^{79}As via proton pickup

S. Mordechai
University of Pennsylvania, Philadelphia, Pennsylvania 19104
and Ben-Gurion University of the Negev, Beer-Sheva, Israel

S. LaFrance* and H. T. Fortune
University of Pennsylvania, Philadelphia, Pennsylvania 19104
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The reaction ^{80}Se(t,α)^{79}As has been investigated with an 18-MeV triton beam. Twenty-six levels of ^{79}As (many of them previously unreported) have been identified up to about 3.5 MeV excitation energy. 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. Behavior of the low-lying negative-parity states for various As isotopes is presented and compared with the predictions of a rotational model with prolate deformation and Coriolis coupling. The observed first and second $9/2^+$ states in odd-A isotopes give further evidence for the shape transition suggested recently for this mass region.

[NUCLEAR REACTIONS ^{80}Se(t,α)^{79}As, E = 18 MeV; measured $\sigma(E_\alpha,\vartheta)$. ^{79}As deduced levels, L, π, (J), spectroscopic factors. DWBA analysis, enriched target.]

I. INTRODUCTION

The odd-even As isotopes with A = 71, 73, 75, 77 have been the subject of a large number of experimental investigations and a considerable amount of information is available on their low-lying level schemes.[1–5] (These are only some of the recent references. The latest compilations[6] give a survey of many earlier references.) Most of the information comes primarily from studies of γ transitions following the β decays of the respective Se and Ge isotopes. Several systematic studies of ^{71,73,75,77}As isotopes have also been reported using charged particle reactions [7,8] and the level schemes, spins, and parities of these isotopes are established up to about 3–4 MeV excitation energy. However, the existing information concerning even the energy levels of ^{79}As is very limited, and only recently a first attempt using a charged-particle (α,p) reaction has been done in order to study its level structure.[9]

Attempts to understand the level structures and other properties of the odd-even As isotopes in terms of a pairing-plus-quadrupole model and in terms of models with single-particle core coupling[10,11] have met with only limited success, although considerable improvement has been obtained by coupling a spherical quasi-particle to an anharmonic phonon.[12] More recently a comprehensive study of ^{71,73,75,77}As using the (^{3}He,d) reaction shows interesting systematics in the level structure of these isotopes which indicate (using calculations based on the unified model and the inclusion of Coriolis coupling)[13] that the deformation of these isotopes is probably prolate, with $\beta \cong 0.2$ (Ref. 7). It was pointed out that the structure of the positive-parity states in As isotopes provides a sensitive test for the sign of deformation. From the structure of the neighboring nuclei in the N = 40 region (i.e., Ga, Ge, Se) new ideas have been recently developed. It was suggested that nuclei in this mass region undergo a shape transition from oblate to prolate deformation with increasing neutron number.[14–17] It is generally agreed[9,24] that the structural change occurs between N = 40 and N = 42 for different isotopes in this mass region. However, no strong evidence was found as yet for such structure in the As (Z=33) isotopes.

In this work we report on the ^{80}Se(t,α)^{79}As reaction. The aim of the present work was to study the level structure of ^{79}As (for which meager information existed) via a direct pickup reaction and thus to extend the knowledge on the systematics of the level structure of the odd mass As isotopes.

II. EXPERIMENTAL PROCEDURE

The experiment was performed with an 18-MeV triton beam from the University of Pennsylvania tandem accelerator. The reaction α particles were momentum analyzed with a multi-angle spectrograph and recorded on K-1 nuclear emulsion plates in angular steps of 7.5°. The target was enriched to 96.87% in ^{80}Se and its areal density was 65 μg/cm^2. The target thickness was monitored by measuring elastic scattering in a solid-state detector mounted at 40°.

An alpha-particle momentum spectrum measured at a lab angle of 18.75° is shown in Fig. 1. The energy resolution was about 25 keV full width at half maximum for 25-MeV α particles. Alpha-particle groups corresponding to the ground state and 25 excited states in ^{79}As have been identified up to an excitation energy of about 3.5 MeV.

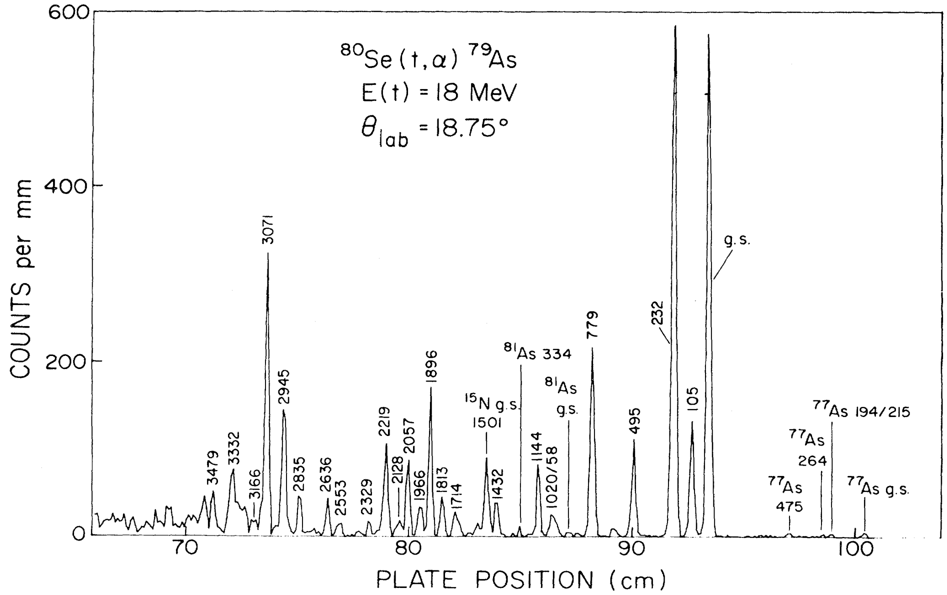

FIG. 1. Alpha spectrum from the ^{80}Se(t,α)^{79}As reaction measured at 18-MeV incident energy and at a lab angle of 18.75°. The levels in ^{79}As are indicated by their excitation energies. Impurity groups are labeled according to their residual nucleus.

The excitation energies were obtained from the measured positions of the α groups along the nuclear emulsion plates at each angle and were averaged to get the values listed in Table I.

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 ^{80}Se target. Impurity peaks are labeled in Fig. 1 according to their final state in the residual nuclei. The Q value for the ^{80}Se(t,α)^{79}As reaction ($Q = 8.407 \pm 0.010$ MeV) was determined by reference to the accurately known Q values for ^{76,77,78}Se(t,α) and ^{16}O(t,α)^{15}N. (Some of these impurity peaks are shown in Fig. 1.) The deduced mass excess for ^{79}As is -73643 ± 14 keV. This result is more accurate and considerably different from the mass excess of -73720 ± 50 listed for ^{79}As in the recent atomic mass table.[18]

III. RESULTS AND ANALYSIS

Measured angular distributions were compared with the results of distorted-wave Born-approximation (DWBA) calculations, using the code DWUCK,[19] and the optical-model parameters listed in Table II. These parameters were obtained from analysis of the ^{87}Rb(t,α)^{86}Kr reaction.[20] No spin-orbit or surface-peaked terms were used in the triton or α potentials. It was found that the inclusion of a spin-orbit term did not have any significant effect on the calculated cross section, or on the deduced spectroscopic factors. 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.

It is well known that the calculated cross section is extremely sensitive to the rms radius of the transferred particle wave function. It is found that an increase of the rms radius by only 1.5% increases the calculated cross section by $\sim$ 10%. The calculations are, however, less sensitive to the other bound state optical parameters. For example, an increase of the diffuseness parameter a, by 10% increases σ_{DW} by $\sim$ 15%. The spin-orbit parameter λ has a negligible effect for $j = l + 1/2$ orbitals, but a significant influence when the transferred particle belongs to an orbital with $j = l - 1/2$. For example, the calculated cross section for $\lambda = 0$ for $f_{5/2}$ orbital is larger by about 50% than that calculated with the same parameters but with $\lambda = 25$. In the present work, we have used $\lambda = 12$, which corresponds to a spin-orbit well depth of $V_{so} = 3.8$ MeV.

Spectroscopic strengths given in Table I were calculated from the relation

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

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. The normalization factor $N = 18$ used in the present analysis has been recently established for the (t,α) reaction.[21]

Table I summarizes the excitation energies, maximum differential cross sections, l values, and spectroscopic factors measured in the present study. Also shown in Table I are the excitation energies, J^π and spectroscopic factors determined from the ^{76}Ge(α,p) reaction,[9] and excitation energies determined in earlier works. A typical feature of the (t,α) reaction in this mass region is the rapid oscilla-

TABLE I. Summary of experimental results from the ^{80}Se(t,α)^{79}As reaction and comparison with previous work.

	Present work						Previous work			
E_x (keV)	$\frac{d\sigma}{d\Omega}$ max (mb/sr)	l	$C^2S(2p_{3/2})$[e]	$C^2S(1f_{5/2})$	$C^2S(3s_{1/2})$	$C^2S(1g_{9/2})$	E_x^a (keV)	$J^{\pi a}$	$S(\alpha,p)^a$	E_x (keV)
0	1.95	1	1.30				0	3/2$^-$	2.2	0
105±7	0.45	1	0.23				109±3			109[c]
232±6	2.6	3		2.29			233±3	5/2$^-$	3	230[b]
495±7	0.37	(1)	(0.24)[e]				499±3	1/2$^-$	1.2	
							607±4			
							633±4			
779±3	0.64	4				0.53	777±4	9/2$^-$	3.6	773[b]
							881±4			
1020±14	0.041	1	0.04				1016±5			
1058±8	0.090	(1,3)	(0.03)	(0.09)			1045±5	(1/2$^-$)	0.18	
1144±3	0.20	3		0.22			1140±6			
							1405±6			
1432±8	0.88	(3,0)		(0.13)	(0.03)		1437±6			
1501±3	0.044	1	0.07							
1714±6	0.084	(1,3)	(0.07)	(0.14)			1702±8			
1813±5	0.094	4				0.09	1806±8	9/2$^+$	1.3	
							1872±8			
1896	0.30	1	0.33[e]				1891±8	1/2$^-$	0.4	
							1942±8			
1966±6	0.088	4				0.07	1964±8	9/2$^+$	1.2	
2057±4	0.17	1	0.14							
2128±10	0.046	(0)			(0.01)					
2219±7	0.23	(1,3)	0.17	(0.36)						
2329±13	0.031	(3,0)		(0.06)	(0.01)					
2553±3	0.049	0			0.02					
2636±13	0.079	0			0.03					
2835±9	0.092	(3,0)		(0.14)	(0.04)					
2945±13	0.34	(3)		(0.53)						
3071±10	0.63	3		1.10						
3166±10	0.053	(4,0)			(0.02)	(0.09)				
3332±8	0.23									
3479±2[d]	0.107									

[a]Reference 9.
[b]Reference 22.
[c]Reference 23.
[d]Assumed.
[e]The spectroscopic factors for the states at 495 keV and 1896 keV have been calculated assuming $2p_{1/2}$ transfer. For all other $l = 1$ transitions a $2p_{3/2}$ configuration has been used.

TABLE II. Optical model parameters used in the analysis of ^{80}Se(t,α)^{79}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 20.
[b]Adjusted to give a binding equal to the experimental proton separation energy.

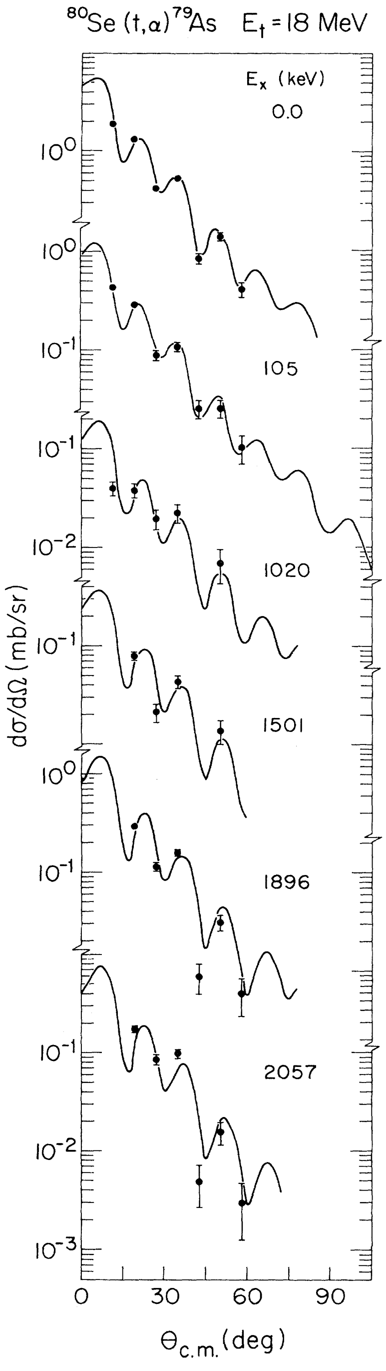

FIG. 2. Angular distributions exhibiting $l = 1$ character in the ^{80}Se(t,α)^{79}As reaction at 18-MeV incident energy. The solid DWBA curves were calculated for $2p_{3/2}$ proton pickup. The calculations used optical-model parameters of Table II.

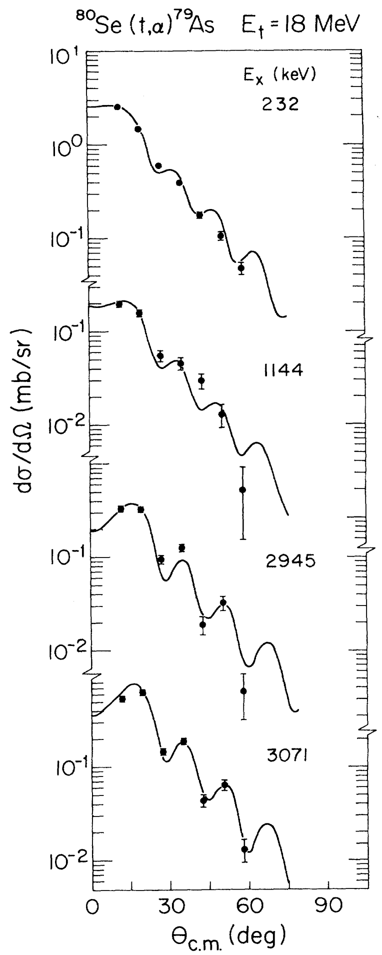

FIG. 3. Same as Fig. 2, but for $l = 3$. The calculated curves assume $1f_{5/2}$ proton pickup.

tions observed in the angular distributions of the outgoing α particles. Therefore unambiguous l values could be assigned for only 14 strong transitions, while for the other transitions only tentative l values are listed. Figures 2–4 present the angular distributions characterized by the different orbital angular momentum transfers. Additional angular distributions are shown in Figs. 5–6 together with the possible l values found to give the best fits with data. Individual transitions are discussed in Section IV.

IV. DISCUSSION

Figure 2 presents the angular distributions for six states in ^{79}As characterized by $l = 1$ proton pickup. The solid lines are the calculated DWBA curves assuming $2p_{3/2}$ transfer. Since the angular distributions are not sensitive to j (the final-state spin), then either $3/2^-$ or $1/2^-$ is possible for the states shown in Fig. 2. Among the six transitions at 0.0, 105, 1020, 1050, 1896, and 2057 keV displayed in Fig. 2, two levels, namely those at 1501 and 2057 keV, were not observed in the (α,p) study, and two were observed (at 109 and 1016 keV) but with no spin assignments in Ref. 9. For the g.s. and the state at 1896 keV our results are in agreement with the (α,p) work. A value of $J^\pi = 3/2^-$ for the g.s. of ^{79}As was deduced also from

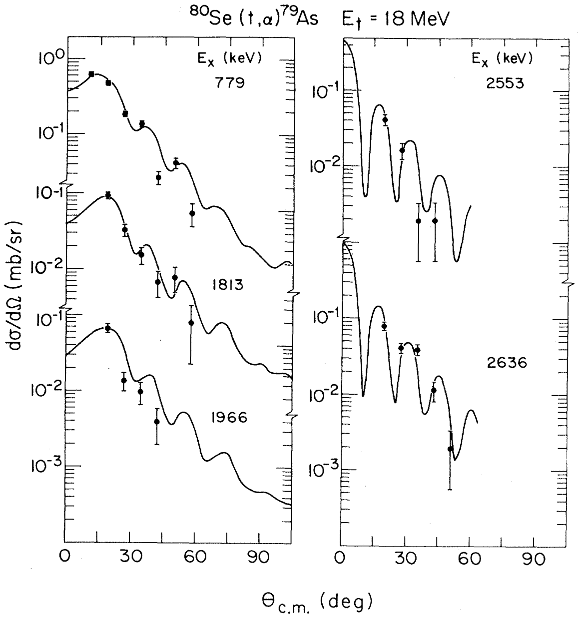

FIG. 4. Same as Figs. 2 and 3, but for $l=0$ and 4. The calculations assume a pickup configuration $3s_{1/2}$ and $1g_{9/2}$.

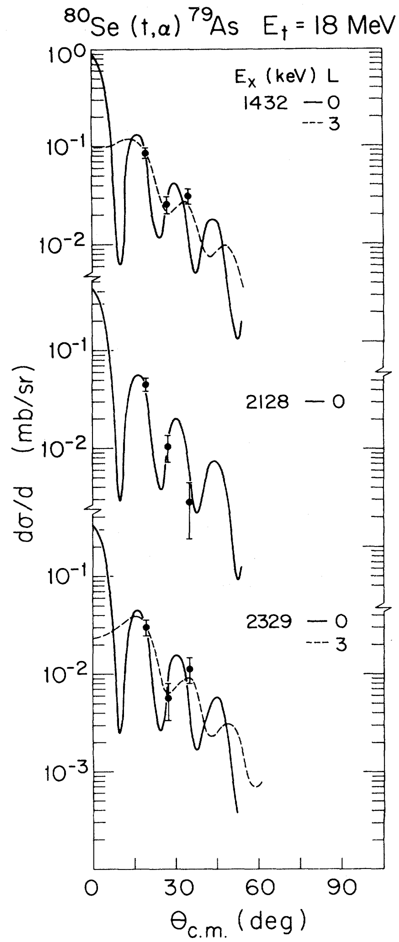

FIG. 6. Same as Fig. 5.

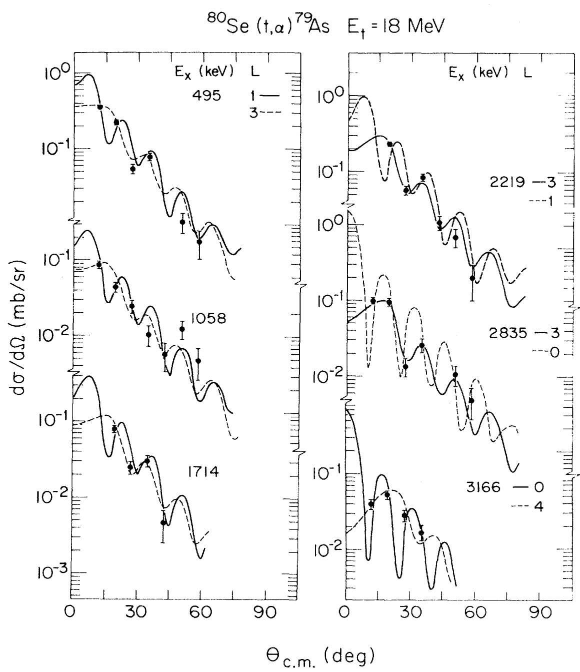

FIG. 5. Angular distributions for levels in ^{79}As reached in the ^{80}Se(t,α)^{79}As reaction. The solid and dashed curves are the DWBA calculations giving the best fits to data.

the measured log ft values in the β decay of ^{79}As.[6]

Figure 3 shows the angular distributions for four transitions exhibiting an $l = 3$ character. These are the transitions at 232, 1144, 2945, and 3071 keV. Based on the simple shell model the low-lying states with $l = 3$ are expected to correspond to $5/2^-$. The first two states have been observed in the (α,p) reaction.[9] Our assignment for the 232-keV state is in agreement with the spin of $J^\pi = 5/2^-$ given for this state;[9] however, no further $5/2^-$ or $7/2^-$ states have been identified in the work of Rotbard *et al.*[9]

Two transitions (Fig. 4) were found to proceed with apparent $l = 0$ pickup, leading to the states at 2553 and 2636 keV, which thus have $J^\pi = 1/2^+$. Neither state was observed previously. Additional $l = (0)$ transitions may be present at 2835, 3166 keV (Fig. 5) and at 1432, 2128, and 2329 keV (Fig. 6). However, the limited number of data points which could be extracted for these transitions do not allow definitive l assignments for these states.

Three states have been identified as $l = 4$ transitions in the present study. These are the states at 779, 1813, and 1966 keV. All three states are weakly populated in the present study but yet are reasonably well fitted by $l = 4$

TABLE III. Sums of spectroscopic strengths ΣC^2S and energy centroids $\langle E \rangle$ (in keV) for the reaction ^{80}Se(t,α)^{79}As.

	$2p$		$1f_{5/2}$		$1g_{9/2}$		$3s_{1/2}$	
	ΣC^2S	$\langle E \rangle$	ΣC^2S	$\langle E \rangle$	ΣC^2S	$\langle E \rangle$	ΣC^2S	$\langle E \rangle$
Unnormalized[a]	2.29	508	3.74	1161	0.70	1036	0.06	2505
Normalized[b]	2.02	508	3.31	1161	0.62	1036	0.05	2505

[a]Assuming a normalization factor of $N=18$ for the (t,α) reaction.
[b]Normalized to the sum rule limit of 6.

curves. These states have been strongly populated in the (α,p) reactions and assigned as $9/2^+$ states in ^{79}As.

Table I presents a comparison between our results and those obtained from the ^{76}Ge(α,p)^{79}As reaction. Under the assumption that the transferred neutron pair in the (α,p) reaction is coupled to zero angular momentum ("spectator model"), the (α,p) reaction behaves as a simple proton transfer reaction. Therefore the results from the (α,p) reaction should be complimentary to those from the present reaction. The spectroscopic factors in the (t,α) reaction give an indication on the proton occupation number for the different orbitals in the target nucleus while those from the (α,p) reaction express the proton vacancies in the target nucleus. For example, in the simple shell model the $1g_{9/2}$ proton orbital is vacant in ^{80}Se ($Z=34$), so that $l=4$ transitions leading to $9/2^+$ states in ^{79}As will be strong in (α,p) but weak in the (t,α) reaction. This behavior is actually observed in Table I. On the other hand, the $2p_{3/2}$-$1f_{5/2}$-$2p_{1/2}$ proton orbitals are roughly half occupied in ^{80}Se g.s. and therefore the negative-parity states should be observed with comparable spectroscopic factors in both reactions.

The first excited state of ^{79}As is observed at 105 keV and characterized by $l=1$. A state was reported in Ref. 9 at 109 keV but without J^π assignment. The systematics of the low-lying states in ^{73,75,77}As show the presence of a low-lying negative-parity triplet with $1/2^-$, $3/2^-$, $5/2^-$ members. Since the 232- and 495-keV states in ^{79}As have been identified as having $5/2^-$ and $1/2^-$ (Table I) then the 105-keV level most likely has $J=3/2$.

The sums of spectroscopic strengths ΣC^2S and the energy centroids $\langle E \rangle$ of single-particle states measured in the present work are summarized in Table III. Only those transitions with definite l value assignment have been included in the table. The deduced sums of spectroscopic strengths for $2p$-$1f_{5/2}$ orbitals is very close to sum rule limit of 6 expected for ^{80}Se. The spectroscopic strengths for the transitions with $l=1$ have been calculated assuming $2p_{3/2}$ transfer, except for those at 495 keV and 1896 keV where the $2p_{1/2}$ configuration has been used. It is noted that the spectroscopic factor calculated with a $2p_{1/2}$ wave function is larger by a factor of 1.25 relative to the value obtained with a $2p_{3/2}$ configuration. Table III shows also that the sum of spectroscopic strengths is 0.06 for $3s_{1/2}$ and 0.70 for the $1g_{9/2}$ orbitals. Thus, only a small fraction (3% and 7% respectively) of the total strength of the above orbitals is occupied in ^{80}Se g.s.

In Table III we show also the normalized sums of spec-

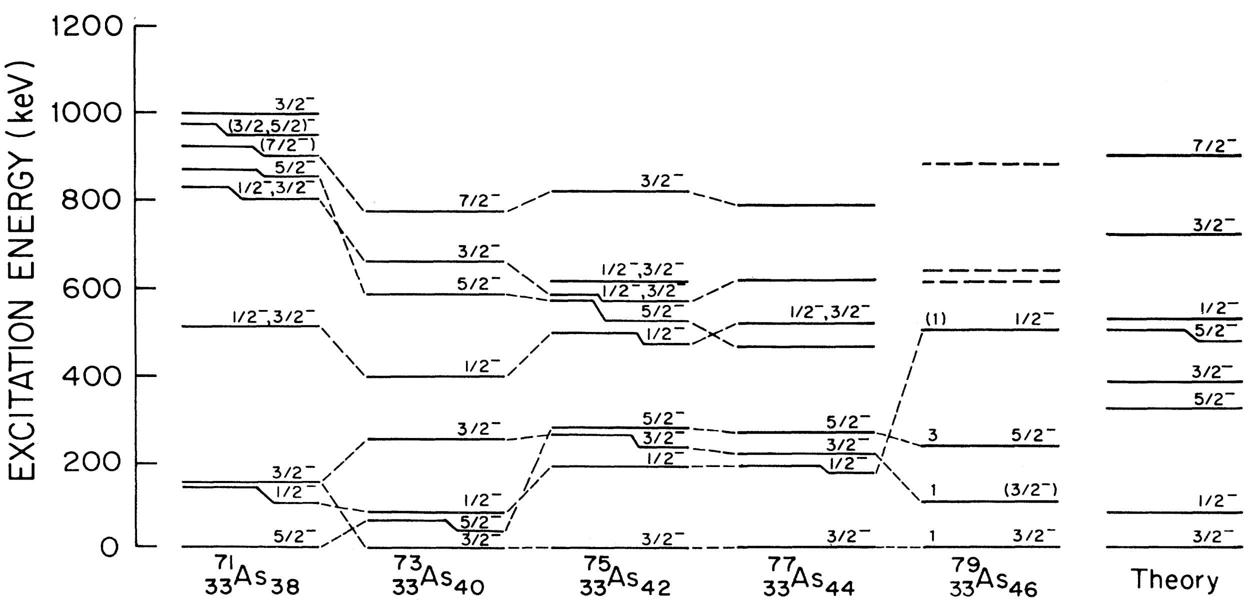

FIG. 7. Comparison of the negative-parity states of ^{79}As observed in the (t,α) reaction and previous work up to 1.0 MeV with the levels of the lighter isotopes of As, and with the model calculations (see text). The calculated spectrum is not specific of one particular As isotope. Symbols on the lines are the transferred angular momentum in the present work. Dashed lines represent levels which have been observed in the ^{76}Ge(α,p) reaction but not in the (t,α) work.

TABLE IV. Systematics of $9/2^+$ states in odd-A As isotopes. The results for ^{79}As are from the present work.

J^π	^{71}As E_x(MeV)	^{73}As E_x(MeV)	^{75}As E_x(MeV)	^{77}As E_x(MeV)	^{79}As E_x(MeV)	Theory E_x(MeV)
$9/2_1^+$	1.004	0.418	0.304	0.482	0.779	0.77[a]
$9/2_2^+$	3.26	1.861	1.815	1.988	1.813	2.26

[a]The theoretical excitation energy of the first $9/2^+$ state has been adjusted to fit the measured energy for the same state in ^{79}As.

troscopic strengths obtained assuming a sum rule limit of 6 for the total pickup strengths. These values are close to the proton occupation numbers of 3.1 for $1f_{5/2}$ and 2.9 for $2p$ orbitals calculated recently by Kota *et al.*[25] for ^{80}Se. There is also an excellent agreement between the measured and the calculated single particle energy difference for the above orbitals.

In the following sections we discuss in more detail the systematics of the positive- and negative-parity states in odd-A As isotopes as well as the comparison with model calculations.

A. Systematics of low-lying negative-parity states and comparison with model calculations

Figure 7 presents the comparison between the low-lying states of ^{79}As with all the lighter odd-A As isotopes. Several features can be observed from this figure:

(i) Except for ^{71}As which has a $5/2^-$ g.s., all the heavier isotopes have a $J^\pi = 3/2^-$ g.s. This difference may arise from the opening of the $1f_{5/2}$ neutron orbit, and thus indicating the influence of the number of neutrons on the proton structure. In the present study the g.s. is populated with $l = 1$ and therefore is in agreement with the previous $J^\pi = 3/2^-$ assignment.

(ii) The lowest three excited states in ^{79}As observed in the present study at 105, 232, and 495 keV are populated by $l = 1$, $l = 3$ and $l = (1)$ pickup respectively. These states correspond to the well-known negative-parity triplet of states with $1/2^-$, $3/2^-$, and $5/2^-$ observed in the lighter isotopes. However, the spacing between the members in ^{79}As is significantly larger than that observed in ^{73,75,77}As. This phenomenon might be due to the fact that ^{79}As is approaching the $N = 50$ neutron closed shell.

(iii) Comparison with model calculations: Fig. 7 shows the comparison between the low-lying negative-parity levels of ^{79}As and the results of calculations based on the statistically deformed model with Coriolis coupling and pairing interaction.[13,7] In an earlier communication,[7,8] it was noted that only the Coriolis coupling model with prolate deformation could provide satisfactory explanation of the ordering and stripping strength for the positive-parity levels. We thus compare the results of the calculations done with a deformation parameter of $\beta = +0.2$ with the scheme of ^{79}As constructed from the present work and from Ref. 9. The calculations are not specific of one particular As isotope. The comparison shows a reasonably good agreement between experimental results and theoretical predictions for the lighter isotopes ^{73,75,77}As. In all cases there are experimental counterparts to the theoretical levels. Up to 1 MeV the calculations predict five $l = 1$ and three $l = 3$ states. In ^{79}As we observe below 1 MeV excitation energy only three definite $l = 1$ transitions leading to the g.s. 105- and 495-keV states and one $l = 3$ transition to the 232-keV state. The additional three states have been reported in the (α,p) reaction at 607, 633, and 881 but without spin assignments. These states (represented by the dashed lines in Fig. 7) were not observed in our study and apparently have a very small pickup strength.

B. Systematics of positive-parity states

Three transitions were found in the present study to proceed with $l = 4$ proton pickup leading to $9/2^+$ states at 779, 1813, and 1966 keV. An additional tentative $l = (4)$ assignment was given to the state at 3166 keV. Two definite $l = 0$ transitions have been identified to states at 2553 and 2636 keV which therefore have $J^\pi = 1/2^+$, and a tentative $l = 0$ assignment was given to the state at 2128 keV. No transitions with $l = 2$ have been observed, and none might be expected from the simple shell model.

Table IV summarizes the systematics of the $9/2^+$ states in odd-A As isotopes. A sharp change is observed in the energy systematics. The first $9/2^+$ state decreases in energy when going from ^{71}As to ^{75}As but then increases back in ^{77}As and ^{79}As. From the model mentioned in the previous section it can be concluded that the minimum energy of the $9/2^+$ state should correspond to maximum deformation.[13] Experimentally this minimum for As isotopes occurs in ^{75}As which thus has the maximum deformation. It is interesting to note that a similar minimum is also observed in the excitation energy of the first 2^+ state in the neighboring even-even Se and Ge isotopes.[24] This indicates that there is a clear parallelism between the deformed structure of odd-A nuclei and their even-even cores.

A different approach was also given recently for this mass region. Vergnes *et al.*[14] have studied the variation of the ratio $R = \sigma(0_2^+)/\sigma(0_{\rm g.s.}^+)$ for both the (t,p) and (p,t) reactions on even Ge isotopes. An abrupt maximum in this ratio was found at $N = 42$ in the (t,p) and $N = 40$ in the (p,t) data. These effects are similar to those obtained in the known transition region and were interpreted as indicating that these isotopes undergo a shape transition from oblate to prolate deformation with increasing neutron number. The structural transition is expected to be between $N = 40$ and $N = 42$.

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*Present address: RCA Astro-Electronics, Princeton, NJ 08540.

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