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Distribution of 0^+ strength in Ge(t,p) reactions

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We have measured the A dependence of absolute Ge(t,p) cross sections using a natural Ge target and an enriched ^{74}Ge target of known composition.

The structure of nuclei in the $N=40$ region is still a rather puzzling matter. Several discontinuities observed in the structure of the low-lying states of nuclei in this mass region [i.e., Ga, Ge, and Se (Ref. 1)] as well as other results from one nucleon transfer reactions[1] have been interpreted as possibly indicating that nuclei in this region undergo a shape transition from oblate to prolate deformation with increasing neutron number. Vergnes *et al.*[2] have recently suggested further evidence for such a shape transition based on the variation of the ratio $R=\sigma(0_2^+)/(0_{\text{g.s.}}^+)$ for both the (t,p) and (p,t) reactions on the even Ge isotopes. An abrupt maximum in this ratio was found at $N=42$ in the (t,p) and $N=40$ in the (p,t) data. These effects are similar to those observed in the known transition regions and were interpreted as indicating that the structural transition in Ge and in Ga isotopes occurs between $N=40$ and $N=42$.

In order to look for further information on the structure of nuclei in this region, we have studied[3–6] the (t,p) reaction at 15 MeV on all the stable Ge isotopes using the multiangle spectrograph at the University of Pennsylvania tandem accelerator. Such a two-nucleon transfer reaction is an extremely useful probe for examining the details of nuclear structure and in observing transitional features. This sensitivity has been demonstrated in the region of Sm isotopes[7] and near $A=100$.[8] The usefulness of the (t,p) reaction for these purposes is increased when the study is carried out over a series of isotopes and the trend of particular states may be observed. In addition, the (t,p) reaction yields valuable information on the overlapping between the ground states and excited 0^+ states.

TABLE I. Composition of the Ge targets.

	Isotopic abundance (%)	
Isotope	"Natural" target	"^{74}Ge" target
^{70}Ge	20.7	1.71
^{72}Ge	27.5	2.21
^{73}Ge	7.7	0.9
^{74}Ge	36.4	94.48
^{76}Ge	7.7	0.7

Relative 0^+ cross sections for each even Ge isotope, as well as approximate absolute g.s.→g.s. (t,p) cross sections, are tabulated in Refs. 3–6. In order to more accurately determine the relative g.s. cross sections, we repeated the experiment with a natural Ge target. We also present results for three different Ge nuclei obtained from the "^{74}Ge" target. Isotopic compositions of these two targets were provided by the supplier and are listed in Table I.

Spectra for these two targets are displayed in Fig. 1. Yields were extracted at three forward angles and converted to absolute cross sections, using the stated abundances and target thickness obtained from elastic-scattering mea-

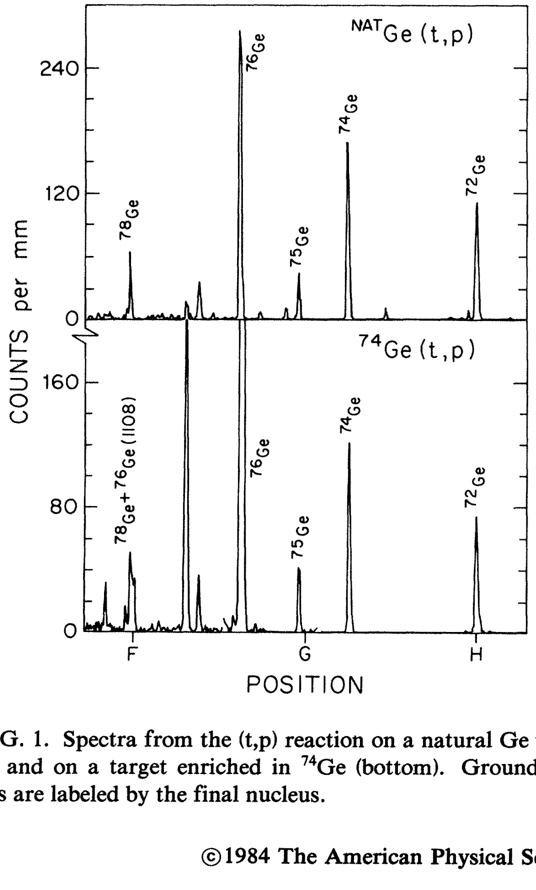

FIG. 1. Spectra from the (t,p) reaction on a natural Ge target (top) and on a target enriched in ^{74}Ge (bottom). Ground-state peaks are labeled by the final nucleus.

TABLE II. Absolute cross sections for g.s. (t,p) reactions on Ge isotopes.

Target nucleus	$\theta_{\text{c.m.}}$ (deg)	$\sigma_{\text{c.m.}}$ (mb/sr) "Natural" target	"^{74}Ge" target
70	4.1	4.16 ± 0.16	3.54 ± 0.17
	11.5	1.55 ± 0.09	1.37 ± 0.10
	19.1	0.18 ± 0.03	
72	4.1	3.88 ± 0.13	3.70 ± 0.15
	11.5	1.48 ± 0.07	1.32 ± 0.08
	19.1	0.17 ± 0.03	
74	4.1	4.83 ± 0.12	4.34 ± 0.02
	11.5	1.68 ± 0.07	1.64 ± 0.01
	19.1	0.12 ± 0.02	
76	4.1	4.17 ± 0.24	
	11.5	1.56 ± 0.14	
	19.1	0.22 ± 0.05	
73[a]	4.1	2.94 ± 0.18	
	11.5	1.02 ± 0.10	

[a] For the $\frac{9}{2}^+$ state in ^{75}Ge at $E_x=200$ keV.

surements. These are listed in Table II.

Results from the two targets agree as well as one might expect from elastic-scattering target thickness determinations. Relative cross sections as a function of isotope exhibit a similar trend for both targets, but there appears to be a systematic difference of a few percent between results from the two targets.

TABLE III. Average g.s.→g.s. Ge(t,p) cross sections at $\theta_{\text{c.m.}}=4.1°$.

Target nucleus	$\sigma_{\text{c.m.}}$ (mb/sr)
^{70}Ge	3.85 ± 0.10
^{72}Ge	3.79 ± 0.10
^{74}Ge	4.58 ± 0.10
^{76}Ge	4.17 ± 0.24

For the purposes of the present paper, we have averaged the results for the two targets. These results are listed in Table III, and the resulting cross sections for all excited 0^+ levels observed in (t,p) are given in Table IV.

The most conspicuous feature in the strength distribution of the 0^+ states is the dominance of the ground-state transition. Except for the first excited 0^+ state in ^{74}Ge which has about 20% of the $0^+_{\text{g.s}}$ intensity, the transition to the ground state is about two orders of magnitude larger than any other transition to an excited 0^+ state up to 4 MeV excitation. This feature is even more prominent in ^{72,76,78}Ge where the first excited 0^+ state is also extremely weak. This is in strong contrast to the behavior of the (t,p) spectra near shell closures where transitions to excited 0^+ states often are stronger than the transition to the ground state.

TABLE IV. Distributions of 0^+ strength in Ge(t,p) reactions in (μb/sr) at $\theta_{\text{c.m.}}=4.1°$.

70→72 E_x (keV)	70→72 $(d\sigma/d\Omega)_{\max}$	72→74 E_x (keV)	72→74 $(d\sigma/d\Omega)_{\max}$	74→76 E_x (keV)	74→76 $(d\sigma/d\Omega)_{\max}$	76→78 E_x (keV)	76→78 $(d\sigma/d\Omega)_{\max}$
0	3850	0	3790	0	4580	0	4170
688	8						
1709	9	1485	769			1539	168
2029	127	1913	2.8	1911	229		
		2164	16				
		2229	79			(2326)	(39)
2753	97	2610	2.2				
2899	30	2758	20	2901	97		
(3128)	11	3356	75	(3314)	(11)	3350	224
3579	18	3779	59	(3472)	(114)	3667	348
3775	30	3918	41	(3539)	(140)	3898	134
3998	44					4015	359
$\Sigma\sigma(0^+,\text{exc})$	374		1063		591		1272
$\Sigma_{\text{exc}}+\sigma_{\text{g.s.}}$	4224		4853		5171		5442
Centroid σ(exc)	2732 keV		1930 keV		2786 keV		3411 keV
$\Sigma_{\text{exc}}/\sigma_{\text{g.s.}}$	0.097		0.280		0.129		0.305

TABLE V. Comparison of present and previous results for ground states.

	Present[b]			Previous[c]		
A_{final}	Absolute[a] (mb/sr)	Relative	$\sigma_{\text{exp}}/\sigma(g_{9/2})^2$	Absolute[d] (μb)	Relative	$\sigma_{\text{exp}}/\sigma(g_{9/2})^2$
72	3.85	1.0	23	1661	1.0	16
74	3.79	0.98	23	1580	0.95	17
76	4.58	1.19	29	2210	1.33	28
78	4.17	1.08	29			28

[a] Differential cross section at $\theta_{\text{c.m.}}=4.1°$.

[b] Using $\sigma_{\text{exp}}=230\sigma_{\text{DWBA}}$.

[c] References 10 and 11.

[d] Angle-integrated cross section.

We compare our results for the A dependence of g.s. Ge(t,p) cross sections with previous results[10,11] in Table V. Our data are for a bombarding energy of 15 MeV and a c.m. angle of 4.1 deg. Earlier data are angle-integrated cross sections obtained at 17 MeV. We also present in Table V the ratios of experimental to theoretical DWBA cross sections calculated assuming a $(1g_{9/2})^2$ microscopic transfer. This latter comparison is merely an attempt to remove from the A dependence the effects of differences in Q values.

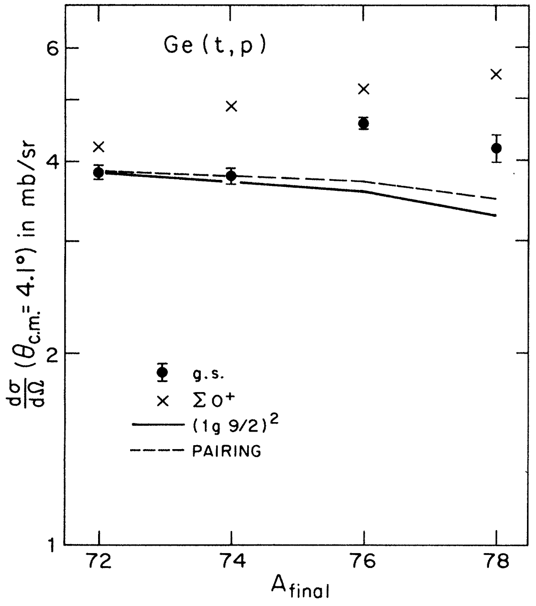

FIG. 2. Absolute g.s.→g.s. (t,p) cross sections (at $\theta_{\text{c.m.}}=4.1°$) on Ge isotopes, plotted vs A of final nucleus. The straight line indicates DWBA cross sections calculated with potentials of Refs. 3–6 and assuming $(1g\frac{9}{2})^2$ transfer, normalized at ^{72}Ge. Dashed line is similar DWBA, but for transfer amplitudes

$$0.992[(2p\tfrac{3}{2})^2/\sqrt{4}+(2p\tfrac{1}{2})^2/\sqrt{2}+(1f\tfrac{5}{2})^2/\sqrt{6}$$
$$-(1g\tfrac{9}{2})^2/\sqrt{10}]\ .$$

It can be noted from the table that our 72/74 ratio agrees with that of the earlier work, as does our 76/78 ratio. However, there is a remarkable discrepancy between the two experiments for the 74/76 ratio. Our 4.1° 76/74 cross-section ratio is 1.21, while the ratio of 17-MeV angle-integrated cross sections is 1.40. The ratio $\sigma_{\text{exp}}/\sigma(g_{9/2})^2$ shows an even larger discrepancy—1.26 compared to 1.65. We know of no reason for this discrepancy, nor does Vergnes.[9] The relative g.s. cross sections obtained with a natural Ge target should have uncertainties of only about 3%. So the difference is way outside that expected on experimental grounds. It is unlikely that the 2 MeV difference in bombarding energy could result in such a dramatic discrepancy for only the 74/76 ratio. It is disturbing that the discrepancy is even greater after correcting for DWBA than in the raw data. The difference in structure between the light and heavy Ge isotopes is less pronounced in our data than in the data of Vergnes *et al.*

The A dependence of the g.s. Ge(t,p) cross sections is plotted in Fig. 2. It is somewhat difficult to ascertain the magnitude of A dependence remaining after correcting for Q value, since Q-value effects in DWBA are different for different configurations of the transferred neutrons. For $(1g_{9/2})^2$ transfer, we get the solid line in Fig. 2, whereas a "pairing" form factor gives the dashed line.

In Table IV, we list the summed excited 0^+ state cross section, its energy centroid, its ratio to the g.s., and the total 0^+ cross section, including that of the g.s.

The summed excited 0^+ strength has a saw-tooth pattern, being large for 72→74 and 76→78, but small for the other two cases. But for the two cases of large cross section, one (^{74}Ge) has the strength centered at quite low E_x, while in the other it is significantly higher. In the two nuclei ^{72}Ge and ^{76}Ge, the centroids are nearly equal and roughly halfway in between those for ^{74}Ge and ^{78}Ge.

The summed 0^+ strength (including the g.s.) increases monotonically from ^{72}Ge to ^{78}Ge, though the heavier two are roughly equal. It is not clear to what extent the variation with A reflects mixing of low-lying 0^+ states that changes with A and/or merely a changing neutron occupation as one goes through the Ge isotopes. Of course, a complete theoretical treatment of these nuclei should certainly account for all these effects.

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