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Alpha-particle transfer to 0^+ states in the germanium nuclei and the role of proton pairing correlations

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Alpha transfer to the ground and first excited 0^+ states of the Ge isotopes has been studied by means of the ^{64,66,68,70}Zn(^{6}Li,d)^{68,70,72,74}Ge reactions at 34-MeV incident energy. The sharp variation in strength between ^{72}Ge and ^{74}Ge is shown to result from a change in the proton structure of these two isotopes as the neutron number changes from $N = 40$ to 42.

[NUCLEAR REACTIONS ^{64,66,68,70}Zn(^{6}Li, d)^{68,70,72,74}Ge, E=34 MeV; measured $\sigma(\theta)$ for 0^+ states, DWBA analysis, deduced S.]

A number of recent reports[1-4] have shown that alpha-particle transfer reactions provide an important method for studying proton and neutron pairing correlations in nuclei. However, most of the results thus far are concerned with nuclei near closed shells where the low-lying states of interest involve primarily either neutron or proton pair excitations. For such states a close correspondence has been found between alpha-transfer and two-nucleon transfer reactions. In this communication, we report some initial results of (^{6}Li,d) experiments leading to the germanium isotopes, which lie in a region between major shell closures, so that both protons and neutrons are expected to be active at low excitation energies.

The Ge isotopes have been the subject of intense experimental and theoretical interest because they appear to exhibit a sharp change in structure in the region of neutron number $N = 40$, and especially between $N = 40$ and 42. Various explanations have been proposed to explain this behavior including a possible shape transition,[5] a neutron subshell closure or sudden changes in the proton orbital configurations that alter the pairing correlations.[6,7] The latter explanation is consistent with one proton transfer data as well as two-neutron pickup and stripping results. However, experimental proton pairing information, which could be expected to play an important role in understanding these nuclei, is largely absent, and in the crucial case of ^{74}Ge is impossible to obtain by two-proton transfer. Thus in addition to exploring the behavior of alpha transfer in nuclei removed from closed shells, a further aim of the present experiment is to study proton pairing correlations specifically in the Ge nuclei, assuming that alpha transfer continues to be a sensitive probe in such cases. The following discussion will focus on the 0^+ states observed in the ^{64,66,68,70}Zn(^{6}Li,d)^{68,70,72,74}Ge reactions.

The experiments were performed with a beam of ^{6}Li ions of 34 MeV incident energy from the Los Alamos Tandem Van de Graaff accelerator. Deuterons produced by reactions in the targets were identified and measured in a Q3D magnetic spectrograph using a one meter long detector in the focal plane. The final energy resolution was about 60 keV and was caused mainly by target thickness effects. Angular distributions are shown in Fig. 1 for the $L = 0$ transitions observed in the (^{6}Li,d) reaction leading to ^{68,70,72,74}Ge. All of the final states indicated in the figure are previously know 0^+ states, and there is reasonable agreement between the experimental angular distributions and distorted-wave Born approximation (DWBA) predictions assuming $L = 0$ and an alpha-cluster form factor. The optical model and bound state parameters used in the calculations are the same as previously employed and are shown in Table I.

Relative spectroscopic strengths were extracted from the quantity $S = [(d\sigma/d\Omega)_{\rm exp}/(d\sigma/d\Omega)_{\rm DW}]$ and are given in Table II along with strengths for transitions to the same final states from the (t,p) and (^{3}He,n) reactions, where available.[8,9] The (^{6}Li,d) and (t,p) strengths[8] for the ground (0_1^+) and first excited (0_2^+) states are illustrated schematically in Fig. 2. The (^{6}Li,d) ground-state strength is seen to be fairly constant for ^{68,70,72}Ge but then drops sharply by about 40% at ^{74}Ge. Conversely, the strength for the 0_2^+ states rises rapidly between ^{70}Ge and ^{74}Ge, reaching a value of 70% of the ground-state strength in ^{74}Ge. This latter behavior of $S(0_2^+)$ is at least partially reflected in the (t,p) data by the sharp rise that occurs between ^{72}Ge and ^{74}Ge. It is noteworthy that the (t,p) ground-state strengths for these two nuclei do not exhibit the same falloff as in (^{6}Li,d), but rather they remain approximately constant. The other 0^+ states are relatively weak in the two reactions except for the 2.75 MeV state in ^{72}Ge which is moderately strong in both, and the 3.63 MeV state in ^{74}Ge which is very strong in (^{6}Li,d) but not observed and presumed weak in (t,p). Thus, as anticipated, the (^{6}Li,d) reaction leading to the Ge nuclei shows some correspondence with two-neutron transfer, but also some distinct differences which we will now try to relate to the behavior of the protons as the neutron number changes across the Ge isotopes.

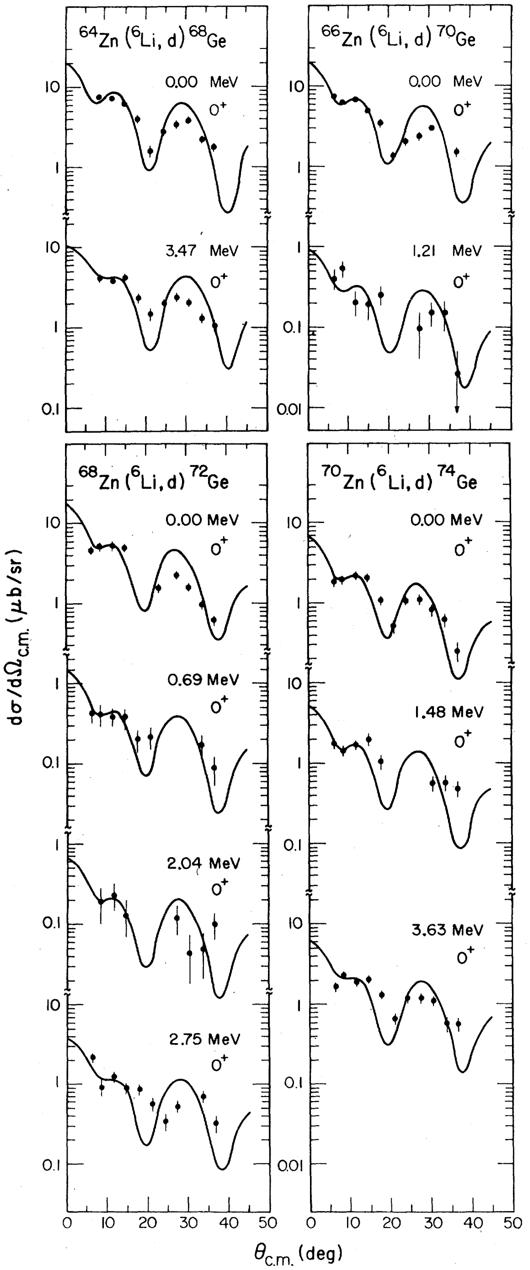

FIG. 1. Angular distributions measured for Zn(^{6}Li, d)Ge $L = 0$ transitions. Curves are the result of DWBA calculations assuming an alpha-cluster form factor. Parameters are shown in Table I.

TABLE I. Table of optical potentials used for (^{6}Li,d) DWBA calculations.

Channel	^{6}Li[a]	d[b]	Bound state
V (MeV)	$237.2 + 0.38 A_T$	$90.2 + 0.89\ Z/A^{1/3}$	
r_0 (fm)	1.30	$0.968 + 0.029 A^{1/3}$	1.30
a_0 (fm)	0.70	0.814	0.65
W_I (MeV)	$26.0 - 0.075 A_T$		
r_I (fm)	1.70		
a_I (fm)	0.90		
W_0 (MeV)		$4.33 + 2.20 A^{1/3}$	
r_s (fm)		$1.09 + 0.80 A^{-1/3}$	
a_s (fm)		$0.554 + 0.059 A^{1/3}$	
V_{so} (MeV)		7.0	
r_c (fm)	1.30	1.30	1.30

[a] L. T. Chua *et al.*, Nucl. Phys. A273, 243 (1976).
[b] E. Newman *et al.*, Nucl. Phys. A100, 225 (1967).

In order to explain previous experiments it has already been found necessary[6,7] to postulate a different structure in ^{72}Ge from ^{74}Ge for the four ground-state protons beyond the closed $Z = 28$ shell. The present alpha-transfer results provide additional evidence for this effect, since with no change in proton structure, similar behavior would be expected for (^{6}Li,d) and (t,p) ground state transitions in the region of $N = 40$. According to the simple model for the Ge isotopes introduced earlier,[6] the changing ground-state proton configurations are accompanied by orthogonal behavior of the first excited 0^+ states. The proton wavefunctions for the first two 0^+ states in the Ge nuclei are assumed to result from configuration mixing of $(p\frac{3}{2})^4$ and $(f\frac{5}{2})^2\ (p\frac{3}{2})^2$ four-proton configurations (see Table II). To calculate the alpha-transfer overlaps, wave functions are also needed for the Zn target nuclei, where the model simplifies to $(p\frac{3}{2})^2$ and $(f\frac{5}{2})^2$ two-proton configurations (Table II). For both Ge and Zn, the neutron wavefunctions are postulated to be the same for all levels with the same neutron number, and hence the relative strengths of the transitions of interest will not depend on the neutron configurations. Use of this simple model is justified by its success in describing most of the salient features of one-proton pickup and stripping experiments as well as the recent two-neutron transfer data. Although alpha transfer is potentially more complicated, we will now show that the model succeeds at least qualitatively in explaining the principal behavior observed in the Zn(^{6}Li,d) Ge reactions to the ground and first excited 0^+ states.

TABLE II. Comparison of experimental and model (^{6}Li,d), (t,p), and (^{3}He,n) spectroscopic strengths for 0^+ states in Ge isotopes. Proton wave functions used in the model (Ref. 6): $|^A\mathrm{Ge(g.s.)}\rangle = \alpha_A(p\tfrac{3}{2})^4 + \beta_A(p\tfrac{3}{2})^2(f\tfrac{5}{2})^2$; $|^A\mathrm{Ge}(0_2^+)\rangle = \beta_A(p\tfrac{3}{2})^4 - \alpha_A(p\tfrac{3}{2})^2(f\tfrac{5}{2})^2$, with $\alpha_{70}=\sqrt{0.43}$, $\alpha_{72}=\sqrt{0.37}$, $\alpha_{74}=\sqrt{0.03}$; $\beta_{70}=\sqrt{0.57}$, $\beta_{72}=\sqrt{0.63}$, $\beta_{74}=\sqrt{0.97}$. $|^{68}\mathrm{Zn(g.s.)}\rangle = |^{70}\mathrm{Zn(g.s.)}\rangle = \sqrt{0.95}(p\tfrac{3}{2})^2 + \sqrt{0.05}(f\tfrac{5}{2})^2$.

	(^{6}Li,d)		(t,p)		(^{3}He,n)	
0^+ states Ex (MeV)	$S(0^+)$ Exp	$S(0^+)$ Model[a] set 1-(set 2)	$S(0^+)$ Exp	$S(0^+)$ Model[c]	$S(0^+)$ Exp[d]	$S(0^+)$ Model
^{68}Ge						
0.0	3.40		Target not available			
3.47	0.16					
^{70}Ge						
0.0	3.03		Target not available		100	100
1.21	0.14				<10	0.1
^{72}Ge						
0.0	3.19	3.19(3.19)	3.19[b]	3.19[b]		86
0.69	0.27	0.19(0.91)	0.02	0.06		5.1
2.05	0.13		0.12			
2.75	0.66		0.15			
^{74}Ge						
0.0	1.74	1.92(1.31)	3.38	3.38	Target not available	
1.48	1.23	1.46(2.79)	0.76	0.90		
2.30	<0.04		0.11			
2.75	<0.04		0.03			
3.63	<1.44[e]		not observed			

[a] Calculated values normalized to the experimental ^{68}Zn(^{6}Li,d)^{72}Ge g.s. transition for sets 1 and 2 (see text).

[b] Normalized to the experimental ^{68}Zn(^{6}Li,d)^{72}Ge g.s. transition.

[c] Reference 6.

[d] Reference 9. The experimental ^{70}Ge g.s. transition has been used to normalize the model values.

[e] Upper limit due to a possible underestimate of a contaminant ^{72}Ge level.

A simple method may be used for calculating alpha-transfer strengths based on the work of Kurath and Towner[2] who showed that the four-particle amplitude may be factored into products of neutron and proton pair transfer amplitudes. This technique has proved reasonably successful in describing previous alpha-transfer data in the Ca, Ni, and Zn regions.[2-4] In the present work, we assume that the neutron pair transfer strength remains unchanged for the $L=0$ transitions of interest between the even Ge isotopes. This assumption is justified by the previous agreement between the model[6] and (t,p) and (p,t) results for 0^+ states in Ge, where the isotope dependence was shown to be mainly a function of the proton structure in the initial and final states. For (^{6}Li,d), the transfer strength depends on the proton structure much more closely than in (t,p). The alpha transfer should be directly proportional to the proton

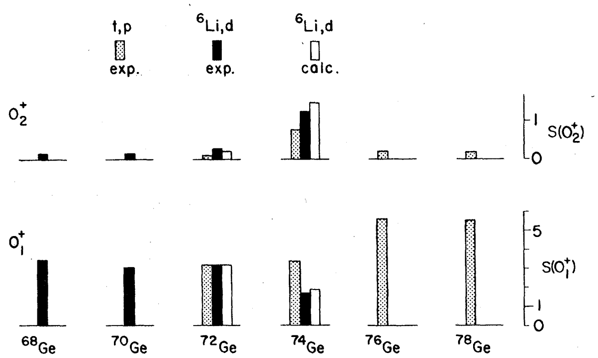

FIG. 2. Relative transition strengths from (^{6}Li,d) (black bars) and (t,p) (shaded bars) reactions to the $^{68-78}$Ge 0_1^+ and 0_2^+ states. Calculations (open bars) are presented for (^{6}Li,d) reactions. All three quantities have been normalized to the same value for the ^{72}Ge 0_1^+ transition.

pair transfer strength, which can be calculated using the Ge and Zn wave functions quoted in Table II. Coefficients are shown for 0_1^+ and 0_2^+ in ^{70,72,74}Ge based on previous experiments.[6] The coefficients for the Zn isotopes are much less reliable, but suggested values are given in Table II for the ^{68,70}Zn ground states from ^{71,69}Ga(d^3He) experiments.[10] Using this set of coefficients, the alpha-transfer strength is first estimated by calculating the transfer of two protons, either ${p_{3/2}}^2$ or ${f_{5/2}}^2$, coupled to $L = 0$ in the transitions ^{68}Zn → ^{72}Ge and ^{70}Zn → ^{74}Ge. The relative amplitudes for ${p_{3/2}}^2$ and ${f_{5/2}}^2$ transfer are taken as $\sqrt{19}$ and 1, respectively, as suggested by DWBA calculations and these factors are then multiplied by the corresponding wave-function coefficients before summing coherently. The results of this calculation for the alpha-transfer strengths are shown and labeled set 2 in Table II (column 3), where they reproduce certain qualitative aspects of the data but not the quantitative details. The set 2 calculations correctly describe the decrease in $S(0_1^+)$ and the increase in $S(0_2^+)$ from ^{72}Ge to ^{74}Ge. But there are large discrepancies in the relative magnitudes of $S(0_2^+)$ for both nuclei relative to $S(0_1^+)$. In both cases the predicted values are too strong by a factor of about 3; however, the calculations are admittedly designed to provide only a rough estimate of the expected strengths.

A first step in improving the calculations is to compute the actual structure factors G_{NSLJ} for transfer of a proton pair in place of the simulated transfer strengths presented above. The relative alpha strengths may then be written as approximately proportional to the coherent sums over the N modes of these structure factors, where once again the neutron pair strengths are assumed to cancel. Using the same wave function coefficients as previously mentioned, the alpha strengths were calculated from the G factors and the results are shown in Table II as set 1. These model predictions now provide much better agreement with the experimental magnitudes and the trend of all four (^{6}Li,d) transitions. According to the model, the two prinicipal features of the (^{6}Li,d) data, namely the sharp decline in ground-state strength between ^{72}Ge and ^{74}Ge and the sharp rise for 0_2^+, occur as a result of the rapid change in proton configurations between these two nuclei. It should be emphasized, however, that the calculations are also very sensitive to small changes in the Zn wave functions. Hence it would be useful to have better independent data concerning the proton structure in the Zn isotopes (from proton pickup experiments, for instance).

Despite the various uncertainties, the picture that emerges for the 0_1^+ and 0_2^+ states in the Ge isotopes is the existence of appreciable mixing of the ${p_{3/2}}^4$ and ${p_{3/2}}^2 {f_{5/2}}^2$ proton configurations for $N < 40$. In ^{74}Ge, however, the ${p_{3/2}}^2 {f_{5/2}}^2$ configuration suddenly dominates the ground state, while ${p_{3/2}}^4$ resides mostly in the first excited 0^+ state. It is this change that causes the decrease in $S(0_1^+)$ and increase in $S(0_2^+)$ from ^{72}Ge to ^{74}Ge for the (^{6}Li,d) reaction. Similar behavior has been reported[4] for the (d,^{6}Li) reaction in the region of $Z = 40$. There, sharp changes in the alpha pickup strength between ^{94}Zr and ^{96}Zr were also attributed to a change in the proton pairing structure as the neutron number changes.

Two conclusions are forthcoming from the present work. First, the description of alpha-transfer reactions in terms of the product of proton and neutron pairing amplitudes, which was first demonstrated with closed shell nuclei, appears also to be useful for the Ge nuclei in the transitional region of $N = 40$. By comparing the present (^{6}Li,d) with previous (t,p) reaction strengths, information is obtained about two-proton correlations in these nuclei, which provides a more stringent test of model predictions[6] than has been possible based on other experiments that are only indirectly sensitive to the proton structure. It should be emphasized that proton pairing information from the (^{3}He,n) reaction is often unavailable, as indicated by the sparsity of the data in the (^{3}He,n) column in Table II.

The second conclusion is that the hypothesis of a rapid change in proton structure near $N = 40$ and especially between ^{72}Ge and ^{74}Ge is confirmed by the present results. This strong dependence of the proton structure on the neutron number may be related to the onset of strong neutron occupation of the $g_{9/2}$ orbit, which may cause a sharp change in the neutron-proton interaction in the vicinity of $N = 40$–42. This microscopic behavior of the neutron and proton orbitals is the likely factor underlying much of the experimental results that have led to the postulation of a shape transition in the Ge isotopes between $N = 40$ and 42.

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