On the other hand, the cross sections observed for reactions to the $4^+$ and $6^+$ levels in $Ti^{50}$ together are only about a quarter of the observed cross section for the 3.32-MeV group. On the basis of the cross section and angular distribution, the presence of a third state with spin $3^-$ in this vicinity does not appear improbable. In $Ti^{46}$ which has four neutron holes in the $f_{7/2}$ shell, three closely spaced $3^-$ states are observed with the center of gravity near 3.6 MeV, with perhaps a second group at higher excitation energies. It appears that the lowest $3^-$ strength, which is concentrated in one level in $Ti^{50}$, is fractionated among two or more levels in the other isotopes—perhaps by interaction with the incomplete neutron shell.

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# Study of Analog States by the $(p,n)$ Reaction*

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Isobaric-analog states were studied by measuring the total neutron yield from the $(p,n)$ reaction on $^{65}Cu$, $^{70}Zn$, $^{74}Ge$, $^{76}Ge$, $^{75}As$, and $^{80}Se$. A large number of resonances were observed, and total widths extracted for approximately 50 of these resonances. Detailed comparison is made with the level schemes of nuclei formed by $(d,p)$ reactions on the same targets. Coulomb displacement energies were extracted for all isotopes studied.

## INTRODUCTION

Isobaric-analog resonances[1,2] have been observed in a variety of nuclei since the discovery of analog states in the compound nucleus by Fox, Moore, and Robson.[3] Methods used include the $(p,p)$, $(p,p')$, $(p,\gamma)$, and $(p,n)$ reactions.[4] Measurement of the total neutron yield remains the fastest and simplest way to locate analog states, to measure total widths of these states, and to determine Coulomb displacement energies.

Since the neutron decay of analog states is isospin-forbidden, the observed resonances cannot have pure isospin. The properties of the $(p,n)$ reaction channel are of considerable importance since they give insight into the nature of the mixing between the $T$-lower states ($T_< = T_t - \frac{1}{2}$; where $T_t$ is the isobaric spin of the target ground state) and $T$-greater states ($T_> = T_t + \frac{1}{2}$). Measurement of the total neutron yield also serves as a guide to further experiments involving elastic (or inelastic) scattering or detailed neutron studies.

In the present work,[5] the total neutron yield from six intermediate-mass nuclei was measured as a function of incident proton energy. All excitation curves display a number of sharp resonances. A comparison was made between the observed resonances and available level schemes obtained from $(d,p)$ reactions on the same target. In this way many isobaric-analog states of the compound nucleus were identified. Level widths were determined for practically all resonances which were sufficiently well isolated. Coulomb displacement energies were extracted for all isotopes studied, and compared with predictions of a semiempirical formula.

## EXPERIMENTAL PROCEDURE

A proton beam was obtained from the Columbia University Van de Graaff accelerator. The relative energy spread of the beam ($\Delta E/E$) was approximately 0.1%. All targets were prepared by evaporation onto 0.010-in. Ta backings. The enrichments of the separated isotopes were: $^{70}Zn$(78.3%), $^{74}Ge$(91.7%), $^{76}Ge$(84.7%), and $^{80}Se$(97.75%); natural Cu and As targets were used. Target thickness ranged from 75 to 150 $\mu g/cm^2$, with maximum nonuniformities of 5–10%. The proton beams employed ranged from 0.05 to 0.50 $\mu A$. Neutrons were

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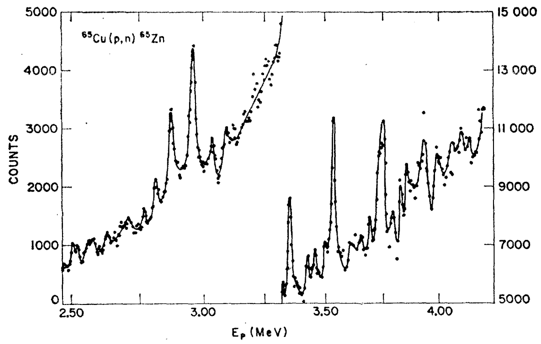


FIG. 1. Neutron excitation curve for the $^{65}Cu(p,n)^{65}Zn$ reaction. Left-hand ordinate scale applies to the low-energy portion of curve; the counts for the higher-energy part are read from the right-hand scale.

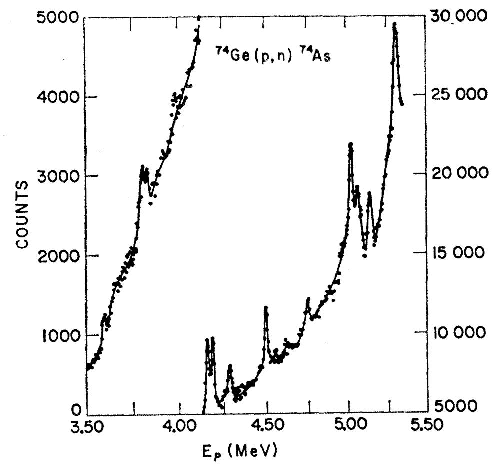


FIG. 3. Neutron excitation curve for the $^{74}Ge(p,n)^{74}As$ reaction. Ordinates read as in Fig. 1.

detected at 0° with a $^{3}$He-filled proportional counter[6,7] embedded in paraffin.

## RESULTS AND DISCUSSION

The excitation curves obtained from the $(p,n)$ reaction on $^{65}$Cu, $^{70}$Zn, $^{74}$Ge, $^{76}$Ge, $^{75}$As, and $^{80}$Se are shown in Figs. 1–6, respectively. In each case, the continuous distinct resonances superimposed on a rapidly increasing neutron background.

The resonances observed are listed in Table I. Parentheses around the energies signify that the resonances were very weak. The absolute energy of each resonance is determined to better than 10 keV; the uncertainty in spacing between resonances is somewhat less. Level widths listed in Table I include a contribution due to finite target thickness. In all cases these target thicknesses ranged from 5–10 keV for the proton energies employed. The error in the observed widths is approximately 5 keV.

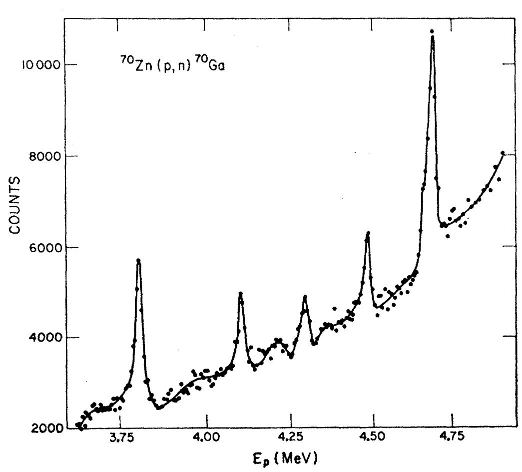


FIG. 2. Neutron excitation curve for the $^{70}Zn(p,n)^{70}Ga$ reaction.

Table I also contains a comparison of the level spacings observed in this work with results obtained from both $(d,p)$ studies and other $(p,n)$ studies of the same target nuclei. The unambiguous identification of those

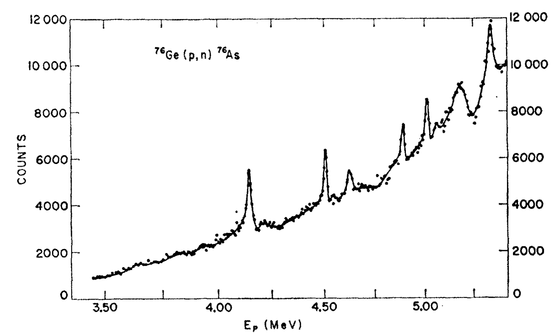


FIG. 4. Neutron excitation curve for the $^{76}Ge(p,n)^{76}As$ reaction.

resonances which correspond to levels seen in $(d,p)$ work was aided by prediction of the Coulomb displacement energy, calculated from a semiempirical formula.[8]

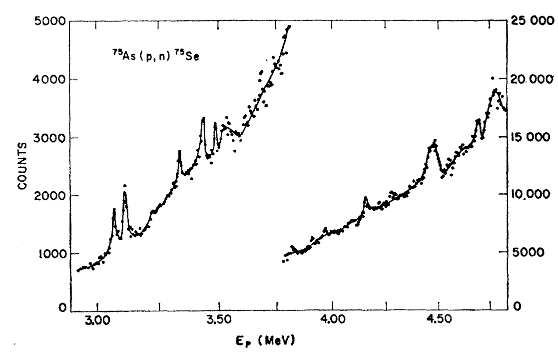


FIG. 5. Neutron excitation curve for the $^{75}As(p,n)^{75}Se$ reaction. Ordinates read as in Fig. 1.

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TABLE I. Resonances observed in the $(p,n)$ excitation curves and comparison with results from $(d,p)$ experiments and from other $(p,n)$ experiments. Parentheses indicate a weak resonance.

| Target | Present work $E_p$ (MeV) | Present work $E_{\text{C.M.}}$ (MeV) | Present work Γ (keV) | Levels from other $(p,n)$ studies $E$ (MeV) | Levels from other $(p,n)$ studies Γ (keV) | Levels from other $(p,n)$ studies Ref. | Levels from $(d,p)$ studies $E$ (MeV) | Levels from $(d,p)$ studies Ref. |
|---|---|---|---|---|---|---|---|---|
| $^{65}$Cu | | | | | | | 0 | 9 |
| | 2.506 | 2.450+0.018 | | | | | | |
| | 2.523 | 2.450+0.035 | | | | | | |
| | 2.569[a] | 2.450+0.080[a] | 30[a] | | | | | |
| | 2.627 | 2.450+0.137 | 15 | | | | | |
| | | | | | | | 0.183 | 9 |
| | 2.707[a] | 2.450+0.216[a] | 30[a] | | | | | |
| | 2.769 | 2.450+0.277 | 12 | | | | 0.272 | 9 |
| | 2.814 | 2.450+0.321 | 17 | | | | | |
| | 2.874 | 2.450+0.380 | 18 | 0.383 | 20 | 23 | 0.383 | 9 |
| | 2.959 | 2.450+0.464 | 22 | 0.467 | 26 | 23 | 0.462 | 9 |
| | 3.035 | 2.450+0.539 | 25 | | | | | |
| | | | | | | | 0.589 | 9 |
| | | | | | | | 0.724 | 9 |
| | (3.318) | (2.450+0.818) | | | | | | |
| | 3.342 | 2.450+0.841 | 19 | 0.835 | 21 | 23 | 0.819 | 9 |
| | 3.418 | 2.450+0.916 | 14 | | | | | |
| | 3.450 | 2.450+0.948 | 17 | | | | | |
| | 3.528 | 2.450+1.025 | 14 | 1.031 | 16 | 23 | 1.015 | 9 |
| | | | | 1.058 | | 23 | 1.051 | 9 |
| | 3.681 | 2.450+1.175 | | | | | 1.152 | 9 |
| | 3.732[a] | 2.450+1.225[a] | 39[a] | 1.227 | | 23 | 1.209 | 9 |
| | 3.782 | 2.450+1.275 | | | | | 1.247 | 9 |
| | 3.819 | 2.450+1.311 | 13 | | | | | |
| | 3.846 | 2.450+1.338 | 15 | | | | 1.339 | 9 |
| $^{70}$Zn | 3.797 | 3.744 | 21 | | | | 0 | 10 |
| | | | | | | | 0.16 | 10 |
| | 4.092 | 3.744+0.290 | 23 | | | | 0.28 | 10 |
| | 4.277 | 3.744+0.473 | 34 | | | | 0.47 | 10 |
| | 4.470 | 3.744+0.663 | 24 | | | | 0.66 | 10 |
| | 4.669 | 3.744+0.859 | 23 | | | | 0.85 | 10 |
| $^{74}$Ge | 3.586 | 3.538 | 24 | | | | 0 | 13 |
| | | | | | | | 0.042 | 13 |
| | 3.787 | 3.538+0.198 | 40 | | | | 0.195 | 13 |
| | 3.828 | 3.538+0.241 | 22 | | | | 0.241 | 13 |
| | | | | | | | 0.306 | 13 |
| | 4.153 | 3.538+0.560 | 17 | 0.559 | 25 | 24 | 0.573 | 13 |
| | 4.183 | 3.583+0.589 | 15 | 0.587 | 23 | 24 | | |
| | (4.246) | (3.538+0.651) | | 0.652 | | 24 | 0.665 | 13 |
| | 4.279 | 3.538+0.684 | 21 | 0.679 | 17 | 24 | | |
| | 4.492 | 3.538+0.894 | 17 | 0.887 | 19 | 24 | 0.865 | 13 |
| | (4.551) | (3.538+0.952) | | | | | | |
| | (4.694) | (3.538+1.093) | 16 | | | | | |
| | (4.719) | (3.538+1.118) | 22 | 1.131 | 32 | 24 | | |
| | 4.743 | 3.538+1.142 | 16 | | | | | |
| | 5.012 | 3.538+1.407 | 23 | 1.386 | 38 | 24 | | |
| | 5.055 | 3.538+1.450 | 47 | 1.432 | 29 | 24 | | |
| | | | | 1.483 | | 24 | | |
| | 5.130 | 3.538+1.514 | 36 | 1.511 | | 24 | | |
| | 5.289 | 3.538+1.689 | 34 | 1.669 | 38 | 24 | | |
| $^{76}$Ge | 4.129 | 3.916+0.159 | 20 | 0.159 | 30 | 23 | 0.159 | 13 |
| | | | | | | | 0.229 | 13 |
| | 4.486 | 3.916+0.512 | 17 | 0.506 | 26 | 23 | 0.495 | 13 |
| | 4.606 | 3.916+0.630 | 24 | 0.622 | 27 | 23 | 0.621 | 13 |
| | 4.873 | 3.916+0.894 | 19 | 0.884 | 26 | 23 | 0.869 | 13 |
| | 4.990 | 3.916+1.009 | 20 | 1.005 | 42 | 23 | 1.004 | 13 |
| | 5.156 | 3.916+1.173 | 77 | 1.185 | 80 | 23 | 1.219 | 13 |
| | 5.315 | 3.916+1.330 | 50 | 1.332 | 56 | 23 | | |
| $^{75}$As | 3.066 | 3.026 | 17 | 0 | 11 | 16 | | |
| | 3.109 | 3.026+0.042 | 21 | 0.041 | 11 | 16 | | |
| | (3.219) | (3.026+0.151) | 23 | | | | | |
| | (3.243) | (3.026+0.174) | | | | | | |
| | 3.331 | 3.026+0.261 | 14 | | | | | |
| | 3.427 | 3.026+0.356 | 20 | | | | | |
| | 3.482 | 3.026+0.410 | 16 | | | | | |
| | 4.144 | 3.026+1.063 | 19 | | | | | |
| | 4.456[a] | 3.026+1.371[a] | 54[a] | 1.39 | | 17 | | |
| | 4.676 | 3.026+1.588 | 24 | 1.50 | | 17 | | |
| $^{80}$Se | 3.827 | 3.780 | 16 | | | | 0 | 20 |
| | 3.934 | 3.780+0.105 | | | | | 0.103 | 20 |
| | | | | | | | 0.294 | 20 |
| | 4.302 | 3.780+0.469 | | | | | 0.469 | 20 |

[a] Resonance may consist of two or more unresolved states.

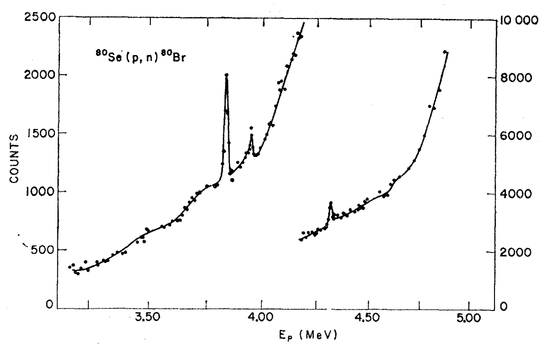


FIG. 6. Neutron excitation curve for the $^{80}$Se$(p,n)^{80}$Br reaction. Ordinates read as in Fig. 1.

In the case of As, where no results from $(d,p)$ experiments are available and little is known about the level scheme of $^{76}$As, the resonances are simply listed without further comment.

### $^{65}$Cu

The excitation curve for $^{65}$Cu is very complex. The first resonances are weak and do not correspond to levels observed in the $(d,p)$ study[9] of this isotope. It is thus unlikely they are isobaric analogs of levels in $^{66}$Cu. These resonances illustrate a common problem in the identification of analog states. Clearly all resonances observed are not analog states, although it is very probable that the strong ones can be explained by this mechanism. The converse is certainly not true. Analog resonances corresponding to higher orbital angular momentum transfer are strongly attenuated by penetrability effects and are indistinguishable from resonances in the compound system. For these weak resonances supporting evidence is clearly desirable before labeling them as analog states. At higher energies, a number of very strong resonances appear. The identification of isobaric analog states was made by matching the strong resonances with levels seen in the $(d,p)$ experiment. Since the agreement between the strong resonances and levels seen in $(d,p)$ work is very good, the extracted Coulomb displacement energy should be quite reliable.

### $^{70}$Zn

The excitation function shows a number of strong resonances. The resonance at 3.797 MeV was assumed to be the analog of the ground state of $^{71}$Zn. [This resonance was expected to be rather prominent, since it is formed by $l=1$ protons and is well above the $(p,n)$ threshold.] With this assignment, the subsequent level spacings are in excellent agreement with states observed in a $^{70}$Zn$(d,p)^{71}$Zn experiment.[10] No state was observed which corresponded to the first excited state of $^{71}$Zn; this is consistent with the orbital angular momentum transfer of 4, determined in the $(d,p)$ experiment. The Coulomb displacement energy calculated from this level assignment agrees with previous general results for Zn obtained from charge-exchange scattering.[11]

### $^{74}$Ge

The $^{74}$Ge excitation curve displayed strong resonances in the region above 4 MeV. The resonance that is assumed to be the ground-state analog was observed weakly at 3.586 MeV. The diminished strength of this state can perhaps be attributed to a low neutron penetrability. [This state is only about 200 keV above the $(p,n)$ threshold, and decays to the ground state of $^{74}$As by emitting $l=2$ neutrons.[12]] The agreement between this work and an independent $(d,p)$ experiment[13] is very good. The doublets at 4.153, 4.183 MeV, and 4.246, 4.279 MeV were not resolved in the $(d,p)$ work.

### $^{76}$Ge

The ground-state analog was not observed in the $^{76}$Ge$(p,n)$ excitation curve. This state was not seen in a $^{76}$Ge$(d,p)^{77}$Ge experiment[13] either. The shell model predicts a spin of $(\frac{7}{2}+)$ for this state. Since an $l=4$ proton is thus required to form this analog state, one would not expect to see the state in this experiment. The first strong resonance observed was assumed to be the analog of the first excited (159-keV) state in $^{77}$Ge. The strength of this resonance is consistent with the $(\frac{1}{2}-)$ spin assignment[14] for this state. Using this assumption, there is a close correspondence between the resonances observed and states of $^{77}$Ge determined from the $(d,p)$ measurements. Preliminary analysis of elastic scattering data[15] on Ge$^{76}$ yields results in good agreement with the present work. The Coulomb displacement energies determined for the two Ge isotopes are consistent with the value quoted by Anderson *et al.*[11]

### $^{75}$As

The first doublet observed in the $^{75}$As excitation curve presumably corresponds to the ground and first excited states of $^{76}$As. This same doublet, with a separation of about 40 keV, has been observed by other investigators.[16,17] The strong resonances seen in this

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work do not conform to level schemes proposed for $^{76}$As from the study of $\gamma$-ray spectra, obtained in the $^{75}$As$(n,\gamma)^{76}$As reaction.[18] However, the Coulomb displacement energy, derived from our ground-state assignment is in excellent agreement with the value reported by Anderson *et al.*[19]

### $^{80}$Se

The data for $^{80}$Se showed well-isolated resonances. The analog of the $^{81}$Se ground state is formed by $l=1$ proton capture. The first strong resonance observed was assumed to correspond to this state. It is somewhat surprising that we see the analog of the first excited (103-keV) state in $^{81}$Se, which is supposedly formed by $l=4$ proton capture. This is especially interesting since we do not observe the analog of the 294-keV state in $^{81}$Se, which is much more strongly populated by the $(d,p)$ reaction,[20] and which is also given an $l=4$ assignment. Otherwise there is good agreement with the $^{81}$Se level scheme derived from the $(d,p)$ experiment.[20] The Coulomb displacement energy falls within the experimental error of the value reported by Anderson *et al.*[19]

### General Comments

Coulomb displacement energies are listed in Table II. The first column is a summary of the displacement energies determined in the present work, using the

TABLE II. Coulomb displacement energies. $\Delta E_c$ (exp) is the displacement energy determined in the present work, while $\Delta E_c$ (calc) is the result predicted from Eq. (1). The uniform radius parameter $r_0$ is calculated from $\Delta E_c$ (exp).

| | $\Delta E_c$(exp) (MeV) | $\Delta E_c$(calc) (MeV) | $r_0$(exp) ($F$) |
|---|---|---|---|
| $^{66}$Zn$-^{66}$Cu | 9.51±0.02 | 9.36 | 1.267±0.003 |
| $^{71}$Ga$-^{71}$Zn | 9.78±0.05 | 9.46 | 1.222±0.007 |
| $^{75}$As$-^{75}$Ge | 10.02±0.02 | 9.95 | 1.252±0.003 |
| $^{76}$Se$-^{76}$As | 10.35±0.02 | 10.25 | 1.265±0.003 |
| $^{77}$As$-^{77}$Ge | 9.95±0.05 | 9.86 | 1.250±0.007 |
| $^{81}$Br$-^{81}$Se | 10.49±0.02 | 10.35 | 1.240±0.002 |

nuclear-mass data of Mattauch *et al.*[21] The indicated errors include both our experimental errors and uncertainties in the nuclear-mass differences.

The second column lists the energies calculated from the semiempirical formula[8]

$$\Delta E_c(\text{calc}) = -1.032 + 1.448(Z/A^{1/3}), \qquad (1)$$

which is a least-squares fit of most previous data to a form linear in $Z/A^{1/3}$. The last column shows the values of the uniform radius parameter $r_0$ obtained by using the values in column 1 in the expression[22]

$$\Delta E_c(Z+1, Z) = \{0.60(2Z+1) - 0.613Z^{1/3} - (-1)^Z 0.30\} e^2/r_0 A^{1/3}. \qquad (2)$$

It is interesting to note that our experimental displacement energies are all somewhat higher than the calculated values.

We also studied neutron excitation curves of $^{69}$Ga, $^{79}$Br, and $^{81}$Br. A number of distinct resonances (some of which are certainly analog states) were observed in each of these isotopes. Unfortunately, there is little information available about the excited states of $^{70}$Ga, $^{80}$Br, and $^{82}$Br; it was thus not possible to identify any of these resonances as a particular analog state. As a consequence, Coulomb displacement energies could not be extracted. More independent experimental evidence [e.g., $(d,p)$ studies] is necessary before these data can be interpreted.

After the completion of the present experimental work, studies of the $^{65}$Cu, $^{74}$Ge, and $^{76}$Ge$(p,n)$ reaction were published.[23,24] Our agreement with this work is generally very good. A few weak states not reported in Refs. 23 and 24 were seen in the present experiment; most noteworthy are the analogs of the ground state, the 195-keV state, and the 241-keV state of $^{75}$Ge. The coulomb energies determined in each case are in excellent agreement.

### ACKNOWLEDGMENTS

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