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^{76}Ge(t, p)^{78}Ge reaction

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The ^{76}Ge(t,p) reaction has been studied in order to extend the known level structure in the Ge isotopes to ^{78}Ge and to further investigate the proposed shape transition in the Ge nuclei. About 30 states were observed in ^{78}Ge, which was previously uninvestigated. Angular distributions were measured and were analyzed using zero-range microscopic two-nucleon transfer distorted-wave calculations to extract L values. Based on the energy of the first excited 0^+ level, it would appear that ^{78}Ge does not continue the trend toward prolate deformation but begins to return toward the critical or "supersoft" region.

[NUCLEAR REACTIONS ^{76}Ge(t,p), E = 15.0 MeV; measured $\sigma(\theta, E_p)$. ^{78}Ge deduced levels, L, π, J. DWBA analysis.]

I. INTRODUCTION

Extensive experimental studies have recently been reported[1-5] for the even mass $^{68-76}$Ge isotopes. These investigations were prompted by evidence[1] that the Ge nuclei undergo a shape transition from an oblate to prolate deformation with increasing neutron number. Recent work[1,6] suggests that the energies of the first excited 0^+ levels, $E_{0_2^+}$, can be correlated with this oblate to prolate shape transition as can also the energy differences between the first 4^+ and the second 2^+ levels, $E_{4_1^+} - E_{2_2^+}$. Despite the recent interest in this mass region, only the ground state Q value has been measured[7] for the neutron rich ^{78}Ge nucleus. This is primarily due to the fact that there are no stable nuclei that could be used as targets for single nucleon transfer studies. In fact, the only light-ion direct transfer reaction that can reach ^{78}Ge is ^{76}Ge(t,p) ^{78}Ge. Because of the dearth of triton beams, this nucleus has been completely neglected. In the work reported here, our goals were to establish a level scheme for ^{78}Ge and to look for further evidence for a shape transition in the Ge nuclei.

II. EXPERIMENTAL PROCEDURE

The present work is part of a series of experiments made possible by the recent temporary availability of a tritium ion source at the University of Pennsylvania. The present experiment was performed with a 15-MeV triton beam from the Penn FN tandem Van de Graaff accelerator. The ^{76}Ge target, evaporated on a carbon backing, was enriched to 93.6% and was ~80 μg/cm^2 thick. Outgoing protons were momentum analyzed in a multiangle spectrograph, and spectra (see Fig. 1) were recorded on nuclear emulsion plates in 7.5° steps starting at 3.75°. Absorber foils placed directly in front of the plates stopped all particles except protons. Contaminant peaks due to ^{12}C and ^{16}O were identified. The resolution was about 25 keV full width at half maximum (FWHM).

TABLE I. Optical-model parameters used in the analysis of the ^{76}Ge(t,p)^{78}Ge reaction.

	V_0 (MeV)	r_0 (fm)	a (fm)	W (MeV)	$W' = 4W_D$ (MeV)	r_0' (fm)	a' (fm)	r_c (fm)	
^{76}Ge + t	168.0	1.20	0.65	13.5		1.60	0.87	1.3	Ref. 9
^{78}Ge + p	50.5	1.25	0.65		60.0	1.25	0.47	1.3	Ref. 10
^{76}Ge + nn	a	1.27	0.67						

[a] Adjusted to give a binding energy to each particle of 0.5[$Q(t,p)$ + 8.482] MeV.

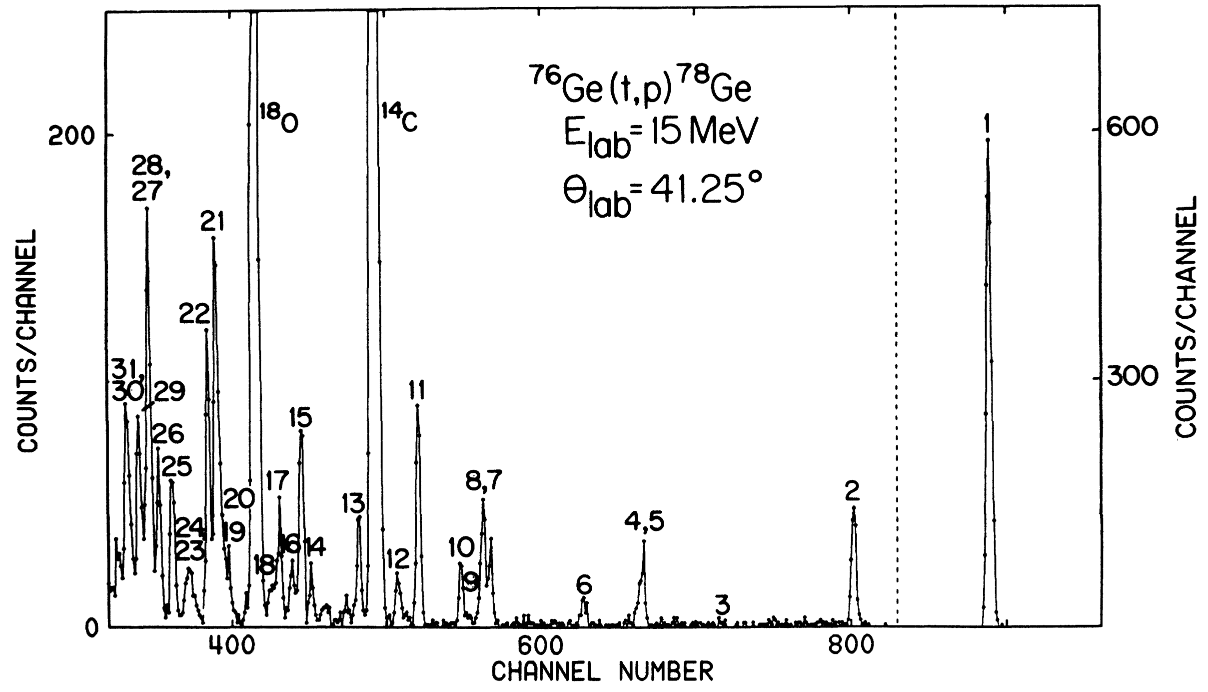

FIG. 1. Typical proton spectrum of the ^{76}Ge(t, p) ^{78}Ge reaction.

The main uncertainty in the absolute experimental cross sections arises from the uncertainty in the target thickness. Since the thickness could not be determined reliably from weighing, it was estimated by normalizing the cross section for elastic scattering, measured at 40°, to the cross section predicted with the triton optical model parameters (see Table I) used in the analysis of the (t, p) transfer data. Consequently, the absolute cross sections are reliable only to within 40–50%.

III. DWBA ANALYSIS AND RESULTS

Angular distributions are displayed in Figs 2–6. The solid curves are the results of zero-range microscopic two-nucleon transfer calculations with the code DWUCK.[8] The triton optical model parameters were those obtained by Hardekopf *et al.*[9] from elastic scattering on ^{90}Zr, the nearest nucleus to Ge for which optical model parameters are available. For the exit channel, the global proton parameter set of Perey[10] was used. Both the triton and proton parameter sets used are listed in Table I.

Since no shell model wave functions were available for ^{78}Ge, no attempt has been made to compare the magnitudes of the theoretical and experimental cross sections because many two-neutron configurations are possible in the form factor calculations. In this study, a $\nu(1g_{9/2})^2$ configuration

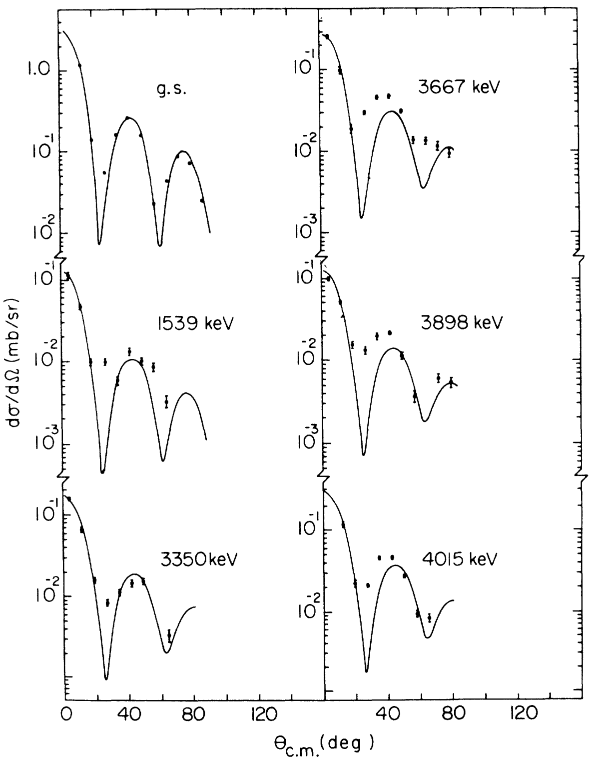

FIG. 2. Angular distributions of the protons leading to states in ^{78}Ge from the ^{76}Ge(t, p) reaction. The solid lines are the distorted-wave Born approximation calculations for $J = 0$.

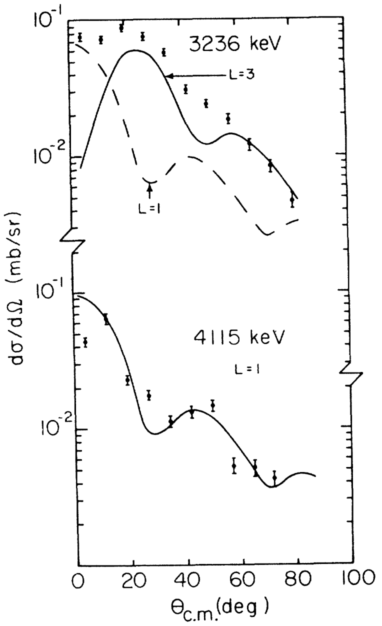

FIG. 3. Angular distributions for levels in ^{78}Ge from the ^{76}Ge(t,p) reaction. The solid lines are DWBA calculations for $J = 1$ and 3.

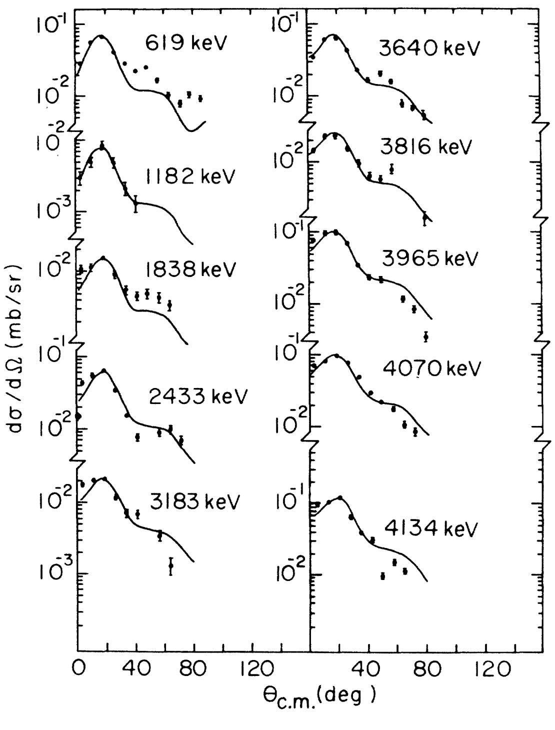

FIG. 4. Angular distributions for levels with $J = 2$ reached in the ^{76}Ge(t,p) reaction. The solid lines are DWBA calculations.

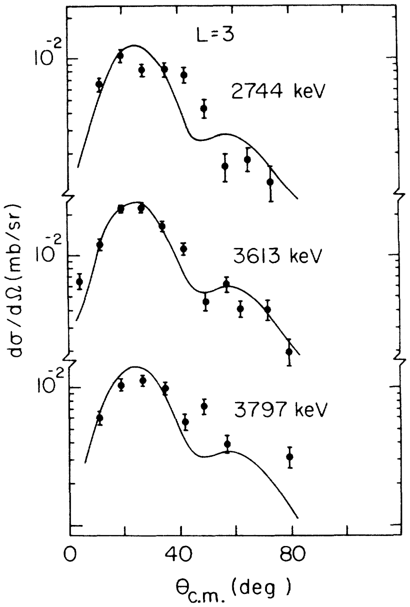

FIG. 5. Angular distributions for $J = 3$ levels reached in the ^{76}Ge(t,p) reaction. The solid lines are DWBA calculations.

was used for the even L transfers, a $\nu(1g_{9/2}, 2p_{3/2})$ for the $L = 3$ and 5 cases, and a $\nu(2p_{1/2}, 3s_{1/2})$ for $L = 1$. Pure configurations were sufficient since the characteristic shapes of the angular distributions were obtained with these particular configurations. The distorted-wave Born approximation (DWBA) shapes for the different

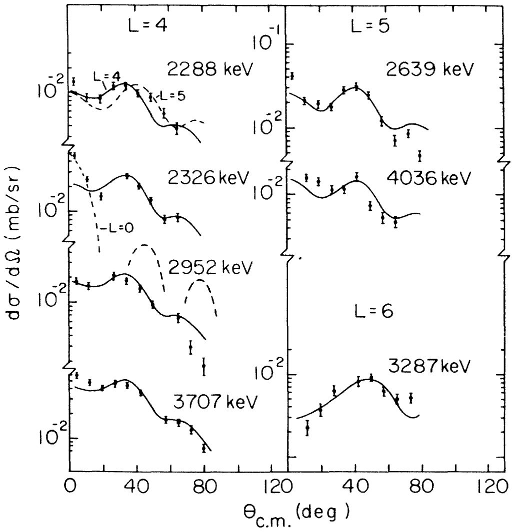

FIG. 6. Angular distributions for levels in ^{78}Ge reached in the ^{76}Ge(t,p) reaction. The solid lines are DWBA calculations for $J = 4$, 5, and 6, as indicated.

L transfers were quite distinct, making unambiguous spin and parity assignments possible.

IV. RESULTS AND DISCUSSION

As seen in Fig. 2, the ground state (gs) angular distribution is well fitted by the $L=0$ DWBA calculations. Angular distributions for other states exhibit the small angle rise and general shape that is characteristic of $J^{\pi}=0^{+}$. These are also displayed in Fig. 2. Angular distributions which may be characterized by $L=1$ shapes are seen in Fig. 3. The level at 3236 keV required both $L=1$ and 3 components to adequately describe the data. Figure 4 contains angular distributions for 10 states which, on the basis of the shapes, are assigned $L=2$. Four angular distributions were fitted with the $L=3$ shapes (see Figs. 3 and 5). Angular distributions characteristic of higher L are shown in Fig. 6. Four angle distributions are best fitted by $L=4$, two by $L=5$, and one by $L=6$.

The present experimental results for energies and J^{π} of levels in ^{78}Ge are summarized in Table II. (More complete experimental data are deposited in the Physics Auxiliary Publications Service.[11]) From the spectrum in Fig. 1, the peak at 1539 keV appears to be a doublet. From its angular distribution and from energy systematics in the other Ge isotopes, we conclude that it consists of a weak 4^{+} state in addition to the strong 0^{+} state. In Fig. 6, an anomalous small angle rise in the angular distribution for the 2326-keV state suggests a weak $J^{\pi}=0^{+}$ state unresolved from the stronger $J^{\pi}=4^{+}$ state.

TABLE II. Present results for the energy levels and J^{π} in ^{78}Ge from the ^{76}Ge(t,p) reaction.

Peak no.	E_x [a] (keV)	J^{π}	Peak no.	E_x [a] (keV)	J^{π}
1	0	0^{+}	17	3350	0^{+}
2	619	2^{+}	18	3386	
3	1182	2^{+}	19	3613	3^{-}
4	1539	0^{+}	20	3640	2^{+}
5		(4^{+})	21	3667	0^{+}
6	1838	2^{+}	22	3707	4^{+}
7	2288	$(4^{+}, 5^{-})$	23	3797	3^{-}
8	2326 [b]	$4^{+}, (+0^{+})$	24	3816	2^{+}
9	2404		25	3898	0^{+}
10	2433	2^{+}	26	3965	2^{+}
11	2639	5^{-}	27	4015	0^{+}
12	2744	3^{-}	28	4036	5^{-}
13	2952	4^{+}	29	4070	2^{+}
14	3183	2^{+}	30	4115	1^{-}
15	3236 [b]	$3^{-}+1^{-}$	31	4134	2^{+}
16	3287	6^{+}			

[a] Energy uncertainties are ±5 for $E<3$ MeV and ±7–10 for $E>3$ MeV.

[b] Possible doublet.

The level schemes for the even mass Ge isotopes are compared in Fig. 7. These are adopted level schemes from the Nuclear Data Sheets – updated wherever possible by more recent work.[12-17] The levels connected by solid lines were suggested by Ardouin[1] to have similar structure, from energy or population intensity arguments. The levels connected by dashed lines have been associated again by both energy and population intensity systematics by this study.

Our interest in the present work was to extend the known level structure of the Ge isotopes to ^{78}Ge, in order to further investigate the occurrence of a shape transition in the Ge nuclei. As discussed by Ardouin *et al.*,[1] Kumar[6] has found that both the energy of the first excited 0^{+} state, $E_{0_2^+}$, and the energy difference between the first 4_1^{+} level and second 2_2^{+} level, $E_{4_1^+}-E_{2_2^+}$, can be correlated with an oblate to prolate shape transition. In addition, Cailliau *et al.*[18] have suggested that the local minimum at $N=40$ for the energy of the 0_2^{+} state in the Ge isotopes characterizes a zone of critical or "supersoft" nucleus arising from the coexistence of spherical and deformed shapes. This characteristic has also been observed in the Zn, Se, Kr, and Sr isotopes.

It is not clear on the basis of energy considerations alone which 0^{+} level (1539 or ~2326 keV) in ^{78}Ge should be associated with which 0^{+} level in the other Ge isotopes. For $N \geq 40$, the Ge 0_2^{+} levels demonstrate an almost linear increase in energy with increasing neutron number and an energy of 2326 keV in ^{78}Ge is consistent with this trend. On the other hand, the 0_3^{+} level in most of the Ge isotopes has an energy of approximately 2.2 MeV – not inconsistent with an excitation energy of 2326 keV in ^{78}Ge. The problem is complicated further by the fact that in ^{76}Ge no 0_3^{+} level has been identified which would correspond in energy to the 0_3^{+} levels in the $^{68-74}$Ge isotopes. It is conceivable that this level has dropped in energy and therefore should be associated with the 1539-keV level in ^{78}Ge.

In a recent ^{74}Ge(t,p) study,[19] no evidence was found for a 0^{+} level near 2.2 MeV in ^{76}Ge. The lowest two excited 0^{+} states were observed at 1911 and 2900 keV. The 2900-keV level is probably too high in energy to correspond to the 0_3^{+} in ^{74}Ge but might be correlated with the 0^{+} level at 3107 keV in ^{70}Ge and/or the 0^{+} level at 3350 keV in ^{78}Ge. The 1911-keV state in ^{76}Ge has a relative population of ~10% of the ground state strength. Thus, it would appear that the 0_2^{+} level is strongly

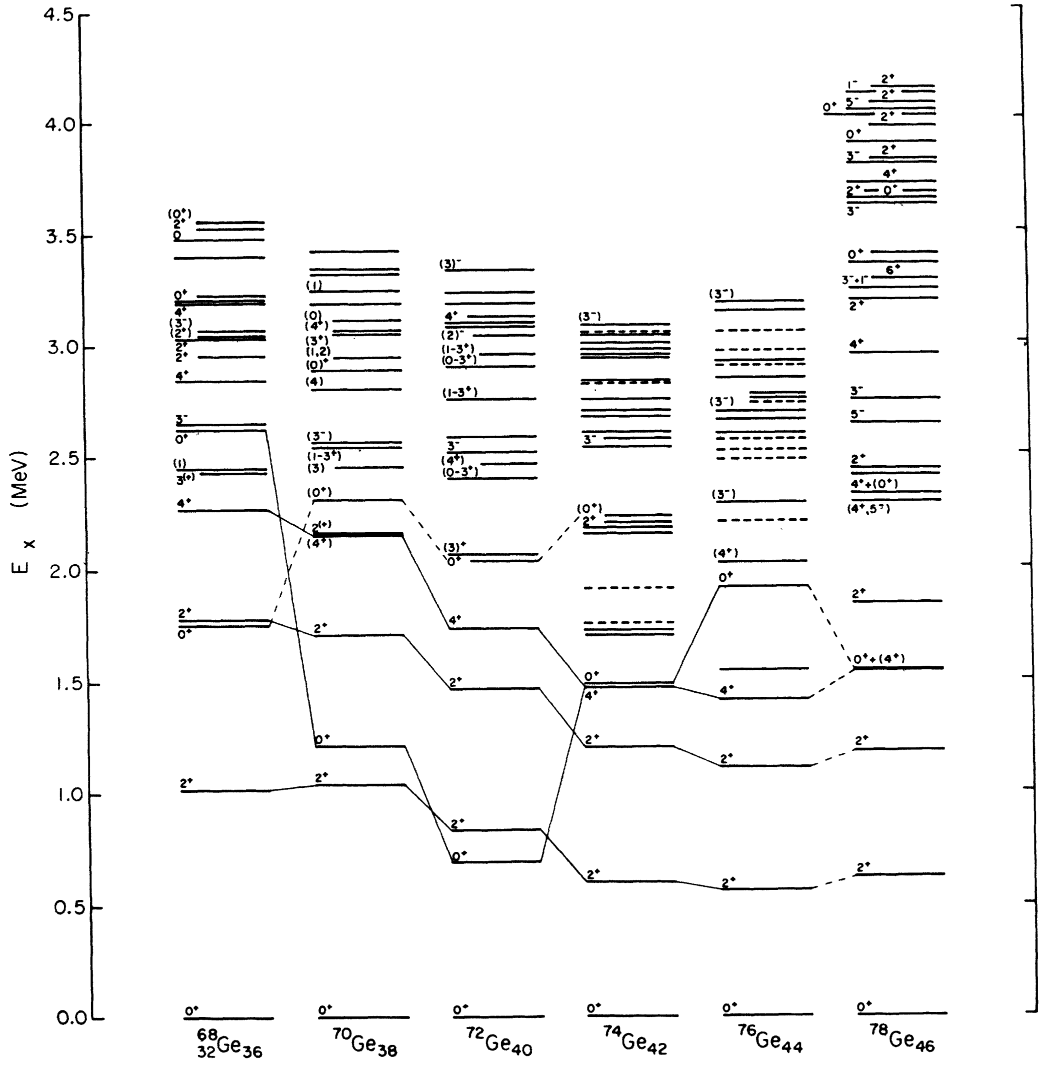

FIG. 7. Comparison of energy levels and J^π from the present ^{76}Ge(t,p) ^{78}Ge work with the information from the literature on other even-even Ge isotopes. See Refs. 4, 12, and 13 for ^{68}Ge, 1 and 14 for ^{70}Ge, 3 and 15 for ^{72}Ge, 5 and 16 for ^{74}Ge, and 17 and 19 for ^{76}Ge.

populated in the (t,p) reaction but that the 0_3^+ level is not. In ^{78}Ge, a relative population of the 1539-keV level was ~5% of the ground state strength, whereas the relative population of the 2326-keV level has an upper limit of no more than 1%. On this basis, the 0_2^+ levels in the $^{68-76}$Ge nuclei should be correlated with the 1539-keV 0^+ level in ^{78}Ge, and the 2326-keV level in ^{78}Ge should be associated with the 0_3^+ levels in the $^{68-76}$Ge isotopes.

This represents a significant decrease in the energy of the 0_2^+ state which would not have been predicted from the energy systematics of this level with increasing mass. As can be seen in Fig. 8, adapted from Ref. 1, the Se isotopes show a leveling out in energy of the 0_2^+ level as the neutron number increases from 42 to 46 but not a sharp decrease. In contrast, the Kr isotopes exhibit a consistent energy increase as the neutron number increases. The energy decrease in the 0_2^+ state in ^{78}Ge suggests that the Ge nuclei might be exhibiting the interesting characteristic of returning toward a region of "supersoftness" as one approaches the neutron closed shell at 50.

From energy systematics (see Fig. 7) we suggest that the second member of the 1539-keV doublet is the 4_1^+ state. The $E_{4_1^+} - E_{2_2^+}$ energy differences for these nuclei are shown in Fig. 9 (also adapted from Ref. 1). If the second state at 1539 keV is indeed a 4^+ level, this energy dif-

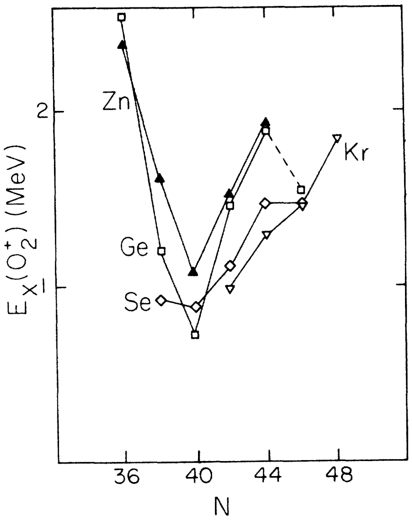

FIG. 8. Energies of the second 0^+ states in the Zn, Ge, Se, and Kr isotopes.

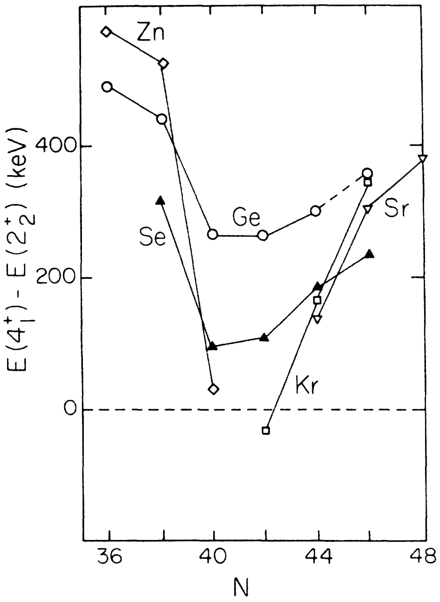

FIG. 9. Energy differences between 4_1^+ and 2_2^+ states in the Zn, Se, Ge, Kr, and Sr isotopes.

ference has increased slightly, which is similar to the behavior of the $E_{4_1^+} - E_{2_2^+}$ energy differences in the Se isotopes. This is again in marked contrast to the strong increase in this quantity for the Kr and Sr nuclei.

In conclusion, this study suggests a similarity between the Ge and Se isotopes which becomes more evident as the mass increases. The results of this work would suggest that the Ge nuclei might be returning toward a region which has been characterized as "supersoft" or critical where both spherical and deformed tendencies coexist.

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[11] See AIP document No. PAPS PRVCA-17-2047-4 for four pages of cross sections for ^{76}Ge(t,p) vs angle for $E_t = 15$ MeV. Order by PAPS number and journal reference from American Institute of Physics, Physics Auxiliary Publications Service, 335 East 45th Street, New York, New York 10017. The prices are $1.50 for microfiche or $5 for photocopies. Airmail additional. Make checks payable to the American Institute of Physics. This material also appears in *Current Physics Microfilm*, the monthly microfilm edition of the complete set of journals published by AIP, on frames immediately following this journal article.

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