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Systematics of the proton stripping reaction on ^{69,71}Ga, ^{75}As, ^{79,81}Br isotopes and nuclear structure of the Ge-Se isotopes

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The ^{69}Ga(^{3}He, d)^{70}Ge and ^{75}As(^{3}He, d)^{76}Se reactions have been studied at 25 MeV incident energy using a split-pole spectrometer. The over-all resolution is 18–21 keV. Sixty-two ^{70}Ge levels, 16 of which observed for the first time, are populated below 5.2 MeV excitation energy. Seventy-one ^{76}Se levels are separated, 44 of which had never been observed. Angular distributions are obtained and comparison with distorted-wave–Born-approximation calculations allows parity assignment and spin limits for many levels. Spectroscopic factors are deduced for most of the observed transitions. In order to test our mixing of orbital momenta, the ^{69}Ga(α, t)^{70}Ge reaction has also been performed at 39.35 MeV incident energy. A cursory investigation of the ^{79,81}Br(^{3}He, d) reactions has been performed and systematics are drawn for the first excited levels between $N=38$ and 46. The model previously presented to account for the strong population of the ^{72}Ge 0_2^+ level in our earlier study of ^{72}Ge with the same reaction is discussed and compared with the present results. From present and previously known experimental systematics, conclusions are drawn concerning the possibility of an oblate to prolate shape transition between $N=36$ and 46, the softness of the nuclei in the $N=40$ region, and the noncollective structure of the 0_2^+ state. Potential energy surfaces obtained by Hartree-Fock calculations using the Skyrme interaction are presented and confirm the above conclusions.

NUCLEAR REACTIONS ^{69,71}Ga(^{3}He, d), ^{75}As(^{3}He, d), $E=25$ MeV, measured $\sigma(\theta)$; $^{79-81}$Br(^{3}He, d) spectra; ^{69}Ga(α, t)^{70}Ge spectrum, $E=39.35$ MeV; ^{70,72}Ge, ^{76}Se, ^{80,82}Kr deduced levels, J, π, S; deduced and presented systematics.
NUCLEAR STRUCTURE $^{68-78}$Ge; calculated potential energy surfaces. Hartree-Fock method; Skyrme interaction.

I. INTRODUCTION

Few calculations are now available on the Ge-Se even nuclei. Stewart and Castel[1] published a calculation of the $^{70-72}$Ge isotopes in terms of a vibration-rotation coupling using effective matrix elements. Their results are consistent with experimental $E2$ rates of the first excited states except for the $2_2^+\to 0_2^+$ transition. This crude model gives some understanding of the Ge structure. Recent quasiparticles calculations with quadrupole plus dipole core interaction were made[2] by de Vries. A good fit of the first levels is obtained but the model fails to reproduce the low lying 0^+ state at 0.690 MeV in ^{72}Ge and 1.216 MeV in ^{70}Ge. Preliminary pairing plus quadrupole calculations[3] tried to interpret the first excited 0^+ state by a second minimum in the collective potential energy surface but the excited states do not appear well reproduced. Furthermore, this interpretation disagrees with the data, a root mean square deformation β_{rms} smaller than the ground-state one being known[4,5] for this excited 0^+ state. These nuclei, considered in the past as vibrational, belong in fact to the transitional nuclei for which more correct calculations begin to appear.

The difficulties in understanding the Ge-Se nuclear structure may arise partly because too little experimental information is available concerning the excited states of the even Ge-Se nuclei. In order to locate the energy levels, to study the fragmentation of single proton strength and to follow these properties, as systematically as possible, the (^{3}He, d) reaction was carried out on ^{69,71}Ga, ^{75}As, and ^{79,81}Br targets. Our results of the ^{71}Ga(^{3}He, d)^{72}Ge reaction were already published.[6] It appears interesting to gather systematics either from the present work or from previous experimental studies and to compare them to criteria previously retained[7,8] to characterize zones of shape transition in nuclei. Furthermore, Hartree-Fock calculations using Skyrme's interaction make possible an investigation of the shape stability.

II. EXPERIMENTAL PROCEDURE

The ^{69}Ga(^{3}He, d)^{70}Ge, ^{75}As(^{3}He, d)^{76}Se, ^{79,81}Br(^{3}He, d)^{80,82}Kr reactions have been performed with the Orsay MP tandem accelerator at 25 MeV incident energy. The experimental setup and procedure were the same as in our previous study[6] of the ^{71}Ga(^{3}He, d)^{72}Ge reaction. The over-all energy resolution was 18–21 keV full width at half maximum. For the ^{69}Ga (99.75% isotopically enriched) and As targets, data were taken in 4° steps from 5 to 41°, which is sufficient taking account of the main features of the angular distributions observed in our study of the ^{71}Ga(^{3}He, d)^{72}Ge reaction. Only two angles were recorded for the Br natural target. For the ^{69}Ga(^{3}He, d)^{70}Ge reaction the possibility of contaminant groups originating from ^{71}Ga was ruled out by direct comparison with our study of the ^{71}Ga(^{3}He, d)^{72}Ge reaction.

Absolute cross sections were obtained from measured elastic cross sections as explained in Ref. 6 and are accurate to about 20%. However, comparison between ^{70}Ge and ^{72}Ge is more precise because data taken for the ^{70}Ge and ^{72}Ge ground states using a natural gallium target yields an accuracy of 3% on the relative ^{70}Ge-^{72}Ge normalization.

III. EXPERIMENTAL RESULTS

A. ^{69}Ga(^{3}He,d)^{70}Ge results

1. General analysis

Two deuteron spectra (for two successive magnetic fields) recorded at a laboratory angle of 21° are shown in Fig. 1. The numbers on top of the peaks refer to nuclear levels in ^{70}Ge. The corresponding excitation energies are reported in Table I with an uncertainty of 3 keV except for the weakly excited levels where it can reach 5 keV. In the same table are presented the previously known levels reported in the compilation[9] of the Nuclear Data Group. The results of a study similar to ours, published very recently[10] and after the completion of this work, are not included in the table, but shall be discussed in Sec. III A 6.

Sixteen levels are observed for the first time. The first ones are seen at 3.733, 4.024, and 4.613 MeV; all of the levels above 4.687 MeV excitation energy were previously unknown. The procedure for the distorted-wave-Born-approximation (DWBA) analysis of the angular distributions has been described in Ref. 6. The optical potentials

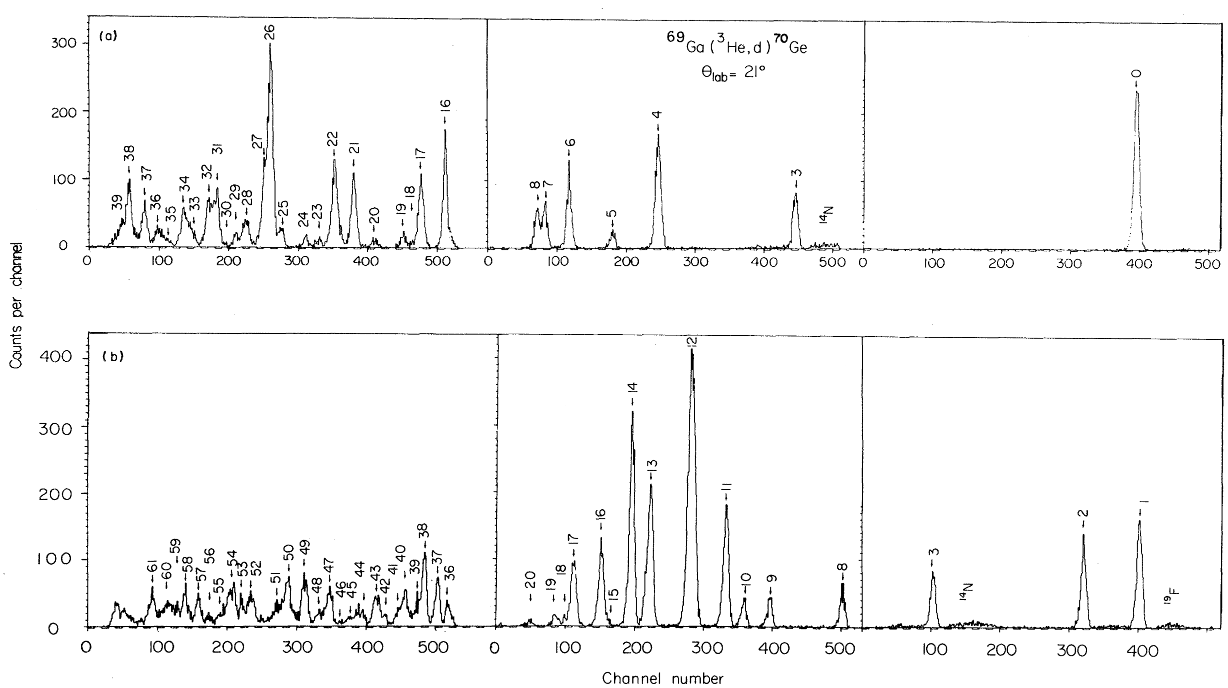

FIG. 1. Deuteron energy spectra from the ^{69}Ga(^{3}He, d)^{70}Ge reaction at 21° lab. The spectra (a) and (b) refer to successive exposures of the three detectors at two different magnetic fields (see text).

TABLE I. Levels observed in the reaction $^{69}Ga(^3He, d)^{70}Ge$ at 25 MeV.

	Present work			Literature [a]		$(2J+1)C^2S$ (Present work)				
Level No.	E_x (MeV)	l	J^π [b]	E_x (MeV)	J^π	$2p_{3/2}$ [c]	$1f_{5/2}$	$1g_{9/2}$	$2d_{5/2}$	$3s_{1/2}$
0	0.0	1	0^+-3^+	0.0	0^+	2.0				
1	1.040	1+3	1^+-3^+	1.0396	2^+	0.96	0.96			
2	1.216	1	0^+-3^+	1.2158	0^+	0.87				
3	1.709	1+3	1^+-3^+	1.7080	2^+	0.39	0.48			
				2.1530	(4^+)					
4	2.157	1+3	1^+-3^+	2.1568	$2^{(+)}$	0.81	0.66			
5	2.307	1(+3)	$\underline{0}^+-3^+$	2.3071	(0^+)	0.13	<0.03			
6	2.452	3(+1)	1^+-5^+ [d]	2.4516	(3)	<0.07	2.27			
7	2.535	1+3	1^+-3^+	2.5355		0.16	0.62			
8	2.563	4(+2)	2^--6^-	2.5623	(3^-)			1.31	<0.09	
9	2.808	3	1^+-5^+ [d]	2.8067	(4)		1.14			
10	2.888	1(+3)	$\underline{0}^+-3^+$	2.8871	(0)	0.22	<0.05			
11	2.941	1+3	1^+-3^+ [e]	2.9453	(1, 2)	0.37	2.71			
12	3.053	3(+1)	1^+-5^+ [d]	{ 3.0468	(3^+)	<0.25	11.7			
				{ 3.0592	(4^+)					
				3.1072	(0)					
13	3.182	1+3	1^+-3^+	3.1810		0.84	1.55			
14	3.243	1+3	1^+-3^+	3.2406	(1)	1.22	1.0			
15	3.314	2(+4)	0^--4^-	3.3147				<0.02	0.07	
16	3.335	1(+3)	$\underline{0}^+-3^+$	3.3356		0.59	<0.14			
17	3.422	1+3	1^+-3^+	3.419		0.36	0.45			
18	3.452			3.456						
19	3.481	1+3	1^+-3^+	3.4823		0.05	0.12			
20	3.567	4(+2)	2^--6^-	3.570				0.21	<0.02	
21	3.628	1(+3)	$\underline{0}^+-3^+$	3.6317		0.49	<0.12			
22	3.687	1+3	1^+-3^+	3.691		0.51	0.63			
23	3.733	1+3	1^+-3^+			0.05	0.03			
24	3.775	1+3	1^+-3^+	3.777		0.03	0.18			
25	3.854	4+2(+0)	2^--4^-	3.857				0.41	0.02	<0.02
26	3.888	1+3	1^+-3^+	3.891		0.82	1.52			
27	3.903	1+3	1^+-3^+	3.9039		0.31	0.26			
28	3.964	4+2(+0)	2^--4^-	3.959				0.74	0.04	<0.02
29	3.995			3.990						
30	4.024									
31	4.060	1+3	1^+-3^+	4.062		0.27	0.15			
32	4.080	1+3	1^+-3^+			0.20	0.31			
33	4.129	4+2+0	2^--4^- [f]	4.132				1.03 [g]	0.02	0.02
34	4.157	1+3	1^+-3^+	4.153		0.26	0.22			
35	4.212			4.219						
36	4.238	1+3	1^+-3^+	4.242		0.09	0.27			
37	4.287	1+3	1^+-3^+	4.282		0.22	0.26			
38	4.330	4+2(+0)	2^--4^-	4.334				1.37	0.07	<0.03
39	4.352	4+2(+0)	2^--4^-	4.357				0.80	0.04	<0.03
40	4.391	1+3	1^+-3^+	4.392		0.20	0.37			
41	4.419	4+2	2^--4^-	4.421				0.08	0.09	
42	4.446			4.448						
43	4.473	1+3	1^+-3^+	4.475		0.12	0.48			
44	4.520	4+2	2^--4^-	4.520				0.53	0.05	
45	4.555			4.557						
46	4.574			4.578						
47	4.613	1+3	1^+-3^+			0.12	0.48			
48	4.642	4+2(+0)	2^--4^-	4.641				0.40	0.04	<0.02
49	4.687	4+2(+0)	2^--4^-	4.689				2.09	0.13	<0.04
50	4.736	(4+2+0)	(2^--4^-)					(1.14)	(0.13)	(0.04)
51	4.768	4+2(+0)	2^--4^-					0.56	0.06	<0.03
52	4.847	4+2(+0)	2^--4^-					0.74	0.08	<0.03
53	4.877	4+2+0	2^--4^- [f]					1.03 [g]	0.03	0.02
54	4.905	(4+2+0)	(2^--4^-)					(1.01)	(0.11)	(0.05)

TABLE I *(Continued)*

Level No.	Present work E_x (MeV)	l	J^{π} [b]	Literature [a] E_x (MeV)	J^{π}	(2J+1)C²S (Present work) $2p_{3/2}$ [c]	$1f_{5/2}$	$1g_{9/2}$	$2d_{5/2}$	$3s_{1/2}$
55	4.943	4+2(+0)	2^-–4^-					0.47	0.05	<0.03
56	4.979	4+2(+0)	2^-–4^-					0.23	0.03	<0.01
57	5.008	4+2+0	2^-–4^- [f]					1.43 [g]	0.04	0.03
58	5.048	4+2+0	2^-–4^- [f]					1.79 [g]	0.02	0.01
59	5.078	1+3	1^+–3^+			0.08	0.02			
60	5.102	1+3	1^+–3^+			0.12	0.02			
61	5.145	(4+2+0)	(2^-–4^-)					(0.79)	(0.09)	(0.04)

[a] Reference 9.
[b] Underlined values refer to most probable assignments (see text).
[c] If $2p_{1/2}$ transfer is assumed, one can find $s_{1/2} \sim 1.17\ s_{3/2}$.
[d] $J^{\pi} = 4^+$ is the most probable assignment (see text).
[e] $J^{\pi} = 1^+$ or 2^+ is the most probable assignment (see text).
[f] $J^{\pi} = 2^-$ is the most probable assignment (see text).
[g] Spectroscopic factor calculated assuming $g_{7/2}$ transfer (see text).

used are the same. These distributions are now presented according to their characteristics.

2. $l=1$ angular distributions

The ground state (0_1^+) and first excited 0^+ level (0_2^+) at 1.216 MeV are very well reproduced by $l=1$ calculations (Fig. 2), the spectroscopic factor for the 0_2^+ level being 45% of the ground-state one.

Besides these two levels, four other levels at 2.307, 2.888, 3.335, and 3.628 MeV are populated by an $l=1$ transfer (i.e., the fit is good for a pure $l=1$ calculation but a weak $l=3$ component may exist with relative strength smaller than 0.2). The selection rules permit spin and parity $J^{\pi} = 0^+$-3^+: It is only among these levels that a 0^+ state could have been observed in this work (a 0^+ state can only be populated by a pure $l=1$ transfer).

The 2.307 and 2.888 MeV levels have been proposed[4,9] as $J^{\pi} = (0^+)$ levels; the recent work[11] of Ball *et al.* in a Ge(p,t) experiment confirms this hypothesis for the 2.307 MeV level by the observation of an $L=0$ transition feeding this level. The spin-parity assignments $J^{\pi} = 0^+$ seem therefore well founded for these two levels. We emphasize the great similarity between the 2.307 MeV level (^{70}Ge) and the new level[6] at 2.029 MeV (^{72}Ge) concerning both the spectroscopic factor found and the excitation energy measured. The facts mentioned above concerning the 2.307 and 2.888 MeV levels lead us to propose $J^{\pi} = (0)^+$ as a tentative assignment for the 3.335 and 3.628 MeV levels. Here again a similarity does exist with the 3.619 MeV, $J^{\pi} = (0)^+$ level[6] of ^{72}Ge.

3. $l=3$ angular distributions

Three pure $l=3$ angular distributions are found for the levels at 2.452, 2.808, and 3.053 MeV. The selection rules limit the J^{π} values to 1^+-5^+. Moreover, as the $f_{7/2}$ shell is quasifilled, large $l=3$ spectroscopic factors must correspond to $f_{5/2}$ transfer and limits the J^{π} values to 1^+-4^+. As a 4^+ level can be populated only by a pure $l=3$ transfer, the value $J^{\pi} = 4^+$ may be proposed as a tentative value. This tentative value is in agreement with the previous proposition[9] $J=(4)$ for the 2.808 MeV level but is contradicted for the 2.452 MeV level by the results $J=3$ of Hinrichsen, Van Patter, and Shapiro[4] and de Ruiter, Verheul, and Konijn.[12]

For the strongly excited level observed at 3.053 MeV, the reaction may indeed populate the two levels at 3.047 and 3.059 MeV. These two levels have been proposed[9] as $J^{\pi} = (\underline{3}^+$-$4^+)$ and $J^{\pi} = (4^+)$, respectively.

4. $l=1+3$ angular distributions

The two known[9] 2_1^+ and 2_2^+ levels at 1.040 and 1.709 MeV, respectively, are populated by $l=1+3$ transitions. The level at 2.157 MeV was known[9] as $J^{\pi} = 2^{(+)}$. Although a part of the $l=3$ spectroscopic amplitude may be attributed to the unresolved $J^{\pi} = (4^+)$ level at 2.153 MeV our result ($l=1+3$ transition) definitively establishes the $\pi = +$ value for this level. No spin-parity assignments were previously known for the 2.535 MeV level: we can deduce $J^{\pi} = 1^+$-3^+ from the $l=1+3$ DWBA calculations. The same results are found for the 2.941 MeV level previously known[9,4] as $J=(1,2)$; we can propose $J^{\pi} = 1^+$-2^+ for this level. Hinrichsen[4] proposed $J=(1)$ for the 3.243 MeV level in agreement with our $J^{\pi} = 1^+$-3^+ assignment.

Besides the preceding levels, 18 $l=1+3$ transitions are observed between 3.18 and 5.15 MeV. Among them, the levels at 3.733, 4.080, 4.613, 5.078, and 5.102 MeV are seen for the first time. All of these levels receive $J^{\pi} = 1^+$-3^+ assignments.

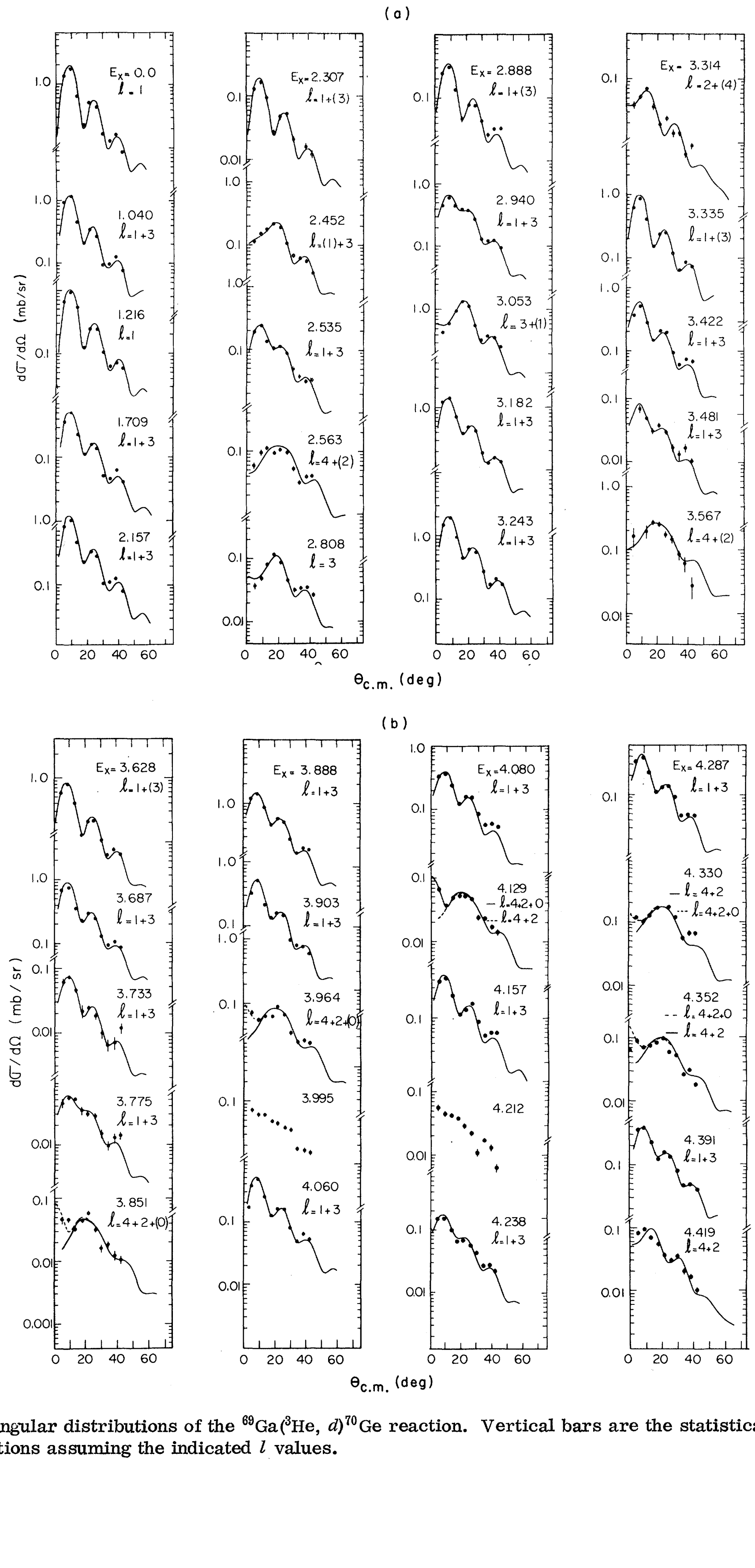

FIG. 2. (a)–(c) Angular distributions of the $^{69}Ga(^3He, d)^{70}Ge$ reaction. Vertical bars are the statistical errors. Curves are DWBA predictions assuming the indicated l values.

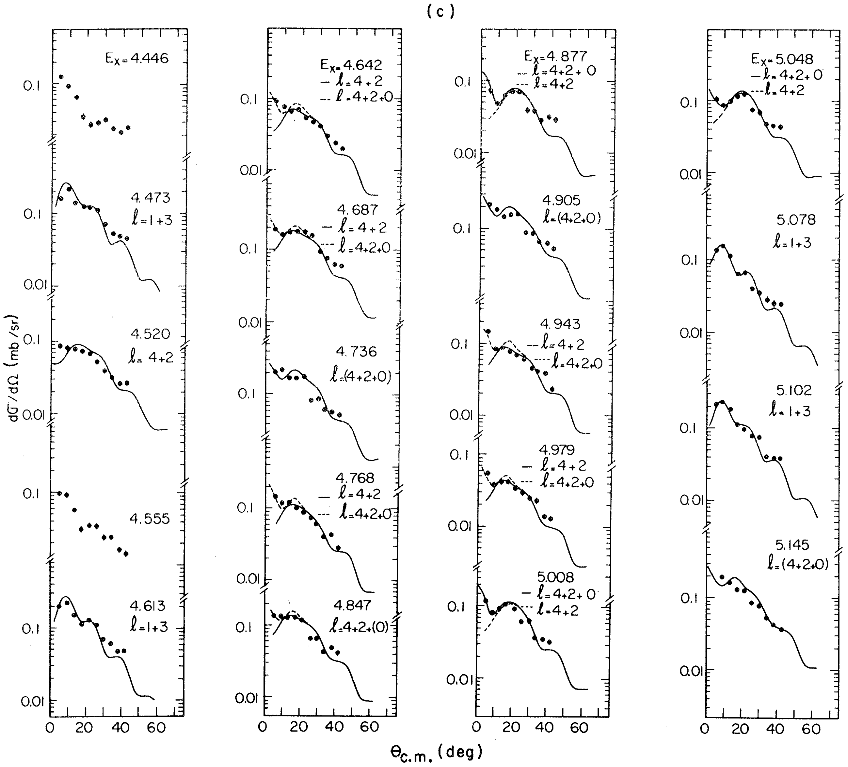

FIG. 2. *(Continued).*

5. $l=2+4$ angular distributions

The levels at 2.563 and 3.314 MeV are found to be populated by $l=4+2$ transitions. The selection rules limit the spin-parity values to $J^{\pi}=2^{-}$-6^{-} for an $l=4$ transfer. In the first case, if the very weak $l=2$ component does exist, it restricts the limits to $J^{\pi}=2^{-}$-4^{-}. The previously proposed[9] value was $J^{\pi}=(3^{-})$. The $l=4$ admixture observed for the level at 3.314 MeV is very weak and could very well be absent; this would lead to $J^{\pi}=0^{-}$-4^{-} in agreement with the result of Hinrichsen[4] $J=(1)$.

Eighteen other levels, 10 of which are new, are observed with $l=4+2$ or $4+2+(0)$ patterns: $J^{\pi}=2^{-}$-4^{-} assignments are then proposed. However, the presence of an $l=0$ admixture seems more plausible for the levels at 4.129, 4.877, 5.008, and 5.048 MeV. This would mean that we observe $g_{7/2}$ transitions and lead to $J^{\pi}=2^{-}$ for these four levels.

6. Comparisons with recent ${}^{69}Ga({}^{3}He,d){}^{70}Ge$ results and with the (α,t) reaction

A similar study of the same reaction at 22.5 MeV incident energy, has been published by Labrie, Habib, and Preibisz.[10] Levels were observed up to 4.293 MeV excitation energy. As compared to the present work, there is a good qualitative agreement for the observed spectrum and a very good agreement for the measured spectroscopic factors for the angular distributions reported in our work as pure $l=1$ or 3 transitions. However, some discrepancies appear.

First, the excitation energies reported in Ref. 10 are systematically higher than ours. The difference increases slowly with excitation energy from 4–7 keV in the 2.5–3 MeV region to 13–15 keV in the 4 MeV region. As a result, the last two levels observed by Labrie *et al.* at 4.253 and 4.293 MeV appear as new levels, while our results are in good agreement with the known[9] levels at 4.242 and 4.282 MeV. During our study of the ${}^{69}Ga(\alpha,t){}^{70}Ge$ reaction (see discussion later), the energy calibration was performed again: The corresponding excitation energies given in Table II (column 2) appear in good agreement with our $({}^{3}He,d)$ results.

Second, discrepancies appear concerning all of the negative-parity levels reported in our work below 3.9 MeV. The first of them at 2.563 MeV is not reported; the three others at 3.314, 3.567, and 3.854 MeV are reported as populated by an $l=3$ transfer. This would mean that the parity of these levels is positive, but the only published fit (for the 3.314 MeV level) is poor.

TABLE II. Comparison of some ^{70}Ge excitation energies and yields measured for the (α,t) reaction (this work) with the results of the $(^3\mathrm{He},d)$ reaction (this work and Ref. 10).

E_x (keV) $(^3\mathrm{He},d)$ [a]	(α,t) [a]	$(^3\mathrm{He},d)$ [b]	$N(\alpha,t)$ Exp. [a]	Calc. [c]	Calc. [d]
0	0	0	630	400(1)	430
1040	1035	1041	390	580(+)	200
1216	1215	1217	200	170(1)	180
1709	1705	1709	240	270(+)	80
2157	2152	2159	620	430(+)	180
2307	2310	2309	25	25(1)	25
2452	2449	2455	900	900(3)	1260
2535	2533	2539	300	280(+)	510
2563	2564		1435	1310(4)	
2808	2806	2811	500	456(3)	454
2888	2887	2892	30	44(4)	50
2941	2946	2950	1200	1160(+)	1950
3053	3054	3054	4620	4680(3)	3850
3182	3193	3187	570	790(+)	210
3243	3240	3246	470	645(+)	280
3335	3337	3342	130	120(1)	140
3628	3631	3638	90	100(1)	110
3687	3680	3694	450	360(+)	100
3854	3851	3866	500	410(4)	260
3888 3903	3897	3898 3916	930	940(+)	230
3964	3967	3975	470	740(4)	
4330	4335		1350	1370(4)	
4687	4688		830	1000(4)	
5048	5055		605	900(4)	

[a] This work.
[b] Reference 10.
[c] Intensity obtained using our $(^3\mathrm{He},d)$ spectroscopic factors (see text). The character of the transition is indicated in parentheses: 1 means $l=1$, 3 means $l=3$, + means $l=1+3$, 4 means predominantly $l=4$.
[d] Intensity obtained using spectroscopic factors of Ref. 10.

Finally, all of the levels reported in our work, populated by mixed $l=1$ and $l=3$ transfer, are reported in Ref. 10 as populated by pure $l=1$ transfer.

This last discrepancy can be explained by the fact that the matching conditions of orbital angular momentum favor the $l=1$ transfer; the shape of the angular distribution for a transition with about the same spectroscopic intensity for $l=1$ and $l=3$ differs from the shape corresponding to a pure $l=1$ transition mainly in the region of $\theta\approx 20°$ where the $l=3$ contribution tends to fill in the $l=1$ minimum. The possibility of detecting the $l=3$ component depends, therefore, very critically upon the quality and statistics of the data in this region. In order to test the validity of our propositions, data have been taken at 9° and 21° for the ^{69}Ga$(\alpha,t)^{70}$Ge reaction at an incident energy of 39.35 MeV. Matching conditions of orbital angular momenta are then known to favor $l=3$ and 4 transitions for this reaction which therefore appears as a useful qualitative tool for our purpose. A comparison between the number of counts in the integrated peaks of the (α,t) spectrum at 9° and the spectroscopic factors obtained for the transitions considered as pure in the two $(^3\mathrm{He},d)$ studies, permits to conclude that the approximate yield for a unit spectroscopic factor, of the (α,t) reaction is: 200 counts for $l=1$, 400 for $l=3$, and 1000 for $l=4$.

The energies found for most of the levels observed in the (α,t) reaction between 0 and 4 MeV excitation energy are compared in Table II to the energies measured in the two $(^3\mathrm{He},d)$ reactions. Comparison is also made for three levels strongly populated between 4 and 5.05 MeV. In column 4 of this table is given the integrated number of counts in the peaks of the experimental (α,t) spectrum. In columns 5 and 6, calculated values (equal to $200S_1+400S_3$ for mixed $l=1+3$ transitions and $1000S_4$ for pure $l=4$ transitions) are given using, respectively, the spectroscopic factors determined in the two $(^3\mathrm{He},d)$ studies. This procedure cannot account for exact Q effects in the yields of both the (α,t) and $(^3\mathrm{He},d)$ reactions but gives a direct qualitative confirmation of our propositions. We consider that the agreement between our $(^3\mathrm{He},d)$ and (α,t) results is good and implies that there is really mixing of $l=3$ in many $l=1$ transitions. This is particularly evident for the transitions feeding the levels at 1.709, 2.157, 3.182, 3.687, and 3.854 MeV where the (α,t) yield cannot be correctly accounted for with the spectroscopic factors of Ref. 10. The only levels for which general agreement is found are those corresponding to transitions determined as pure $l=1$ or $l=3$ in our work.

B. ^{75}As$(^3\mathrm{He},d)^{76}$Se results

1. *General analysis*

Seventy-one levels are populated up to 5.1 MeV among which 46 are observed for the first time. The results are reported in Table III together with the previously known[13-23] energy, spin, and parity values. Excellent agreement is found with the previously known energies; particularly, several levels between 3 and 4.5 MeV previously proposed by Ladenbauer-Bellis, Bakhru, and Bakhru[20] are confirmed by this work.

2. *l=1 angular distributions*

The ground state and the known 0_2^+ level at 1.122 MeV are populated by $l=1$ transitions (Fig. 3) the

TABLE III. Levels observed in the reaction $^{75}As(^3He, d)^{76}Se$ at 25 MeV.

Level No.	Present work E_x (MeV)	l	J^{π} [b]	Literature [a] E_x (MeV)	J^{π}	$(2J+1)C^2S$ (Present work) $2p_{3/2}$ [c]	$1f_{5/2}$	$1g_{9/2}$	$2d_{5/2}$	$3s_{1/2}$
0	0	1	0^+-3^+	0	0^+	1.04				
1	0.558	1+3	1^+-3^+	0.559	2^+	0.16	0.89			
2	1.122	1	0^+-3^+	1.1224	0^+	0.58				
3	1.216	1+3	1^+-3^+	1.2163	2^+	0.21	0.05			
4	1.334	3	1^+-5^+ [d]	1.331	4^+		0.21			
				1.690	(3^+)					
				1.780	(1^+)					
5	1.7905	1+3	1^+-3^+	{1.788, 1.791}	2^+	0.34	0.41			
				1.883	$(0, 3, 4)^+$					
				1.942						
6	2.029	3	1^+-5^+ [d]	2.026	4^+		0.15			
				2.048						
				2.059						
				2.088						
7	2.128	1+3	1^+-3^+ [e]	2.1275	$(1-3)^{\pm}$	0.13	0.73			
8	2.168	1+3	1^+-3^+	2.1715		0.03	0.01			
				2.21						
				2.264	(6^+)					
				2.29	$\pi=-$					
				2.347	$(2, 3, 4)^+$					
				2.364	$(2, 3, 4)^+$					
				2.389						
9	2.433	4	2^--6^-	2.430	3^-			1.32		
				2.446						
				2.454						
10	2.517	1+3	1^+-3^+	2.514	$\pi=+$	0.24	0.10			
				2.527						
				2.542	$(1^-, 2^-, 3^-)$					
11	2.616	3	1^+-5^+ [d]				0.60			
				2.656						
12	2.671	2+4	2^--4^-	2.6701				0.23	0.15	
13	2.830	4(+0)	2^--4^-					2.35		<0.04
14	2.862	4+2	2^--4^-	(2.866)				1.73	0.18	
				2.890						
15	2.923	3	1^+-5^+ [d]				0.14			
16	2.956	4(+2)	3^--6^-	2.949				0.34	<0.02	
				2.990						
17	3.022	1+3	1^+-3^+			0.03	0.03			
				3.068						
18	3.086	1+3	1^+-3^+			0.11	0.11			
				3.16						
19	3.198	1+3	1^+-3^+			0.32	0.59			
20	3.212	1+3	1^+-3^+			0.42	1.82			
21	3.268	4+2	2^--4^-	3.272	(8^+)			1.67	0.18	
22	3.295	1+3	1^+-3^+	3.30	$(\pi=-)$	0.22	0.89			
23	3.345	1+3	1^+-3^+	3.349		0.64	0.64			
24	3.378	1+3	1^+-3^+			0.43	0.05			
25	3.417	4	3^--6^-					2.50		
26	3.442	(1+3)	(1^+-3^+)			(0.11)	(0.16)			
27	3.467	1+3	1^+-3^+			0.59	1.37			
28	3.530	1+3	1^+-3^+	3.54		0.65	0.28			
29	3.558	(1+3)	(1^+-3^+)			(0.08)	(0.56)			
30	3.598	1+3	1^+-3^+	3.600		0.08	0.18			
31	3.634	(1+3)	(1^+-3^+)			(0.08)	(0.32)			
32	3.659	1+3	1^+-3^+			0.20	1.83			
33	3.700	1+3	1^+-3^+			0.49	1.16			
34	3.741	1+3	1^+-3^+			0.30	0.71			

TABLE III *(Continued)*

Level No.	Present work E_x (MeV)	Present work l	Present work J^{π} [b]	Literature [a] E_x (MeV)	Literature [a] J^{π}	$(2J+1)C^2S$ (Present work) $2p_{3/2}$ [c]	$1f_{5/2}$	$1g_{9/2}$	$2d_{5/2}$	$3s_{1/2}$
35	3.790	1(+3)	$\underline{0^+}-3^+$			0.66	<0.16			
36	3.808	1+3	$\underline{1^+}-3^+$			0.32	0.17			
37	3.856	1+3	1^+-3^+			0.21	0.85			
38	3.908	1+3	1^+-3^+	3.910		0.23	0.93			
				3.940						
39	3.955	1+3	1^+-3^+			0.14	0.94			
40	3.997	1+3	1^+-3^+			0.11	0.62			
				4.030						
41	4.054	1+3	1^+-3^+			0.44	0.67			
42	4.103	4+2(+0)	2^--4^-					0.42	0.02	<0.01
43	4.137	1+3	1^+-3^+	4.140		0.29	0.43			
44	4.184	{4+2 1+3	2^--4^- 1^+-3^+							
45	4.218	1+3	1^+-3^+			0.26	0.62			
46	4.250	{4+2 1+3	2^--4^- 1^+-3^+	4.27						
47	4.301	4+2	2^--4^-					0.24	0.13	
48	4.343	{4+2 1+3	2^--4^- 1^+-3^+							
49	4.375	{4+2 1+3	2^--4^- 1^+-3^+							
50	4.400	1+3	1^+-3^+			0.07	0.30			
				4.41						
51	4.425	1+3	1^+-3^+	4.420		0.18	0.41			
52	4.459	1+3	1^+-3^+			0.08	0.35			
53	4.475			4.49						
54	4.527									
55	4.567			4.570						
56	4.603	1+3	1^+-3^+			0.10	0.57			
57	4.647	1+3	1^+-3^+			0.15	0.60			
58	4.677	2+4	2^--4^-					0.65	0.12	
59	4.729	1+3	1^+-3^+			0.07	0.44			
60	4.755	1+3	1^+-3^+			0.06	0.43			
61	4.814	1+3	1^+-3^+			0.18	0.53			
62	4.836	1+3	1^+-3^+			0.10	0.31			
63	4.858	1+3	1^+-3^+			0.07	0.41			
64	4.911	1+3	1^+-3^+			0.11	0.32			
65	4.938									
66	4.974	1+3	1^+-3^+			0.14	0.81			
67	5.013	1+3	1^+-3^+			0.07	0.30			
68	5.043	2+4	2^--4^-					0.23	0.12	
69	5.091	2+4	2^--4^-					0.47	0.28	
70	5.510									
71	6.005									

[a] References 13–23.
[b] Underlined values refer to most probable assignments (see text).
[c] If $2p_{1/2}$ transfer is assumed, one can find $s_{1/2} \sim 1.17 s_{3/2}$.
[d] $J^{\pi}=4^+$ is the most probable assignment (see text).
[e] $J^{\pi}=1^+$ or 2^+ is the most probable assignment (see text).

intensity of the latter being 60% of the ground state one.

Another transition feeding a level at 3.790 MeV is well reproduced by an $l=1$ calculation. This is a new and strongly populated level for which we propose $J^{\pi}=\underline{0^+}-3^+$.

3. *l*=3 angular distributions

Two levels at 1.334 and 2.029 MeV were already known to have spin-parity $J^{\pi}=4^+$. These levels are populated by pure $l=3$ transfer in our reaction.

From the observation of quasipure $l=3$ patterns,

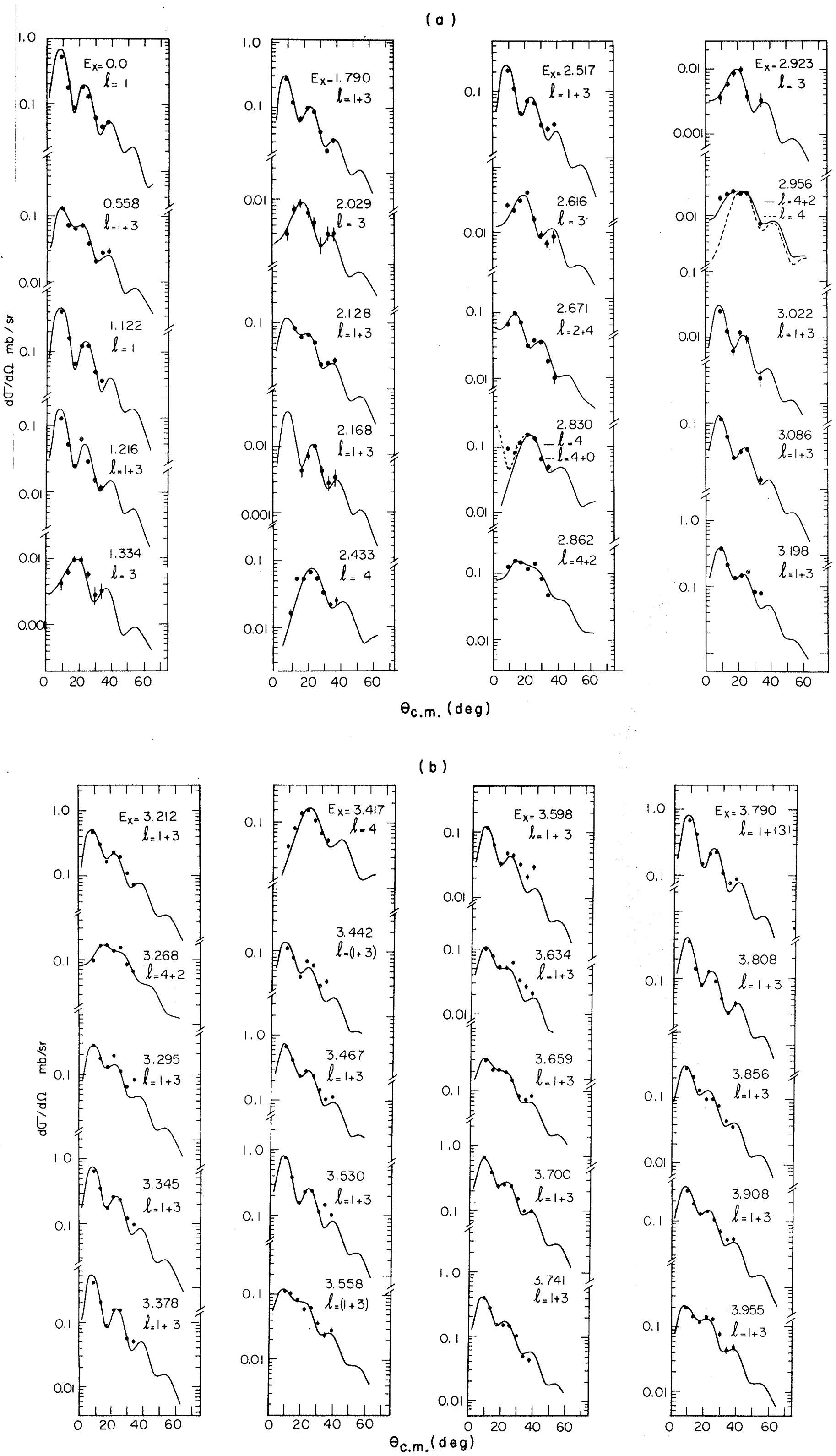

FIG. 3. (a)–(d) Angular distributions of the ^{75}As(^{3}He, d)^{76}Se reaction. Vertical bars are the statistical errors. Curves are DWBA predictions assuming the indicated l values.

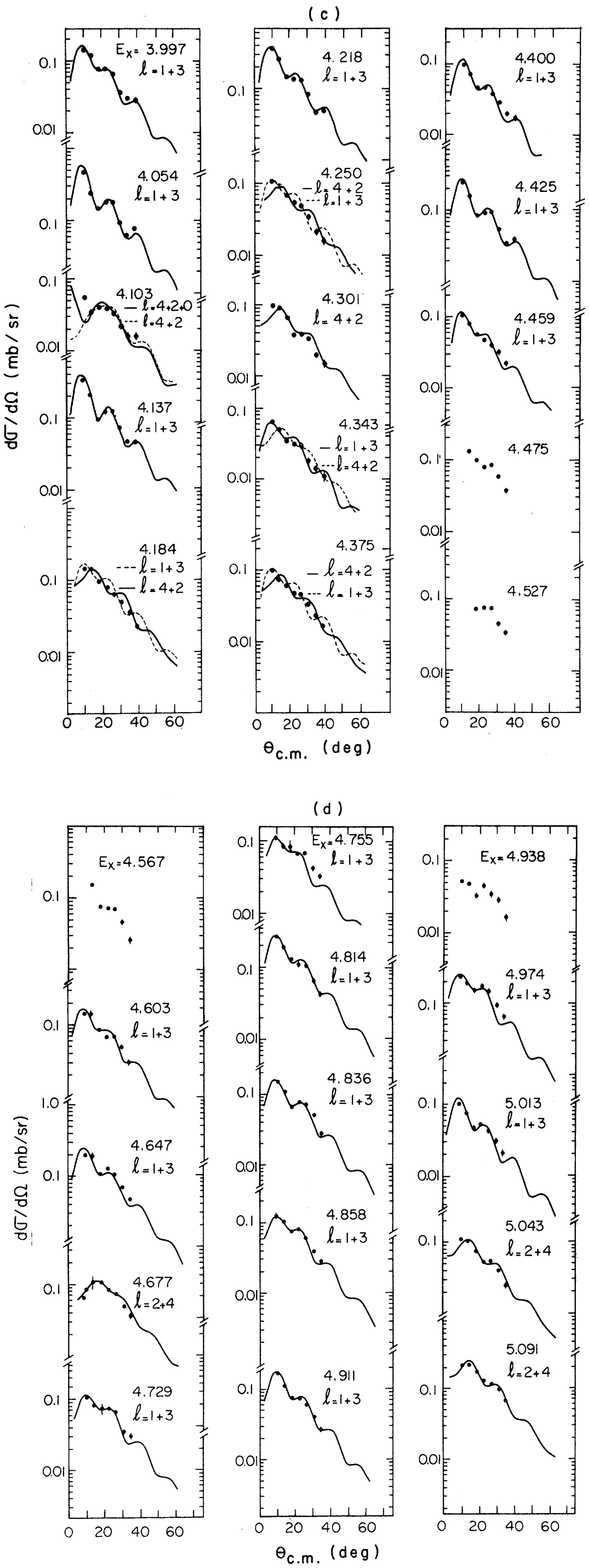

FIG. 3. *(Continued).*

the spin limits for the two new levels at 2.616 and 2.923 MeV are $J^\pi = 1^+$-4^+ and $J^\pi = 4^+$ may be proposed as a tentative value.

4. $l=1+3$ angular distributions

Unambiguous $l=1+3$ patterns are observed for 41 levels of ^{76}Se. The three known 2^+ levels at 0.558, 1.216, and 1.790 MeV are populated by such mixed transitions. It must be noticed that a level at 1.791 MeV, distinct from the known 2^+ level at 1.788 MeV, was proposed by Funel[13] and Ardisson *et al.*[14] The possibility that our reaction populates this level rather than the 1.788 MeV level cannot be excluded.

From the proposed values $J=(1, 2)$ of Funel[13] and $J^\pi = (1, 2, 3^-)$ of Ardisson *et al.*[14] we can deduce $J^\pi = 1^+, 2^+$ for the 2.128 MeV level populated by an $l=1+3$ transition. Among the previously known levels (see Table III), many were proposed in the work of Ladenbauer-Bellis[20] and are confirmed by our study. All of them receive $J^\pi = 1^+$-3^+ assignments as well as other new levels (see Table III) populated by $l=1+3$ transitions.

5. $l=2+4$ angular distributions

The first known negative-parity level ($J^\pi = 3^-$) at 2.433 MeV is populated by a pure $l=4$ transition. The level at 2.956 MeV is probably the level observed at 2.949 MeV by Landenbauer-Bellis.[20] The admixture of $l=2$ being very weak and doubtful, we can only deduce, assuming a $g_{9/2}$ transfer: $J^\pi = 3^-$-6^-. The same is true for the strong $l=4$ transition at 3.417 MeV $[(2J+1)C^2S=2.5]$. Other levels at 2.671, 2.830, 2.862 (confirmed by this work), 3.268, 4.103, 4.301, 4.677, 5.043, and 5.091 MeV, populated by $l=4+2$ transfer, receive $J^\pi = 2^-$-4^- assignments. For the 3.268 MeV level, this assignment seems to be in disagreement with the value $J^\pi = (8^+)$ proposed by Lieder and Draper[15] for a level observed at 3.272 MeV.

6. Ambiguous distributions

For four of the remaining levels, at 4.184, 4.250, 4.343, and 4.375 MeV, respectively, it is impossible to make a choice between $l=1+3$ and $l=2+4$ calculations, this being mainly due to too closely spaced levels and consequent doubtful separation. As indicated in Table III, these levels cannot receive J^π assignments from our data.

C. ^{79,81}Br(^{3}He,d)^{80,82}Kr results

The ^{79,81}Br(^{3}He, d)^{80,82}Kr reactions have been performed at 9° and 21° only, with the same incident energy of 25 MeV, on a natural sodium bromide target. This permits us to observe the first

TABLE IV. Levels observed in the reactions ^{79,81}Br(^{3}He, d)^{80,82}Kr.

			^{80}Kr				
E (MeV)	0.0	0.618	1.256	1.319	1.440		
$J^{\pi\,a}$	0^+	2^+	$2^{(+)}$	$0^{(+)}$	4^+		
I^b	1	0.25	0.90	0.42	0.06		
			^{82}Kr				
E (MeV)	0.0	0.777	1.475	1.487	1.820	1.885	1.962
$J^{\pi\,a}$	0^+	2^+	2^+	(0^+)	4^+		
I^b	1	0.30	0.60	0.38		0.40	0.20

^{a} References 24–30.
^{b} Peak intensity normalized to the ground-state one.

^{80}Kr and ^{82}Kr excited levels (0_1^+, 0_2^+, 2_1^+, 2_2^+, and 4_1^+ states) and to extend our systematics for these levels between $N=38$ and 46. Few $^{80-82}$Kr excited levels are actually known.[24–30] A recent compilation of the first known levels in this region appears in the work of Haderman.[24] We have reported in Table IV the levels observed in our spectra together with the J^π values previously known or proposed. Their respective yields, normalized to the ground-state one, at a laboratory angle of 9°, are also reported on the third line.

The levels at 1.256 [$J^\pi = 2^{(+)}$] and 1.319 MeV [$J^\pi = 0^{(+)}$] in ^{80}Kr, at 1.475 [$J^\pi = 2^+$], 1.487 [$J^\pi = (0^+)$], and 1.962 MeV in ^{82}Kr are confirmed by this work. A new ^{82}Kr excited level is proposed at 1.885 MeV. The levels at 1.319 (^{80}Kr) and 1.487 MeV (^{82}Kr) previously proposed[24] as the 0_2^+ states appear strongly populated (~40% of the ground-state cross section) as in the Ge-Se isotopes.

D. Discussion and comparison of the data

1. *Spectroscopic strengths*

The distribution of the observed spectroscopic factors is shown in Figs. 4(a) and 4(b) for ^{70}Ge and ^{76}Se, respectively. Similarities to the ^{72}Ge results (see Fig. 3 of Ref. 6) are obvious and will be emphasized in the discussion. Table V contains the observed strengths $G_{lj} = \sum_i (2J_i+1)(2J_0+1)^{-1}C^2S^i_{lj}$

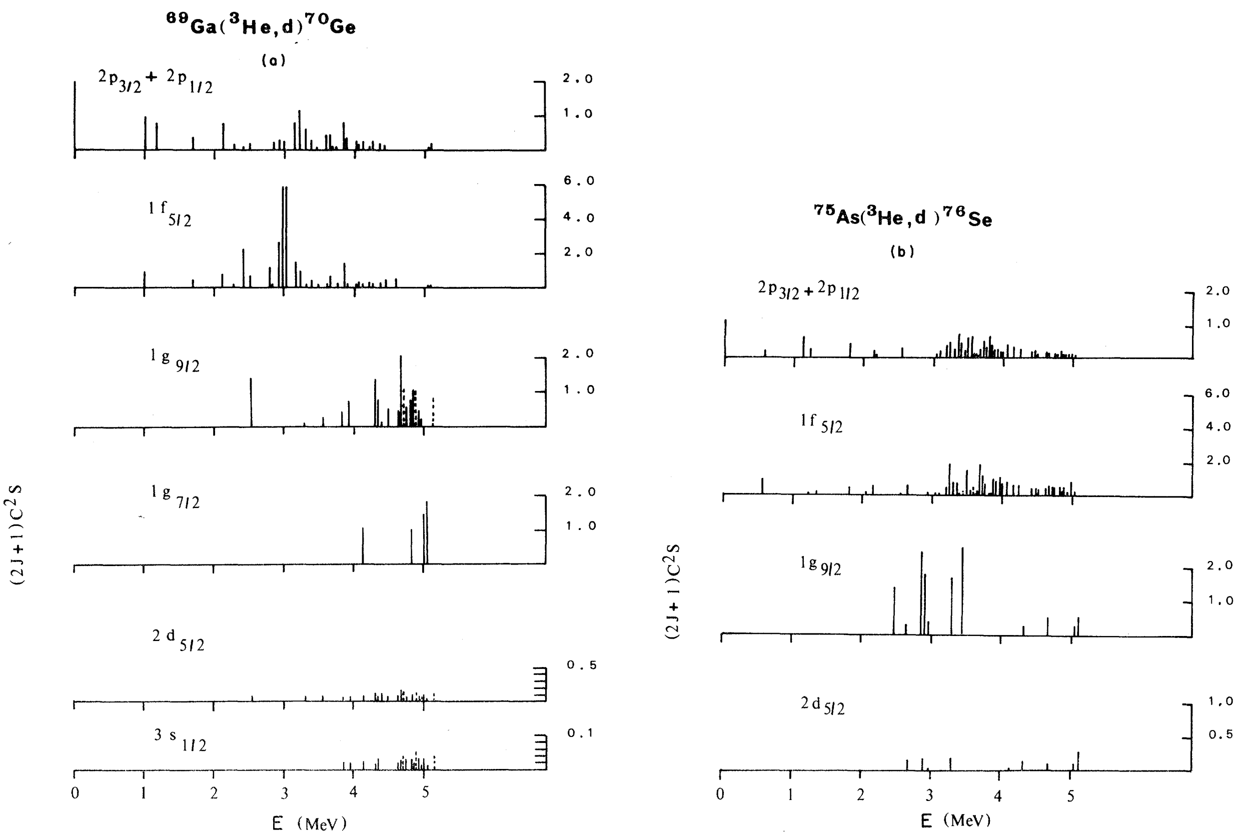

FIG. 4. Spectroscopic strengths distribution obtained for the ^{69}Ga(^{3}He, d)^{70}Ge [Fig. 5(a)] and ^{75}As(^{3}He, d)^{76}Se [Fig. 4(b)] reactions. The $(2J+1)C^2S$ values for each l transition are represented by the length of the vertical bars. The strong $l=3$ intensity for the unseparated 3.047–3.059 MeV ^{70}Ge levels has been arbitrarily represented by two equal bars for height convenience [Fig. 4(a)].

TABLE V. Summed strengths for levels in ^{72}Ge, ^{70}Ge, and ^{76}Se up to 5.2 MeV excitation: $\sum_i (2J_i+1)(2J_0+1)^{-1}C^2S_i$.

	$2p$	$1f_{5/2}$	$2p+1f$	$1g_{9/2}$	$1g_{7/2}$	$2d_{5/2}$	$3s_{1/2}$
^{69}Ga(^{3}He, d)^{70}Ge [a]	3.29	7.41	10.70	2.66 (3.17) [b]	1.06	0.23	0.08
^{71}Ga(^{3}He, d)^{72}Ge [c]	3.90	7.40	11.30	2.40 (2.90) [b]	1.06	0.23	0.05
Sum-rule limit for Ga target	3	6	9	10	8	6	2
^{75}As(^{3}He, d)^{76}Se [a]	2.82	6.12	8.94	3.04		0.27	~0.01
Sum-rule limit for As target	2	5	7	10	8	6	2

[a] Uncertain spectroscopic factors (given in parentheses in Tables I and III) are not included.
[b] Intensity obtained if one does not distinguish between the $1g_{9/2}$ and $1g_{7/2}$ orbitals.
[c] Reference 6.

($J_0=\frac{3}{2}$ being the target ground-state spin). It is clear that the strengths for the $1g_{7/2}$, $2d_{5/2}$, and $3s_{1/2}$ orbitals are far from being exhausted. The $g_{9/2}$ strength is highly fragmented, mainly for ^{70}Ge (as for ^{72}Ge), and only 30% of the sum-rule limit is observed in the three nuclei. The distribution of the observed $f_{5/2}$ spectroscopic factors shows a high concentration on two or three levels for ^{70}Ge, as for ^{72}Ge. This intensity is more fragmented for ^{76}Se. Two distinct groups of levels appear in the $l=1$ transitions but this feature is not as striking as in ^{72}Ge. These two groups may arise from $j=\frac{3}{2}$ and $j=\frac{1}{2}$ transfers as was already discussed.[6]

The summed strengths $(2p+1f)$ (see Table V) show a very good coherency for the three nuclei as comparable values are found for ^{72}Ge and ^{70}Ge, and a value two units smaller is measured for ^{76}Se in agreement with the sum-rule limit for a $Z=33$ target. As in the ^{72}Ge results analysis,[6] this summed strength exceeds the sum-rule limit by about 20% which is within the experimental uncertainties; we have already[6] pointed that a slight overestimation of the $l=3$ component in mixed $l=1+3$ DWBA calculations could also explain this fact.

In the previous analysis of the ^{71}Ga(^{3}He, d)^{72}Ge reaction,[6] a simple model was proposed which could account for the measured values of the summed strengths and the spectroscopic factors of the first two 0^+ states in ^{72}Ge. Taking for the target ground-state a wave function of the type:

$$\psi_{\rm Ga}=\alpha(2p_{3/2})^3{}_{3/2}+\beta(1f_{5/2})^2{}_0(2p_{3/2}), \tag{1}$$

the following orthogonal ^{72}Ge wave functions were written:

$$\psi_{0_1^+}=\alpha'(p_{3/2})^4{}_0+\beta'(f_{5/2})^2{}_0(p_{3/2})^2{}_0, \tag{2}$$

$$\psi_{0_2^+}=\beta'(p_{3/2})^4{}_0-\alpha'(f_{5/2})^2{}_0(p_{3/2})^2{}_0, \tag{3}$$

our spectroscopic factors being compatible with two sets of numerical solutions $\alpha'=(0.88)^{1/2}$ $[\beta'=-(0.12)^{1/2}]$ and $\alpha'=(0.28)^{1/2}$ $[\beta'=(0.72)^{1/2}]$. This model predicts a total strength $G_{1,3/2}=2\beta'^2$ for the ^{72}Ge(^{3}He, d)^{73}As reaction. As the intensity recently measured by Betts *et al.*[31] for the $J^\pi=\frac{3}{2}^-$ ground state of ^{73}As is 1.03, this necessarily leads to $\beta'^2\geq 0.5$. Hence, only one set of solutions is possible:

$$\psi_{0_1^+}(^{72}\text{Ge})=(0.28)^{1/2}(p_{3/2})^4{}_0+(0.72)^{1/2}(f_{5/2})^2{}_0(p_{3/2})^2{}_0 \tag{4}$$

and the orthogonal admixture for the excited 0^+ state.

We have tried to apply this model for the ^{70}Ge and ^{76}Se results. It appears, however, impossible to account for the observed spectroscopic strengths with such wave functions. This suggests the existence in these nuclei of sizable distinct components such as $(p_{1/2})^2(p_{3/2})$ or the coupling of single-particle components with collective excitations as in the recent results of Paar[32] for ^{69}Ga. However, these conclusions, as well as the result contained in (4) for the ^{72}Ge ground state, mean that the $f_{5/2}$ or $p_{1/2}$ subshells are filling before the $p_{3/2}$ subshell is filled. This is qualitatively consistent with the existence of $J^\pi=\frac{3}{2}^-$ ground states observed for all of the nuclei between $Z=29$ and 37 except ^{71}As and ^{83,85}Rb. This would mean also a more collective structure of the concerned nuclei and possible unstable deformations when one considers the high density of the Nilsson orbitals crossing in this region.

2. *Analogies between some levels*

As already discussed in Secs. III A and B for some 0^+ and 4^+ levels, striking analogies appear between ^{70,72}Ge, ^{76}Se, and ^{80,82}Kr levels. They are obvious when looking at the distribution of the spectroscopic factors (Fig. 4) and at the spectroscopic characteristics retained in Tables I and III. The most probable analogies appear as follows:

The first $J^\pi=0^+$ excited level (0_2^+) at 1.216, 0.690, 1.122, 1.320, and 1.487 MeV in ^{70,72}Ge, ^{76}Se, ^{80,82}Kr, respectively, is strongly populated in the reaction.

A weak pure $l=1$ transition is found for the levels at 2.307 and 2.029 MeV in ^{70}Ge and ^{72}Ge, respectively. As the level at 2.307 MeV in ^{70}Ge (Refs. 4 and 11) has been previously proposed as $J^\pi=0^+$ level, these two levels may be the 0_3^+ level in ^{70}Ge and ^{72}Ge. There is a good correspondence between this level and the calculated 0_2^+ state (20% quasiparticle vacuum coupled to the $N=0$ phonon, plus 50% quasiparticle vacuum coupled to the two phonon state) in the quasiparticle calculations of de Vries.[2]

A pure $l=1$ transition is found for the 2.888 and 2.897 MeV levels in ^{70,72}Ge. A value $J=0$ has been previously proposed for the ^{70}Ge level[4] but there may be some arguments[6] against the value $J=0$ for the ^{72}Ge level.

A strong pure $l=1$ transition populates the levels at 3.628, 3.614, and 3.790 MeV in ^{70,72}Ge and ^{76}Se, respectively. They could then receive $J^\pi=(0)^+$ as a tentative value.

Levels populated by both $l=1$ and $l=3$ transitions have $J^\pi=1^+$-3^+. We have pointed that the $l=1$ transitions above 3 MeV excitation energy are probably $2p_{1/2}$ transfer (see Sec. III D 1). This seems unambiguous for the most strongly populated levels which then receive $J^\pi=1^+$-2^+ assignments. They are at 3.182, 3.243, and 3.888 MeV in ^{70}Ge and at 3.036 and 4.047 MeV in ^{72}Ge.

A part of the strong $l=3$ spectroscopic intensity measured at 3.053 MeV in ^{70}Ge must belong to the $J^\pi=(3^+)$ level known[9] at 3.047 MeV. There is a corresponding $J^\pi=1^+$-3^+ level at 3.094 MeV in ^{72}Ge with a strong $l=3$ spectroscopic intensity.[6] It may be also a $J^\pi=3^+$ level.

Levels populated by pure $l=3$ transition may have $J^\pi=4^+$ values. This is the case of the levels at 2.452, 2.808, and 3.059 MeV in ^{70}Ge, 2.466, 3.073, and 3.179 MeV in ^{72}Ge, and 1.334, 2.029, 2.616, and 2.923 MeV in ^{76}Se.

IV. INTERPRETATION OF THE RESULTS

A. Properties and behavior of the first excited states

In order to investigate the structure of the nuclei in the Ge-Se region, we have tried to gather data either from the present or from previous experimental studies.

First, we show on Fig. 5, the relative intensities of the 0_2^+, 2_1^+, 2_2^+, and 4_1^+ levels normalized to the

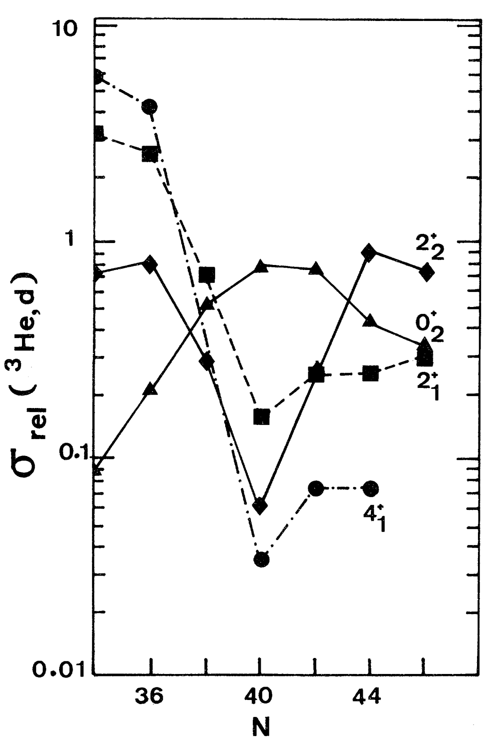

FIG. 5. Cross sections for the 0_2^+, 2_1^+, 2_2^+, and 4_1^+ states (normalized to their respective ground-state one) measured for the (^{3}He, d) reaction between $N=34$ and 46. Data are from our work (this study and Ref. 6 and Ref. 33).

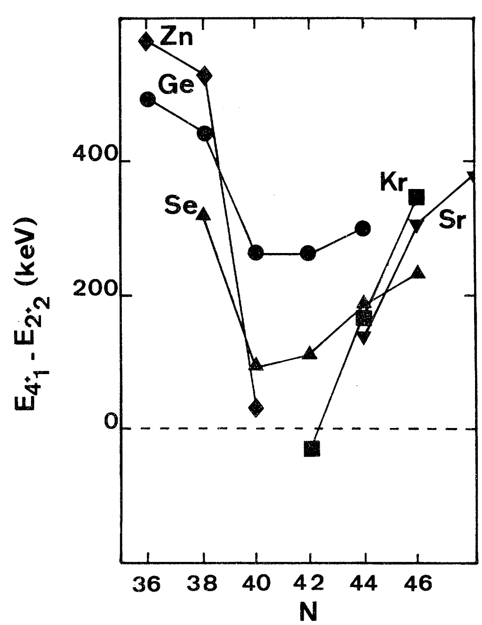

FIG. 6. Behavior of the quantity $E_{4_1^+}-E_{2_2^+}$ between $N=36$ and 48 for Zn, Ge, Se, Kr, and Sr isotopes.

ground state, observed in the (^{3}He, d) reaction between $N=34$ and 46. The ^{69,71}Ga, ^{75}As, and ^{79,81}Br (^{3}He, d) data are from the present work and Ref. 6. The ^{63,65}Cu(^{3}He, d)^{64,66}Zn results are those of Ford *et al.*[33] A deep minimum appears at $N=40$ for the 2^+ and 4^+ states with variations of one or two orders of magnitude. On the contrary, a broad maximum presented by the 0_2^+ state at $N=40$ clearly indicates a different structure for this state. According to the data of Ref. 11 for ^{70,74}Ge and Ref. 34 for ^{68}Ge, respectively, this strong variation exists also for the (p, t) transition leading to the 0_2^+ level of the Ge isotopes. Figure 6 shows the behavior of the difference $E_{2_2^+}-E_{4_1^+}$ with variation of N: Kumar (Ref. 7) found this quantity to be correlated with prolate-oblate solutions difference. Clearly, the sign of this quantity tends to be inverted around $N=40$–42. Figure 7 shows that a local minimum exists at $N=40$ for the energy of the 0_2^+ state for all of the nuclei Zn, Ge, Se, and Kr. The energy values of the 0_2^+ states in ^{80}Kr and ^{68}Ge have been taken from our results: See Sec. II C and Ref. 34. Nolte[35] has reported systematics of the root mean square deformation $\beta_{\rm rms}$ of the ground state. Rather large deformations ($\beta_{\rm rms}$ ~ 0.3 to 0.4) appear between $N=40$ and 44 for all of the nuclei.

According to some Kumar's predictions[7] the first three characteristics reported above may be considered as an indication of a prolate to oblate transition.

The last two systematics have been retained by Cailliau *et al.*[8] as criteria to characterize in heavier nuclei a zone of critical or "supersoft" nuclei

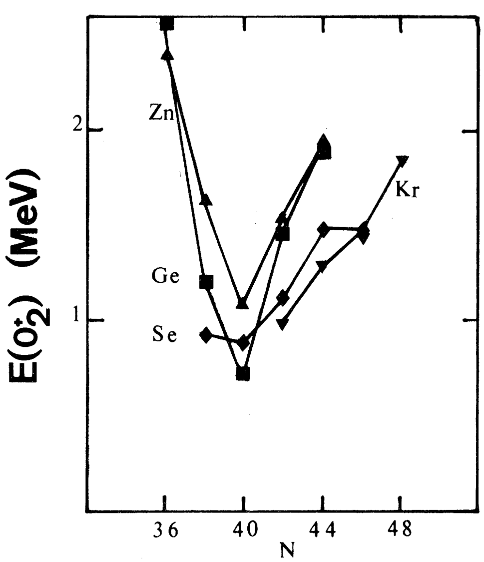

FIG. 7. Behavior of the first excited 0^+ state energy between $N=36$ and 48 for Zn, Ge, Se, and Kr isotopes.

based on the coexistence of spherical and deformed tendencies.

B. Hartree-Fock calculations

In order to test these last conclusions and to investigate theoretically the structure of the Ge isotopes, we have performed a constrained Hartree-Fock (HF) calculation using Skyrme's effective interaction.[36,37] The latter can be written as the sum of a two- and a three-body contact force. The matrix elements of the two-body term in momentum space are

$$\langle \vec{k}|U_2|\vec{k}'\rangle = t_0(1+x_0P_\sigma)+\tfrac{1}{2}t_1(\vec{k}^2+\vec{k}'^2) + t_2\vec{k}\cdot\vec{k}' + i\,w_0(\vec{\sigma}_1+\vec{\sigma}_2)\cdot(\vec{k}\times\vec{k}'),$$

where P_σ is the spin exchange operator.

The three-body term is

$$U_3 = t_3\delta(\vec{r}_1-\vec{r}_2)\delta(\vec{r}_2-\vec{r}_3).$$

The parameters of the interaction used in our calculations are those of the parametrization SIII of the Skyrme interaction[38] and are listed below:

$$t_0=-1128.75\ \mathrm{MeV\,fm^3},\quad t_1=395\ \mathrm{MeV\,fm^5},$$
$$t_2=-95\ \mathrm{MeV\,fm^5},\quad t_3=14000\ \mathrm{MeV\,fm^6},$$
$$x_0=0.45,\quad w_0=120\ \mathrm{MeV\,fm^5}.$$

The treatment of the pairing correlations has been done approximately following the method proposed by Vautherin.[39] A constant gap Δ, equal to 1.3 MeV in our case, in agreement with the one extracted from experimental mass differences of neighboring nuclei, is used. At the BCS approximation, we have then, for the total energy:

$$E=E_{\rm HF}-\tfrac{1}{2}\Delta\sum_i U_iV_i\ ,$$

where U_i and V_i are the usual occupation probabilities.

We have performed two kinds of calculations. In the first the HF wave functions have been expanded on a deformed harmonic oscillator basis with axial symmetry (seven major shells), thus allowing the investigation of axially symmetric shapes only. In the second the stability of the prolate and oblate minima has been tested with respect to triaxial (γ) deformations. In order to do this a Hartree-Fock code[40] has been used, where the HF Hamiltonian is diagonalized in a Cartesian harmonic oscillator basis (seven major shells). In order to obtain the energy of the nucleus outside the equilibrium deformations, a constraint of the quadrupole moment $Q_{20}=\langle 2z^2-x^2-y^2\rangle$ was imposed. The results of the calculation are plotted in Fig. 8, where the total energy of the germanium isotopes ($N=36$–46) is given as a function of Q_{20}.

The most striking feature of these results is the

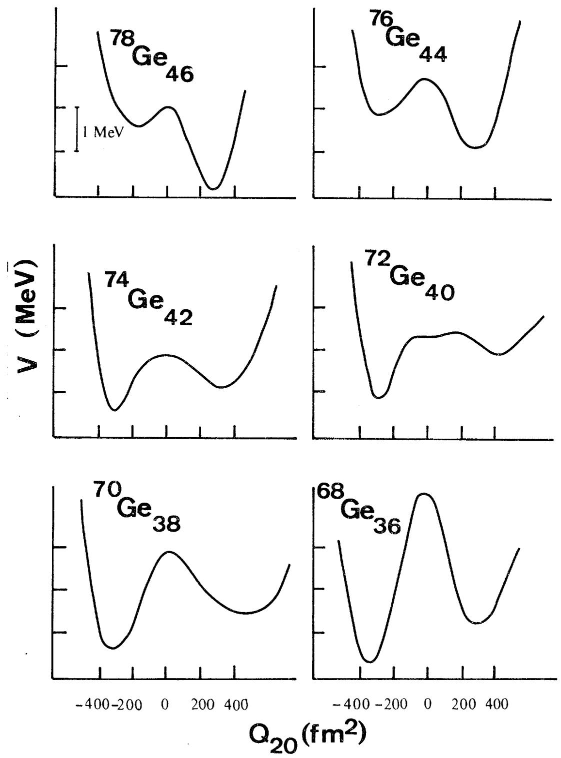

FIG. 8. Potential energy curves from our Hartree-Fock calculations for even-even Ge isotopes.

existence of a transition from oblate to prolate shapes with increasing number of neutrons. Thus the ^{68}Ge is clearly an oblate rotator, while the $N = 44$ and $N = 46$ isotopes are prolate ones. In between the transition proceeds gradually, with nuclei where the prolate-oblate energy difference is very small, and changes sign around $N = 42$. The common feature of these nuclei is that they are soft against β deformations and in the case of ^{72}Ge "critical" (according to the terminology of Ref. 8). In this nucleus, the spherical barrier is so small that the deformed minimum cannot be considered as stable.

The possible existence of oblate equilibrium shapes in this region has been first postulated by Dickmann, Metag, and Repnow[41] in the case of ^{72}Kr. Their calculation, using the Strutinsky prescription, starting from a Nilsson-type one-body potential, has predicted a maximum oblate deformation for $N = 38$, in the case of Kr isotopes. Identical results have been reported by Ragnarsson and Nilsson.[42] More recently, Tanaka and Tomoda,[43] using a pairing plus quadrupole interaction, predicted oblate equilibrium shapes for nuclei with neutron number between 38 and 44.

Our calculations together with our review of the experimental data seem to confirm these predictions. As a second step, we have performed triaxial HF calculations in order to investigate the stability of the axial minima of the potential energy surface against γ deformations. The nuclei examined were the isotopes with $N = 38-44$. In the case of ^{74}Ge, the calculation resulted in a shape with maximum triaxiality ($\gamma \sim 30°$), which lies 0.15 MeV lower than the oblate minimum. In every case examined the nucleus has been found particularly soft in the γ direction. This is in fair agreement with the results of Ref. 44 concerning the dynamical mean values of γ, extracted from the experimental data by the use of Davydov's model, and which lie around $\gamma = 30°$.

The main criticism which can be made, concerning the HF results, is the use of a constant gap Δ for the description of pairing correlations. As a matter of fact, the Hartree-Bogoliubov calculations of Gogny[45] have shown that the gap Δ varies substantially with deformation. However, the same author finds, in the case of the samarium isotopes, that the exact treatment of pairing correlations tends to lower the spherical barriers while leaving the oblate and prolate minima unchanged. So we hope that an exact HF + BCS calculation (which is not possible with a Skyrme force, under its present form, as this force has an antipairing rather than pairing effect) will not invalidate the general trends we have found.

V. CONCLUSIONS

The proton configuration states of ^{70}Ge and ^{76}Se have been investigated using the ^{69}Ga(^{3}He, d)-^{70}Ge, ^{69}Ga(α, t)^{70}Ge, and ^{75}As(^{3}He, d)^{76}Se reactions. Many new levels and spin-parity assignments or limits are proposed. Detailed comparison has been made with our published results of the ^{71}Ga(^{3}He, d)-^{72}Ge reaction. It has been shown that our previous model, which could be used to account for the observed strong transitions to the first 0^+ states and the summed strengths of our reaction in the case of ^{72}Ge, indicates an important admixture of proton configuration of the type $(f_{5/2})^{2n}{}_0(p_{3/2})^2{}_0$ for the nuclei of this region and of other probably more complicated configurations for nuclei other than ^{72}Ge.

An additional study of the ^{79,81}Br(^{3}He, d) reactions allowed us to observe the first excited states of the ^{80,82}Kr isotopes. Striking analogies have appeared between some ^{70,72}Ge, ^{76}Se, and ^{80,82}Kr levels up to 4 MeV excitation energy.

Systematics have been presented from our whole work or previous data leading to the following conclusions: the possibility of an oblate to prolate shape transition between $N = 36$ and 46 for the Ge-

Se nuclei; the possibility of a zone of critical or "supersoft" nuclei around $N = 40$ based on the coexistence of spherical, oblate, and prolate tendencies; the noncollective structure of the first excited 0^+ state in the even-even Ge-Se nuclei. Hartree-Fock calculations have been presented that confirm the above conclusions on the structure of the Ge-Se isotopes.

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