2− Isobaric Analog Resonance in the $^{88}$Y($p,n$)$^{88}$Zr Reaction and the Excited States of $^{88}$Zr

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(Received 10 July 1968)

The ($p,n$) reaction on $^{88}$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 neutron groups which leave $^{88}$Zr in the ground state and the excited states at 0.592 and 1.096 MeV. Angular distributions of the neutron groups which leave $^{88}$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 $^{88}$Y($p,n$)$^{88}$Zr reaction has been studied previously1−4 to investigate the $d_{5/2}$ isobaric analog resonances at 4.807 MeV ($J=2^−$) and 5.01 MeV ($J=3^−$). Johnson et al.4 measured the absolute total cross section using a 4π neutron detector, with an uncertainty of ±4% 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 (∼20 keV) and ±20% 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 $^{88}$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 $^{88}$Y($p,n$) reaction which leaves $^{88}$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 $\frac{3}{2}^−$ or $\frac{1}{2}^+$ was indicated for this state in the study of the $^{90}$Zr($p,d$)$^{90}$Zr reaction by Goodman.5 Angular distributions of the $^{88}$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 $^{88}$Y (∼5 keV thick for 5-MeV protons), evaporated on 0.005-in.-thick gold backings, were bombarded by a pulsed beam of protons (∼7-ns 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 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 $^7$Li($n,\alpha$) $^4$He 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 $^{88}$Y($p,n$) reaction measured with the liquid scintillator at a proton energy of 5.18 MeV, and with the 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 $^{88}$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 $^{88}$Y($p,n$) reaction, which leave $^{88}$Zr in the ground state and the excited states at 0.592 and 1.096 MeV. The relative and ab...
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 ⁸⁹Zr. 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 ⁸⁹Zr(p,n) and ⁸⁶Sr(p,n) reactions.10,9 In the case of the ⁸⁶V(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

$$\sigma(a,b) = \sum_j \sigma_j(a,b) + \sigma_{an}(a,b),$$

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, as the analog state. The second term in Eq. (1) corresponds to the enhanced cross section, e.g., as given by Robson10 and includes compound nucleus states of the

![Figure 1](image1.png)

**Fig. 1.** Time-of-flight spectra from the ⁸⁶V(p,n) reaction measured with (a) the liquid scintillator at a proton energy of 5.18 MeV and a flight path of 1.8 m, and (b) the ⁴Li-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.

![Figure 2](image2.png)

**Fig. 2.** Excitation functions of the n₀, n₁, and n₂ neutron groups from the ⁸⁶V(p,n)⁸⁹Zr 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 ⁴ for the spin and parity of the 1.096-MeV state in ⁸⁹Zr, instead of ⁴− assumed for curves (a) and (b).

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 theory¹,¹¹ 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 $T_a^{eq}T_b/\sum_c T_c$, where $T_a^{eq}$ 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 $T_a^{eq}$ for the entrance channel.⁴

$$T_a^{eq} = T_a(E - E_0 + \Delta)/[(E - E_0)^2 + \Gamma^2],$$ (2)

where $T_a$ is the usual complex-potential transmission coefficient, $E$ is the incident-channel energy, $E_0$ is the resonance energy, $\Delta$ is level shift, and $\Gamma$ 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 $n_5$ group, if one assumes a spin and parity of $\frac{3}{2}^-$ 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 $\frac{1}{2}^-$. 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 $n_5$ 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 $\frac{3}{2}^-$ instead of $\frac{1}{2}^-$ which was assumed for curves (a) and (b). The assumption of $\frac{1}{2}^-$ for this state did not noticeably change the results for $n_5$ and $n_4$ groups. Among the open proton channels, the decays to the ground state ($J^e = \frac{3}{2}^-$) and the excited states at 0.915 MeV ($J^e = \frac{3}{2}^+$), 1.53 MeV ($J^e = \frac{3}{2}^-$), and 1.74 MeV ($J^e = \frac{5}{2}^-$) were taken into account and all three open neutron channels were considered, viz., the ground state ($J^e = \frac{3}{2}^-$) and the excited states at 0.592 MeV ($J^e = \frac{3}{2}^-$) 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 $n_5$ 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 $\frac{1}{2}^-$, 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 $n_5$, $n_{5}$, and $n_{4}$ neutron groups from the $^{89}$Y($p$,n) reactions,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).
The angular distributions for these neutron groups were calculated using the statistical model. The angular distributions were symmetric about 90°, within the experimental error, which is consistent with the statistical model. The solid curves in Fig. 3 show the results of these calculations assuming spins and parities of $\frac{3}{2}^-$, $\frac{1}{2}^-$, and $\frac{3}{2}^+$ for the 1.096-, 1.465-, and 1.645-MeV states in $^{90}$Zr. Assuming $\frac{3}{2}^-$ for the 1.096-MeV state gave incorrect shapes for the $n_2$ angular distributions, as observed by Kim and Robinson. 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. However, no definite conclusions could be drawn about the spins and parities of these states, since assuming spins of $\frac{9}{2}^-$, $\frac{5}{2}^+$, or $\frac{7}{2}^-$ for these states gave results which agreed with the data, within the experimental error.

ACKNOWLEDGMENTS

The computer code used in the statistical model calculations was adapted from a program by W. R. Smith and the Fortran version of it (unpublished) for which the authors wish to express thanks. The assistance of the University of Kentucky Computing Center is acknowledged.