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Levels of ^{84}Se from the ^{82}Se(t, p)^{84}Se reaction*

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The levels of ^{84}Se have been investigated by the ^{82}Se(t,p) reaction with 15-MeV tritons. Proton spectra were recorded with a semiconductor counter telescope at lab angles between 12.5 and 90°. Differential cross sections were measured for 19 levels up to 5.633 MeV and compared with distorted-wave Born-approximation angular distributions. The first excited state in ^{84}Se occurs at 1.455 MeV. Excited 0^+ states were observed at 2.247 and 2.655 MeV, with cross sections equal to that for the ground state. The two-neutron separation energy of ^{84}Se was determined to be $S_{2n}=14.498\pm0.015$ MeV. Eight excited states of ^{82}Se were observed by the ^{80}Se(t,p) reaction.

[NUCLEAR REACTIONS ^{82}Se(t,p), $E=15$ MeV, enriched targets, ΔE-E counter telescope; measured Q, $\sigma(\theta)$, $\theta=12.5$–$90°$, DWBA analysis; ^{84}Se levels E_x, J^π. ^{80}Se(t,p), enriched targets; ^{82}Se levels E_x.]

I. INTRODUCTION

The nucleus ^{84}Se is the lightest of the $N=50$ isotones that is accessible to study by reactions of light projectiles with stable targets. Although the proton-pair pickup reaction (n, ^{3}He) on ^{86}Kr would be very interesting if it were feasible, the only currently practical reaction for the purpose is neutron-pair stripping via (t,p) on ^{82}Se. In this paper we describe the study of the ^{84}Se levels as populated by the latter reaction with 15-MeV tritons. Since closure of the neutron shell in ^{84}Se implies that proton excitations must be the principal contributors to the lower excited states, members of this group are expected to be populated only relatively weakly by neutron-pair stripping, with the exception of the 0^+ levels produced by filling the two neutron holes in the ground state of ^{82}Se. The greater part of the (t,p) reaction strength should appear at higher excitations, where the neutron-shell-crossing 1p-1h and 2p-2h components are important contributors.

There exist few published spectroscopic data for ^{84}Se. Its mass has been determined to within ±0.07 MeV [1] (relative to stable ^{84}Kr) by studies of the $A=84$ β-decay chain.[2,3] A report of the Mainz group[4] on the decay of fission-product ^{84}As shows population of six excited states in ^{84}Se, and subsequent work has developed some additional information.[5] The main goals of our experiment were to examine the levels of ^{84}Se and to obtain a more accurate determination on its mass. In the course of using the ^{80}Se(t,p)^{82}Se reaction to provide the high-energy end of our proton-energy calibration scale, we have obtained a few data also on the level structure of ^{82}Se.

II. EXPERIMENTAL TECHNIQUES

The experiment was performed with 15-MeV tritons at the Los Alamos tandem Van de Graaff facility. The basic apparatus, instrumentation, and procedures were the same as described in earlier publications.[6,7] Reaction product particles were detected with a ΔE-E semiconductor counter telescope, employing a 400-μm totally depleted surface-barrier ΔE detector and a 3-mm Si(Li) E detector mounted in a 0.508-m-diam scattering chamber. Particle identification and energy-spectra recording were performed by an on-line computer. Energy resolution for protons was typically 30 to 40 keV full width at half maximum. Spectra were recorded at 2.5° intervals from 12.5 to 45° and at 5° intervals up to 90°. A stationary detector at 30° was used to monitor the target condition.

The targets, evaporated as films on 50-μg/cm^2 carbon foils, were made from isotopically enriched selenium with the composition 89.1% ^{82}Se, 5.68% ^{80}Se, 2.28% ^{78}Se, 1.6% ^{77}Se, 1.38% ^{76}Se, and 0.05% ^{74}Se. To identify proton lines in the ^{82}Se(t,p) spectra due to the ^{80}Se impurity, targets prepared with 97% ^{80}Se were used. Since pure selenium is relatively volatile under bombardment, we attempted at first to make targets of ^{208}Pb^{82}Se, which is ex-

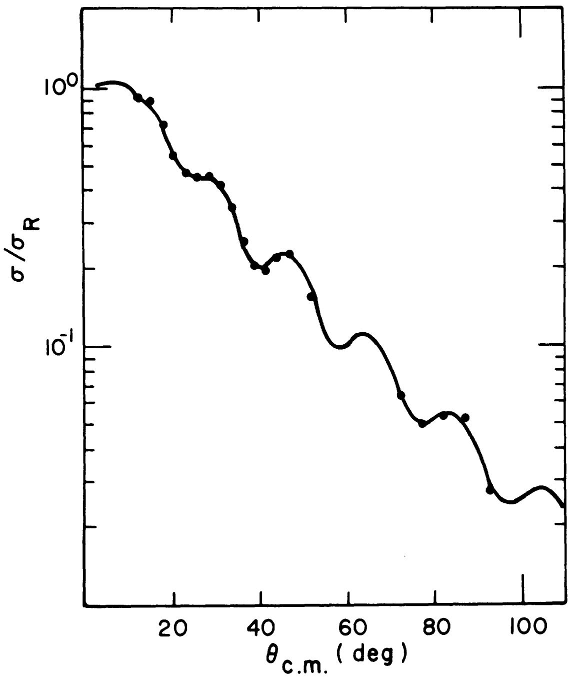

FIG. 1. Differential elastic scattering cross section (divided by the Rutherford differential scattering cross section) for 15-MeV tritons on ^{82}Se. The solid curve shows the optical-model cross section computed with the parameters listed in Table I.

pected to be more stable. However, the evaporated PbSe targets as prepared contained more than the stoichiometric amount of Pb, and the resulting problems from excessive elastic scattering outweighed any improvement in target stability. Accordingly, the final data were taken from measurements conducted with the elemental selenium targets at relatively low beam currents. Evaporation of selenium from the targets did occur during the measurements; but data from the monitor counter, supplemented by periodic repetition of counter-telescope measurements at selected reference angles, provided a quantitative basis for correction for target loss.

TABLE I. Optical-model parameters

	Triton	Proton
V (MeV)	171	55
W (MeV)	22.5	0
V_{so} (MeV)	0	6
W_D (MeV)	0	40
r_0 (fm)	1.16	1.20
a (fm)	0.78	0.65
r_0' (fm)	1.52	1.25
a' (fm)	0.74	0.65
r_c (fm)	1.25	1.25
a_c (fm)	0.65	0.65

III. DATA ANALYSIS AND RESULTS

A. Triton elastic scattering

The elastic scattering data were obtained from a series of short runs with 20-nA beams. Triton peak areas (divided by integrated beam current and fractional live time and corrected for target depletion) were converted approximately to mb/sr by normalizing to the Rutherford cross section at low angles. These data were fitted with optical-model parameters, including a final cross-section normalization factor, by the automatic search program of Perey.[8] Initial values of the parameters were taken from Ref. 9. The results are shown in Fig. 1 and Table I. The only data recorded near 60° in the elastic scattering measurements were taken with PbSe targets, and the uncertainties in the peak areas after subtraction of background from scattering by Pb were so large that these data were not used.

B. Energies

The energy scale for protons from the ^{82}Se(t,p)-^{84}Se reaction was established by peaks from the

TABLE II. Energy levels of ^{84}Se and ^{82}Se and spin assignments of ^{84}Se levels as deduced from (t,p) reaction measurements. ^{82}Se excited states observed at energies (keV): 655±2, 1420±15, 1730±7, 3015±15, 3442±15, 3670±20, 4135±15, 4565±15.

^{84}Se Energy (keV)	J^π	σ[a] (mb)
0	0^+	0.50
1451±5[b]	2^+	0.060
2247±5	0^+	0.50
2655±5	0^+	0.50
2984±5	2^+	1.5
3541±10[b]	$2^+,3^-$	0.30
3693±10	4^+	0.51
4231±10	2^+	0.44
4447±10	4^+	0.71
4606±10		
4729±10	4^+	0.71
5145±10	2^+	0.43
5191±10	$2^+,3^-$	0.25
5297±10	2^+	0.63
5377±10	2^+	0.77
5443±10	1^-	0.74
5511±15	2^+	0.25
5605±15		
5633±15	2^+	0.16

[a] Integrated cross section from $\theta=10-90°$, from distorted-wave Born-approximation (DWBA) calculated angular distribution as fitted to the experimental data.
[b] Levels deduced also from ^{84}As decay γ rays (Ref. 4).

^{80}Se(t,p), ^{12}C(t,p), and ^{16}O(t,p) reactions. The two-neutron separation energies from the 1971 atomic mass tables[1] were used as reference energies: $S_{2n}(^{82}\mathrm{Se}) = 15.973 \pm 0.007$ MeV, $S_{2n}(^{14}\mathrm{C}) = 13.1234 \pm 0.0003$ MeV, and $S_{2n}(^{18}\mathrm{O}) = 12.1892 \pm 0.0003$ MeV. With the standard kinematic corrections and reasonable estimates of the uncertainties due to finite resolution, differential nonlinearity in the electronics, and other systematic errors, the average of seven determinations at different angles gave:

$$Q[^{82}\mathrm{Se}(t,p)^{84}\mathrm{Se}] = 6.016 \pm 0.015 \text{ MeV}$$

or

$$S_{2n}(^{84}\mathrm{Se}) = 14.498 \pm 0.015 \text{ MeV}.$$

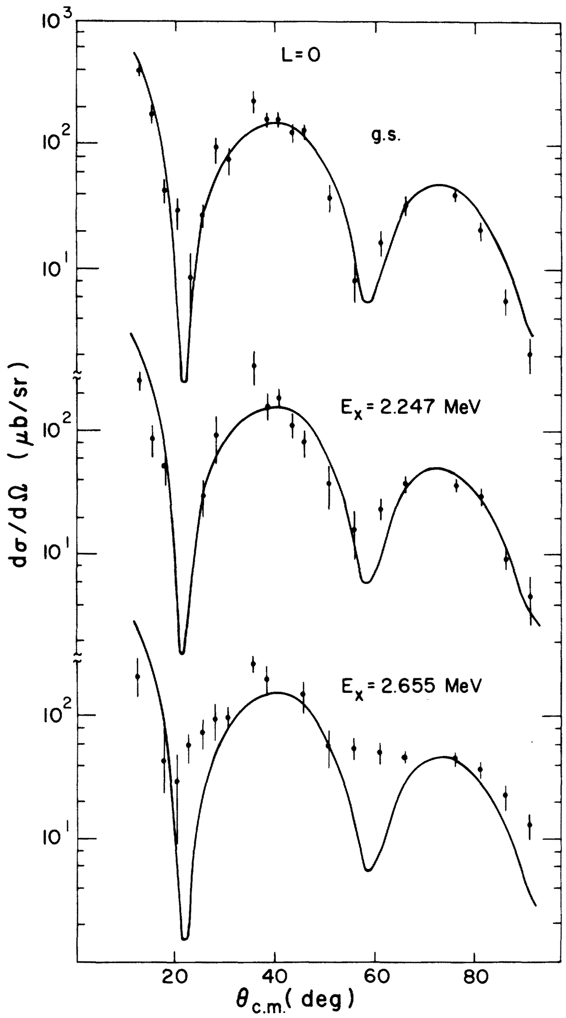

FIG. 2. Differential (t,p) cross sections for levels populated by $L=0$ stripping. Solid curves are DWBA cross sections computed with parameters listed in Table I.

The result is consistent with, but more accurate than, the value $S_{2n}(^{84}\mathrm{Se}) = 14.480 \pm 0.070$ MeV deduced[1] from previously available data[10] including the measured Q_β for ^{84}Se and ^{84}Br.

Energies of the excited states of ^{84}Se are given in Table II. The results shown were derived from averages of values from all angles at which a resolvable peak was observed and include the estimated total uncertainties. The agreement in two

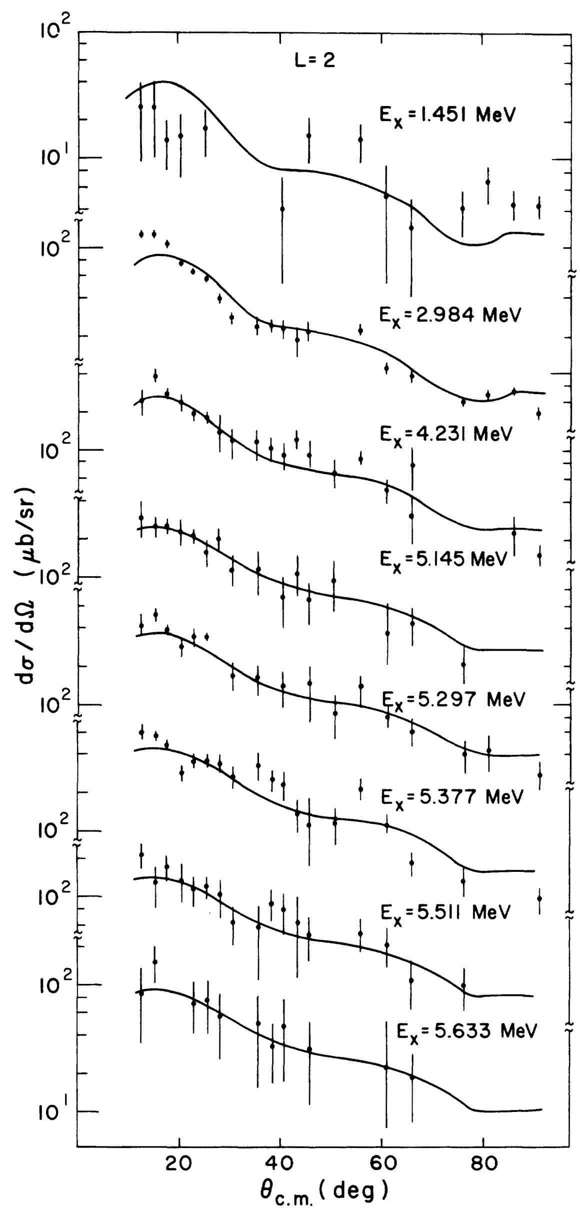

FIG. 3. Differential cross sections assigned $L=2$. The 1.451-MeV level is the first excited state, so it is assumed to have $J^\pi = 2^+$. Population of the other states is attributed to $L=2$ stripping on the basis of fits of the DWBA calculations shown as solid curves.

cases with the more accurate energies reported from Ge(Li) γ-ray measurements of ^{84}As decay[4] confirms these measurements. Locations of the prominent lines in the few ^{80}Se(t,p) spectra recorded give the ^{82}Se excitation energies listed in Table II.

C. Differential (t,p) cross sections

Absolute c.m. ^{82}Se(t,p) cross sections at each angle were computed by dividing the proton-peak counts by the target isotopic abundance, multiplying by the ratio of the lab differential elastic scattering cross sections to the area of the Se elastic scattering peak in the simultaneously recorded triton spectrum, and applying the standard kinematic conversion from lab to c.m. coordinates. Uncertainty in this reaction cross-section calibration, which is based on optical-model analysis of the triton elastic scattering (Sec. III A), is estimated to be approximately 5%. The small number of total counts in the individual proton peaks, typically 10–100, resulted in errors in the peak areas usually much larger than 5%.

Differential cross sections for the 19 levels observed in ^{84}Se are shown in Figs. 2–5. Angular distributions were analyzed by comparison with DWBA cross sections computed with the 1971 two-particle stripping version of the program DWUCK.[11] Triton parameters were taken from the elastic scattering analysis. The neutron potential had radius parameter $r_0 = 1.27$ fm and diffuseness $a = 0.65$ fm, a 25-MeV spin-orbit term, and depth adjusted to give the observed separation energies. The proton optical-model parameters, with initial values taken from Ref. 7, were adjusted to fit the experimental $L=0$ angular distributions (Fig. 2) which have the sharpest and most distinctive structure. The parameters selected are listed in Table I.

The shapes of the calculated angular distributions were insensitive to the choice of neutron orbitals populated. For example, the neutron configuration of the ground state of ^{82}Se should be predominantly

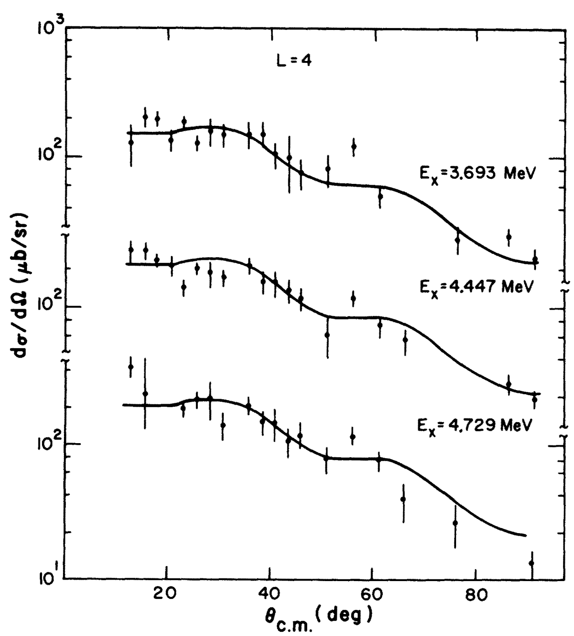

FIG. 4. Differential cross sections assigned $L=4$ on the basis of fits to DWBA calculations (solid curves).

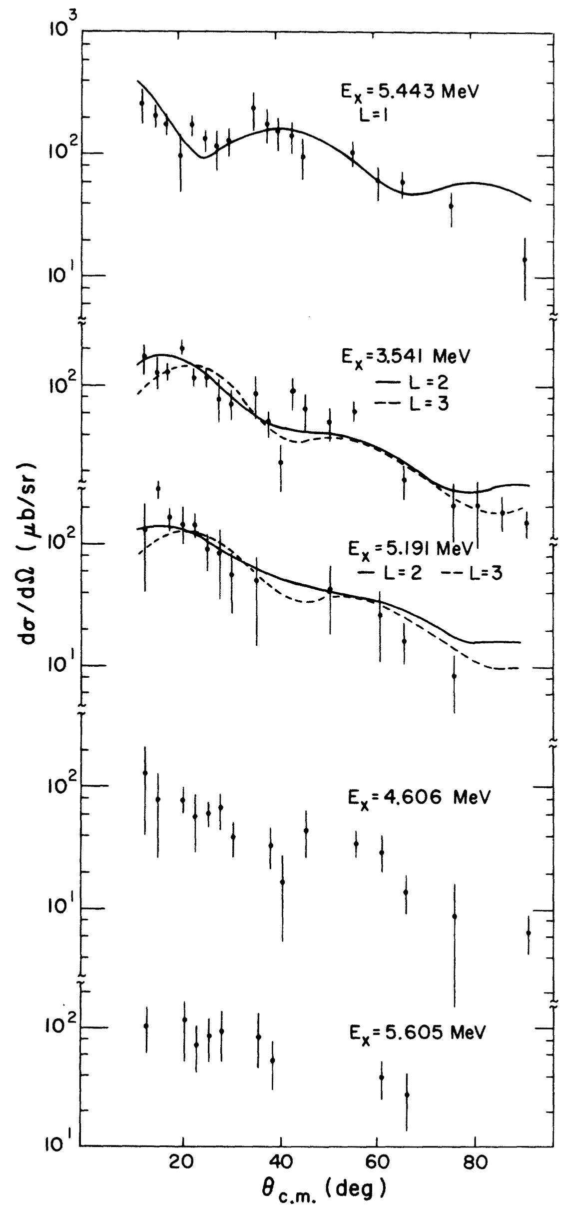

FIG. 5. Remaining differential (t,p) cross sections with tentative L values for the cases with data of adequate statistical quality.

a mixture of $(g_{9/2})_0^{-2}$ and $(p_{1/2})_0^{-2}$, so the low-lying 0^+ levels in ^{84}Se should be produced in the (t,p) reaction by filling these holes. Cross sections computed for stripping pure $(g_{9/2})^2$, pure $(p_{1/2})^2$, and coherent mixtures of the two had essentially indistinguishable shapes. The same was true for all practical purposes for the other final-state spins and parities, including mixtures when the terms were chosen to give constructive interference.

With $J^\pi = 0^+$ for the target and a singlet neutron pair transferred, the orbital angular momentum transfer L uniquely determines the spin and parity of the final state: $J_f = L$ and $\pi_f = (-1)^L$. The three cases with $L = 0$, corresponding to 0^+ levels in ^{84}Se, are shown in Fig. 2. The data for the 2.655-MeV level do not exhibit minima as sharp as the other two cases, but the $L = 0$ theoretical cross section fits the data much better than any other reasonable L value. This proton peak may be a doublet; an unresolved level for which the cross section varies more slowly with angle would produce the observed effect. The uncertainties in the data are too large, however, to permit determination of the L value of such a postulated second component.

For $L \neq 0$ the theoretical cross sections decrease slowly, almost monotonically, over the range of angles covered by the data, without strong maxima or minima to identify easily the possible L values. Cross sections assigned $L = 2$, populating 2^+ levels in ^{84}Se, are shown in Fig. 3. The 1.451-MeV level is assumed to have $J^\pi = 2^+$ because it is the first excited state. Since this state in $N = 50$ nuclei results from predominantly proton excitations, the cross section for production by the (t,p) reaction is very small and the uncertainties in the data are large. In the proton spectra the peak associated with this level was visible only because at most angles there was almost no background at this energy. For ^{84}Se levels above 2 MeV, peaks from cross sections this small would not have been detectable above background. The $L = 2$ fit to the cross section for the 2.984-MeV level, for which we have the most accurate data, is not as good as most of the other cases. Attempts to mix in other L values, as would be appropriate if the line were an unresolved doublet, did not improve the agreement between theory and the data. Although not fully satisfactory, pure $L = 2$ appears to be the best choice. The six other levels in Fig. 3 are fitted well by the $L = 2$ angular distribution.

The remaining cross sections are shown in Figs. 4 and 5. Of these, the angular distributions of three are significantly better fitted by $L = 4$ than by any other value, and one more, at 5.443 MeV, appears to be produced by $L = 1$ stripping. As may be seen, the angular distributions for the states at 3.541 and 5.191 MeV do not permit a choice between $L = 2$ and $L = 3$, and for the states at 4.606 and 5.605 MeV the uncertainties permit only the assignment $L \neq 0$.

In general then, the ^{84}Se spin-parity assignments as summarized in Table II, other than those for

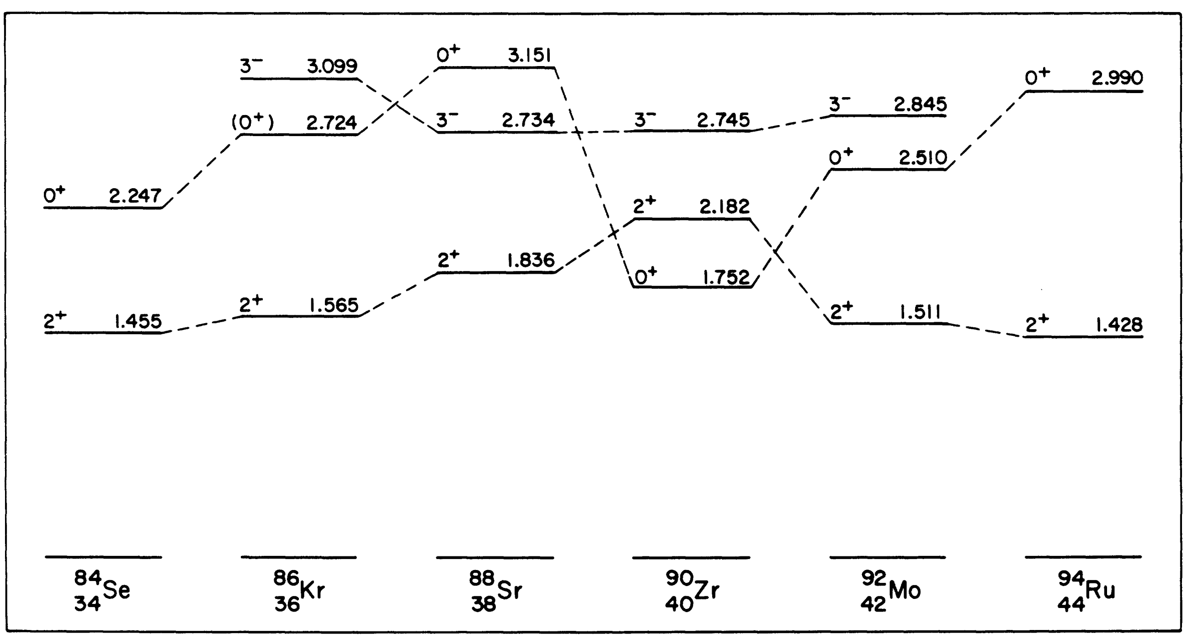

FIG. 6. Comparison of first excited 2^+, 0^+, and 3^- states in even $N = 50$ nuclei.

$J^\pi = 0^+$, must be regarded as "probable" rather than established.

IV. DISCUSSION

A. ^{84}Se

As we have indicated in the introductory section, the only other ^{84}Se level structure information of which we are aware is that deduced by Franz and Kratz[4,5] from γ-ray measurements on fission-product ^{84}As and ^{85}As, the latter populating ^{84}Se levels by way of β-decay branching to neutron-unbound states of ^{85}Se. From singles γ-ray spectra associated with decay of the individual nuclides, these investigators have proposed a partial decay scheme involving ^{84}Se excited states at 1.4551, 2.1222, 2.6997, 5.161, and probably also at 3.2988 and 3.5417 MeV. We point out that the half-lives of ^{84}As and ^{85}As are 5.3 and 2.05 sec, and that the decay measurements had to be preceded by chemical separation of these nuclides from fission-product mixtures. The postulated levels at 1.4551 and 3.5417 MeV very probably are identical with the levels we observed at 1.451 and 3.541 MeV. Our failure to observe the other postulated levels is not surprising; only "natural-parity" states of ^{84}Se should be available to direct population by the single-step (t, p) reaction, and of these, only the ones whose wave functions contain significant contributions from excited-neutron configurations would be expected to have cross sections large enough to permit observation under our experimental conditions.

In Fig. 6 we compare the locations of the first 2^+, 0^+, and 3^- excited states in the even-A $N=50$ isotones as derived from our results and various other current data.[12,13] The 2^+ excitation energy varies smoothly with Z, peaking at ^{90}Zr where the $p_{1/2}$ proton subshell fills. Similarly, the first 0^+ states appear to move upward in energy as the proton subshells fill. The 3^- levels definitely assigned thus far all lie within 0.2 MeV of 2.9 MeV. In our measurements the first ^{84}Se excited state observed with an angular distribution consistent with $J^\pi = 3^-$ occurs at 3.541 MeV, but the (t, p) cross section for population of a low-lying 3^- state is expected to be small, and a state near 2.9 MeV with an integrated cross section (see Table II) less than ≈ 0.2 mb could have gone undetected.

It is noteworthy that the cross sections for population of the three observed ^{84}Se 0^+ levels are equal within the accuracy of our data ($\pm$ 20%), and also that we do not observe any additional 0^+ levels in the remainder of the excitation range covered (up to ≈ 5.7 MeV), although one with an integrated cross section $\gtrsim 0.2$ mb would generally have been detectable. With the reasonable conjecture that the neutron components of the wave functions of these three levels are about the same, the differences in the three being attributed to proton configuration, we note that indeed the three lowest-seniority basis states $[(f_{5/2})^6(p_{3/2})^0]$, $[(f_{5/2})^4(p_{3/2})^2]$, and $[(f_{5/2})^2(p_{3/2})^4]$ can be combined to give three 0^+ levels.

B. ^{82}Se

The data recorded for ^{80}Se(t, p) were intended primarily for background identification and energy calibration and were insufficient for spin-parity assignments on the basis of angular distributions. Comparing the energy levels seen in this experiment (Table II) with those reported in ^{82}As decay scheme studies,[14,15] we observed the first excited state at 0.655 MeV and one or both members of the 2^+, 4^+ doublet at 1.731, 1.735 MeV (unresolved in our spectra). In addition, we found evidence for a level at 1.420 MeV, not seen in ^{82}As decay. Since a (t, p) reaction to a low-lying 0^+ level may be expected to have a measurable cross section, whereas γ cascades following ^{82}As decay may feed such a level only weakly in competition with ground-state transitions, the 1.420-MeV level may be the 0^+ member of the two-phonon triad seen at approximately this energy in other even-A selenium isotopes.

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