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Isobaric Analogue States in Heavy Nuclei. II. Resonances in Ga^{69}†

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Resonances in proton elastic scattering and (p,n) reactions on targets of Zn^{68} are interpreted as isobaric analogues of the excited states of Ga^{69}. Twelve resonances are identified and classified with respect to l_p. The resolution of a previously unresolved energy-level doublet is demonstrated. The Coulomb displacement energy for the isobaric-analogue system Zn^{69}-Ga^{69} is found to be 9.60 MeV, in agreement with other work.

I. INTRODUCTION

RESONANCES in proton scattering and proton-induced reactions on heavy nuclei have been reported by Fox, Moore, and Robson[1] and interpreted as isobaric analogues of the low-lying states of the nucleus that is produced by neutron capture on the same target. In addition to the resonances in Y^{89} and Zr^{90} that are isobaric analogues of the low-lying states of Sr^{89} and Y^{90}, respectively, Robson *et al.* have reported the existence of isobaric analogue resonances in many other nuclei.[2] Further experiments[3] have reported resonances in Nb and Tc. In the present experiment, the reactions $Zn^{68}(p,p)$ and $Zn^{68}(p,n)$ are investigated in order to determine the analogue resonances in Ga^{69}. The present experiment was begun at a time when isobaric analogue resonances had been observed in the nuclei around $A=90$, and the question of whether such resonances were observable in lighter nuclei had not been answered. Lee *et al.*[4] have subsequently reported the observation of isobaric analog resonances in Cu^{65}.

Isobaric analogue resonances do not have single-particle configurations, but their reduced widths are expected to be $1/(2T_0+1)$ of the reduced neutron width of the corresponding target nucleus+neutron state, where T_0 is the isobaric spin of the target. Their experimental widths, of the order of a few keV, makes their observation possible as compound nucleus resonances in the continuum-energy region where the expected width of the other resonant states is of the order of a few eV. For an isolated resonance, the analysis of the proton

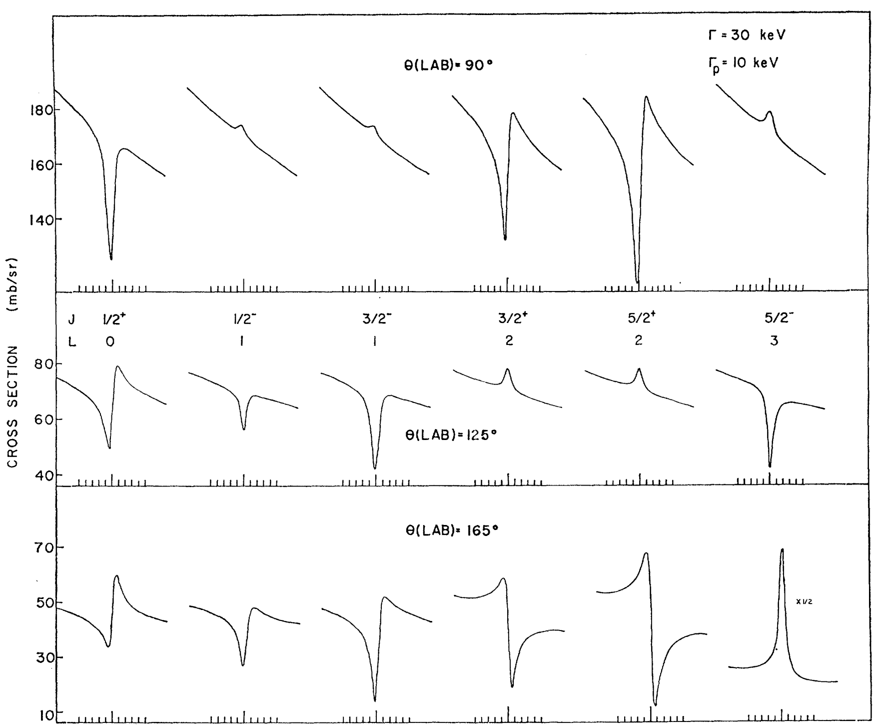

Fig. 1. Single-level shapes calculated for the reaction $Zn^{68}(p,p)$ with 5.25-MeV resonant energy. L = orbital angular momentum quantum number.

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[1] J. D. Fox, C. F. Moore, and D. Robson, Phys. Rev. Letters **12**, 198 (1964).
[2] D. Robson *et al.*, Technical Report No. 6, Florida State University, 1964 (unpublished).
[3] C. F. Moore, Ph.D. dissertation, Florida State University, 1964 (unpublished).
[4] L. L. Lee, Jr., A. Marinov, and J. P. Schiffer, Phys. Letters **8**, 352 (1964).

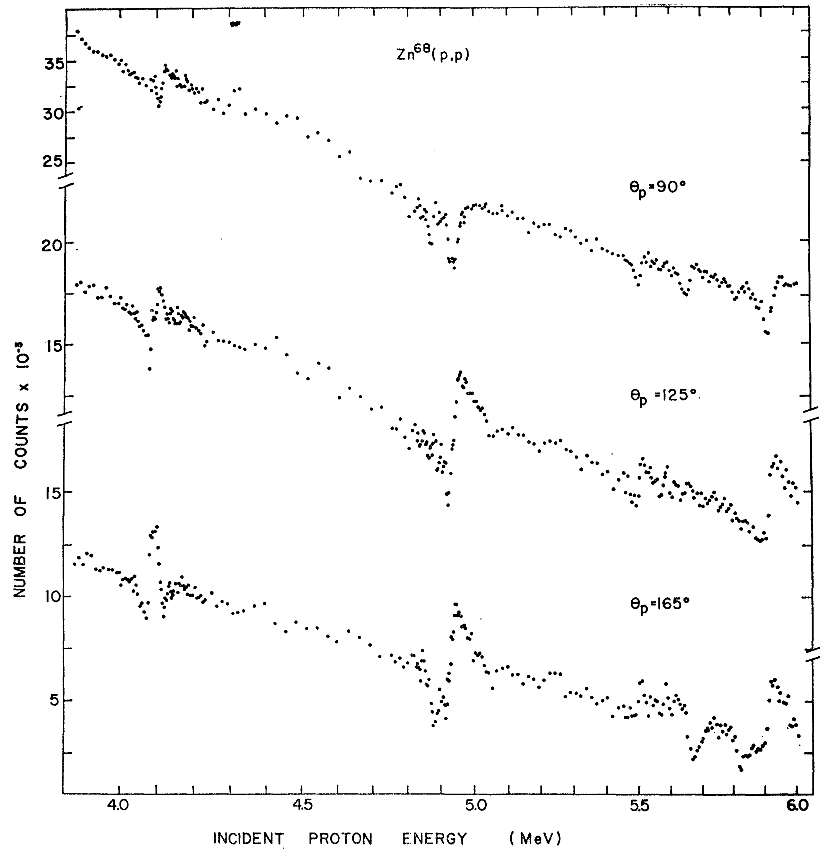

FIG. 2. Proton elastic scattering on Zn^{68}, for incident proton energy between 3.9 and 6 MeV.

elastic scattering can proceed by using the cross-section equation[5,6]:

$$\frac{d\sigma}{d\Omega}=\left.\frac{d\sigma}{d\Omega}\right)_{\text{Coulomb}}+\left.\frac{d\sigma}{d\Omega}\right)_{\text{Interference}}+\left.\frac{d\sigma}{d\Omega}\right)_{\text{Resonance}} \tag{1}$$

derived using R-matrix theory.[7] The shape of the excitation curve near a single level in the compound system, depends almost entirely on the orbital angular momentum of the captured proton. Figure 1 contains shapes of single levels for three different angles and for different values of l and J. They have been calculated for the reaction $Zn^{68}(p,p)$ with 5.25 MeV for the resonance energy, total width $\Gamma=0.03$ MeV and proton width $\Gamma_p=0.01$ MeV. Therefore, for an isolated resonance, the value of l for the state can be obtained by inspection of the experimental data.

This analysis does not depend on a particular reaction mechanism and therefore the l_p value of the proton resonance should be considered more certain than in the case of l_n in the (d,p) reaction with distorted-wave Born approximation (DWBA) stripping analysis. Since the proton resonances are the isobaric analogues of the states produced in the (d,p) reaction, l_p for the proton

[5] C. F. Moore *et al.*, preceding paper, Phys. Rev. **141**, 1166 (1966).
[6] C. F. Moore and P. Richard, Florida State University, 1965 Technical Report, No. 8 (unpublished).
[7] A. M. Lane and R. G. Thomas, Rev. Mod. Phys. **30**, 257 (1958).

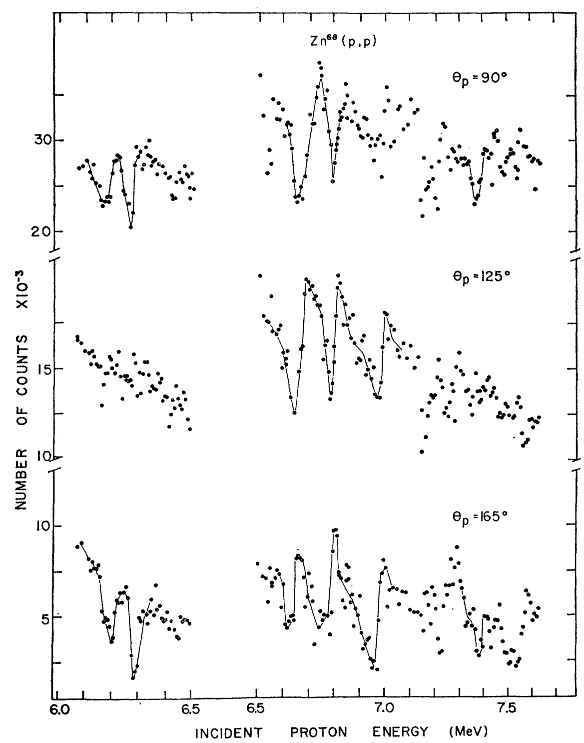

FIG. 3. Proton elastic scattering on Zn^{68}, for incident proton energy between 6 and 7.7 MeV. The region between 6.5 and 7.7 MeV was taken with a different target than the region between 3.9 and 6.5 MeV.

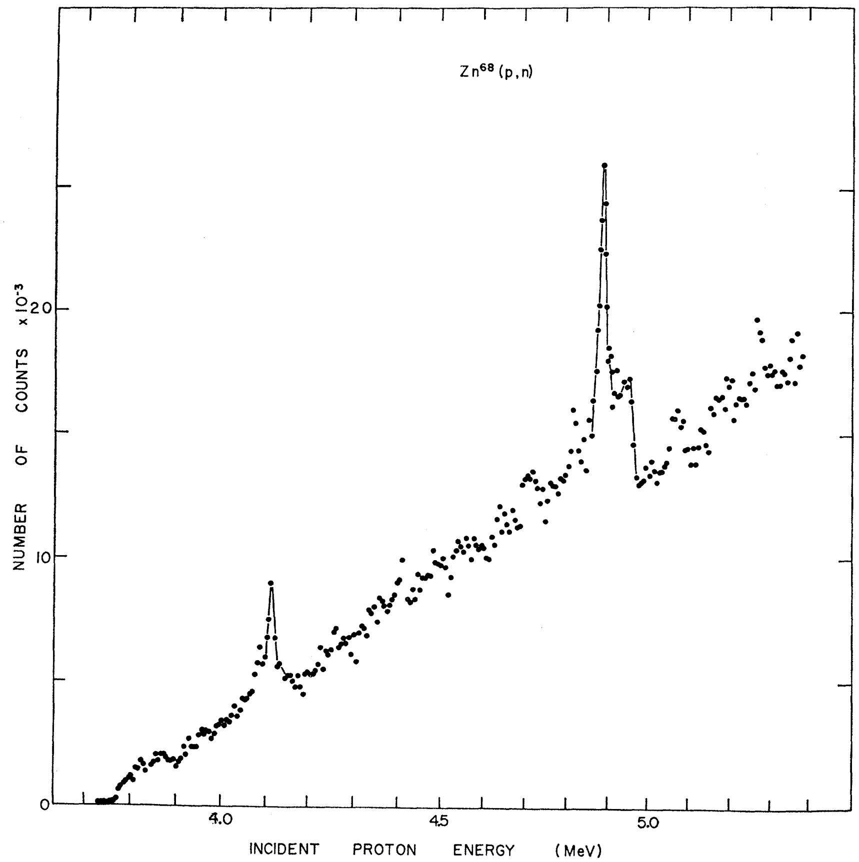

FIG. 4. Neutron excitation function for (p,n) on Zn^{68} for incident proton energy between 3.7 and 5.4 MeV.

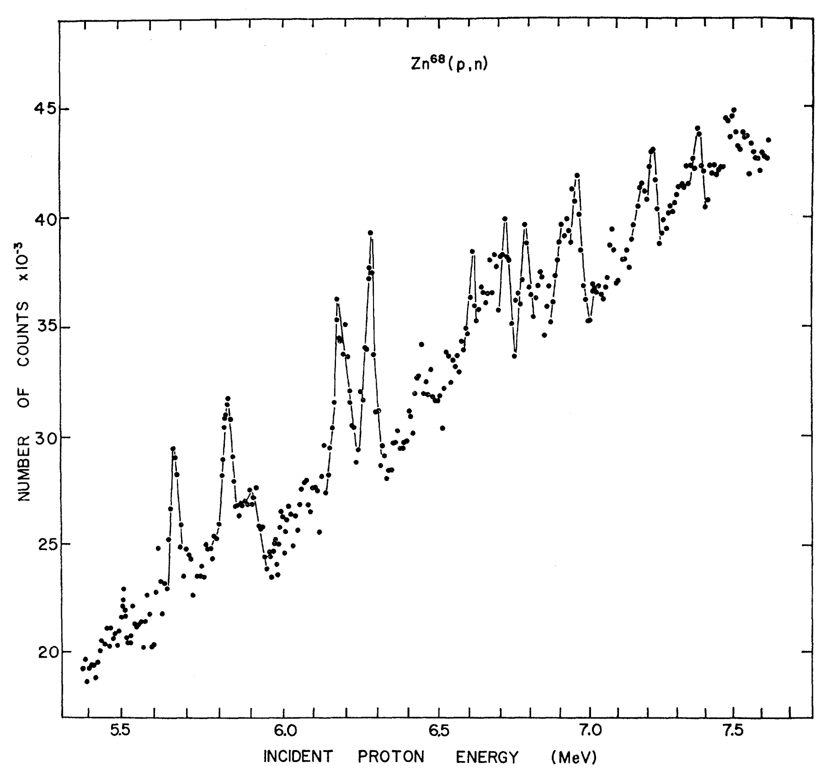

FIG. 5. Neutron excitation function for (p,n) on Zn^{68} for incident proton energy between 5.4 and 7.7 MeV.

resonance is effectively the same quantum number as l_n for the (d,p) reaction. One of the objects of the experiment reported here was to contribute further information concerning the quantum number assignment of levels in Zn^{69} through comparison with the existing (d,p) reaction data.[8]

II. EXPERIMENT

The enriched sample of Zn^{68} (99.3% Zn^{68}) was obtained in the form of zinc oxide from the Isotope Division of the Oak Ridge National Laboratory. The zinc oxide was evaporated from a tantalum boat onto a thin carbon backing. The energy loss in the targets used in the experiment was approximately 4 keV for 5-MeV protons. The proton beam for this work was obtained from the tandem Van de Graaff accelerator at Florida State. For the elastic scattering measurements, surface barrier detectors were placed at 90°, 125°, and 165° to the incident beam. For the (p,n) data, an uncollimated proton beam was used and the neutrons were detected with a shielded BF_3 long counter placed at 90° to the beam and 4 in. from the target. The proton beam was kept to approximately 0.5 μA and an integrated beam of 50 μC was used for each elastic scattering data point; each data point represents 10 μC of integrated beam for the (p,n) work. A more complete discussion of the experimental technique appears in the previous paper.[5]

III. RESULTS

The excitation functions for the elastic scattering and (p,n) data are shown in Figs. 2–5. The experimental information for the resonances observed is summarized in Table I. The proton energy at which the isobaric analogue of the ground-state Zn^{69} is expected is 3.23 MeV and is below the (p,n) threshold. Both the ground-state and first-excited-state analogues could not, therefore, be observed by this method. The analogue of the second excited state lies just above the (p,n) threshold and was also not seen. The elastic scattering data in the vicinity of the ground-state analogue did not reveal a resonance although the data were not as good as at higher energy. The high values of orbital angular momenta expected for the analogues of the first and second excited states probably precluded their being found in this experiment.

The analogues of the next twelve excited states of Zn^{69} were observed as resonances in both the (p,n) and (p,p) reactions at about the energies expected from the (d,p)

TABLE I. Comparison of isobaric analogue resonances in Ga^{69} with low-lying states in Zn^{69} produced via (d,p) reactions.

$Zn^{68}(p,p)$ E_{res}^{lab} (MeV)	$E_p^{c.m.}-3.19$ (MeV)	l_p	$Zn^{68}(d,p)$ E_{exc} (MeV)	l_n
...	...	...	0	1
...	...	...	0.44	4
...	...	...	0.55	3
4.11	0.85	2	0.85	2
4.87	1.60	2	...	...
4.92	1.65	0	1.65	0
5.49	2.22	0	2.25	1
5.67	2.40	2	2.40	2
5.82	2.54	2	2.54	2
5.90	2.62	0	2.60	0
6.20	2.92	2	2.91	2
6.28	3.00	2	2.99	2
6.65	3.36	0	...	...
6.79	3.50	0	3.40	2
6.97	3.68	0	3.65	2
...	...	...	3.94	0
...	...	...	4.09	0
...	...	...	4.17	0
...	...	...	4.24	0

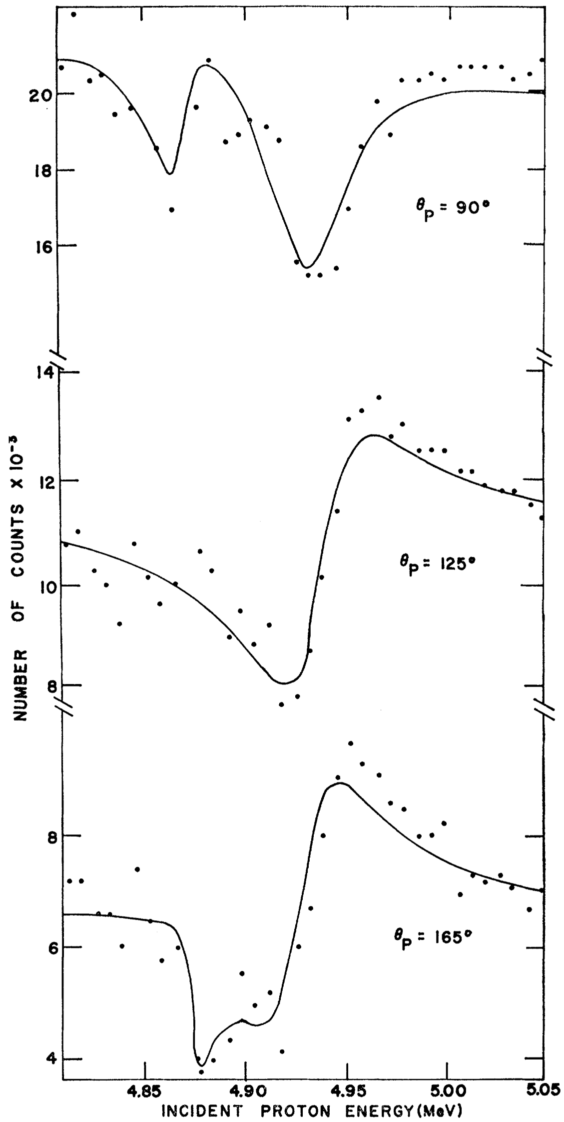

FIG. 6. Theoretical fit to the 1.60–1.65 MeV doublet. Solid line corresponds to the theoretical calculation, points are experimental. For the d state (4797±20 keV) $\Gamma=12\pm5$ keV, $\Gamma_p=2\pm1$ keV; and for the s state (4850±20 keV) $\Gamma=38\pm5$ keV, $\Gamma_p=12\pm3$ keV.

[8] E. K. Lin and B. L. Cohen, Phys. Rev. **132**, 2632 (1963).

work. The resonance in the elastic scattering at 4.11 MeV, corresponding to the 0.85-MeV excited state in Zn^{69} is possibly an unresolved doublet. There is less evidence of this being two resonances in the (p,n) work. Both the (p,n) and (p,p) excitation functions reveal previously unresolved analogue resonances at excitation energies of 1.60 and 1.65 MeV. These are identified as being produced by *d*- and *s*-wave proton capture, respectively. In the (d,p) work, the *s*-wave neutron capture dominated the reaction cross section and the level was reported as an unresolved doublet.

The resonances at 4.11 and 4.88 MeV were previously reported in 1957 by Chapman and Slattery,[9] who studied the (p,n) reaction only, but were not identified as isobaric analogue resonances.

The resonance that probably corresponds to the 2.25-MeV excited state in Zn^{69} is observed at 2.22 MeV above the ground-state-analogue location. The resonance is assigned as *s* wave while the (d,p) state at this energy was assigned as *p* wave. Good agreement with the next few excited states was obtained although the highest energy resonances we are able to identify (3.36, 3.50, and 3.68 MeV above the ground-state analogue) are probably *s* wave while the previous assignment is *d* wave.

Above proton bombarding energies of about 7 MeV, a large number of resonances appears and the data can no longer be analyzed. The Coulomb barrier, which held the proton partial widths and spreading widths[5] to reasonable values, is exceeded at about this energy and individual resonances are no longer able to be identified.

A careful fit to the resonances observed at 4.87 MeV (*d* wave) and 4.92 MeV (*s* wave) corresponding to the isobaric analogues of the 1.60- and 1.65-MeV states of Zn^{69} is shown in Fig. 6. The large resonances observed at higher energy were not amenable to analysis since they appear in nearly overlapping groups of *s*- and *d*-wave resonances.

The Coulomb displacement energy can be determined from the measurements reported here through the relation:

$$E_p^{\text{c.m.}} = E_{\text{Coul}} - B_n\,, \tag{2}$$

where $E_p^{\text{c.m.}}$ is the proton center-of-mass energy for exciting the isobaric analogue ground state and B_n is the binding energy of a neutron to the target nucleus. Taking the neutron binding energy of Zn^{69} to be 6.41 MeV,[10] the Coulomb displacement energy for the isobaric analogues Zn^{69}-Ga^{69} is found to be 9.60 ± 0.05 MeV. This value is consistent with the (p,n) measurements of Anderson *et al.*[11] under the assumption of a uniformly charged spherical nucleus.

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[9] R. A. Chapman and J. C. Slattery, Phys. Rev. **105**, 633 (1957).

[10] L. A. Koenig, J. H. E. Mattauch, and A. H. Wapstra, *1960 Nuclear Data Tables, Part 2* (Printing and Publishing Office, National Academy of Sciences—National Research Council, Washington, D. C., 1961).

[11] J. D. Anderson, C. Wong, and J. W. McClure, Phys. Rev. **138**, B615 (1965).