^{77}Se$(t,p)^{79}$Se reaction at 17 MeV

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(Received 21 August 1991)

By using the ^{77}Se$(t,p)^{79}$Se reaction at 17 MeV, angular distributions have been measured for transitions leading to 34 states or groups of states in ^{79}Se up to an excitation energy of approximately 3.2 MeV. Twelve of these states are reported for the first time. Comparisons with distorted-wave Born-approximation calculations have allowed the L transfer for most of the transitions observed to be determined. Four $L = 0$ transitions are seen, leading to assignments of $J^\pi = \frac{1}{2}^-$ to the states populated. The J^π values for the majority of the other final states have been restricted to one of two values.

PACS number(s): 25.55.Hp, 27.50.+e

I. INTRODUCTION

The nucleus ^{79}Se has been the subject of several experimental investigations including the β decay [1] of ^{79}As, neutron capture [2] on ^{78}Se, $(\alpha, n\gamma)$ reaction [3] on ^{76}Ge, and one-neutron transfer measurements with both polarized [4] and unpolarized beams [5, 6]. These investigations have resulted in identification of 67 states with excitations up to 4.4 MeV. Definite spin and parity assignments have been made for 25 of these states. The majority of the other states have one or more tentative J^π assignments, based mainly on $(\alpha, n\gamma)$ and (d,p) angular distributions [3–5]. The adopted excitation energies and J^π values have been summarized by Singh and Viggars [7]. Even though this compilation is quite old, no relevant papers have been published in the meantime. No two-particle transfer measurements leading to ^{79}Se have appeared in the literature.

The present work reports the results of an investigation of the ^{77}Se$(t,p)^{79}$Se reaction with $E_t = 17$ MeV. Angular distributions have been measured for transitions to states up to $E_x = 3.2$ MeV. A comparison of these with the predictions of distorted-wave Born-approximation (DWBA) calculations has enabled the angular momentum transfer to be determined for most of the levels observed.

II. EXPERIMENTAL PROCEDURE AND RESULTS

The measurements were performed by using a 17-MeV triton beam from the University of Pennsylvania FN tandem accelerator. The outgoing particles were momentum analyzed in a multiangle spectrograph and recorded on nuclear emulsions in the focal plane. All particles except protons were stopped in mylar absorbers placed directly in front of the emulsions. The emulsions were scanned by using the scanning facilities at the University of Bradford [8]. The details of the experimental procedure are published elsewhere [9].

The target was 65 μg/cm^2 in areal density, formed by evaporating enriched ^{77}Se onto 25 μg/cm^2 of ^{12}C and then by covering it with 50 μg/cm^2 of Au to prevent target deterioration during the measurements. With a sandwich of this type, beam currents of up to 250 nA could be used without any noticeable effects on the target. The scattering from the target was monitored by using a surface barrier detector mounted at 45° to the beam. The isotopic composition of the target is given in Table I.

A spectrum of the outgoing protons measured at 18.75° (laboratory) is shown in Fig. 1. The energy resolution is approximately 18 keV (FWHM). The excitation energy of the states in ^{79}Se, corresponding to the proton groups, is given on the top abscissa. The expected positions of the proton groups due to the ground state to ground state transitions for the even Se isotopes are indicated and labeled by the final nucleus. The groups arising from the (t,p) reaction on the Au and C backings and from ^{16}O impurities fall outside the excitation region shown in the spectrum. It should be noted that the ground state of ^{79}Se is not populated to any significant extent in this reaction and, as will be discussed later, the group with the lowest excitation energy corresponds to the transition

TABLE I. Isotopic composition of the target.

Isotope	Enrichment (%)
^{74}Se	0.06 ± 0.01
^{76}Se	0.66 ± 0.02
^{77}Se	94.38 ± 0.15
^{78}Se	3.02 ± 0.05
^{80}Se	1.61 ± 0.10
^{82}Se	0.27 ± 0.01

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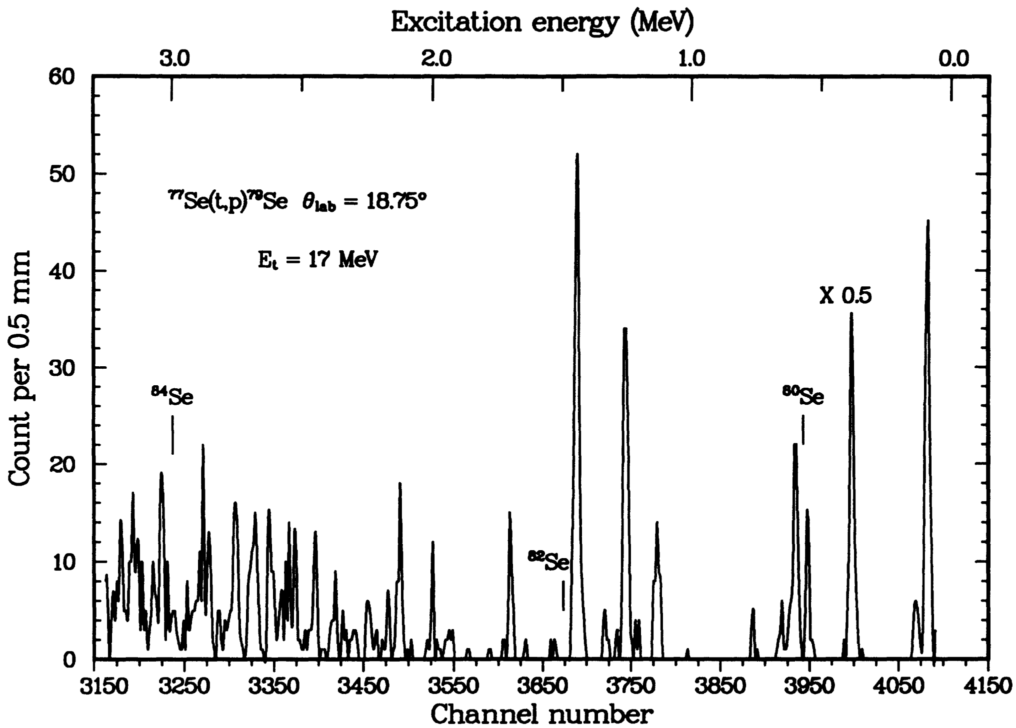

FIG. 1. Energy spectra for the ^{77}Se$(t,p)^{79}$Se reaction at 17 MeV measured at $\theta_{\mathrm{lab}} = 18.75°$.

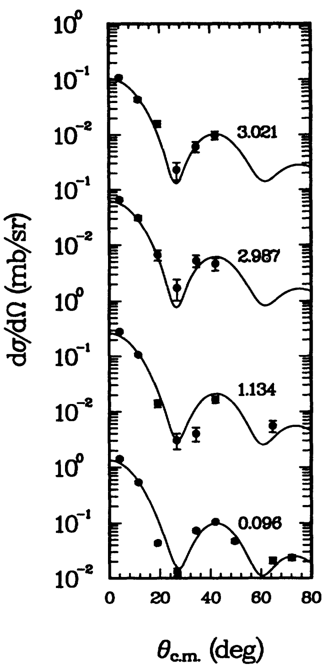

FIG. 2. Experimental angular distributions and DWBA calculations for the transitions that show a characteristic $L = 0$ shape.

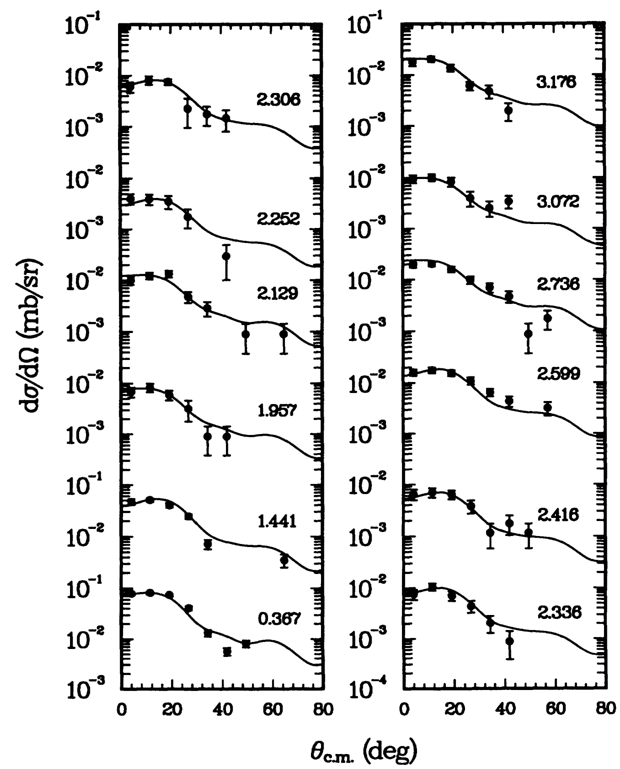

FIG. 3. Experimental angular distributions and DWBA calculations for the transitions that show a characteristic $L = 2$ shape.

TABLE II. Results of the reaction ^{77}Se$(t,p)^{79}$Se and comparison with previous information.

E_x (MeV) Present	Previous[a]	L	J^π Present	Previous[a]	Max. cross section (mb/sr)	ϵ'
	0.0			$\frac{7}{2}^+$		
0.096(3)	0.096	0	$\frac{1}{2}^-$	$\frac{1}{2}^-$	1.418±0.071	46.33
	0.128			$\frac{1}{2}^-$		
0.143(4)	0.137	5	$\frac{9}{2}^+, \frac{11}{2}^+$	$\frac{9}{2}^+$	0.017±0.002	1.80
0.367(3)	0.365	2	$\frac{3}{2}^-, \frac{5}{2}^-$	$\frac{5}{2}^-$	0.081 ±0.006	36.40
	0.499			$(\frac{1}{2}, \frac{3}{2})$		
0.534(4)	0.528	3	$\frac{5}{2}^+, \frac{7}{2}^+$	$\frac{3}{2}^-$	0.011±0.002	0.18
0.586(6)	0.572	1	$\frac{1}{2}^+, \frac{3}{2}^+$	$(\frac{3}{2}^-, \frac{5}{2}^-)$	0.139±0.007	0.77
0.650(12)	0.630	3	$\frac{5}{2}^+, \frac{7}{2}^+$	$\frac{5}{2}^+$	0.004±0.001	0.08
	0.729			$\frac{5}{2}^+$		
0.750(10)		(1)	$(\frac{1}{2}^+, \frac{3}{2}^+)$		0.014±0.002	0.08
	0.790			$(\frac{7}{2}^-, \frac{9}{2}^-)$		
	0.819			$(\frac{7}{2} \rightarrow \frac{9}{2})$		
	0.897			$(\frac{7}{2}^+ \rightarrow \frac{11}{2}^+)$		
	0.975			$\frac{3}{2}^-$		
	0.983			$(\leq \frac{7}{2})$		
	1.008			$(\frac{5}{2} \rightarrow \frac{11}{2})$		
	1.060					
	1.072			$\frac{13}{2}^+$		
	1.080			$(\frac{1}{2} \rightarrow \frac{5}{2})$		
	1.089			$(\frac{1}{2}, \frac{3}{2})$		
	1.110			$\frac{7}{2}^+, \frac{9}{2}^+$		
1.134(8)	1.145	0	$\frac{1}{2}^-$	$\frac{1}{2}^+$	0.283±0.014	9.85
	1.231			$(\frac{5}{2} \rightarrow \frac{9}{2})$		
	1.253			$\frac{5}{2}^+$		
1.261(7)	1.257	3	$\frac{5}{2}^+, \frac{7}{2}^+$	$(\frac{5}{2} \rightarrow \frac{9}{2})$	0.036±0.003	0.49
	1.312					
1.346(9)	1.339	3	$\frac{5}{2}^+, \frac{7}{2}^+$	$(\frac{5}{2}^-, \frac{7}{2}^-)$	0.004±0.001	0.059
	1.385			$(\frac{5}{2}^-, \frac{7}{2}^-)$		
1.441(9)	1.420	2	$\frac{3}{2}^-, \frac{5}{2}^-$		0.051±0.004	25.00
	1.491			$\frac{1}{2}^+$		
	1.589			$\frac{3}{2}^+$		
1.647(10)	1.636	3	$\frac{5}{2}^+, \frac{7}{2}^+$		0.010±0.002	0.15
	1.667			$\frac{5}{2}^+$		
	1.712					
1.737(10)	1.738	1	$\frac{1}{2}^+, \frac{3}{2}^+$	$\frac{3}{2}^+$	0.005±0.001	0.04
	1.760					
	1.817			$(\frac{5}{2}^-, \frac{7}{2}^-)$		
1.865(10)	1.856			$\frac{3}{2}^-$	0.004±0.001	
1.957(6)	1.964	2	$\frac{3}{2}^-, \frac{5}{2}^-$	$(\frac{1}{2}^-, \frac{3}{2}^-)$	0.008±0.001	3.30
	1.968					
	2.062			$(\frac{1}{2}^-, \frac{3}{2}^-)$		
	2.092					
2.129(7)		2	$\frac{3}{2}^-, \frac{5}{2}^-$		0.013±0.002	5.45
2.168(8)	2.171	3	$\frac{5}{2}^+, \frac{7}{2}^+$	$\frac{5}{2}^+$	0.006±0.001	0.07
2.252(10)	2.259	2	$\frac{3}{2}^-, \frac{5}{2}^-$	$(\frac{3}{2}^-)$	0.004±0.001	1.80
2.306(11)		2	$\frac{3}{2}^-, \frac{5}{2}^-$		0.008±0.002	2.80
2.336(7)	2.340	2	$\frac{3}{2}^-, \frac{5}{2}^-$	$(\frac{5}{2}^+)$	0.011±0.002	4.05
	2.373			$\frac{5}{2}^+$		
2.416(9)		2	$\frac{3}{2}^-, \frac{5}{2}^-$		0.007±0.002	3.20
2.467(6)	2.475	1	$\frac{1}{2}^+, \frac{3}{2}^+$	$\frac{5}{2}^+$	0.024±0.003	0.14
2.543(7)					0.032±0.003	
2.552(6)		1	$\frac{1}{2}^+, \frac{3}{2}^+$		0.047±0.004	0.24

TABLE II. (*Continued*).

E_x (MeV) Present	Previous[a]	L	J^π Present	Previous[a]	Max. cross section (mb/sr)	ϵ'
	2.570			$\frac{5}{2}^+$		
2.599(6)		2	$\frac{3}{2}^-,\frac{5}{2}^-$		0.018±0.002	8.35
2.651(5)		3	$\frac{5}{2}^+,\frac{7}{2}^+$		0.021±0.002	0.26
	2.710			$(\frac{5}{2}^+)$		
2.736(6)		2	$\frac{3}{2}^-,\frac{5}{2}^-$		0.020±0.002	7.70
	2.769			$(\frac{5}{2}^+)$		
2.841(8)	2.847		$\frac{5}{2}^+$		0.020±0.003	
	2.941			$\frac{1}{2}^+$		
2.987(8)	2.987	0	$\frac{1}{2}^-$		0.066±0.005	2.91
3.021(6)		0	$\frac{1}{2}^-$		0.109±0.006	4.71
3.072(7)	3.060	2	$\frac{3}{2}^-,\frac{5}{2}^-$	$(\frac{3}{2}^+)$	0.010±0.002	4.60
3.121(5)		3	$\frac{5}{2}^+,\frac{7}{2}^+$		0.016±0.002	0.25
3.176(4)	3.182	2	$\frac{3}{2}^-,\frac{5}{2}^-$	$(\frac{3}{2}^+)$	0.021±0.002	8.75
3.221(7)		1	$\frac{1}{2}^+,\frac{3}{2}^+$		0.046±0.004	0.26

[a] From Ref. [7].

to the first excited state of ^{79}Se. The excitation energies of the ^{79}Se groups were calculated for each angle by using the positions of the groups in the focal plane and the known calibration of the spectrograph. The means of these energies are given in Table II.

In the excitation region up to 3.2 MeV, measurable cross sections have been observed for 34 groups in ^{79}Se, and the angular distributions for the transitions have been measured. These distributions, covering the laboratory angular range 3.75° to 86.75°, in 7.5° steps, are displayed in Figs. 2 to 5. The statistical uncertainties

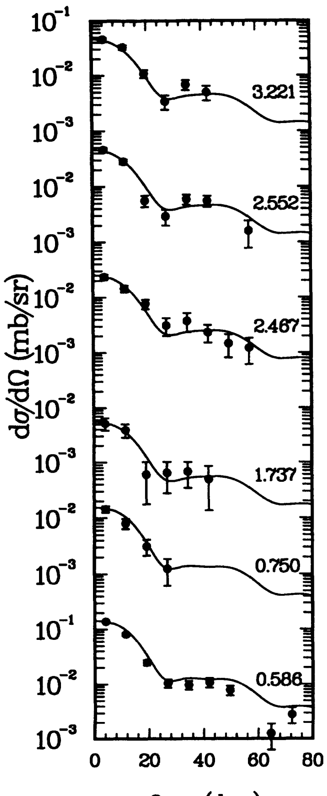

FIG. 4. Experimental angular distributions and DWBA calculations for the transitions that show a characteristic $L = 1$ shape.

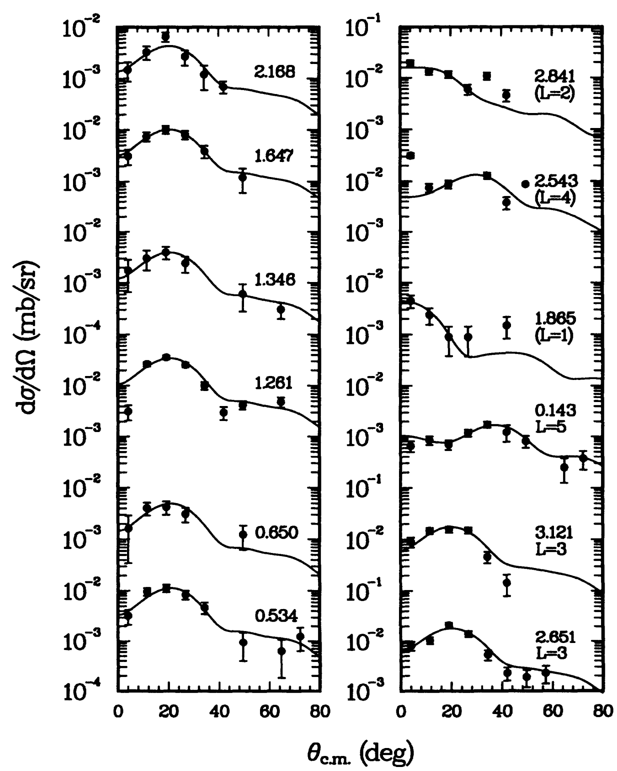

FIG. 5. Remaining angular distributions and DWBA calculations. See text for details.

are shown as vertical lines where they are larger than the experimental points. In addition to these, there is an absolute normalization uncertainty estimated to be ± 10% which arises mainly from the uncertainty in the target thickness.

III. DISCUSSION

A. Excitation energies

A comparison of the excitation energies from the present data with those previously available [7] is given in Table II. As the values from this work have uncertainties of 3 to 12 keV, it is difficult to make a one-to-one comparison with the previous data. In Table II the present excitation energies have been aligned with the previously known group closest in energy, provided that it is within the experimental uncertainty of the present data. This is not meant to indicate that they are measurements of the excitation energy of the same level in ^{79}Se—as will be apparent from the discussion of the J^π values deduced from the current data. From the comparison given in Table II it can be seen that in the present work only approximately half the previously reported levels are observed. Up to E_x=1.8 MeV the majority of the missing levels were previously seen only in the (n,γ) and $(\alpha,n\gamma)$ reactions [2, 3] and not in direct transfers. Above 1.8 MeV the previous data come entirely from one-particle-transfer reactions [4–6], and there are nine groups with energies which have no counterpart in the present data. The fact that we do not observe these states is an indication that the two-neutron component in their wave functions is small. In the present data twelve groups are observed that cannot be linked to previously reported levels. There are no known states from the even Se isotopes that can account for these groups and it is concluded that they are due to states in ^{79}Se not previously reported. A more detailed discussion of these groups is given later.

B. Angular distributions and J^π assignments

The experimental angular distributions have been compared with the results of zero-range microscopic distorted-wave Born-approximation (DWBA) calculations made by using the code DWUCK4 [10]. In the absence of any detailed shell-model calculations for the Se isotopes, pure configurations have been used for the two-neutron-transfer amplitudes. The configurations used were $(1g_{\frac{9}{2}})^2$ for the $L = 0$ and 2 transitions, $(1d_{\frac{5}{2}})^2$ for $L = 4$, $(2p_{\frac{1}{2}},3s_{\frac{1}{2}})$ for $L = 1$, $(2p_{\frac{1}{2}},2d_{\frac{5}{2}})$ for $L = 3$, and $(2p_{\frac{1}{2}},1g_{\frac{9}{2}})$ for $L = 5$. The triton optical-model parameters are the same as those used in the previous analyses of the ^{76,78,80,82}Se(t,p) reactions [9, 11–13] and those for the protons are from the work of Perey [14]. These parameters and those of the bound-state well are given in Table III. The calculated angular distributions are shown as solid curves in Figs. 2–5 and are discussed in detail later in the text.

In general for two-neutron transfers from a target nucleus with a nonzero ground-state spin, multiple L transfers are allowed to a state of given J governed by the selection rules

$$J_f = J_i + L \quad \text{and} \quad \pi_i\pi_f = (-1)^L.$$

In the case of the ^{77}Se$(t,p)^{79}$Se reaction with a ground state of $J^\pi = \frac{1}{2}^-$, parity considerations ensure that only one L transfer is allowed to a given final state. This does, however, allow two possible J^π values for the state except in the case of an $L = 0$ transfer.

The magnitudes of the theoretical and experimental distributions can be compared in order to determine enhancement factors, ϵ, defined by

$$\sigma_{\text{exp}} = N\epsilon\frac{(2J_f+1)\sigma_{\text{DWUCK}}}{(2J_i+1)(2L+1)},$$

if the final state J^π is known. However, for many states J_f^π is not known so in Table II the values $\epsilon' = (J_f+1)\epsilon$ are quoted. The value of N is linked to the optical-model parameters used in the DWBA calculations and a value of $N = 230$ is used in the present work for compatibility with our previously published (t,p) studies [9, 11–13] on the even Se isotopes. From a comparison of the shapes of the experimental and theoretical angular distributions the L transfers have been determined for all but three of the levels observed. These are summarized in Table II along with the maximum differential cross section for each transition. Table II also gives a comparison with the J^π values from previous work [7].

1. *L=0 transitions*

In Fig. 2, those angular distributions with a characteristic $L = 0$ shape are shown. The final state for these transitions must, therefore, have $J^\pi = \frac{1}{2}^-$, the same as the initial state. The transition to the state at E_x=0.096 MeV has the lowest excitation seen in this reaction. As

TABLE III. Optical-model and bound-state parameters used in the analysis of the ^{77}Se$(t,p)^{79}$Se reaction. (Strengths in MeV, lengths in fm.)

	Tritons[a]	Protons[b]	Bound state
V_0	171.0	46.96	c
r_0	1.16	1.25	1.26
a_0	0.78	0.65	0.60
W	22.5		
W_D	12.95		
r_w	1.52	1.25	
a_w	0.74	0.47	
$V_{s.o.}$		7.5	λ=25
$r_{s.o.}$		1.25	
$a_{s.o.}$		0.65	
r_c	1.25	1.25	1.25

[a]From Ref. [13].
[b]From Ref. [14].
[c]Adjusted to give one-half the two-neutron separation energy to each particle.

it has $J^\pi = \frac{1}{2}^-$, it cannot be the ground state to ground state transition because the ground state of ^{79}Se is known to be $J^\pi = \frac{7}{2}^+$ and hence could not be excited through an $L = 0$ transfer. There is evidence at one or two angles for a group with a few counts at the position expected for a group due to the ground-state transition, but it was too weak to extract any significant numbers. We see no evidence in the present work for a $\frac{1}{2}^-$ state at 0.128 MeV, which had previously been reported in (d,p) measurements as an unresolved doublet with a state at 0.137 MeV. In the present data, as is shown in Fig. 6, the angular distribution for the transition to the 0.137-MeV state can be accounted for entirely by an $L = 5$ transfer. Thus, if the state at 0.128 MeV exists, the cross section for two-neutron transfer to it must be very much smaller than those to the other $J^\pi = \frac{1}{2}^-$ states in ^{79}Se.

The group observed at 1.134 MeV has an excitation energy compatible with a state previously reported at 1.145 MeV. However, that state had been assigned $J^\pi = \frac{1}{2}^+$ on the evidence that it is populated via an $l = 0$ transfer in the (d,p) reaction. The excitation of the group at 1.134 MeV in the present work via $L = 0$ implies that the final state has $J^\pi = \frac{1}{2}^-$ and therefore is a different state in ^{79}Se.

The two other $L = 0$ angular distributions shown in Fig. 2 are for transitions to states at E_x= 2.987 and 3.021 MeV. Previously a state had been reported at 2.987 MeV but it had no J^π assignment. The group at 3.021 MeV is one of the previously unreported states seen in the present work. Unambiguous $J^\pi = \frac{1}{2}^-$ assignments can be given to both these states. The proton group from the ground-state transition in the ^{82}Se$(t,p)^{84}$Se reaction would fall midway between these two groups. However, the small amount of ^{82}Se in the target and the known cross section [13] for the ^{82}Se$(t,p)^{84}$Se reaction means that neither of the groups observed in the present data can be due to the impurity reaction.

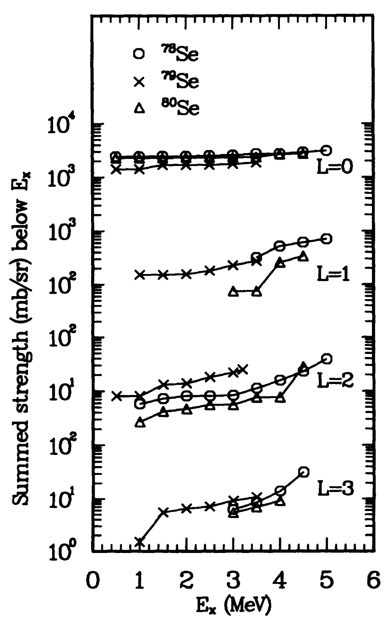

FIG. 6. Comparison of the summed strengths for $L = 0$, 1, 2, and 3 transitions leading to states in ^{78,79,80}Se.

2. L=2 transitions

Figure 3 shows the angular distributions that have characteristics of an $L = 2$ angular momentum transfer. The J^π associated with the final state must, therefore, be either $J^\pi = \frac{3}{2}^-$ or $\frac{5}{2}^-$. For the state at 0.367 MeV our result would agree with the previous assignment of $\frac{5}{2}^-$. A state at 1.964 MeV has previously been given a tentative assignment of $J^\pi = \frac{1}{2}^-$ or $\frac{3}{2}^-$ from its excitation via an $l = 1$ transfer in the (p,d) reaction [6]. The present data would support the $\frac{3}{2}^-$ assignment for this state. The previous tentative $\frac{3}{2}^-$ assignment for the state at 2.252 MeV is also supported by the $L = 2$ transfer observed in the present work. In the (d,p) reaction measurements [4, 5], three states are reported as populated by $l = 2$ transfers. Two of these at 2.340 and 3.060 MeV were given $J^\pi = (\frac{5}{2}^+)$ assignments and the third at 3.182 MeV was assigned $J^\pi = (\frac{3}{2}^+)$. It should, however, be noted that the state at 2.340 MeV was not reported in the polarized (d,p) measurements [4], but only in the earlier unpolarized work [5]. Also, no J^π assignments for the 3.060- and 3.182-MeV states were deduced from the polarized work because the excitation of the states was too weak. The assignments from the unpolarized work are based on the claimed $l = 2$ shape of the (d,p) angular distributions and the assumption that $l = 2$ transitions at $E_x \leq 3$ MeV were due to $J^\pi = \frac{5}{2}^+$ states and those above 3 MeV to $J^\pi = \frac{3}{2}^+$ states. The reliability of these assignments cannot be checked as the angular distributions for these states are not given in the paper [5]. In the present work, groups corresponding to states of similar energies are observed at 2.336, 3.072, and 3.176 MeV that have angular distributions characteristic of $L = 2$ transfer and hence must be due to transitions to states that have either $J^\pi = \frac{3}{2}^-$ or $\frac{5}{2}^-$. These results would indicate that the states we observe are not the same as those previously reported or that the previous assignments are incorrect.

With the exception of that to the state at 1.441 MeV the other $L = 2$ angular distributions cannot be associated with previously known states and $J^\pi = \frac{3}{2}^-$ or $\frac{5}{2}^-$ are assigned to the new states observed at 2.129, 2.306, 2.416, 2.599, and 2.736 MeV. The group at 1.441 MeV is associated with a previously reported state at 1.420 MeV and $J^\pi = \frac{3}{2}^-$ or $\frac{5}{2}^-$ is also assigned to this state.

3. Odd L transitions

The angular distributions that show the characteristics of an odd L transfer, and hence lead to states of even parity, are shown in Figs. 4–5. Those to the groups at 0.586, 0.750, 2.467, 2.552, and 3.21 MeV have an $L = 1$ shape indicating either $J^\pi = \frac{1}{2}^+$ or $\frac{3}{2}^+$ for the final state. The others, with the exception of the $L = 5$ transfer to the group at 0.143 MeV have a characteristic $L = 3$ shape implying that the final state has either $J^\pi = \frac{5}{2}^+$ or $\frac{7}{2}^+$.

Of the $L = 1$ transfers the 0.586-, 1.737-, 2.467-, and possibly the 2.552-MeV groups can be associated with previously known states in ^{79}Se. The group at 0.586 MeV has an energy that is compatible with the known level at 0.572 MeV. However, this state has a tentative assignment of $J^\pi = \frac{3}{2}^-$ or $\frac{5}{2}^-$ from the angular distribution of γ rays from the $(\alpha, n\gamma)$ reaction [3]. Zell *et al.* use the positive value of A_2 for the 0.476-MeV γ-ray angular distribution to the $\frac{1}{2}^-$ state at 0.096 MeV to eliminate a $J^\pi = \frac{3}{2}^+$ assignment. However, the use of the A_2 and A_4 values obtained from $(\alpha, n\gamma)$ angular distributions is not considered a reliable way of deducing J^π values [7]. The present data show that the state at 0.586 MeV has positive parity and either $J^\pi = \frac{1}{2}^+$ or $\frac{3}{2}^+$. It is likely that the present group is due to the same state as seen in the $(\alpha, n\gamma)$ reaction but that the tentative assignment given on the basis of the γ-ray angular distributions is incorrect.

The $L = 1$ shape of the angular distribution for the group at 1.737 MeV again indicates a final state with either $J^\pi = \frac{1}{2}^+$ or $\frac{3}{2}^+$ which is in agreement with the $J^\pi = \frac{3}{2}^+$ previously assigned to a state at 1.738 MeV based on its observation via an $l = 2$ transition in the (d,p) reaction. However, the other two $L = 1$ transitions that can be associated with previously known states at 2.467 and 2.552 MeV do not confirm the previous assignments of $J^\pi = \frac{5}{2}^+$. The previous assignments were made on the basis that shape of angular distributions of the vector analyzing power agreed with that calculated for an $l = 2$ transition to a $J^\pi = \frac{5}{2}^+$ final state.

The remaining two $L = 1$ transitions to groups at 0.750 and 3.221 MeV have no obvious counterparts in the previously published data and the final states associated with them are assigned either $J^\pi = \frac{1}{2}^+$ or $\frac{3}{2}^+$. It is possible that the state at 0.750 MeV could be the same one as previously observed at 0.729 MeV but this has $J^\pi = \frac{5}{2}^+$ assigned—again based on the shape of the angular distribution of the vector-analyzing power to this state. Therefore, it must be concluded that these are two different states.

Figure 5 displays angular distributions that have the characteristics of an $L = 3$ angular momentum transfer and are thus associated with final states with either $J^\pi = \frac{5}{2}^+$ or $\frac{7}{2}^+$. A state at 0.528 MeV, close to the 0.534 MeV group observed in this work, has $J^\pi = \frac{3}{2}^-$ based on its population by an $l = 1$ transition in the (d,p) reaction. This is incompatible with the present assignment of either $J^\pi = \frac{5}{2}^+$ or $\frac{7}{2}^+$. The $L = 3$ transition to the state at 0.650 MeV gives a J^π value in agreement with that assigned previously to a state at 0.630 MeV. The $(\alpha, n\gamma)$ reaction and single-particle transfer reactions populate two states at 1.253 and 1.257 MeV that lie close in energy to the group observed at 1.261 MeV. The resolution of the present experiment would not allow groups from the two states to be separated but the data clearly show an $L = 3$ shape indicating either $J^\pi = \frac{5}{2}^+$ or $\frac{7}{2}^+$ for the state or states involved which agrees with the previous assignments. The group at 1.346 MeV is only weakly excited but the shape of the distribution is clearly that of an $L = 3$ transfer. This disagrees with the tentative $J^\pi = (\frac{5}{2}^-, \frac{7}{2}^-)$ previously given to a state at this energy as a result of the observation of an $l = 3$ transition to it in the (p,d) reaction. However, examination of the (p,d) data [6] suggests that the angular distribution for the transition to this state could equally well be fitted by an $l = 4$ transfer, which would give either $J^\pi = \frac{7}{2}^+$ or $\frac{9}{2}^+$ and would then be in agreement with the present data. In the region of the 1.647-MeV state there are two states reported previously at 1.636 and 1.667 MeV. The state at higher energy has an assignment of $J^\pi = \frac{5}{2}^+$; the lower energy level was unassigned. The $L = 3$ transfer for the angular distribution for the state observed in the present data leads to an assignment of $J^\pi = \frac{5}{2}^+$ to this state. The $L = 3$ transfer to the state at 2.168 MeV is compatible with it being the same state previously observed at 2.171 MeV and assigned $J^\pi = \frac{5}{2}^+$. The other two groups at 2.651 and 3.121 MeV that exhibit an $L = 3$ shape have no obvious candidates in the previous data and these newly observed states are assigned either $J^\pi = \frac{5}{2}^+$ or $\frac{7}{2}^+$.

Only one angular distribution is observed with an $L = 5$ shape, that for the group at 0.143 MeV. This transfer is compatible with it being the state reported at 0.137 MeV and assigned $J^\pi = \frac{9}{2}^+$. There is no evidence for an admixture of an $L = 0$ transfer that would be necessary if the angular distribution resulted from transition to an unresolved doublet with $J^\pi = \frac{1}{2}^-$ and $\frac{9}{2}^+$ as suggested by the (d,p) measurements. The present data, therefore, give no support for a state at 0.128 MeV with $J^\pi = \frac{1}{2}^-$.

4. Unassigned angular distributions

There are three remaining angular distributions the shape of which are not directly comparable with that of a DWBA calculation for a single L transfer. These are for the groups at 1.865, 2.543, and 2.841 MeV and are shown in Fig. 5. Also shown in Fig. 5 are the best fits of the angular distribution to a calculation for a single L transfer. None of these fits are of the quality of those for the other angular distributions shown in Figs. 2–5, and the fitted L transfers lead to J^π assignments, for the states associated with these groups, that are incompatible with any previous assignments for states at these energies. It is possible that they are due to transfers to unresolved doublets. However, each of these groups is close in energy to a previously known state that is not indicated as a doublet in the compilation, but as they were only previously observed in single-particle-transfer reactions the resolution of the previous data may also not have been good enough to resolve the doublets. Attempts to fit the data with incoherent sums of two different L transfers indicate that equally good fits can be obtained using many different combinations of L values. Hence it has not been possible to obtain unambiguous information on the L transfer for the transitions to the states at 1.865, 2.543, and 2.841 MeV.

IV. SUMMARY

By using the ^{77}Se$(t,p)^{79}$Se reaction at 17 MeV angular distributions have been measured for transitions leading to 34 states or groups of states in ^{79}Se. Twelve of the transitions are to states not previously reported. Comparison of the data with DWBA calculations has allowed values of the L transfer to be extracted for the majority of the transitions. Of these, four show unambiguous $L = 0$ shapes allowing assignment of $J^{\pi} = \frac{1}{2}^{-}$ to the final state involved. With the exception of those to the groups at 1.875, 2.543, and 2.841 MeV all the other angular distributions could be fitted with a single L transfer allowing the J^{π} value to the final state involved to be limited to two values.

In a large number of cases the J^{π} assignments deduced from the present measurements differ from those previously assigned and in particular those assigned from single-particle-transfer reactions. This might indicate that we primarily excite a different set of states in two-neutron transfer than in one-particle transfer. However, if this were the case, there would be a much higher density of states than was previously indicated. The possibility does exist, however, that some of the l transfers on which the majority of the previous J^{π} assignments are based are incorrect.

As ^{77}Se is the only stable odd-A Se isotope, comparison of ^{77}Se$(t,p)^{79}$Se with other odd-A cases is not possible. However, it is of interest to compare it with the two adjacent even nuclei. We have, therefore, compared the measured strengths of various L values ($L = 0$–3) for the (t,p) reaction leading to ^{78,79,80}Se. In Fig. 6 are plotted for each L value the sum of the peak cross sections below a given E_x vs that E_x (in 0.5 MeV steps). The relative flatness of the $L = 0$ results for ^{78,80}Se is simply due to the fact that the ground state dominates the $L = 0$ strength in those nuclei. More excited $L = 0$ strength is seen in ^{79}Se, but the total never reaches that of the other two nuclei.

For $L = 1$, the strength begins at a much lower excitation energy in ^{79}Se than in ^{78,80}Se, but as E_x increases the $L = 1$ total for ^{79}Se appears to be approaching a value between those for ^{78,80}Se.

The biggest difference appears for $L = 2$. At a given E_x, the summed $L = 2$ strength up to that E_x in ^{79}Se is two to four times that in ^{78,80}Se. This excessive $L = 2$ strength is manifest by the larger number of strong $L = 2$ states in Fig. 3. The origin of this excess is unknown to us.

For $L = 3$, as for $L = 1$ above, the strength appears at a lower E_x in ^{79}Se than in ^{78,80}Se. The low-lying $L = 1$ and $L = 3$ transitions may simply reflect a preponderance of positive-parity states at low energy in ^{79}Se (each of which has some $2n$-transfer strength) coupled with the negative-parity ^{77}Se(g.s.). On the other hand, the lowest state in even nuclei are always of positive parity, and hence give rise to even L in $2n$ transfer.

The apparent poor agreement between our results and previously known states in ^{79}Se is, at first sight, surprising. In Fig. 7 are plotted the number of levels vs E_x for the present and previously known levels. The decreasing slope of the curve for the previous data makes it obvious that several states must have been missed up to now. In our reaction, the energy spacing decreases more or less monotonically as E_x increases, indicating that we are probably sampling an approximately fixed fraction of the states.

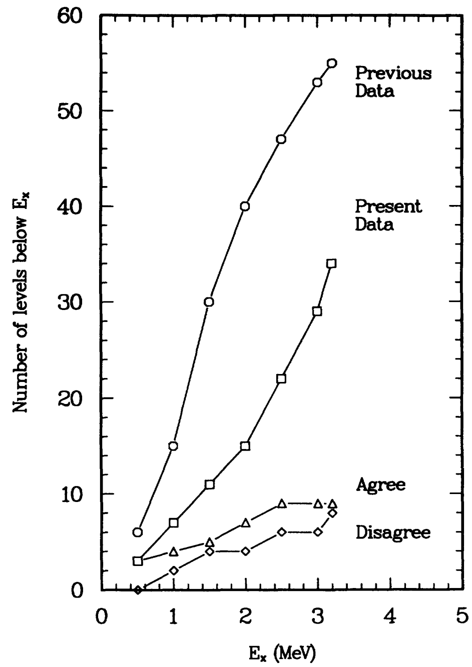

FIG. 7. Comparison of the number of levels between previously known and present data.

In our range of excitation, 55 states were previously known, and we observe 34 states with sufficient yield to extract angular distributions. If we simply make the obvious identifications based on excitation energy, then the J^{π} values for nine of our states are consistent with the previous information, whereas eight are in disagreement. The root-mean-square average energy differences between the present and previous results are virtually the same for the two sets of states: -7.9 and 9.0 keV, respectively. This number is comparable to our average uncertainty in E_x. It is likely that some of the previous J^{π} assignments are indeed incorrect, but we do not suggest that 8 are wrong. Many of our states were obviously previously unknown, probably including some of these 8. If all present and previous J^{π} information is correct, then only 13 of the states for which we make definite L assignments were previously known; 17 are new. Only tentative L assignments are made for the other five. This also would imply that 41 of the previously known states below 3.0 MeV are not populated in the (t,p) reaction with enough strength to analyze.

ACKNOWLEDGMENTS

This work was supported by the Science and Engineering Research Council (U.K.) and the National Science Foundation (U.S.A.).

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