2^- Isobaric Analog Resonance in the $^{89}Y(p,n_2)^{89}Zr$ Reaction and the Excited States of ^{89}Zr†

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The (p,n) reaction on ^{89}Y has been studied around the 2^- isobaric analog resonance at the proton energy of 4.807 MeV. Differential cross sections have been measured for the neturon groups which leave ^{89}Zr in the ground state and the excited states at 0.592 and 1.096 MeV. Angular distributions of the neutron groups which leave ^{89}Zr in the excited states at 1.096, 1.465, and 1.645 MeV have been measured. The results are compared with the predictions of Robson's theory and statistical model.

I. INTRODUCTION

The $^{89}Y(p,n)\,^{89}Zr$ reaction has been studied previously[1–4] to investigate the $d_{5/2}$ isobaric analog resonances at 4.807 MeV ($J^\pi=2^-$) and 5.01 MeV ($J^\pi=3^-$). Johnson *et al.*[4] measured the absolute total cross section using a 4π neutron detector, with an uncertainty of $\pm4\%$ and an energy resolution of 5 keV. They measured a total cross section of 21 mb for the resonant part at the 2^- resonance. The only other previously reported absolute cross-section measurement indicated 8 mb for the sum of the (p,n_0) and (p,n_1) cross sections, but this was measured with poorer energy resolution ($\sim$20 keV) and $\pm20\%$ uncertainty.[3] Johnson *et al.* observed a sharp threshold rise in the (p,n) total cross section just below the 2^- resonance, even after subtracting the smooth background, which suggested an appreciable yield in the (p,n_2) cross section for the 2^- resonance.[4] No measurement of the $^{89}Y(p,n_2)$ cross section around this resonance has been reported previously.

The present work was undertaken primarily to measure the cross section around the 2^- analog resonance in the $^{89}Y(p,n_2)$ reaction which leaves ^{89}Zr in the excited state at 1.096 MeV, since this will yield some information on the spin and parity of this state. A spin and parity of $\frac{1}{2}^-$ or $\frac{3}{2}^-$ was indicated for this state in the study of the $^{90}Zr(p,d)\,^{89}Zr$ reaction by Goodman.[5] Angular distributions of the $^{89}Y(p,n_2)$ reaction have been measured by Kim and Robinson,[6] who assigned a spin and parity of $\frac{3}{2}^-$. Since the second-excited-state threshold is only 50 keV below the energy of the 2^- resonance, a resonance yield for the n_2 group neutrons would indicate outgoing s-wave neutrons confirming the $\frac{3}{2}^-$ assignment for the spin and parity of this residual state.

II. EXPERIMENTAL METHODS

Targets of ^{89}Y ($\sim$5 keV thick for 5-MeV protons), evaporated on 0.005-in.-thick gold backings, were bombarded by a pulsed beam of protons ($\sim$7-nsec pulse width) which had been accelerated in the University of Kentucky Van de Graaff accelerator. In order to detect the low-energy neutrons (<50 keV) of the n_2 neutron group and at the same time discriminate against other neutron groups, a thin ^{6}Li-loaded glass scintillator was used. This, in conjunction with the flight-time measurement using a flight path of 20 cm, made it possible to separate the n_2 neutron group from higher-energy neutron groups and the γ peak. Since the scintillator was thin, it was possible to bias out most of the pulses due to γ rays. An open geometry was used, since the detector was very sensitive to low-energy neutrons. The relative neutron detection efficiency of this detector was assumed to be proportional to the $^6Li(n,\alpha)\,^3H$ total cross section, and this was taken from the work of Gabbard *et al.*[7] and Bame and Cubitt.[8] The absolute cross sections were obtained by normalizing the data measured with this detector to the cross sections measured at the higher energies, using a liquid-scintillator detector biased at 50-keV proton energy, whose absolute neutron detection efficiency was calibrated as described previously.[9] Figures 1(a) and 1(b) show the time-of-flight spectra from the $^{89}Y(p,n)$ reaction measured with the liquid scintillator at a proton energy of 5.18 MeV, and with the ^{6}Li-loaded glass scintillator at a proton energy of 4.96 MeV, respectively. The target thickness was measured by counting the number of protons elastically scattered at an angle of 140° from the ^{89}Y target evaporated on an aluminum backing, using incident protons of 2-MeV energy. At this low proton energy the scattering was assumed to be pure Coulomb scattering, and the target thickness was calculated using the Rutherford formula.

III. RESULTS AND DISCUSSION

A. 2^- Analog Resonance

Figure 2 shows the excitation functions of the n_0, n_1, and n_2 neutron groups from the $^{89}Y(p,n)$ reaction, which leave ^{89}Zr in the ground state and the excited states at 0.592 and 1.096 MeV. The relative and ab-

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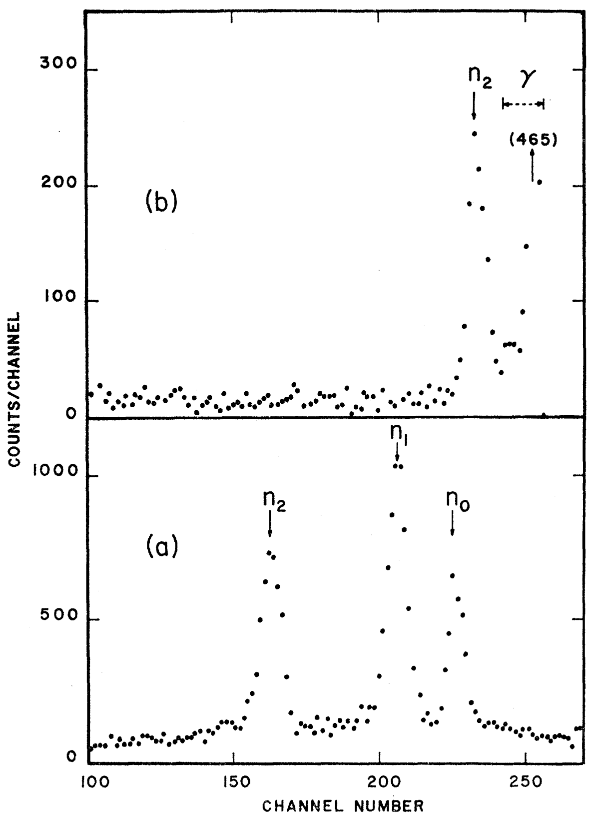

FIG. 1. Time-of-flight spectra from the $^{89}Y(p,n)$ reaction measured with (a) the liquid scintillator at a proton energy of 5.18 MeV and a flight path of 1.5 m, and (b) the ^{6}Li-loaded glass scintillator at a proton energy of 4.96 MeV and a flight path of 20 cm. The arrows show the positions of the neutron groups. The interval labeled γ in (b) refers to the position of the γ rays and higher-energy neutron groups. The time resolution was about 10 nsec.

solute uncertainties in the cross section are estimated to be $\pm 10\%$ and $\pm 20\%$, respectively. These large uncertainties arise mainly from uncertainties involved in the subtraction of the background in the time-of-flight spectrum which varies with energy and angle and from uncertainty in the target thickness. It is seen from Fig. 2 that the 2^- analog resonance is excited in all three neutron groups. The experimental width of the resonance is about 25 keV. Although the (p,n) total cross sections have not been measured in the present work, rough estimates of these could be made from the excitation functions and a knowledge of the shape of the angular distribution.[1,2] A value of 30 mb is estimated for the total nonresonant cross section $(n_0+n_1+n_2)$ at the 2^- resonance, which compares with the 27 mb observed by Johnson *et al.*[4] For the resonant part, a cross section of 19 mb is estimated for the three neutron groups. This includes an estimated resonant cross section of 4.5 mb for the n_2 group. In comparison, Johnson *et al.*[4] give a value of 21 mb for the total $(n_0+n_1+n_2)$. It may be pointed out that the present results are obtained from measurements of neutron time-of-flight spectra subject to varying background conditions, and hence the errors involved are expected to be greater than in the 4π detection method used by Johnson *et al.*[4]

An analysis of the 2^- resonance has been carried out using the theory of Robson *et al.*[10] (see also Refs. 1 and 4) mainly to extract information about the spin and parity of the second excited state in ^{89}Zr. Robson's development of the theory for (p,n) reactions involving analog resonances assumes that the analog state is dominated by a single channel (e.g., the entrance proton channel) and that mixing of the analog state with the background states occurs in the external region only. Although neutron decay from the analog state is forbidden by isospin selection rules, mixing of the analog state with the background states gives rise to neutron emission. Good agreement with experiment has been obtained using this theory, in the cases of the $^{92}Zr(p,n)$ and $^{88}Sr(p,n)$ reactions.[10,9] In the case of the $^{89}Y(p,n)$ reaction, disagreement with the theory has been reported by Johnson *et al.*[4] for the 3^- resonance at a proton energy of 5.01 MeV.

In a general way,[1,4] the cross section for a reaction from channel a to channel b can be written as

$$\sigma(a,b)=\sum_J \sigma_J(a,b)+\sigma_{J_0}{}^{\text{en}}(a,b)\,, \tag{1}$$

where the summation is over all compound-nucleus spins which can be formed by the incident partial waves except for states of the same spin and parity J_0 as the analog state. The second term in Eq. (1) corresponds to the enhanced cross section, e.g., as given by Robson[4,10] and includes compound nucleus states of the

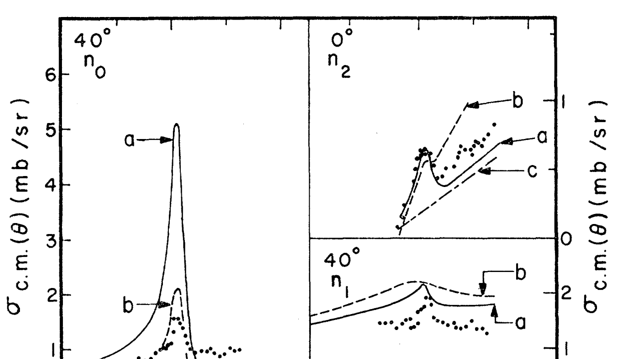

FIG. 2. Excitation functions of the n_0, n_1, and n_2 neutron groups from the $^{89}Y(p,n)^{89}Zr$ reaction at the angles indicated. Curves (a) and (b) are the results of the calculations, using Robson's theory, and two different sets of complex-potential parameters. See text for details of the parameters. Curve (c) is the result using the same parameters as for curves (a), but assuming $\frac{1}{2}^-$ for the spin and parity of the 1.096-MeV state in ^{89}Zr, instead of $\frac{3}{2}^-$ assumed for curves (a) and (b).

[10] D. Robson, J. D. Fox, P. Richard, and C. F. Moore, Phys. Letters 18, 86 (1965).

TABLE I. Parameters of the complex-potential model.

	V (MeV)	r_v (F)	a_v (F)	W (MeV)	r_w (F)	a_w (F)	V_{so} (MeV)
Proton (a)	$59.5-0.5E_p$[a]	1.25	0.65	5	1.25	0.47	7.5
(b)	60	1.25	0.65	3	1.35	0.40	7.5
Neutron (a)	47	1.25	0.65	3	1.25	0.47	7.0
(b)	47	1.30	0.62	5	1.30	0.71	7.0

[a] E_p is the c.m. energy of the protons in MeV.

same spin and parity as the analog state. The separation of the cross section in the manner shown in Eq. (1) implies that the randomness and completeness assumptions of the statistical model theory are valid.[1]

The first term in Eq. (1) can be calculated using the statistical model theory[1,11] which is expected to be valid in the present study, since there is good averaging among the compound-nucleus states as evidenced by the fact that the excitation functions are smooth functions of energy away from the analog resonances and the angular distributions are symmetric about 90°. The second term in Eq. (1) which is responsible for the resonance is proportional to $T_a^{\text{en}}T_b/\sum_c T_c$, where T_a^{en} is the enhanced transmission coefficient in the entrance channel and T_b and T_c are the transmission coefficients in channels b and c and the summation includes all channels into which the compound nucleus can decay, including T_a^{en} for the entrance channel.[4]

$$T_a^{\text{en}}=T_a(E-E_0+\Delta)^2/[(E-E_0)^2+\tfrac{1}{4}\Gamma^2], \qquad (2)$$

where T_a is the usual complex-potential transmission coefficient, E is the incident-channel energy, E_0 is the resonance energy, Δ is level shift, and Γ is the resonance width. It is seen that the enhanced cross section is proportional to the transmission coefficient in the outgoing channel T_b. In the case of the n_2 group, if one assumes a spin and parity of $\frac{1}{2}^-$ for the 1.096-MeV excited state of ^{89}Zr, the transmission coefficient will be two orders of magnitude (d-wave neutrons) less than the s-wave transmission coefficient involved if the spin and parity of this state is assumed to be $\frac{3}{2}^-$. Hence, the resonance is expected to be suppressed if the spin and parity are $\frac{1}{2}^-$. The calculated result as shown in Fig. 2 substantiates this point.

Using this formalism, the differential cross sections for the three neutron groups have been calculated around the 2^- analog resonance. The transmission coefficients were calculated using the complex-potential model for several potential parameters. In Fig. 2, curves (a) and (b) show the results using two different sets of complex-potential parameters. The potentials used in the fitting procedure are shown in Table I for curves (a) and (b). The real potentials are of the derivative Woods-Saxon form except that the imaginary potential for the neutrons in curve (b) is of the Gaussian type; and the spin-orbit potentials are of the Thomas type. The proton potential parameters for curve (a) were taken from Johnson *et al.*[12] The proton parameters of curve (b) were obtained by Johnson *et al.*[13] by fitting the resonant part of the 3^- analog resonance and the neutron parameters (b) were taken from Moldauer.[14]

For curve (c) of the n_2 group, the potential parameters used for curves (a) were used, but the spin and parity of the 1.096-MeV state in ^{89}Zr was assumed to be $\frac{1}{2}^-$ instead of $\frac{3}{2}^-$ which was assumed for curves (a) and (b). The assumption of $\frac{1}{2}^-$ for this state did not noticeably change the results for n_0 and n_1 groups. Among the open proton channels, the decays to the ground state ($J^\pi=\frac{1}{2}^-$) and the excited states at 0.915 MeV ($J^\pi=\frac{9}{2}^+$), 1.53 MeV ($J^\pi=\frac{5}{2}^-$), and 1.74 MeV ($J^\pi=\frac{5}{2}^-$) were taken into account and all three open neutron channels were considered, viz., the ground state ($J^\pi=\frac{9}{2}^+$) and the excited states at 0.592 MeV ($J^\pi=\frac{1}{2}^-$) and at 1.096 MeV. The enhancement-factor parameters used were E_0 (c.m.) = 4.756 MeV, $\Delta=-0.060$ MeV, and $\Gamma=0.023$ MeV.

It is seen from Fig. 2 that theory does not give good agreement with the experimental data. Several different sets of complex-potential parameters were tried, but none of them gave good simultaneous agreement to the data for all three neutron groups. In particular, the theory predicts much greater enhancement in the cross section for the n_0 group. It is unlikely that any realistic parameters for the complex potential and the enhancement factor will give good agreement to the data. This disagreement probably implies that the single-channel assumption made in Robson's theory is not valid in the case of ^{89}Y.

However, it is important to note that a spin of $\frac{1}{2}^-$ for the 1.096-MeV state of ^{89}Zr does not enhance the cross section, since the spin of this state must be $\frac{3}{2}^-$, which is consistent with the earlier reports.[5,6] In these calculations, no corrections for level width fluctuations were made. These corrections may be important near thresholds, but it is thought that they do not affect greatly the conclusions drawn here.

B. Excited States of ^{89}Zr

Figure 3 shows the angular distributions of the n_2, n_3, and n_4 neutron groups from the ^{89}Y(p,n) reactions,

[11] W. Hauser and H. Feshbach, Phys. Rev. **87**, 366 (1952).

[12] See p. 26 of Ref. 4.

[13] See p. 31 of Ref. 4.

[14] P. A. Moldauer, Phys. Rev. Letters **9**, 17 (1962) (see curve 3, Fig. 2).

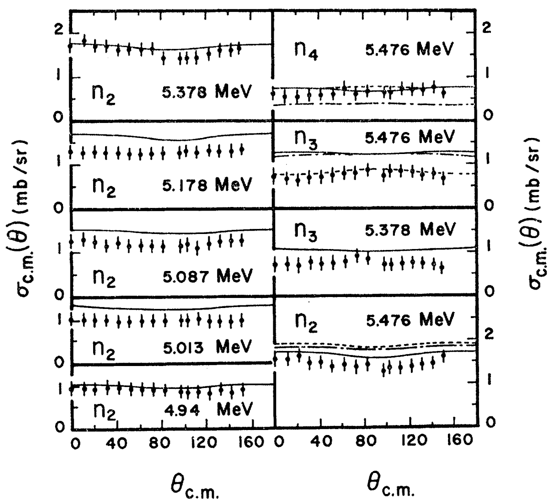

FIG. 3. Angular distributions of the n_2, n_3, and n_4 neutron groups from the $^{89}Y(p,n)$ reaction, leaving ^{89}Zr at the 1.096-, 1.465-, and 1.645-MeV states, respectively, at the laboratory proton energies indicated. The solid curves are the results of the statistical model calculations assuming spins and parities of $\frac{3}{2}^-$, $\frac{3}{2}^-$, and $\frac{5}{2}^-$ for the 1.096-, 1.465-, and 1.645-MeV states, respectively. See text for complex-potential parameters used. For the 5.476-MeV angular distributions, the dashed curves (---) are the results assuming $\frac{3}{2}^-$, $\frac{7}{2}^-$, and $\frac{3}{2}^-$ for the above respective states and the dot-dashed curves (—·—) are the results assuming $\frac{3}{2}^-$, $\frac{5}{2}^-$, and $\frac{7}{2}^-$ for these states.

leaving ^{89}Zr at the 1.096-, 1.465-, and 1.645-MeV states, respectively, at the laboratory proton energies indicated. The angular distributions are symmetric about 90°, within the experimental error, which is consistent with the statistical model.[11] The angular distributions for these neutron groups were calculated using the statistical model. The proton potentials were taken from Johnson *et al.*[12] and the neutron potentials of Moldauer[14] were used (see previous section). The solid curves in Fig. 3 show the results of these calculations assuming spins and parities of $\frac{3}{2}^-$, $\frac{3}{2}^-$, and $\frac{5}{2}^-$ for the 1.096-, 1.465-, and 1.645-MeV states in ^{89}Zr. Assuming $\frac{1}{2}^-$ for the 1.096-MeV state gave incorrect shapes for the n_2 angular distributions, as observed by Kim and Robinson.[6] The spin and parity for this state is $\frac{3}{2}^-$ as discussed in the previous section. The calculations were made for several combinations of spins and parities for the 1.465- and 1.645-MeV states. The results for two different combinations of these are shown in Fig. 3 for the 5.476-MeV angular distributions as indicated in the figure caption. However, no definite conclusions could be drawn about the spins and parities of these two states, since assuming spins of $\frac{3}{2}$, $\frac{5}{2}$, or $\frac{7}{2}$ for these states gave results which agreed with the data, within the experimental error.

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[15] W. R. Smith, Oak Ridge National Laboratory Report No. ORNL-TM-1117, 1965 (unpublished).