similarities observed between these transitions and the $^{12}C(^{12}C,\alpha)$ transition to the 7.83-MeV 2^+ eight-particle, four-hole state in ^{20}Ne suggest a possible eight-particle, three-hole configuration for the 3.66- and 3.89-MeV states of ^{21}Ne.

In an earlier study[1] of the $^{12}C(^{13}C, \alpha)$ reaction, performed at a center-of-mass energy of 14.4 MeV, the two states at $E_x = 3.66$ and 3.89 MeV in ^{21}Ne were observed to be selectively populated. The angular distributions were highly asymmetric —that of the 3.89-MeV state was strongly forward peaked and that of the 3.66-MeV state strongly backward peaked. The shapes of the angular distributions were highly suggestive of a direct reaction mechanism, and the present investigation was undertaken to explore this possibility.

Asymmetric angular distributions are not necessarily inconsistent with a compound-nucleus reaction mechanism, particularly if measured at a single incident energy. However, the statistical model of the compound nucleus predicts symmetry about 90° for an angular distribution obtained by averaging over an energy interval corresponding to several states in the compound system. Averaged angular distributions have been obtained using the University of Pennsylvania multiangle spectrograph and tandem accelerator. For these data, the incident energy (center of mass) was varied between 14.28 and 14.52 MeV in eleven equal steps. Good energy resolution was retained by readjusting the magnetic field of the spectrograph at each incident energy to compensate for the variation in the energy of the emitted α particles. The energy loss in the targets was about 80 keV (lab), which is comparable to the step size in which the incident energy was varied.

The resulting angular distributions for the 3.66- and 3.89-MeV states are displayed in Fig. 1. The forward-angle data (circles) were measured using a ^{12}C target and a ^{13}C beam. The back-angle data (crosses) were obtained by interchanging target and projectile and observing this reaction, at forward angles, over the same range of center-of-mass energies. To avoid confusion, the