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^{80}Se from the ^{78}Se(t,p) reaction

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The reaction ^{78}Se(t,p)^{80}Se has been investigated with 17-MeV tritons. Twenty-eight levels of ^{80}Se were observed up to an excitation energy of 5.2 MeV, and angular distributions have been extracted for twenty-two of them. Comparisons are made with distorted-wave Born-approximation calculations, allowing J^{π} assignments to be made for most of the levels observed.

I. INTRODUCTION

The nucleus ^{80}Se has been the subject of several investigations, primarily using inelastic scattering of protons,[1-3] deuterons,[4] and heavy ions.[5-7] Additional information has come from the study of γ rays following the β^- decay of ^{80}As (Refs. 8 and 9) and from ^{82}Se(p,t) (Ref. 10). In spite of this, very few unambiguous spin-parity (J^{π}) assignments have been made. Available excitation energies and J^{π} values are summarized in the latest compilation.[11] This paper presents the results of an investigation of the ^{78}Se(t,p)^{80}Se reaction, which was performed to learn more about the levels of ^{80}Se and as part of a systematic study[12,13] of 2n transfer on nearby nuclei.

II. EXPERIMENTAL PROCEDURE AND RESULTS

The measurements were performed using a 17-MeV triton beam from the University of Pennsylvania FN tandem. The outgoing protons were momentum analyzed in a multiangle spectrograph. The full details of the experimental technique are described in previous publications (e.g., Ref. 12). The target was nominally 65 μg/cm^2 of enriched (98.6%) ^{78}Se evaporated onto a 25 μg/cm^2 carbon backing. The experiment was performed with a triton beam current of 100 nA. Even with this low current, noticeable deterioration of the target occurred. The elastic count rate in a monitor detector decreased by about 40% during the run. We have normalized the data to a monitor spectrum collected simultaneously with the (t,p) data. The average ^{78}Se target thickness thus obtained is 52.9 μg/cm^2 and is believed to be accurate to within 15%. With this normalization, the ^{78}Se(t,p)^{80}Se(g.s.) cross section at $\theta_{\text{c.m.}}=4.1°$ is (2.29 ± 0.11) mb/sr. In a separate experiment[13] on a natural Se target, this cross section was measured to be 2.20 ± 0.11 mb/sr.

A proton spectrum taken at 11.25° (lab) is displayed in Fig. 1. The resolution is approximately 20 keV FWHM. The peaks due to states in ^{80}Se are labeled by their excitation energy, and those due to the ^{16}O and ^{12}C impurities are shown shaded. The excitation energies were calculated using the measured peak positions and the known calibration of the spectrograph. The values shown in Fig. 1 and also quoted in Table I are the averages of those obtained at all angles at which the peak was observed. We have observed 28 states with sufficient intensity to obtain the excitation energy; of these we have measured angular distributions for 22. These angular distributions are displayed in Figs. 2 and 3. With the possible exception of those at 3160, 3350, 4464, 4712, and 5180 keV, all the states seen in the present work have counterparts in the literature.[11]

III. ANALYSIS AND DISCUSSION

Local, zero-range distorted-wave Born-approximation (DWBA) calculations have been performed at the excitation energies corresponding to the angular distributions shown in Figs. 2 and 3. In the absence of any detailed shell-model calculations of the Se isotopes, pure configurations have been used for the two-neutron transfer amplitudes, with the exception of the ground state. The configurations used were $(1g_{9/2})^2$ for $L=0$, 2, 4, and 6; $(2p_{1/2},3s_{1/2})$ for $L=1$; $(2p_{1/2},2d_{5/2})$ for $L=3$, and $(2p_{1/2},1g_{9/2})$ for $L=5$. The two-neutron transfer amplitude for the ground state transition was calculated in the quasiparticle limit[14] assuming that the $(1g_{9/2})$, $(1f_{5/2})$, $(2p_{3/2})$, and $(2p_{1/2})$ orbitals are available. Full details of this procedure are given in Ref. 13. The DWBA calculations were carried out using the code DWUCK4 (Ref. 15) with the optical-model parameters given in Table II. The results of the calculations, shown as solid lines, are compared with the data in Figs. 2 and 3. The L transfers deduced from these comparisons are shown in the figures and are quoted in Table I. The magnitudes of the theoretical and experimental angular distributions have been compared in order to determine the enhancement factors, ϵ, defined by:

$$\sigma_{\text{exp}}(\theta)=230\epsilon\sigma_L(\theta)_{\text{DWBA}}\ .$$

The choice of the factor 230 is discussed several places in the literature (e.g., Ref. 12). These enhancement factors, summarized in Table I, give a measure of the relative transition strength that is independent of Q-value effects.

Except for the ground state, all the low-lying levels of

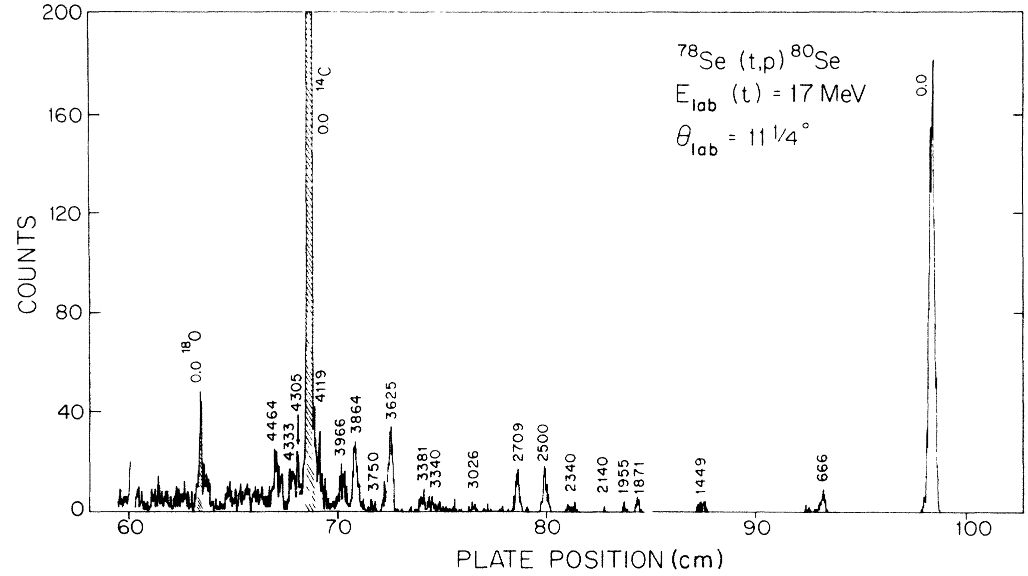

FIG. 1. Spectrum of the ^{78}Se(t,p)^{80}Se reaction at a triton energy of 17 MeV and a laboratory angle of 11.25°.

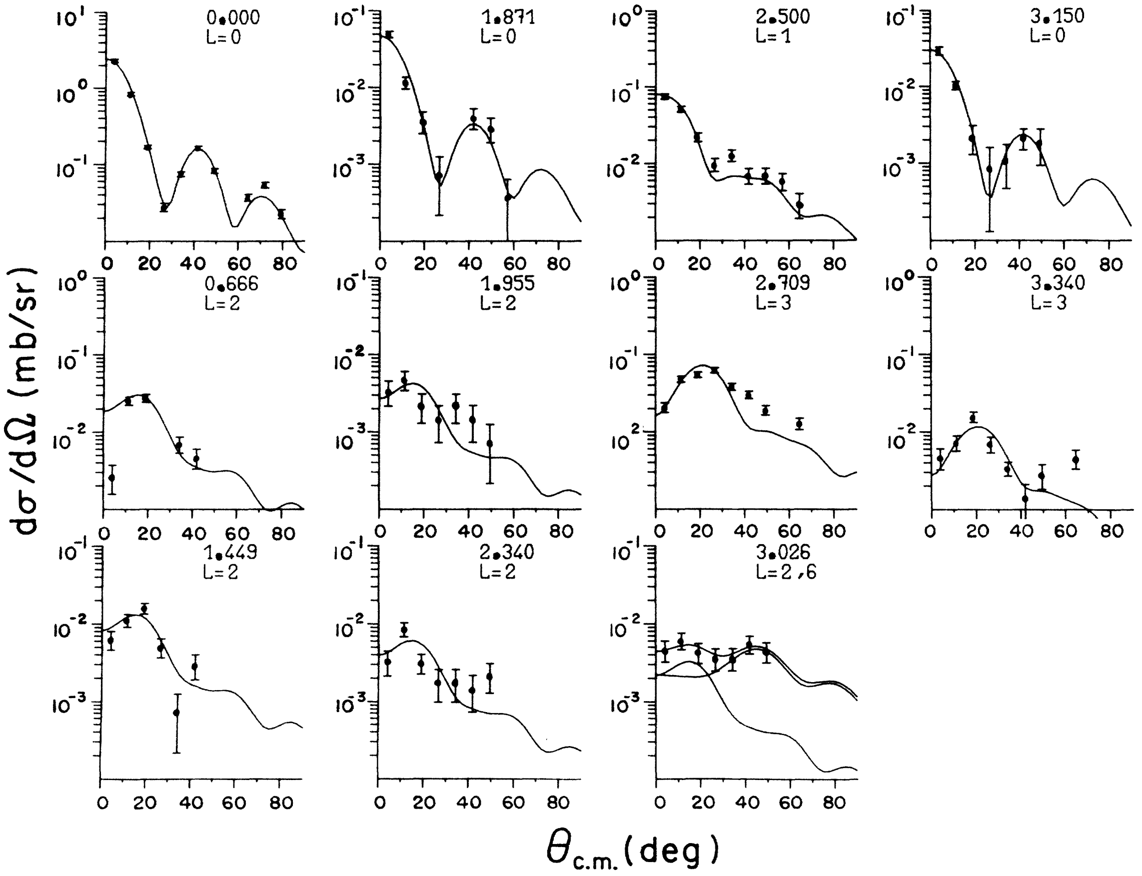

FIG. 2. Angular distributions for the ^{78}Se(t,p)^{80}Se reaction at 17 MeV incident energy. The excitation energies are given in MeV. The curves are the result of DWBA calculations, the details of which are given in the text.

TABLE I. Summary of experimental data for the ^{78}Se(t,p)^{80}Se reaction.

Previous[a]		Present			
E_x (keV)	J^π	E_x (keV)	L	$\sigma_{\max}\left[\frac{\mu b}{sr}\right]$	ϵ
0.0	0^+	0.0	0	2297±115	2.88
666.18	2^+	676±11	2	27±3	1.22
1449.33	2^+	1461±9	2	15±2	0.53
1479.10	0^+	b		<17	
1701.50	4^+	b		b	
1873.42	$(0^+,2)$	1881±11	0	50±5	0.74
1960.18	2^+	1965±14	2	4.7±1.3	0.17
2121.1	(≤4)	2150±19		b	
2311.5	(1,2)				
2344.1	$(1,2^+)$	2350±5	(2)	8.6±1.8	0.23
2495.3	(2,3,4)	2510±11	1	75±6	2.37
2514.29	(2^+)				
2627.2	(0,1,2)				
2717.4	3^-	2719±6	3	54±4	0.62
2774.3	$(1,2^+)$				
2787					
2814.2	(2^+)				
2825.5					
2827.24	(2^+)				
2836.3	$(1,2^+)$				
2947.5	(≤4)				
2998					
3025.0	$(1,2^+)$				
3038.7	(1,2)	3036±10	(2+6)	6.0±1.5	(L =2 0.14) (L =6 0.34)
3126.25	(2^+)	3160±9	0	28±3	0.51
3175.4	$(1,2^+)$				
3199.5	(2)				
3226.6	(1,2)				
3248.5	(2^+)				
3280.4	$(1,2^+)$	3280±30		b	
3314					
3316.6	(0)				
3350.43	(1^+)	3350±12	(3)	15±2	0.10
3391.0	(2^+)	3391±9	(2)	18±2	0.52
3441.4	(0^+)				
3491		3484±30		b	
3606.5	(2)				
3619.7	(0^+)	3635±5	0	308±15	5.85
3640					
3655.7	(0,1,2)				
3675.5					
3727.4	(0,1,2)				
3754		3760±10	(3)	(22±3)	0.01
3774					
3815.4	(2−6)				
3826					
3845					
3870.3	(1,2)	3874±5	(1)	111±7	4.39
3930					
3952.0	(1,2)				
3965		3976±8	(1)	73±5	2.72
4011					
4023					
4047.1	(≤4)				
4062.4	(0^+)	4063±16	(2)	10±2	0.71
4125		4129±8	0	66±5	3.08
4169		4176±5	2	73±5	2.79

TABLE I. (*Continued*).

Previous[a] E_x (keV)	J^π	Present E_x (keV)	L	$\sigma_{\max}$ $\left[\frac{\mu b}{sr}\right]$	ϵ
4233		4247±7	2	34±3	1.65
4302		4315±14	(2)	44±4	1.94
4333		4343±13	2	47±4	1.82
		4464±5	(1)	80±6	3.38
		4712±30			
		5180±30			

[a]Reference 11.

[b]Groups that are too weakly excited to allow excitation energy and/or cross section to be determined.

^{80}Se are extremely weakly excited. The first excited 0^+ level, at 1479 keV (Ref. 11), is unresolved from a nearby 2^+ state, at 1449 keV, but the latter is so weak that an upper limit of 17 μb/sr can be placed on the 0^+ cross section at 4.1°. This limit is 7×10^{-3} of the ground-state cross section.

The first 2^+ and 4^+ states are also quite weak, the latter too weak to extract a cross section. The state we observe at 1881±11 keV has an $L=0$ angular distribution and is probably to be identified with the 1873-keV level in the compilation, with $J^\pi=(0^+,2)$. Our angular distribution allows an unambiguous assignment of $J^\pi=0^+$. The measured forward-angle cross section of 49.6±4.6 μb/sr is $(2.16\pm0.20)\times10^{-2}$ times that of the ground state.

One of the two 0^+ states at 1479 and 1873 keV is likely to be an intruder, the other being the 0^+ member of the "two-phonon triplet" containing the 2^+ and 4^+ states at 1449 and 1701 keV, respectively. Correspondence with lighter Se nuclei might suggest that it is the 1873-keV state that is the intruder.

States at 1965, 2150, and 2350 keV are also quite weakly populated. The first is probably to be identified with a known 2^+ level at 1960 keV. The second, for which we have no angular distribution, may be the state previously

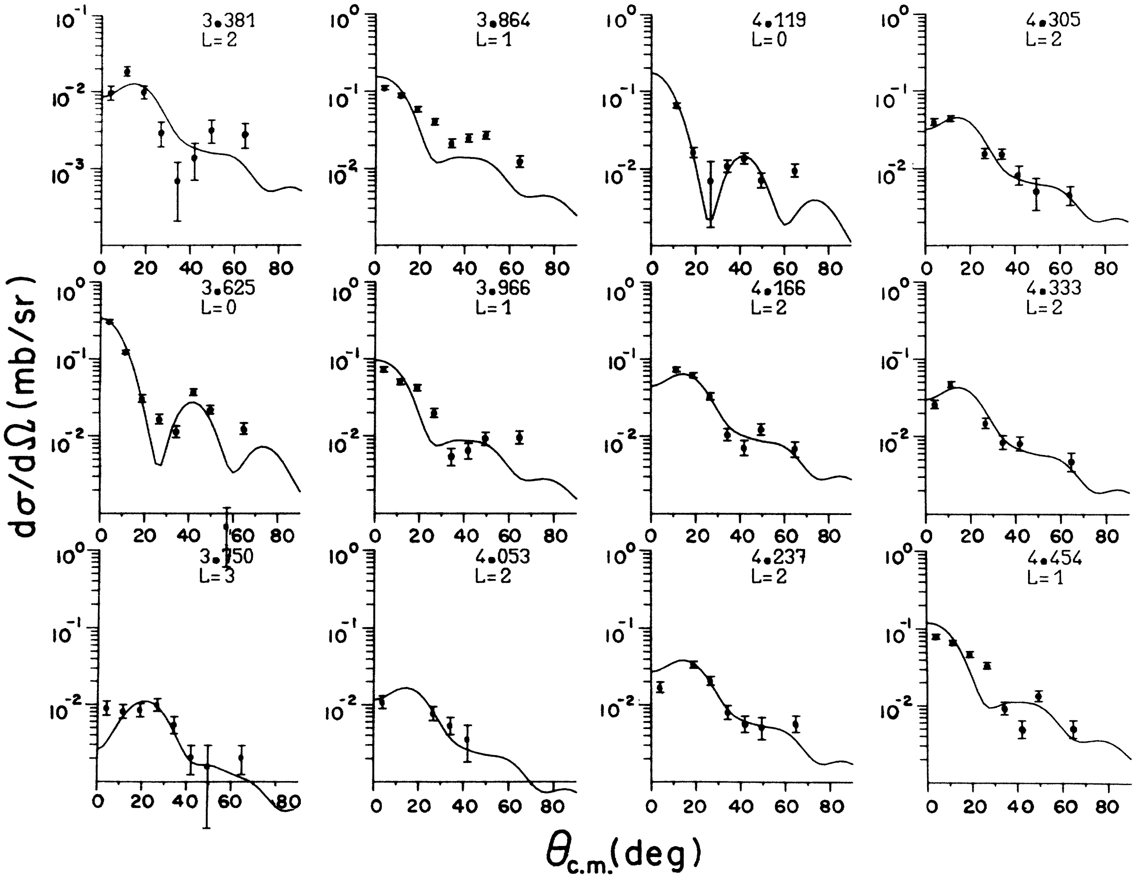

FIG. 3. The same as Fig. 2, except for $E_x > 3.35$ MeV.

TABLE II. Optical-model parameters used in the DWBA calculations. Potentials in MeV, lengths in fm.

Channel	V	r_0	a_0	W	W_D	r_W	a_W	V_{SO}	r_c
$^{78}Se + t$[a]	171	1.16	0.78	22.5		1.52	0.74		1.25
$^{80}Se + p$[b]	46.9	1.25	0.65		12.95	1.25	0.47	7.5	1.25
Bound states	c	1.26	0.60					$\lambda=25$	1.25

[a] Reference 16.
[b] Reference 17.
[c] Adjusted to give a binding energy of half the two-neutron separation energy to each particle.

known at 2121 keV, with $J \leq 4$. Its location and extremely small cross section make it a candidate for the first 3^+ state of ^{80}Se. The level we observe at 2350±5 keV is near two levels previously known—at 2311 keV [with $J=(1,2)$] and 2344 keV [with $J^{\pi}=(1,2^+)$]. Inelastic deuteron scattering[4] assigns positive parity to a state at 2320 keV, and the present data indicate that it is a 2^+ state.

Below 2.4 MeV excitation we have two 0^+ angular distributions, both of which are quite well fitted by $L=0$ DWBA curves, and four angular distributions of known or suspected 2^+ states. None of the latter are well fitted by $L=2$ DWBA curves, but the yields are quite weak and the error bars are large. The sum of these four angular distributions is plotted in Fig. 4, and compared with an $L=2$ DWBA curve. The agreement is acceptable.

Our 2510-keV state, which is strong, lies between known states at 2495 keV [with $J=(2,3,4)$] and 2514 keV [with $J^{\pi}=(2^+)$]. Its angular distribution is not characteristic of any single L value, or of any combination of L values allowed by the previous assignments. The 2495-keV state has gamma branches to lower 2^+ and 4^+ levels, and the 2514-keV state decays to the ground state and to the first 2^+ level. In (d,d′), Lin[4] reports negative parity

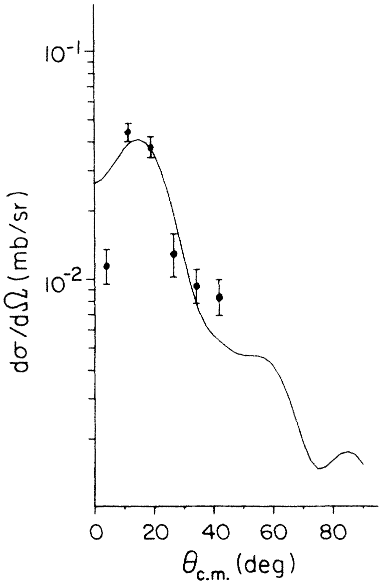

FIG. 4. Comparison of the summed $L=2$ strength for $E_x < 2.5$ MeV with the prediction of a DWBA calculation with $L=2$.

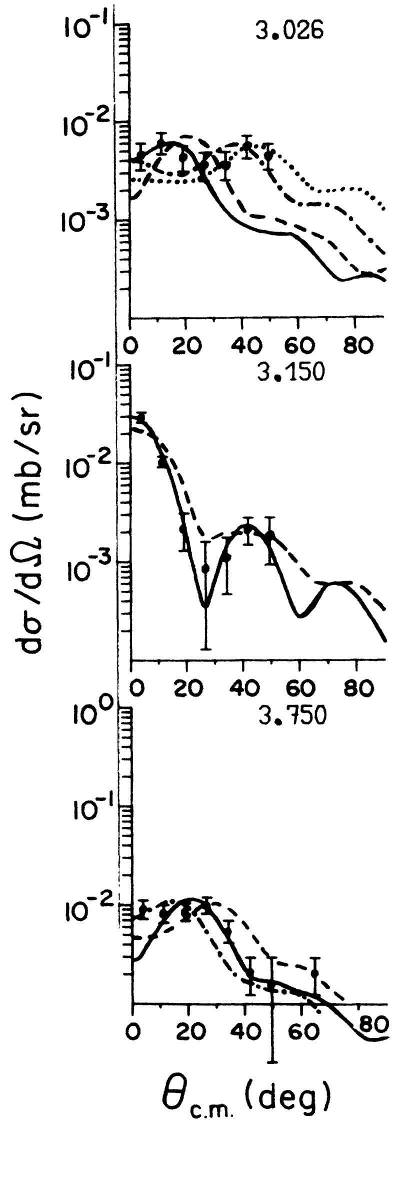

FIG. 5. Top part: comparison of the experimental angular distribution for the group at $E_x=3.036$ MeV with DWBA calculation performed for $L=2$ (solid curve), 3 (dashed), 5 (dot-dash), and 6 (dotted) angular momentum transfers. Middle part: comparison of the angular distribution for the group at $E_x=3.160$ MeV with DWBA calculation for $L=0$ (solid curve) and 1 (dashed). Bottom part: comparison of the angular distribution for the group at $E_x=3.760$ MeV with DWBA curves calculated for $L=2$ (dot-dash curve), 3 (solid), and 4 (dashed).

for a level at 2500 keV. Other work reports a closely spaced doublet.[11] We compare our data with an $L=1$ curve, which fits reasonably well. Hence, it would appear that a 1^- state is responsible for our cross section.

We see no evidence for a state at 2627 keV, previously assigned $J=(0,1,2)$. The state we observe at 2719 keV is undoubtedly the 3^- level known[11] at 2717 keV. Its angular distribution is reasonably well fitted with an $L=3$ DWBA curve. Between this state and $E_x=3.0$ MeV, we observe none of the previously known[11] eight states with enough yield to allow extraction of excitation energies or cross sections.

The state observed at 3036 keV may correspond to the $(1,2^+)$ state at 3025 keV in the compilation, or it may also contain contributions from the 2998- and 3039-keV levels. The former has no existing J^π information, whereas the latter has $J=(1,2)$. Our angular distribution is nondescript—somewhat indicative of high J or of a nondirect process. We compare the data with a variety of DWBA curves in Fig. 5. The best fit is obtained with a sum of $L=2+6$ which is compared to the experimental angular distribution in Fig. 3. Thus the group at 3036 keV is most likely due to transitions to an unresolved doublet with components $J^\pi=2^+$ and 6^+. By comparison with other even Se isotopes, this excitation energy is quite reasonable for the location of the first $J^\pi=6^+$ state in ^{80}Se, though our assignment is only tentative.

Our 3160-keV state is midway between states at 3122 and 3175 keV, previously assigned J^π (2^+) and $(1,2^+)$, respectively. The shape of the distribution is consistent only with an $L=0$ transfer. No $J^\pi=0^+$ state is known or suspected near this energy, but we can find no impurity that might be responsible. The angular distribution is compared with $L=0$ and 1 DWBA curves in Fig. 5. $L=0$ is the preferred transfer.

The next state for which we have an angular distribution is at 3350 ± 12 keV. States near this energy are 3314 (no J^π information), 3317 $[J=(0)]$, and 3350 $[J^\pi=(1^+)]$ keV. In (d,d′) a level at 3300 keV is assigned positive parity. Our angular distribution is between that expected for $L=2$ and 3, with perhaps some preference for the latter. We note that Lin[4] assigns negative parity to a level at 3370 keV.

Our state at 3391 ± 9 keV has an angular distribution that appears to be characteristic of $L=2$, and is probably to be identified with the (2^+) state at 3391 keV in the compilation.

The 3635-keV state has a clear $L=0$ angular distribution, allowing an unambiguous assignment of $J^\pi=0^+$. A level at 3620 in the compilation had a tentative (0^+) assignment. Our forward-angle cross section of 308 μb/sr is 13% of that for the ground state. In ^{80}Se(t,p)^{82}Se (Ref. 12), significant excited 0^+ strength also began to appear about 3.5 MeV above the ground state. The 3760-keV level is near a (0,1,2) level at 3727 keV given in the compilation, a probable state at 3754 keV, and a state at 3774 keV—the latter two having no J^π information. In (d,d′) a 3780-keV state was assigned[4] negative parity. We compare the data with $L=2$, 3, and 4 DWBA curves in Fig. 5, clearly showing a preference for $L=3$.

Our 3874-keV state may contain contributions from two previously known states at 3845 and 3870 keV. Our angular distribution is compared, in Fig. 3, with a DWBA calculation for $L=1$. It appears that there could be a contribution from a second L value at approximately 30°. However, the groups at 3976 and 4464 keV have very similar shapes. It could well be that this is the characteristic shape of an $L=1$ transition at these excitation energies and that a simple DWBA calculation using pure configurations is unable to reproduce it. The quality of the fits does, however, mean that our $J^\pi=1^-$ assignments to these levels is only tentative.

A state at 4047.1 keV has a previous assignment of $J\leq4$. Our 4063-keV angular distribution has two points missing because of an impurity peak, but the data are consistent with $L=2$.

The 4129-keV state is obscured by an impurity at the most forward angle, but at other angles, an $L=0$ curve fits quite well. A state at 4062 keV has a tentative assignment of (0^+), but is too far away to be the state we observe.

A state at 4169 keV has a negative-parity assignment[4] from (d,d′). Our angular distribution for a state at 4176 keV is similar to an $L=2$ DWBA curve, as is that for the state at 4247 keV.

Angular distributions for states at 4315 and 4343 keV are similar to one another and appear to be characterized by $L=2$. The 4464-keV state has an $L=1$ angular distribution similar in shape to the states observed at 3874 and 3976 keV.

IV. SUMMARY AND CONCLUSIONS

We have measured excitation energies for 28 levels up to $E_x=5.2$ MeV in ^{80}Se, and angular distributions for 22 of them. Comparisons with DWBA calculations have allowed J^π assignments to be made for most of the levels for which we have angular distributions. At low excitation energies all excited states are weak, implying that configurations other than ^{78}Se(g.s.)$\otimes$2n dominate. At higher energies, many transitions show a considerable increase in strength. The negative-parity levels probably involve excitations into the next major shell. If so, they should be weakly populated in ^{82}Se(p,t)^{80}Se, whereas the low-lying positive-parity states might be strong. Unfortunately the available ^{82}Se(p,t) data[10] consist only of one angular distribution for the ground-state transition. It would be very interesting to have a comprehensive study of this reaction to compare with the present data to help unravel the structure of ^{80}Se.

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