Excitation of ^{81}As by the ^{82}Se(t,α) reaction

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(Received 19 October 1981)

The level structure of ^{81}As is probed for the first time and many new states have been identified. Angular distributions were measured and compared with distorted-wave Born approximation calculations, in order to extract L values and spectroscopic factors. Most of the expected strength for pickup from the $2p$ and $1f_{5/2}$ orbitals is observed. The level structure of ^{81}As is fairly similar to that of ^{79}As but differs significantly from that of lighter As isotopes.

[NUCLEAR REACTIONS ^{82}Se$(t,\alpha)^{81}$As, $E=18$ MeV; measured $\sigma(E_\alpha,\theta)$. ^{81}As deduced levels, L, π, (J), spectroscopic factors. DWBA analysis. Enriched target.]

I. INTRODUCTION

The odd-even As isotopes have been the subject of a large number of experimental and theoretical investigations. However, most of the existing information is limited to the lighter isotopes with $A=71$, 73, 75, and 77.[1–7] In a previous communication we reported on the study of ^{79}As.[8] The present work presents our results for ^{81}As for which almost no information has been previously reported. The only existing information comes from β decay of ^{81}Ge and is limited to the g.s. and the 336-keV state.[9] The g.s. of ^{81}As was tentatively assigned as having $J^\pi=(\frac{1}{2},\frac{3}{2})^-$ based on the β transition to ^{81}Se g.s.

Much experimental evidence has been obtained in the past few years about the existence of a nuclear shape transition in the region $A=70-80$, e.g., the abrupt decrease in the energy of the first $\frac{9}{2}^+$ state in odd-A Ge, As, and Br isotopes, or the corresponding first 2^+ excitation in the even-even cores of Ge, Se, and Kr isotopes.[10] Additional evidence was given based on the variation of the (t,p) and (p,t) cross section as a function of N.[11] Theoretical calculations done by Kumar using the dynamic deformation theory,[12] and recent calculations of proton occupancies in the ground states of nuclei in this range[13] gave further support to the existence of a structural change around $N=40-44$. A survey of the even-even nuclei in the Ge region was recently given by Vergnes.[10]

We present here our results for the ^{82}Se$(t,\alpha)^{81}$As reaction. A level scheme for practically unknown ^{81}As is established. The observed excitation energies of the first and second $\frac{9}{2}^+$ states in ^{81}As are found to be similar to those in ^{79}As, in contrast to the behavior in other neighboring nuclei, i.e., Rb and Y.

II. EXPERIMENTAL PROCEDURE

The experiment was performed with an 18-MeV triton beam from the University of Pennsylvania tandem accelerator. The outgoing α particles were momentum analyzed with a multiangle spectrograph and recorded on K-1 nuclear emulsion plates in angular steps of 7.5 degrees. The target was enriched up to 87.8% in ^{82}Se and its areal density was 65 μg/cm^2.

An alpha particle momentum spectrum measured at a lab angle of 26.25 degrees is shown in Fig. 1. The energy resolution was about 25 keV full width at half maximum for 25-MeV α particles. Alpha

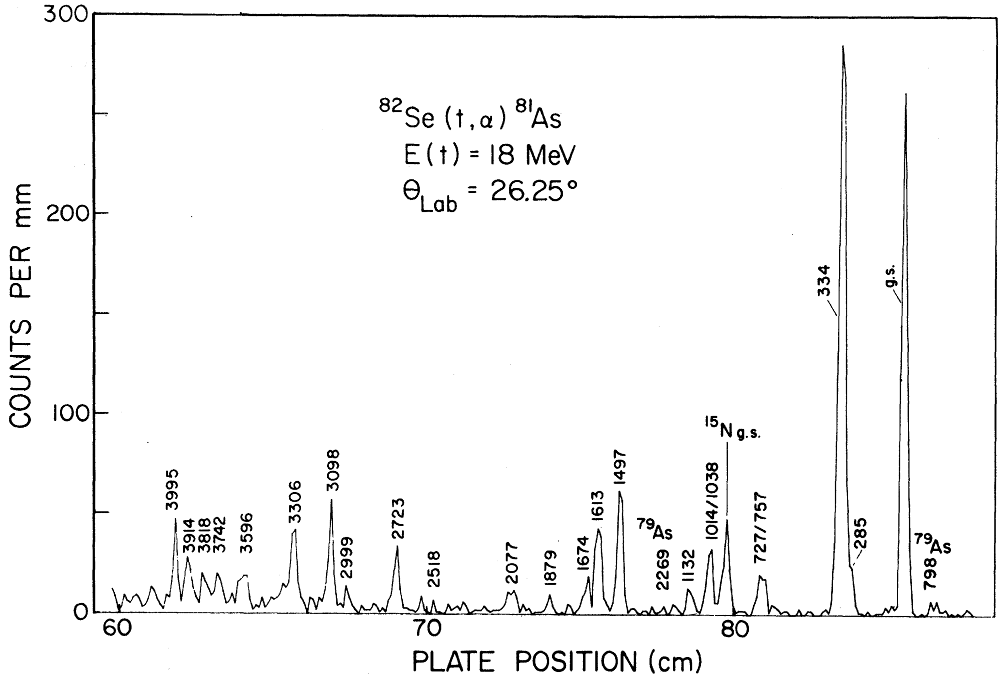

FIG. 1. Alpha spectrum from the ^{82}Se(t,α)^{81}As reaction measured at 18 MeV incident energy and at a lab angle of 26.25 degrees. The levels in ^{81}As are indicated by their excitation energies. Impurity groups are labeled according to their residual nucleus.

particle groups corresponding to the ground state and 23 excited states in ^{81}As have been identified up to an excitation energy of about 4 MeV. The excitation energies were obtained from the measured positions of the α groups at each angle and were averaged to get the values listed in Table I. A more detailed description of the experimental procedure was given in a previous report.[8]

A separate (t,α) run was performed on a natural Se target to assist in identifying impurity peaks due to the presence of small amounts of other stable Se isotopes in the ^{82}Se target. The Q value for the ^{82}Se(t,α)^{81}As reaction ($Q=7.467\pm0.006$ MeV) was determined by reference to the accurately known Q values for ^{76,77,78}Se(t,α) and ^{16}O(t,α). (Some of these impurity peaks are shown in Fig. 1.) The deduced mass excess for ^{81}As is -72528 ± 16 keV. This result is much more accurate than the mass excess of -72640 ± 100 listed for ^{81}As in the recent atomic mass table.[14]

III. ANALYSIS

Theoretical angular distributions were calculated using the local zero-range approximations to distorted-wave Born approximation (DWBA) by the computer code DWUCK.[15] The optical-model parameters used in the analysis are listed in Table II. These parameters were obtained from the analysis of the ^{87}Rb(t,α)^{86}Kr reaction[16] and successfully employed in analysis of the ^{80}Se(t,α) reaction.[8] The transferred protons were assumed to move in a Woods-Saxon potential well with radius parameter 1.26 fm and diffuseness parameter $a=0.65$ fm, the depth of the well being adjusted to give the correct binding energy.

Spectroscopic strengths $C^2S(l,j)$ given in Table I were calculated from the relation

$$\sigma_{\rm exp}(\theta)=NC^2S(l,j)\frac{\sigma_{\rm DWBA}(\theta)}{2j+1}\ ,$$

where $\sigma_{\rm exp}$ and $\sigma_{\rm DWBA}$ are the experimental and model differential cross sections and $S(l,j)$ is the spectroscopic factor for pickup of proton with orbital angular momentum l and total angular momentum j. A normalization factor of $N=18.2$ for the (t,α) reaction[17] was used in the present analysis.

Table I summarizes the excitation energies, maximum differential cross sections, l values, and spectroscopic strengths measured in the present study.

TABLE I. Summary of experimental results from the ^{82}Se$(t,\alpha)^{81}$As reaction and comparison with previous work.

	Present work						Previous work	
E_x (keV)	$\frac{d\sigma}{d\Omega}\Big\|_{max}$ (mb/sr)	l	$C^2S(2p_{3/2})$	$C^2S(1f_{5/2})$	$C^2S(3s_{1/2})$	$C^2S(1g_{9/2})$	E_x[c] (keV)	J^{π}[d]
0.0	1.68	1	1.37				0.0	$(\frac{1}{2},\frac{3}{2})^-$
285±6[b]	0.105	(1,3)	(0.09)	(0.17)				
334±4	2.2	3		2.75			336.2±0.4	
727±9	0.027	3		0.12				
757±9	0.032	4				0.07		
1014±5	0.055	1	0.07					
1038±6[c]	0.043	?						
1132±8[a]	0.046	?						
1497±8	0.29	1	0.24					
1613±5	0.25	0			0.08			
1674±5	0.12	(3)		(0.18)				
1879±8[b]	0.030	4				0.04		
2077±13[a]	0.11	(1,3)	(0.09)	(0.17)				
(2518±1)[b]	0.011	?						
2723±9	0.086	1	0.07					
2999±3	0.020	1	0.01					
3098±6	0.41	3		0.72				
3306±9[a]	0.30	?						
3480±7	0.073	0			0.02			
3596±12[a]	0.23	0			0.03			
3742±9	0.14	?						
3818±12	0.034	1	0.04					
3914±8	0.18	(0,3)		(0.35)	(0.07)			
3995±7	0.20	(0,3)		(0.38)	(0.05)			

[a]Doublet.
[b]Assumed.
[c]Observed only at few angles.
[d]Reference 9.

Also shown in the table is the previous information existing on the ^{81}As isotope. Figure 2 presents the angular distributions for the g.s. and five excited states in ^{81}As characterized by $l=1$ proton pickup. These are the states at 1014, 1497, 2723, 2999, and 3818 keV. None of these states was known previously. The lines are the calculated DWBA curves assuming $2p_{3/2}$ proton pickup. Either $\frac{3}{2}^-$ or $\frac{1}{2}^-$

TABLE II. Optical-model parameters used in the analysis of ^{82}Se$(t,\alpha)^{81}$As.

	Set	V (MeV)	r_0 (fm)	a (fm)	W (MeV)	r_0' (fm)	a' (fm)	r_{0c} (fm)	a_c (fm)	V_{SO} (MeV)
Tritons[a]	$T2$	122	1.23	0.76	12.0	1.63	0.68	1.25	0.65	
α particles[a]	$A2$	178	1.25	0.70	20.0	1.23	0.68	1.30	0.65	
Bound state proton		b	1.26	0.65				1.26		3.8

[a]Reference 16.
[b]Adjusted to give a binding equal to the experimental proton separation energy.

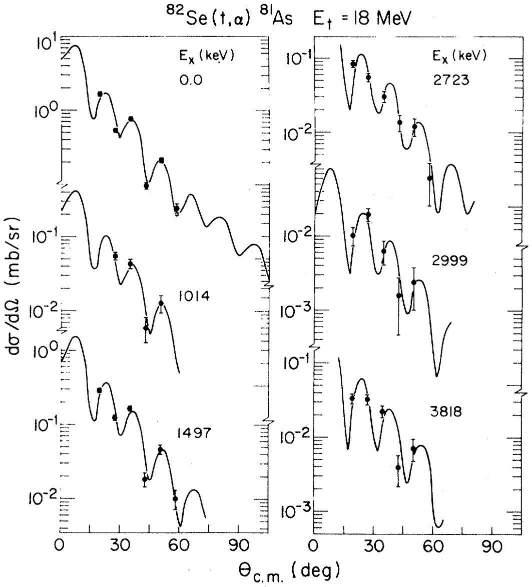

FIG. 2. Angular distributions exhibiting $l=1$ character in the ^{82}Se$(t,\alpha)^{81}$As reaction at 18 MeV incident energy. The solid DWBA curves were calculated for $2p_{3/2}$ proton pickup. The calculations used optical-model parameters of Table II.

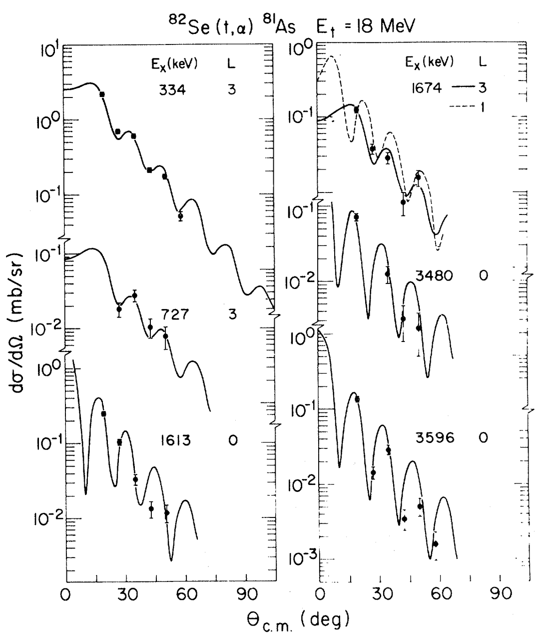

FIG. 3. Same as Fig. 2, but for $l=3$ and $l=0$ transitions. The calculated curves assume $1f_{5/2}$ and $3s_{1/2}$ proton pickup.

spin value is possible for the states shown in this figure. The g.s. of ^{81}As has been tentatively assigned as $(\frac{1}{2},\frac{3}{2})^-$ based on the β transition to ^{81}Se g.s. (Ref. 9) and thus is in agreement with the present assignment. It is, however, most likely that the g.s. of ^{81}As has $J^\pi=\frac{3}{2}^-$ since this is consistent with the g.s. spin values of all lighter As isotopes (with $A=73$, 75, 77, and 79). ^{71}As is the only exception, and known to have $\frac{5}{2}^-$ g.s. That difference may arise from the opening of the $1f_{5/2}$ neutron orbit in ^{71}As.

Figure 3 shows the angular distributions for six transitions exhibiting an $l=3$ or $l=0$ character in the (t,α) reaction. Only one of these excited states has been reported in the past, namely, the 334-keV state.[9] The data for this state are well fitted with an $l=3$ DWBA curve. Either $\frac{5}{2}^-$ or $\frac{7}{2}^-$ is possible for states populated with an $l=3$ transition, but based on the simple shell model, the low lying $l=3$ states are expected to correspond to $J^\pi=\frac{5}{2}^-$.

Only $\frac{1}{2}^+$ is possible for an $l=0$ transition. Thus

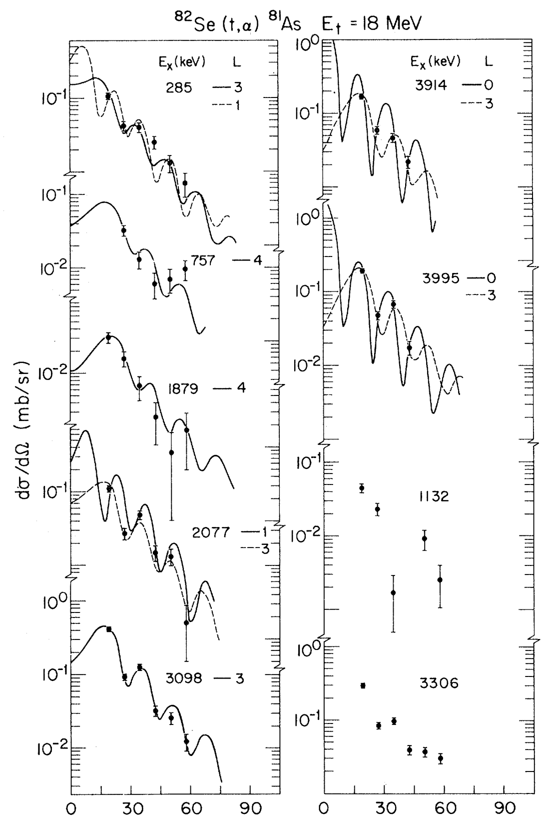

FIG. 4. Angular distributions for levels in ^{81}As reached in the ^{82}Se$(t,\alpha)^{81}$As reaction. The solid and dashed curves are the DWBA calculations giving the best fits to data.

TABLE III. Sums of spectroscopic strengths ΣC^2S and energy centroids $\langle E \rangle$ in keV measured in the ^{82}Se$(t,\alpha)^{81}$As reaction.

	2p		$1f_{5/2}$		$1g_{9/2}$		$3s_{1/2}$	
	ΣC^2S	$\langle E \rangle$	ΣC^2S	$\langle E \rangle$	ΣC^2S	$\langle E \rangle$	ΣC^2S	$\langle E \rangle$
Unnormalized[a]	1.80	438	3.59	901	0.11	1131	0.13	2310
Normalized[b]	1.92	438	3.82	901	0.12	1189	0.14	2310
^{80}Se$(t,\alpha)^{79}$As[c]	1.98	464	3.34	1161	0.63	1036	0.05	2505
Theory[d]	2.9	464	3.1	1244	0		0	

[a]Assuming reaction normalization constant of 18.2.
[b]Normalized to the sum rule limit of 6.
[c]Normalized spectroscopic strengths and energy centroids measured in the ^{80}Se$(t,\alpha)^{79}$As reaction (Ref. 8).
[d]Proton occupancies and single particle energies calculated for ^{80}Se in the recent work of Kota *et al.* (Ref. 13). The single particle energies in Ref. 13 have been adjusted to fit the experimental value for the 2*p* shell in ^{80}Se.

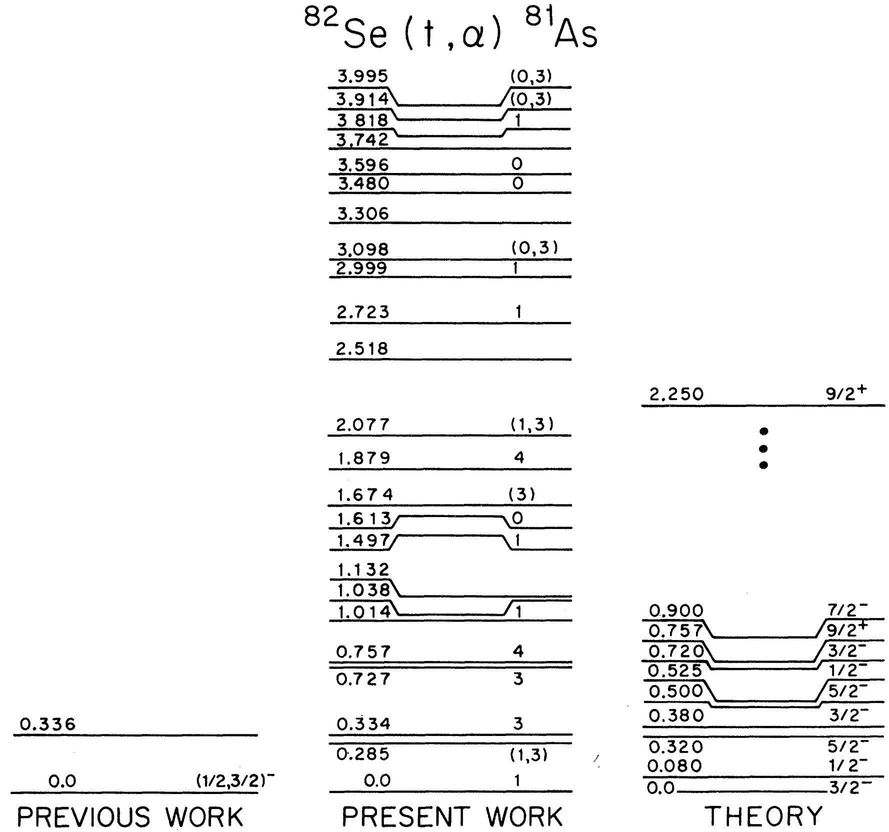

FIG. 5. Comparison between the level scheme of ^{81}As established from the present study using the ^{82}Se(t,α) reaction with previous work, and with the model calculations (see text). Symbols next to the lines are the transferred angular momentum in the present work.

the states at 1613, 3480, and 3596 keV have $J^{\pi}=\frac{1}{2}^{+}$. No definite l value could be assigned for the transition at 1674 keV. This is primarily due to the rapid oscillatory structure observed for the outgoing α particles, which is a characteristic feature of the (t,α) reaction in this mass region. However, since the $l=3$ DWBA curve for the above transition gives an improved fit, we make a tentative $l=(3)$ assignment for this state. Similar ambiguities exist for additional transitions displayed in Fig. 4. The solid and dashed curves represent the two possible l values for these transitions.

Two transitions at 757 and 1879 keV are populated by $l=4$ proton pickup leading to $\frac{9}{2}^{+}$ states in ^{81}As. Close lying $\frac{9}{2}^{+}$ states have been observed in ^{79}As. The structure of these positive parity states will be discussed later.

The sums of spectroscopic strengths $\sum C^2S$ and the energy centroids $\langle E \rangle$ of the single particle states measured in the present work are summarized in Table III and compared with the corresponding values obtained from the ^{80}Se$(t,\alpha)^{79}$As reaction[8] and with theoretical calculations done recently by Kota *et al.*[13] Only those transitions with definite l value assignments have been included in the table. The observed strengths for the $1f_{5/2}$ and $2p$ orbitals are close to those observed in the ^{80}Se(t,α) reaction and to the proton occupation numbers calculated for ^{80}Se using the spectral distribution methods.[13] However, there is a significant decrease in the observed strength for the $1g_{9/2}$ orbital in comparison with the value obtained in the ^{80}Se$(t,\alpha)^{79}$As reaction. It is reasonable to assume that this phenomenon is connected to the change in deformation and to the systematics of the $\frac{9}{2}^{+}$ states discussed later. In any case the $g_{9/2}$ occupation number is quite small in both nuclei. The single particle energies of the $2p_{3/2}$, $1f_{5/2}$, and $3s_{1/2}$ orbitals decrease by 26, 260, and 195 keV, respectively (relative to ^{79}As) but that of the $1g_{9/2}$ orbital has an opposite trend and in fact increases by about 150 keV relatively. We note here that although the first $\frac{9}{2}^{+}$ state in ^{79}As and ^{81}As have roughly the same excitation energy, the energy centroid of the $1g_{9/2}$ orbital in ^{81}As is higher by about 150 keV relative to ^{79}As.

Figure 5 shows the level scheme of ^{81}As established from the present study together with the previous information on ^{81}As and the theoretical level scheme (up to 1 MeV excitation energy) calculated based on the statistically deformed model with Coriolis coupling and pairing interaction.[7,18] The observed states in ^{81}As have corresponding close-lying states in the calculations, but below 1 MeV the theory predicts an additional four negative parity states (two $\frac{1}{2}^{-}$, one $\frac{3}{2}^{-}$, and one $\frac{5}{2}^{-}$). These states may correspond to higher energy levels observed above 1 MeV excitation energy in ^{81}As. Figure 5 also shows the observed $\frac{9}{2}^{+}$ states in ^{81}As and the corresponding states in the theoretical level scheme. The calculations done with a deformation parameter $\beta=+0.2$ (Ref. 18) account quite well for the energy difference between the observed two $\frac{9}{2}^{+}$ states in ^{81}As.

The systematics of the $\frac{9}{2}^{+}$ states in odd-A nuclei in the $28 \le Z, N \le 50$ region has prompted a number of studies.[10,19] In the odd Z nuclei (i.e., $_{35}$Br, $_{37}$Rb, $_{39}$Y) the excitation energies of the $\frac{9}{2}^{+}$ states increase abruptly as N goes from 42 to 50 instead of being constant as should be expected from the shell model. Figure 6 presents the systematics of the first $\frac{9}{2}^{+}$ state in odd-A nuclei for several isotopes in the region $38 \le N \le 52$, and the first 2^{+} state in the corresponding even-A isotopes using the most recent available data. The results from the present study and from ^{80}Se(t,α) are shown as small circles. There is a local minimum in the excitation energy of the first 2^{+} state at $N=42$ for Ge, Se, and Sr.

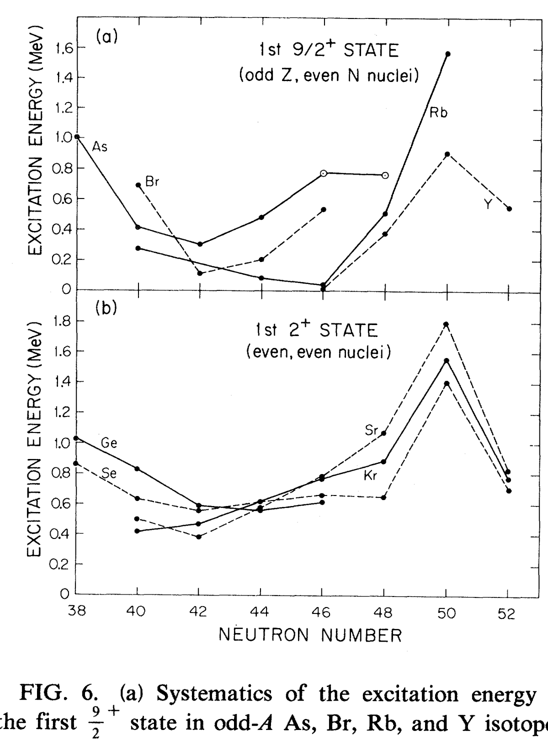

FIG. 6. (a) Systematics of the excitation energy of the first $\frac{9}{2}^{+}$ state in odd-A As, Br, Rb, and Y isotopes. The results from the present study and ^{80}Se(t,α) are shown as solid circles. (b) Systematics of the excitation energy of the first 2^{+} state in even-A Ge, Se, Kr, and Sr isotopes.

The location of the minimum of the first $\frac{9}{2}^+$ state changes smoothly versus Z. For Br and As isotopes it is around $N=42$, while for Rb and Y the minimum occurs at $N=46$. Such a minimum has been interpreted by Scholz and Malik[18] (by considering the Coriolis force plus a residual interaction of pairing type) as corresponding to maximum deformation. Thus there is an increase in nuclear deformation towards the middle of the shell. With increasing deformation the $1g_{9/2}$ orbital is expected to penetrate more into the $1f$-$2p$ shells, leading to the observed lowering in the excitation energy.

Figure 6 shows clearly that there is a parallelism between the deformed structure of odd-A nuclei and their even-even cores. There is, however, a difference between the various isotopes when approaching $N=50$ closed shell. While the excitation energy of the first $\frac{9}{2}^+$ state in As isotopes tends to level out, those of Rb and Y isotopes still increase. A similar phenomenon could be observed in the corresponding even Se isotopes which also level out between $N=46-48$. The sudden increase in energy of the first 2^+ state when approaching a closed shell, which leads to a spherical symmetry, is a general feature and could be clearly seen in other regions, for example, in the $N=28$ region (i.e., Ca isotopes) or in the $N=82$ region (i.e., Xe or Ce isotopes). Such interpretation is consistent with the observed trend in the experimental $B(E2)$ values of the first 2^+ states in doubly even nuclei. The $B(E2)$ values reach a maximum around $N=42$ and a lowest value around $N=38$ and $N=50$.

We acknowledge financial aid and support from the National Science Foundation.

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