# $^{82}$Se from the $^{80}$Se(t,p)$^{82}$Se reaction

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The reaction $^{80}$Se(t,p)$^{82}$Se has been studied with a 15 MeV triton beam. Twenty-four energy levels in $^{82}$Se have been identified up to approximately 5.0 MeV excitation, 12 of which were previously unreported. Angular distributions were measured and compared with distorted-wave Born approximation calculations in order to make $L$ (and hence $J^{\pi}$) assignments.

## I. INTRODUCTION

Data on the energy levels of the selenium isotopes are available covering the range from $^{70}$Se to $^{84}$Se.[1–5] The only comprehensive two-particle transfer measurements have been on the $^{82}$Se(t,p)$^{84}$Se reaction,[5] in which angular distributions were measured for states up to 5.6 MeV excitation. In that work a small amount of information was obtained for the $^{80}$Se(t,p)$^{82}$Se reaction on the $^{80}$Se impurity in the target. However, the data obtained were not of sufficient quality to allow spin-parity assignments based on the angular distributions. Most of the other data available[4] on $^{82}$Se come from $^{82}$As decay scheme studies.[6]

The present paper reports the results of measurements of the $^{80}$Se(t,p) reaction at 15 MeV. Angular distributions have been obtained for 24 levels up to an excitation energy of 5.0 MeV. Comparison of these with the predictions of microscopic distorted-wave Born approximation (DWBA) calculations has enabled the determinations of $L$ transfers (and hence $J^{\pi}$) for many of the levels seen.

## II. EXPERIMENTAL PROCEDURE

The measurements were made at the University of Pennsylvania using a 15-MeV triton beam from the FN tandem accelerator. The outgoing protons were momentum analyzed in a multiangle spectrograph and recorded on Ilford L4 nuclear emulsions in the focal plane. Thick mylar absorbers were placed directly in front of the emulsions to stop all particles except protons. The emulsions were scanned with the scanning facilities[7] at the University of Bradford.

Angular distributions were measured over the angular range 3.75°–86.25° (lab) in 7.5° steps. The target was nominally 60 $\mu$g/cm$^2$ of Se enriched to 96.9% in $^{80}$Se. To prevent evaporation of the target it was made in the form of a sandwich with the Se evaporated onto a 20 $\mu$g/cm$^2$ carbon backing and then covered with approximately 100 $\mu$g/cm$^2$ Au. With a target of this type it was possible to use beams up to 250 nA without any observable deterioration of the target. The scattering from the target was monitored with a surface barrier detector mounted at 40° to the beam. The data from this detector were also used to estimate the target thickness by normalizing the measured elastic scattering yield to the cross section predicted by optical model calculations with the parameters (Table I) used in the DWBA analysis. The magnitude of this predicted elastic scattering cross section at 40° (lab) is somewhat sensitive to the optical parameters chosen, but with the parameters of Table I, the measured monitor yield gives a Se target thickness of 57.6 $\mu$g/cm$^2$, quite close to the nominal value of 60. For calculation of absolute cross sections, we have assumed 60 $\mu$g/cm$^2$.

## III. RESULTS AND ANALYSIS

The spectrum of the outgoing protons observed at 11.25° (lab) is shown in Fig. 1. Energy resolution is approximately 20 keV (FWHM). Proton groups that arise from states of $^{82}$Se are numbered consecutively starting with the ground-state group as zero. Corresponding excitation energies were obtained for each angle using the position of the group in the focal plane and the known ener-

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

| Channel | $V$ | $r_0$ | $a_0$ | $W$ | $W_D$ | $r_W$ | $a_W$ | $V_{SO}$ | $r_c$ |
|---|---|---|---|---|---|---|---|---|---|
| $^{80}$Se+t[a] | 171 | 1.16 | 0.78 | 22.5 | | 1.52 | 0.74 | | 1.25 |
| $^{82}$Se+p[b] | 48.9 | 1.25 | 0.65 | | 13.0 | 1.25 | 0.47 | 7.5 | 1.25 |
| Bound states | c | 1.26 | 0.60 | | | | | $\lambda=25$ | 1.25 |

[a]Reference 5.
[b]Reference 10.
[c]Adjusted to give a binding energy of half the two neutron separation energy to each particle.

 

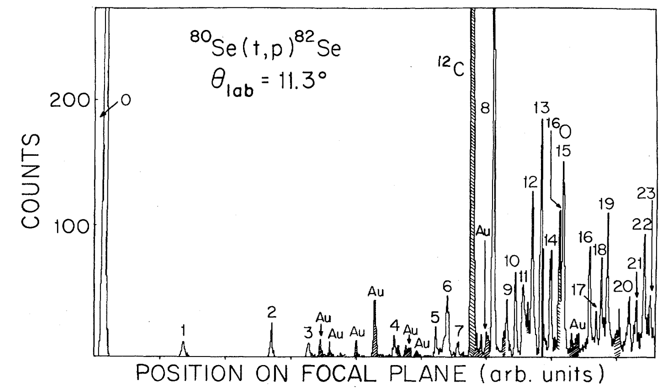


FIG. 1. Spectrum of the $^{80}$Se(t,p)$^{82}$Se reaction at a triton energy of 15.0 MeV and a laboratory angle of 11.25°.

gy calibration[8] of the spectrograph. The averages of the values obtained are given in Table II. In Fig. 1 impurity peaks due to Au, $^{12}$C, and $^{16}$O are shaded and labeled with the impurity nucleus.

Measurable cross sections were observed for 24 levels up to 5.03 MeV excitation in $^{82}$Se, and angular distributions were obtained for all these states. These angular distributions have been compared with the results of zero-range DWBA calculations using the code DWUCK.[9] The triton parameters used in the analysis were taken from the fit to the $^{84}$Se(t,t) elastic scattering data by Knight *et al.*[5] The exit channel proton parameters were taken from the work of Perey.[10] The parameters used are given in Table I.

Figure 2 displays the angular distribution for the ground state of $^{82}$Se together with others that possess a possible $L=0$ shape as observed in the present work. The curves are results of DWBA calculations. The angular distributions characterized by $L=2$ angular momentum transfer are given in Fig. 3 and those with possible $L=4$ character are given in Fig. 4. Angular distributions characterized by odd $L$ values are shown in Fig. 5 and those for which no $L$ value assignment could be made are shown in Fig. 6. On several of the angular distributions some data points are missing for angles at which the data were masked by an impurity group or the cross section was too small for reliable extraction.

As no shell-model wave functions were available for $^{82}$Se, we have assumed pure configurations for the transferred neutron pair. It was found that the shapes of the DWBA curves were relatively insensitive to the as-

TABLE II. Summary of experimental data for the $^{80}$Se(t,p)$^{82}$Se reaction.

| Previous | | Present | | | | | |
|---|---|---|---|---|---|---|---|
| $E_x$[a] (MeV) | $J^{\pi}$[b] | Level No. | $E_x$ (MeV) | $\sigma_{max}$ (mb/sr) | $L$ | $J^{\pi}$ | $\epsilon$ |
| 0.0 | $0^+$ | 0 | 0.0 ±0.006 | 2.371±0.039 | 0 | $0^+$ | 35.0 |
| 0.655 | $2^+$ | 1 | 0.656±0.006 | 0.016±0.002 | 2 | $2^+$ | 0.68 |
| 1.420 | $(0^+)$ | 2 | 1.412±0.006 | 0.036±0.003 | 0 | $0^+$ | 0.54 |
| 1.731 | $2^+$ | 3 | 1.735±0.008[c] | 0.052±0.002 | 2,4 | $2^+$ and $4^+$ doublet | 1.90($2^+$) |
| 1.735 | $4^+$ | | | | | | 3.05($4^+$) |
| 2.551 | $3^+$ | 4 | 2.546±0.012 | 0.010±0.002 | | | |
| 2.894 | $4^-$ | 5 | 2.897±0.006 | 0.017±0.002 | | | |
| 3.015 | | 6 | 3.012±0.004 | 0.058±0.004 | 3 | $3^-$ | 0.07 |
| 3.08 | | 7 | 3.101±0.009 | 0.011±0.002 | (5) | $(5^-)$ | 0.065 |
| 3.454 | $(5^-)$ | 8 | 3.449±0.004[d] | 0.846±0.042 | 0 + (5) | $0^+ + (5^-)$ | 13.8 |
| | | 9 | 3.581±0.008 | 0.035±0.003 | 2 | $2^+$ | 1.5 |
| 3.670 | | 10 | 3.669±0.006 | 0.057±0.003 | 2 | $2^+$ | 2.5 |
| | | 11 | 3.748±0.013 | 0.063±0.004 | 2 | $2^+$ | 2.7 |
| | | 12 | 3.834±0.008 | 0.271±0.01 | 0 | $0^+$ | 4.6 |
| | | 13 | 3.921±0.006 | 0.238±0.012 | 2 | $2^+$ | 10.2 |
| | | 14 | 4.010±0.005 | 0.064±0.004 | 2 | $2^+$ | 2.8 |
| 4.091 | $(4,5^-)$ | | | | | | |
| 4.135 | | 15 | 4.134±0.006 | 0.143±0.007 | 2 | $2^+$ | 6.1 |
| 4.321 | | | | | | | |
| | | 16 | 4.396±0.006 | 0.064±0.004 | 2 | $2^+$ | 2.7 |
| | | 17 | 4.466±0.004 | 0.013±0.002 | (4) | $(4^+)$ | 0.91 |
| | | 18 | 4.518±0.009 | 0.040±0.003 | (4) | $(4^+)$ | 2.8 |
| 4.565 | | 19 | 4.578±0.006 | 0.033±0.003 | (4) | $(4^+)$ | 2.3 |
| | | 20 | 4.809±0.013 | 0.051±0.003 | (1) | $(1^-)$ | 0.52 |
| | | 21 | 4.881±0.013 | 0.013±0.002 | (4) | $(4^+)$ | 0.90 |
| | | 22 | 4.969±0.011 | 0.092±0.005 | | | |
| | | 23 | 5.029±0.012 | 0.036±0.003 | (1) | $(1^-)$ | 0.36 |

[a]Taken from Ref. 4.
[b]Taken from Ref. 6.
[c]Known doublet.
[d]Possible unresolved doublet.

sumed configurations, and therefore the following were used in the DWBA calculations: $(1g_{9/2})^2$ for $L=0$, 2, and 4 transitions, $(2p_{1/2},3s_{1/2})$ for $L=1$, $(2p_{1/2},2d_{5/2})$ for $L=3$, and $(2p_{1/2},1g_{9/2})$ for $L=5$. The magnitudes of the theoretical and experimental angular distributions have been compared in order to determine the enhancement factors, $\epsilon$, defined by

$$\sigma_{\exp}(\theta)=9.7N\epsilon\sigma_L(\theta)_{\mathrm{DWBA}} .$$

As the absolute magnitudes of the DWBA cross sections depend on the choice of optical-model parameters, the value of $N$ is tied to the choice of optical model. We have used $N=23$ to extract enhancement factors. These enhancement factors, summarized in Table II, give a measure of the relative transition strength that is independent of $Q$-value effects.

In addition to the measured excitation energies, Table II also summarizes the maximum differential cross section, $L$ value, and spin-parity assignments from the present work. These are compared in the table with the excitation energies and $J^\pi$ values reported in Refs. 4 and 6. With the exception of possible levels at 3.705 and 4.09 MeV, all the levels previously reported are observed in the present work and the excitation energies measured are typically within 10 keV of the previously measured values. Additionally, 12 new levels not previously reported in $^{82}$Se are seen in this work.

## IV. DISCUSSION

### A. $L=0$ angular distributions

Figure 2 displays data for the ground state of $^{82}$Se and for states at 1.412, 3.449, and 3.834 MeV. These four angular distributions have an $L=0$ character, as can be seen from the DWBA curves, and hence correspond to states in the final nucleus with $J^\pi=0^+$.

Previously only the ground state had been definitely assigned $J^\pi=0^+$. Knight *et al.*[5] suggested that a state seen by them at 1.420 MeV could have $J^\pi=0^+$ from the systematics of other even-$A$ selenium isotopes. The present data allow a definite $0^+$ assignment to be made to this level.

From the decay[6] of $^{82}$As, a state at 3.454 MeV had been provisionally assigned $(5^-)$. In the present data, a state at 3.449 MeV has an angular distribution that is predominantly due to an $L=0$ transition. However, compared to the other $L=0$ transitions the minima in this angular distribution are comparatively shallow. It is possible therefore that the state we see is an unresolved doublet with one member having $J^\pi=0^+$ and the other $J^\pi=5^-$. The broken line shown on this distribution is for an incoherent sum of $L=0$ and $L=5$ transitions. The good fit reinforces the conjecture that the group seen is in fact an unresolved doublet with $J^\pi=0^+$ and $5^-$ components. The state at 3.834 MeV in Fig. 2 had not been previously reported but the quality of the fit allows us to make a definite $J^\pi=0^+$ assignment to this level.

### B. The $L=2$ angular distributions

Figure 3 shows nine angular distributions to which an $L=2$ angular momentum transfer has been assigned. The states at 0.656 and 1.735 MeV are only weakly excited and definite assignment is not possible solely on the comparison between the DWBA curves and the data. The 0.656 MeV state is assumed to have $J^\pi=2^+$ since it is the

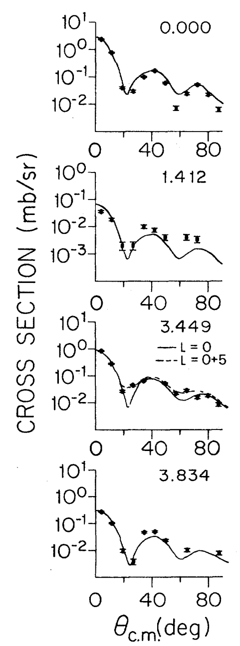


FIG. 2. Angular distributions exhibiting $L=0$ character in the $^{80}$Se(t,p)$^{82}$Se reaction at 15 MeV incident energy. The curves are the results of DWBA calculations, the details of which are given in the text.

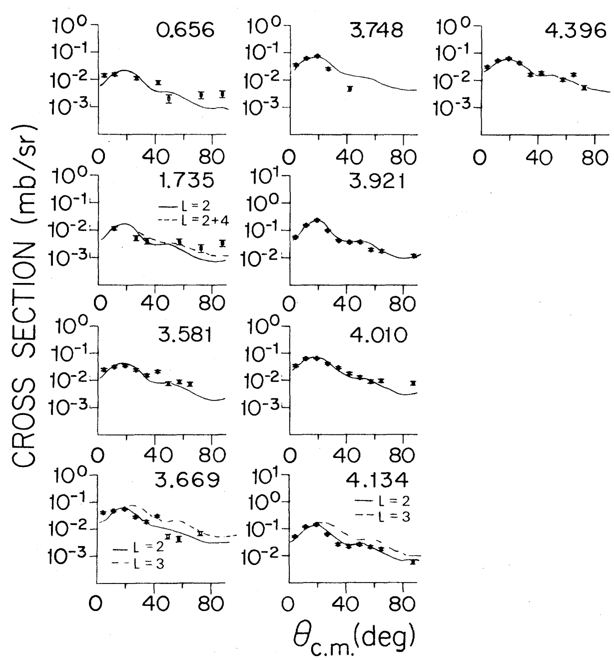


FIG. 3. Angular distribution characterized by $L=2$ angular momentum transfer in $^{80}$Se(t,p)$^{82}$Se.

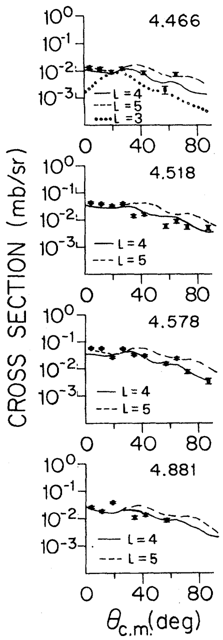


FIG. 4. $L=4$ angular distributions in the $^{80}$Se(t,p)$^{82}$Se reaction.

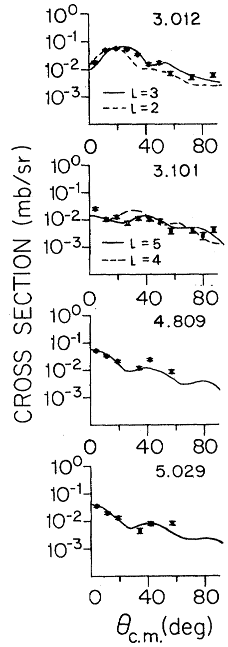


FIG. 5. Angular distributions for transitions to negative-parity states in $^{82}$Se.

first excited state, and the 1.735 MeV group is due to an unresolved doublet whose members have previously been assigned[6] as $J^{\pi}=2^{+}$ and $4^{+}$. The broken curve on this distribution is a combination of $L=2$ and 4 transfers. No other $J^{\pi}=2^{+}$ states have previously been assigned in $^{82}$Se. The other seven angular distributions shown in Fig. 3 can be seen to be due to $L=2$ transitions. On the angular distributions for levels at 3.669 and 4.134 MeV, the broken line shows for comparison the DWBA curve due to an $L=3$ transfer. The levels at 3.581, 3.669, 3.748, 3.921, 4.010, 4.134, and 4.396 MeV are assigned $J^{\pi}=2^{+}$ from the present data.

### C. The $L=4$ angular distributions

The assignment of angular momentum transfers of $L=4$ to the angular distributions is much more difficult than for $L=0$ or 2. Figure 4 shows those angular distributions for which $L=4$ transfer is preferred to other values. The uncertainty is usually between $L=4$ and higher transfers, and in each case an $L=5$ DWBA curve is shown for comparison as a broken line. For the 4.466-MeV angular distribution an $L=3$ angular distribution is also shown, as a dotted line. For the levels shown in Fig. 4 the $L=4$ transfer is preferred and the corresponding final states are tentatively assigned $J^{\pi}=4^{+}$.

### D. The angular distributions characterized by odd $L$ transfer

Figure 5 shows those distributions where an odd $L$-value transfer is preferred. The $L=3$ DWBA curve reproduces very well the angular distribution for the state at 3.012 MeV, for which an $L=2$ curve is shown for comparison. Hence this state is assigned $J^{\pi}=3^{-}$. It can be seen from the DWBA curves shown on the distribution for the 3.101-MeV state that $L=5$ is preferred to $L=4$ and the corresponding final state is tentatively assigned $J^{\pi}=5^{-}$. The other two distributions shown in Fig. 5 are assigned $L=1$ angular momentum transfer, but as there are only a few points in each angular distribution, these assignments can only be regarded as tentative.

### E. Other states observed in the $^{80}$Se(t,p) reaction

Figure 6 shows three angular distributions for which it has not been possible to assign an $L$ value to the transfer.

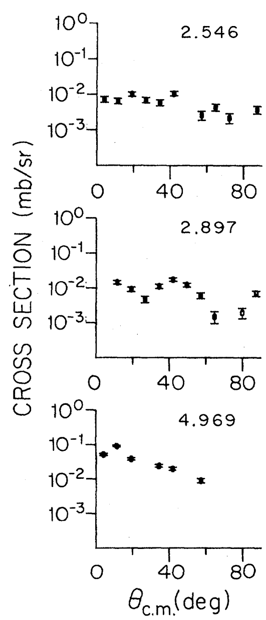


FIG. 6. Angular distributions from the $^{80}$Se(t,p)$^{82}$Se reaction for which no characteristic $L$ value could be assigned.

The states at 2.546 and 2.897 MeV have previously been tentatively assigned $J^{\pi}=3^{+}$ and $4^{-}$, respectively. As such unnatural parity states cannot be excited in a single step process using the (t,p) reaction, it is not expected that our DWBA calculations would reproduce the data. It is possible that the state at 4.969 MeV is also of unnatural parity, but the fact that it is much more strongly excited than the levels at 2.546 and 2.897 MeV makes this unlikely.

## V. SUMMARY

Measurements on the $^{80}$Se(t,p)$^{82}$Se reaction have yielded spin-parity assignments for 21 levels up to an excitation energy of 5.03 MeV in $^{82}$Se. The majority of these are new $J^{\pi}$ assignments and 12 of the levels have not been previously reported. In particular, we have located three excited $0^{+}$ states at 1.412, 3.449, and 3.834 MeV and the third and fourth $2^{+}$ states at 3.581 and 3.669 MeV, and tentatively identified the second $4^{+}$ state at 4.466 MeV.

Certain points can be noted from the comparison of the present data with the $^{82}$Se(t,p) measurement of Knight *et al.*[5] In particular, they observe three $0^{+}$ states of approximately equal strength, whereas in the present work we observe four $0^{+}$ states with widely differing strengths (see Table II). Knight *et al.* suggest that in their case the neutron components of the wave functions of the $0^{+}$ states they observe are approximately the same and any difference in the states could be attributed to the proton configurations. The widely differing transfer strengths in the present data would indicate that the neutron configurations of these states are different. Furthermore, the ratio of the strengths changes dramatically from 0.007 to 0.12 for the $^{80}$Se(t,p) and $^{82}$Se(t,p) reactions, respectively. This is again indicative of a different structure for $^{82}$Se and $^{84}$Se. This might be expected as one approaches the $N=50$ closed shell at $^{84}$Se.

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