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Angular correlation measurements over the intermediate structure in ^{71}As

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Angular correlations in the ^{70}Ge$(p,p'\gamma)^{70}$Ge reaction have been measured for two of the five substructures nested in the reported $1/2^+$ intermediate structure in ^{71}As centered at $E_p = 5.05$ MeV. The spins of both substructures were determined as being 5/2 or greater casting doubt on the interpretation of this cluster of states as an example of intermediate structure.

[NUCLEAR REACTIONS ^{70}Ge$(p,p'\gamma)^{70}$Ge, $E=4.95$ to 5.19 MeV. Deduced spins of resonances at $E=5.04$ and 5.14 MeV. Enriched target.]

I. INTRODUCTION

One of the more interesting phenomena observed in nuclear resonance studies is the presence of simple modes of excitations of the nucleus leading to structures with widths intermediate between those for the compound-nucleus states and those for single-particle states.[1,2] The cleanest example of intermediate structure in the energy dependence of the cross section is that of isobaric analog resonances. Intermediate structures have been observed in capture-γ-ray and photonuclear reactions, heavy-ion collisions, and in fission. Only a few examples of intermediate structure other than analog states have been observed in the elastic and inelastic scattering of protons. Among these are the $2p$-$1h$ doorway state in ^{41}Sc reported by Mittig, Cassagnou, Cindro, Papineau, and Seth[3] and various width structures observed in the polarized proton scattering from ^{26}Mg and ^{27}Al by Glashausser, Robbins, Ventura, Baker, Eng, and Kaita.[4]

In 1971, Temmer, Maruyama, Mingay, Petrascu, and Van Bree[5] reported evidence for a new type of intermediate structure, theretofore unobserved in charged particle reaction channels. They reported the appearance of five substructures contained within a $J^\pi = \frac{1}{2}^+$ analog resonance in ^{71}As observed in elastic and inelastic scattering of protons on ^{70}Ge. The width of the analog resonance was about 63 keV and that of the five substructures on the order of 20 keV. Four of the five substructures had $l=0$ signatures in the elastic channel; no angular momentum transfer or J value was reported for the fifth substructure. In addition, the substructures were correlated in several proton inelastic decay channels. For this energy region in ^{71}As, the ultimate fine structure of $J^\pi = \frac{1}{2}^+$ states was estimated to have a level density of about 3/keV and a level width of about 20 eV. From this they concluded that the substructures encompass about 70 individual fine-structure states. Hence, the experiment showed the existence of some form of substructure having widths between the ultimate fine structure and that of the intermediate structure of the analog resonance. No theoretical explanation of this substructure has yet been reported. The elastic and inelastic excitation curves measured over the region of the $\frac{1}{2}^+$ analog resonance at $E_p = 5.05$ MeV are shown in Fig. 1. Arrows on the figure indicate the position of the 5 substructures noted by Temmer *et al.*

It was the decay channel to the first 2^+ state in ^{70}Ge which initially caught our interest. Two of the substructures observed as $l=0$, $J^\pi = \frac{1}{2}^+$, resonances in the elastic channel had appreciable strength in the inelastic decay channel to the 2^+ first-excited state in ^{70}Ge. These structures were at $E_p = 5.05$ and 5.14 MeV. In all of our previous studies of the spins of resonant states using the Goldfarb-Seyler[6] particle-γ-ray angular correlation technique,[7] we had not observed any appreciable spin-$\frac{1}{2}^+$ resonance decay strength through the 2^+ decay channel in (p,p') reactions. Presumably this is due to penetrability effects since the lowest l value available for $\frac{1}{2}^+$ resonant decay to the 2^+ excited state is $l=2$. Consequently, we performed a number of ^{70}Ge$(p,p'\gamma)^{70}$Ge angular correlation measurements in the Goldfarb-Seyler geometry over the energy region of these two resonances. The results of our measurements indicated that in fact the spins of these two structures were $\frac{5}{2}$ or greater and not $\frac{1}{2}$. However, the inelastic proton yield was small and our statistics rather large so that we did not wish to report such potentially interesting results without further corroboration. We then performed analyzing

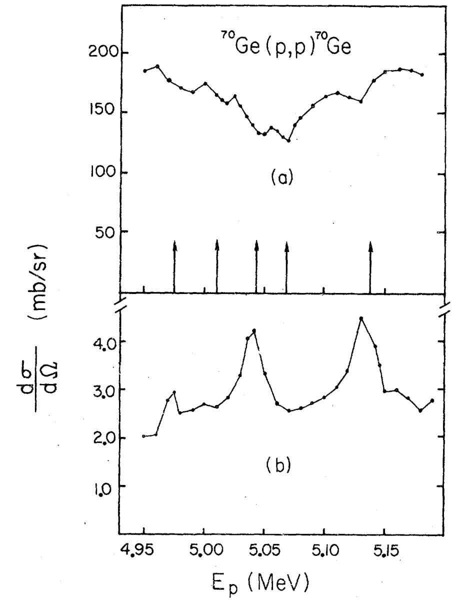

FIG. 1. Elastic and inelastic yield curves over the intermediate structure near $E_p = 5.05$ MeV measured at $\theta_p = 90°$. (a) The ^{70}Ge$(p,p_0)^{70}$Ge elastic yield curve. (b) The ^{70}Ge$(p,p_1')^{70}$Ge yield curve to the first excited 2^+ state in ^{70}Ge at 1.04 MeV. The solid lines through the data points are not a fit to the data but serve merely to guide the eye. The arrows point to the positions of the five substructures in the vicinity of the $\frac{1}{2}^+$ analog resonance at $E_p = 5.05$ MeV.

power measurements in the elastic channel, with the polarized proton beam from the Ohio State University Van de Graaff accelerator, over the energy region of the structure in ^{71}As at 5.05 MeV in order to verify the results of the angular correlation measurements. The results of the analyzing power measurements have been reported elsewhere,[8] and indeed support the correlation results. This paper reports on the angular correlation measurements in the inelastic proton decay channel to the first-excited 2^+ state in ^{70}Ge at 1.04 MeV.

II. EXPERIMENTAL PROCEDURE AND RESULTS

The targets were prepared from germanium enriched in ^{70}Ge to 98.8%. The ^{70}GeO$_2$ was evaporated on thin carbon backings and target thicknesses were typically ~3 keV. Scattered protons were detected at 90° (cm) to the incident beam direction and the decay γ rays were detected by two 10.2×12.7 cm NaI(Tl) detectors which moved independently in a plane perpendicular to the reaction plane. In actual practice, the proton detector was mounted vertically and the γ-ray detectors moved in the horizontal plane. Conventional fast-slow coincidence electronics, allowing pileup rejection for both γ detectors and the proton detector, were used to gate the linear γ signals. An on-line IBM-1800 computer was used to collect a real-plus-accidental and accidental spectrum for each γ-ray detector. Channel-by-channel subtraction of the two spectra then allowed corrections for the accidental events.

Angular correlations were measured in the Goldfarb-Seyler geometry in which the γ-ray detectors move on the surface of a cone about the proton-detector direction. We chose an angular correlation geometry with a cone angle of 90°. If the axis of quantization $\hat{z}$ is taken along the momentum direction of the outgoing particle, the angular correlation function between these particles and the corresponding decay γ rays (measured in a plane perpendicular to $\hat{z}$) is given by

$$W(\theta_\gamma = \tfrac{1}{2}\pi, \phi_\gamma) = \sum_{\substack{K=0\\K=\text{even}}}^{K_{\max}} A_K \cos(K\phi_\gamma)\,,$$

where

$$K_{\max} \leq \min[2j_c, 2L_{\max}, 2(l_1)_{\max}, (2j_b - 1)_{\max}]\,,$$

the angle ϕ_γ is measured such that the x axis lies in the reaction plane, j_c is the spin of the γ-emitting state, l_1 is the orbital angular momentum of the incident particle, $L_{\max}$ is the multipolarity of the emitted γ ray, and j_b is the spin of the resonant state of interest. For the resonant decay to the first-excited 2^+ state in ^{70}Ge, $j_c = 2$, $L_{\max} = 2$, and l_1 is a unique value for scattering on a 0^+ target nucleus. The relationship between the correlation complexity ($K_{\max}$) and the spin of the resonance is shown in Table I.

Since the Goldfarb-Seyler formalism is strictly valid only for an isolated resonance, it is important to obtain the behavior of the correlation coefficients off resonance as a function of energy to avoid erroneous assignments due to contribution from the tails of nearby states. Hence, angular correlations were measured at 20 energies over the region of interest of the two most prominent peaks centered at $E_p = 5.05$ and 5.14 MeV in the inelastic proton decay channel. Five angular correlations, measured across the resonance at $E_p = 5.05$ MeV, are shown in Fig. 2. The correlation data were then fitted by means of a least-squares program to determine the coefficients A_K. Determining the value of the resonating coefficient with the largest K permitted placing a lower limit on the spin of the resonant state.

The extracted angular correlation coefficients, over the energy region of interest, are shown in Fig. 3. In both the A_0 and A_2 coefficients there was

TABLE I. Correspondence between correlation complexity and the spin of the resonant state.

$K_{\max}$	j_b
0	$\frac{1}{2}$
2	$\frac{3}{2}$
4	$\geq\frac{5}{2}$

a slowly varying contribution as a function of energy which was presumably due to contributions from the large number of compound nuclear states. The A_4 coefficients showed no such background contribution and had a zero value off resonance. The values plotted in Fig. 3 have this slowly varying background component subtracted from the A_0 and A_2 coefficients. All three of the coefficients resonated as the energy was varied over the region of the two states at 5.05 and 5.14 MeV. Because of time limitation, angular correlations were not measured over the other prominent resonance in the inelastic proton decay channel at $E_p = 4.97$ MeV due to its small cross section.

According to Table I, the fact that the A_4 correlation coefficient resonated over both states at $E_p = 5.05$ and 5.14 MeV indicated that the spins of both states were $\geq\frac{5}{2}$. If the spins of these two states had been $\frac{1}{2}$, then neither the A_2 nor A_4 coefficient would have shown resonant behavior. The solid curves in the figure were calculated using the formalism of Ref. 7. The fit to the energy dependence of the correlation coefficients was obtained using a pure $S_{1/2}$ proton decay to the 2^+ excited state in ^{70}Ge. No other l_j decay fit the data. The inelastic decay width in this channel was 25% of the total width. The results of the angular correlation measurements, together with the results of the analyzing power measurements of Ref. 8, are summarized in Table II.

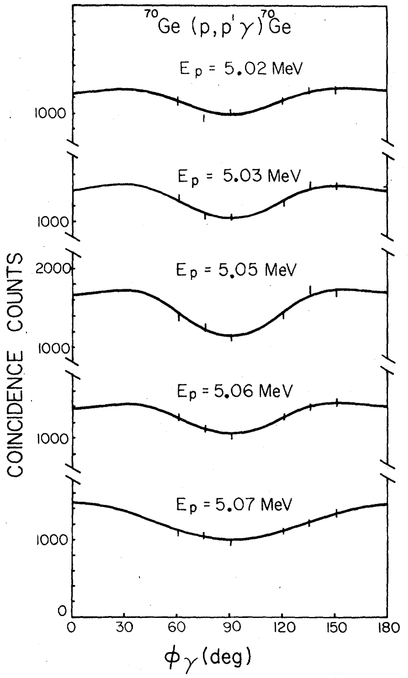

FIG. 2. The ^{70}Ge($p,p'\gamma$)^{70}Ge angular correlations measured at five energies over the $E_p = 5.04$ MeV resonance in ^{71}As. The solid curves are least-square fits to the corrected angular correlation data.

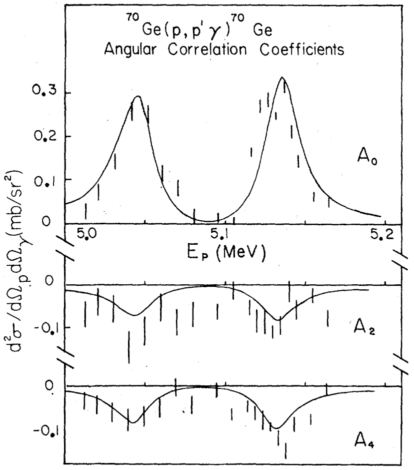

FIG. 3. Angular correlation coefficients extracted from the ^{70}Ge($p,p'\gamma$)^{70}Ge reaction over the $E_p = 5.04$ and 5.14 MeV substructures. The solid curves are fits to the energy dependence of the angular correlation coefficients. A slowly varying background of approximately 50% of the total A_0 and A_2 coefficients was subtracted prior to the fit.

III. DISCUSSION

As seen in Table II, the results of the analyzing power measurements in the elastic channel are in agreement with the spin assignments determined from the angular correlation measurements. From these combined results we conclude that three of the five substructures in the vicinity of the broad $\frac{1}{2}^+$ analog resonance centered at $E_p = 5.05$ MeV have spins other than $\frac{1}{2}$.

In trying to assess the nature of these unusual substructures, it is informative to attempt to associate the various resonances studied with possible parent states in ^{71}Ge. The excitation energies of the possible parent states in ^{71}Ge, assuming all the resonances were analog states, have been calculated using a Coulomb displace-

TABLE II. Parameters for the resonances near the large $l=0$ state at 5.052 MeV.

E_p (MeV) [c]	Γ (keV) [a]	Γ_p (keV) [a]	$\Gamma_{p'}(p_1)$ (keV) [b]	J $(p,p'\gamma)$ [b]	J^π [a]
4.974	18	1.0	···	···	$\frac{3}{2}^-$
5.010	17	1.4	···	···	$\frac{1}{2}^+$
5.044	25	0.8	4.4	$\geq\frac{5}{2}$	$\frac{5}{2}^+$
5.052	63	21.0	···	···	$\frac{1}{2}^+$
5.068	28	1.1	···	···	$\frac{1}{2}^+$
5.138	21	2.1	4.2	$\geq\frac{5}{2}$	$\frac{5}{2}^+$

[a] Reference 8.
[b] Present work.
[c] Laboratory bombarding energy, ±10 keV.

TABLE III. Comparison of the ^{71}As resonances with parent states in ^{71}Ge.

Present work			^{70}Ge$(d,p)^{71}$Ge	
Resonance energy E_p (MeV)	J^π	Ex (parent) (MeV) [a]	Ex[b]	ln[b]
4.974	$\frac{3}{2}^-$	2.142	2.12	(3)
5.010	$\frac{1}{2}^+$	2.178	2.17	···[c]
5.044	$\frac{5}{2}^+$	2.212	···[d]	···[d]
5.052	$\frac{1}{2}^+$	2.220	2.22	0
5.068	$\frac{1}{2}^+$	2.226	···[d]	···[d]
5.138	$\frac{5}{2}^+$	2.306	2.27	2

[a] Calculated using $\Delta E_c = 10.176$ MeV.
[b] Reference 9.
[c] Not determined.
[d] Not observed.

ment energy of 10.176 MeV. The results of this calculation are shown in Table III. The $\frac{5}{2}^+$ resonance at 5.138 appears to be the analog of the $l_n=2$ parent state observed in the ^{70}Ge$(d,p)^{71}$Ge reaction at 2.27 MeV excitation energy[9]; the $\frac{3}{2}^-$ resonance at 4.97 MeV is a possible candidate for the analog of the state at 2.12 MeV excitation in ^{71}Ge which had a tentative $l_n=3$ assignment from the (d,p) measurement. The parent state of the $\frac{5}{2}^+$ resonance at 5.044 MeV is probably obscured in the (d,p) experiment by the intense $l_n=0$ state at 2.22 MeV excitation. The results of this exercise seem to indicate that only the 5.138 MeV state and the 5.052 MeV $\frac{1}{2}^+$ state can definitely be assigned as being analogs of known parent states in ^{71}Ge.

We should point out that one of the five substructures reported by Temmer *et al.*, at an energy of 5.138 MeV, was not assigned by that group as a $\frac{1}{2}^+$ resonance. In fact, it was given no assignment at all even though its shape in the reported elastic yield curve was similar to other substructures assigned as $\frac{1}{2}^+$. Consistent with our findings that the spin of this resonance is $\frac{5}{2}^+$ are the results of Baudinet-Robinet and Mahaux,[10] who applied statistical criteria to unpublished high resolution ^{70}Ge$+p$ elastic scattering cross section data and determined that the spin of the 5.138 MeV substructure was other than $\frac{1}{2}^+$ although they were unable to assign a spin. However, they noted significant nonrandom $\frac{1}{2}^+$ structures at 4.97, 5.04, and 5.06 MeV, respectively. Presumably these structures were the resonances we observed at 4.97, 5.05, and 5.06 MeV, although we assigned the 4.97 MeV state as $\frac{3}{2}^-$ from the analyzing power measurements.

Where then do we stand in our understanding of this most unusual structure? Even if we assume that the $\frac{5}{2}^+$ state at 5.138 MeV is not a member of the intermediate structure but rather the analog of a parent state in ^{71}Ge, two of the remaining four substructures have spins other than $\frac{1}{2}$ and hence are also not members of the intermediate structure. That leaves two remaining substructures at 5.01 and 5.06 MeV as still having the $\frac{1}{2}^+$ spin of the broad doorway state at $E_p=5.05$ MeV. Certainly the most unusual characteristic of the originally reported structure is the fact that the widths of the substructures are intermediate between those of the ultimate fine structure and that of the analog resonance at $E_p=5.05$ MeV. However, the widths of the $\frac{5}{2}^+$ analog resonance at 5.138 MeV and those of the $\frac{3}{2}^-$ and $\frac{5}{2}^+$ resonance at 4.974 and 5.044 MeV are comparable with the widths of the remaining $\frac{1}{2}^+$ substructures at 5.01 and 5.06 MeV. It is possible, of course, that the original interpretation of this unusual structure as a new form of intermediate structure is incorrect. In this region of the periodic table between major closed shells, level structures are quite complicated and it may not be unreasonable for the remaining two $\frac{1}{2}^+$ substructures in ^{71}As to be analogs of parent states in ^{71}Ge, such as core-excited states, which are only weakly excited in a (d,p) reaction.

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[1] B. Block and H. Feshbach, Ann. Phys. (N. Y.) 23, 47 (1963).

[2] A. K. Kerman, L. S. Rodberg, and J. E. Young, Phys. Rev. Lett. 11, 422 (1963).

[3] W. Mittig, Y. Cassagnou, N. Cindro, L. Papineau, and K. K. Seth, Nucl. Phys. A231, 316 (1974).

[4] C. Glashausser, A. B. Robbins, E. Ventura, F. T. Baker, J. Eng, and R. Kaita, Phys. Rev. Lett. 35, 494 (1975).

[5] G. M. Temmer, M. Maruyama, D. W. Mingay, M. Petrascu, and R. Van Bree, Phys. Rev. Lett. 26, 1341 (1971).

[6] L. J. B. Goldfarb and R. G. Seyler, Phys. Lett. 28B, 164 (1967).

[7] N. Tsoupas, H. J. Hausman, N. L. Gearhart, and G. H. Terry, Phys. Rev. C 13, 510 (1976).

[8] G. H. Terry, H. J. Hausman, T. R. Donoghue, H. R. Suiter, and P. H. Wallace, Phys. Rev. Lett. 41, 934 (1978).

[9] L. H. Goldman, Phys. Rev. 165, 1203 (1968).

[10] Y. Baudinet-Robinet and C. Mahaux, Phys. Rev. C 9, 723 (1974).