Nuclear Structure Studies in the Selenium Isotopes with (*d,p*) and (*d,t*) Reactions*

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Levels of Se^{77}, Se^{78}, Se^{79}, Se^{81}, and Se^{83} below about 5 MeV were investigated by observation of the energy and angular distributions of protons emitted in the (*d,p*) reactions at 15-MeV bombarding energy. Values of the transferred-neutron angular momenta and of the spectroscopic factors for levels were derived from the measurements by distorted-wave Born approximation calculations. The results for the degree of filling of shell-model states and locations of the "centers of gravity" of the shell-model levels were compared with the pairing theory of Kisslinger and Sorensen. It was found that the $\frac{3}{2}^-$, $\frac{5}{2}^-$, and $\frac{1}{2}^-$ subshells are less full and the $g_{9/2}$ more full than expected. General agreement with pairing theory was obtained with the following parameters: $\epsilon_{9/2^+}=3.0$ MeV, $\epsilon_{1/2^-}=2.5$ MeV, $\epsilon_{5/2^-}=1.0$ MeV, $\epsilon_{3/2^-}=0$, and $\Delta=1.65$ MeV from the odd-even mass difference. In Se^{83}, an isomer of spin $\frac{1}{2}^-$ at 0.22 MeV was identified. Measurements on (*d,t*) reactions indicate that the $d_{5/2}$ subshell from the next (50-82) major shell is filling (~0.6 particle) in the Se nuclei, even though the lower (28-50) major shell is not completely full.

I. INTRODUCTION

As is well known, the (*d,p*) stripping and (*d,t*) pickup reactions directly measure, respectively, the emptiness and fullness of the shell-model state in the target nucleus. Experimental results obtained on these reactions can be interpreted in terms of the pairing theory of Kisslinger and Sorensen.[1] It has been shown that[1–4] the single-closed-shell nuclei can be treated with considerable success in the pairing model. In recent years, the pairing theory has been applied[5,6] to the vibrational nuclei. Kisslinger and Sorensen[5] have carried out calculations including a pairing force between like nucleons and a quadrupole interaction between all nucleons, and have found in their analysis that the long-range residual interactions have an appreciable effect on the nuclear energy levels. Experimentally, vibrational nuclei with neutrons in the 50-82 shell, such as Mo, Pd, and Cd isotopes, have been extensively studied by several authors,[7–10] but not many vibrational nuclei with neutrons in the 28-50 shell have been investigated to compare with pairing theory. In a previous paper,[11] a study in this mass region was reported for the zinc isotopes; because of insufficient energy resolution, such a study falls far short of giving consistent quantitative results. In this paper, we extend the study to the isotopes of selenium, in which the neutrons are filled up to the $1g_{9/2}$ subshell; and the protons, to the $1f_{5/2}$ subshell. It is interesting to use the highest possible energy resolution to study the detailed level structure of these nuclei and to examine how well the pairing theory describes experiments.

Carter[12] has measured the level energies in Se^{79} and Se^{81} from (*d,p*) reactions without further study of the properties of these levels. Macefield *et al.*[13] have studied the reaction $Se^{76}(d,p)Se^{77}$ at an incident deuteron energy of 7.8 MeV. They reported some low-lying levels and their tentatively assigned spins. No investigation on Se^{78} and Se^{83} from stripping reactions has been previously reported. The present work was carried out with improved energy resolution (~40 KeV), and the higher bombarding energy allows more identifications to be made on all nuclei of the five Se isotopes investigated in the (*d,p*) reactions. Also, a more extensive study of the (*d,t*) reactions was performed, and therefore, more quantitative results were obtained.

The data were analyzed with the distorted-wave Born approximation (DWBA) calculations, using a set of appropriate optical-model parameters, from which the degree of occupation or fullness and the spectroscopic factor were extracted, and the single-quasiparticle energy for the shell-model states populated in the (*d,p*) reactions were determined to compare with the pairing predictions.

II. EXPERIMENTAL

The 15-MeV deuteron beam of the University of Pittsburgh cyclotron was used to produce (*d,p*) and (*d,t*) reactions. The reaction products were analyzed by a magnetic spectrograph and detected by photographic plates. The experimental method was essentially the same as that used in Ref. 11, except that the resolution was improved by the use of thinner and more uniform targets. Five thin enriched targets of isotopic foil (72.5% for Se^{76}, 73.5% for Se^{77}, 90.2% for Se^{78}, 94.4% for Se^{80}, and 74.7% for Se^{82}) were prepared by the vacuum evaporation on thin gold backings (~0.2

* Work performed at Sarah Mellon Scaife Radiation Laboratory and supported by the National Science Foundation.

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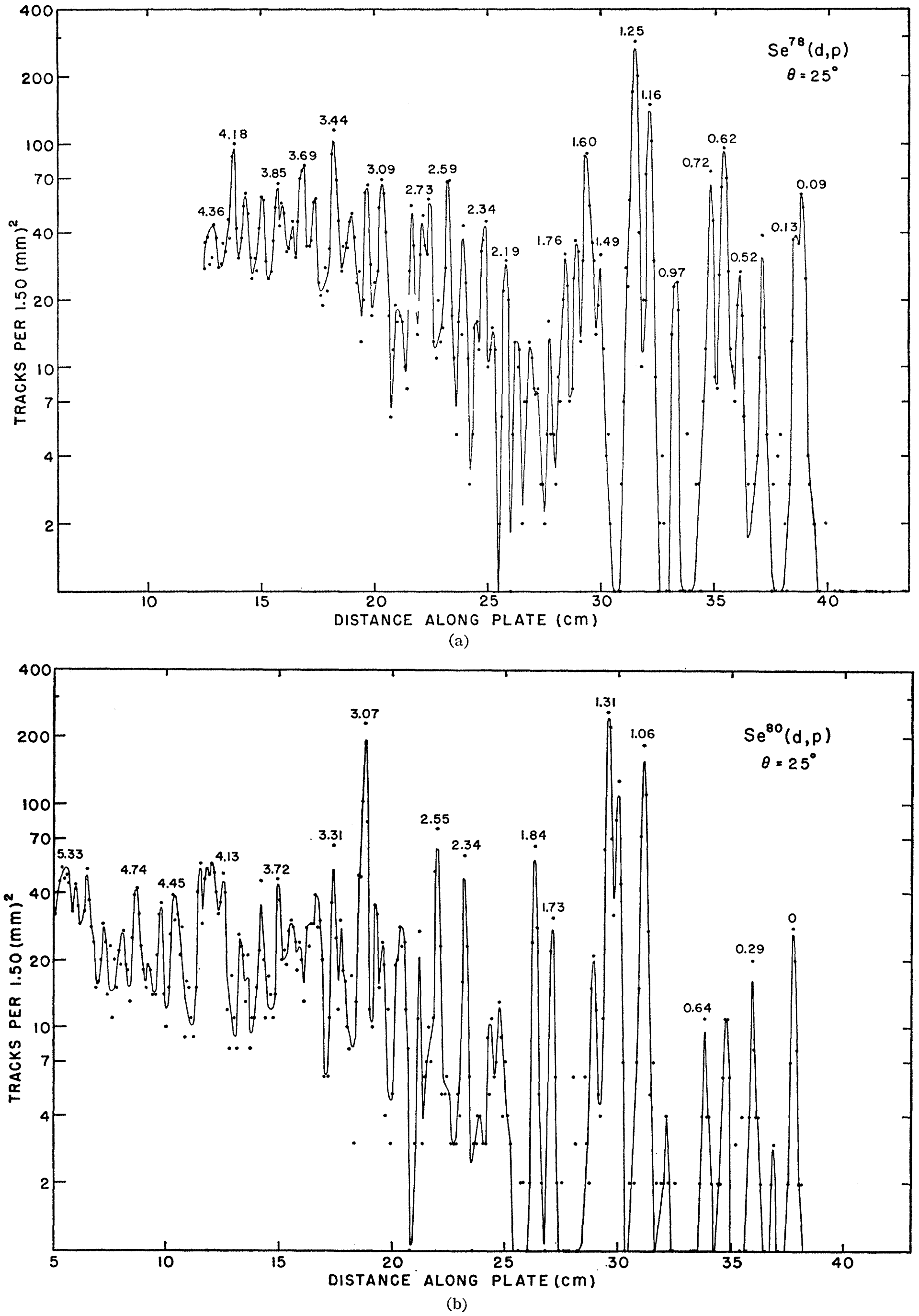

FIG. 1. (a) Measured proton energy spectrum from $Se^{78}(d,p)Se^{79}$ observed at 25°. Numbers above peaks are energies of final states in MeV. (b) Measured proton energy spectrum from $Se^{80}(d,p)$-Se^{81} observed at 25°.

mg/cm²). The thinnest foil obtained was measured to be ~0.45 mg/cm². The energy resolution in the present experiments is ~40 keV. A typical proton spectrum is shown in Fig. 1. Data were recorded for each isotope at eight angles between 10° and 50° to obtain angular distributions. Since the triton spectra were taken at two or three angles, no angular distributions of tritons from (d,t) reactions were obtained. The low-lying levels of Se^{76}, Se^{77}, Se^{79}, and Se^{81} were observed from the corresponding (d,t) reactions. A typical triton spectrum is shown in Fig. 2. The observed proton and triton groups in Figs. 1 and 2 are generally well separated from neighboring peaks and extended high above background. The latter is negligibly small in the low-energy region ($E<2.5$ MeV). For higher excitation, the background subtraction, in some cases, may introduce an error as much as 10% in the absolute cross section. The background, due to known impurities in the case

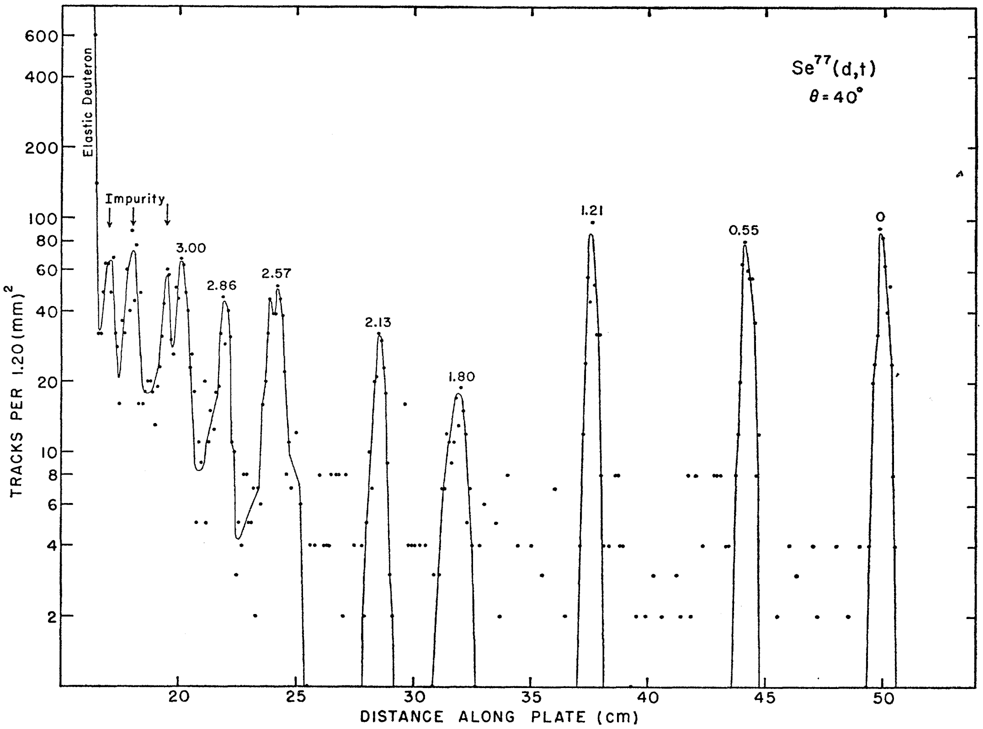

FIG. 2. Measured triton energy spectrum from Se^{77}(*d*,*t*)-Se^{76}. See caption for Fig. 1.

where the targets are of low enrichment, is carefully subtracted by taking into account the intensities of the peaks of the known isotopic impurities. Correction for the Au background, due to the target backing, was also made. Measurements were taken on pure Au target at several angles, and these normalized intensities were subtracted from the Se data.

The differential cross sections were computed from the number of trackes observed in the emulsion. Errors can be introduced in the cross section due to errors in plate reading and the measurement of the target thickness, which may give a possible uncertainty of about 20% in the absolute cross sections. Relative cross sections are accurate to within the statistical error involved.

III. RESULTS

Measured angular distributions of protons from (*d*,*p*) reactions are shown in Figs. 3–8. The assignment of l values was made by comparison with DWBA calculations,[14] including neutron and proton spin-orbit potentials. Typical examples of experimental data fitted to the DWBA calculations are shown in Fig. 3. Table I lists the 15-MeV deuteron optical parameters[15] used in this work. In the calculations, the binding energy of the transferred neutrons was taken as the separation energy of the nuclear levels formed by the reaction. The fits to experimental data are better if the lower cutoff (6.15 F in this case) is used in the DWBA calculations. It is seen that the agreement between theory and experiment is quite good, except for the $l=0$ case, especially at large angles where the quality of the fit deteriorates. Nevertheless, the angular distribution is sufficiently good to determine l values for almost all states. A separate DWBA calculation was made with the neutron binding energy held at the binding energy of the single-particle state (~8 MeV in Se isotopes), independent of the separation energy of the nuclear level. It was found that the fits to experimental data are worse; and the calculated cross sections for all l values become smaller, approximately by a factor of 2 for $Q=3$ MeV and by an increasingly large factor for small Q values.

In the selenium region, the low-lying shell-model states excited in (*d*,*p*) reactions—$p_{3/2}$, $f_{5/2}$, $p_{1/2}$, $g_{9/2}$, $d_{5/2}$, $s_{1/2}$, and $d_{3/2}$—are expected. The spin assignment to the observed levels can be made for $l=0$, $l=3$, and $l=4$ levels by using the shell model. There remain ambiguities between $p_{3/2}$ and $p_{1/2}$ in the $l=1$ levels, and

TABLE I. 15-MeV deuteron optical-potential parameters for Se used in this work. The notation is that used in Ref. 15.

Element	V (MeV)	r_0 (F)	a (F)	W' (MeV)	r_0' (F)	a' (F)	Remarks
Se	93.5	1.15	0.81	66.2	1.34	0.68	Set b of Perey[a]

[a] Reference 15.

[14] R. M. Drisko (private communication). The calculations were performed at the University of Pittsburgh Computation Center, which is partially supported by the National Science Foundation under Grant No. G-11309.

[15] C. M. Perey and F. G. Perey, Phys. Rev. 134, B353 (1964).

$d_{3/2}$ in the $l=2$ levels. The ambiguity in spin assignments of lower $l=1$ levels is resolved by available information in the literature, and by the comparison of (d,p) and (d,t) cross sections for exciting the levels. Since, in the Se isotopes, the $p_{3/2}$ state is deeply bound and, therefore, more full than the $p_{1/2}$ state, the $p_{3/2}$ state should have a larger (d,t) cross section and a smaller (d,p) cross section than the $p_{1/2}$ state, and the ratio of (d,t) to (d,p) cross section is thereby larger for a $p_{3/2}$ level than for a $p_{1/2}$ level. For the higher $l=1$ levels, the spins are assigned as $\frac{3}{2}^-$ on the basis of theoretical expectations. The choice between the $d_{5/2}$ and $d_{3/2}$ in the $l=2$ levels is made by comparing the cross sections for exciting levels with sum rules which govern the expected strengths of the levels. The systematics of spin-orbit splittings of single-particle states indicate that the $d_{3/2}$ state lies much higher ($\Delta E\sim 2.50$ MeV in the Zr region) than the $d_{5/2}$ state. Thus one does not expect the $d_{3/2}$ state to appear prominently at low energies. The low-lying $l=2$ levels are then assigned as $d_{5/2}$ states and the higher $l=2$ levels, as $d_{3/2}$ states. In the intermediate energy region the ambiguity still remains. There are some levels found to be overlapping with a mixture of two different

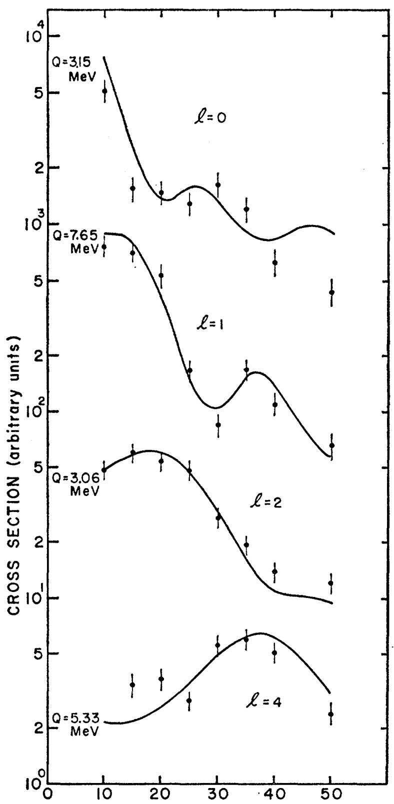

FIG. 3. Measured angular distributions for certain peaks from $Se^{77}(d,p)Se^{78}$ and comparison with DWBA calculations (see text). The solid points are experimental, and the curves are the results of DWBA calculations. These are some examples of angular distributions fitted by $l=0$, 1, 2, and 4, respectively.

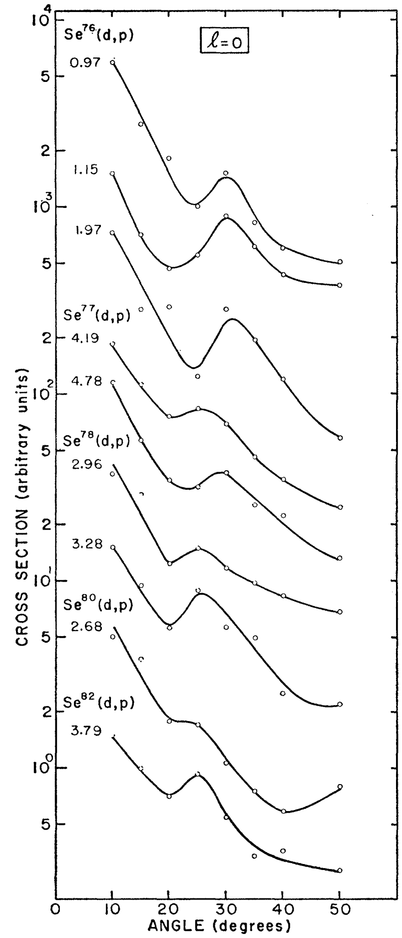

FIG. 4. Measured angular distributions of certain peaks assigned to $l=0$ from (d,p) reactions on selenium targets. Figures attached to the curves are excitation energies (in MeV) of level in final nucleus.

l values. Figure 9 shows some examples of fitting the experimental data to an appropriate mixture of the theoretical angular distributions.

For an even-even target nucleus, the cross section for exciting a level of spin I by a (d,p) reaction is given by

$$d\sigma/d\Omega=(2I+1)\sigma_{\mathrm{DW}}S, \tag{1}$$

where σ_{DW} is the result of the DWBA calculations. Experimentally, the product $(2I+1)S$, and hence the spectroscopic factor S, is obtained from the ratio of the measured cross section at the first peak in the angular distribution to the cross section calculated by DWBA. For an odd target nucleus such as Se^{77}, we define[11] S' by

$$d\sigma/d\Omega=(2j+1)\sigma_{\mathrm{DW}}S', \tag{2}$$

where j is the total angular momentum of the stripped neutrons.

The results for the (d,p) reactions are summarized in Tables II–VI in which the observed energy levels, orbital angular momenta, cross sections, spins, reduced

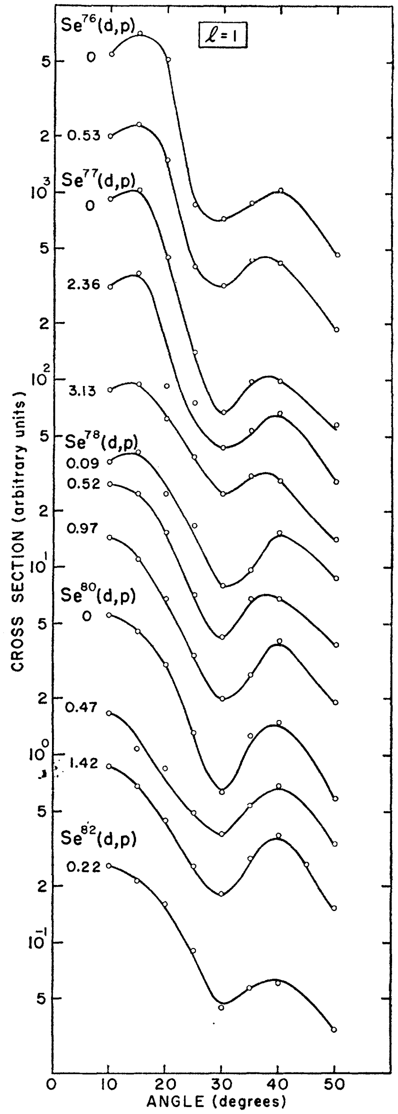

FIG. 5. Measured angular distributions of certain peaks assigned to $l=1$ from (d,p) reactions on selenium targets. See caption for Fig. 4.

widths $(2j+1)S$, and spectroscopic factors S are listed. The results for the (d,t) reactions are shown in Table VII, where a comparison with data from (d,p) and (d,d') reactions is also given.

A. Se^{76}(d,p) Reaction

This reaction has been previously investigated at a deuteron energy of 7.8 MeV by Macefield *et al.*[13] They accurately determined the energies of the low-lying levels in Se^{77}, and assigned l values by comparing measured angular distributions with the DWBA calculations. The present work is performed at a higher deuteron energy, and thus much higher energy levels are studied. There are about 40 levels observed up to an excitation energy of 4.75 MeV in Se^{77}. The Se^{76} target used is of $\sim 73\%$ in the isotopic enrichment. The background, due to isotopic impurities, was carefully subtracted. The proton spectrum observed at 35° is similar to that found by Macefield *et al.* The agreements between low-lying level energies are excellent. The ground state is strongly excited with $l=1$, as expected from the known spin, $\frac{1}{2}^-$. Three groups which contributed to the second strong peak are resolved as 0.17-, 0.25- and 0.31-MeV states. The 0.17-MeV state was previously known[16] to be a $\frac{7}{2}^+$ isomer (17.5 sec) followed by an $E3$ transition to the ground state of Se^{77}. Macefield *et al.* found the proton angular distribution to be either $l=3$ or $l=4$ for the 0.17-MeV state in the Se^{76}(d,p) reaction. It is strongly excited here, and the observed angular distribution cannot be fitted with a single l value. As shown in Fig. 9, the angular distribution seems to correspond to a mixture of $l=1$ and $l=4$.

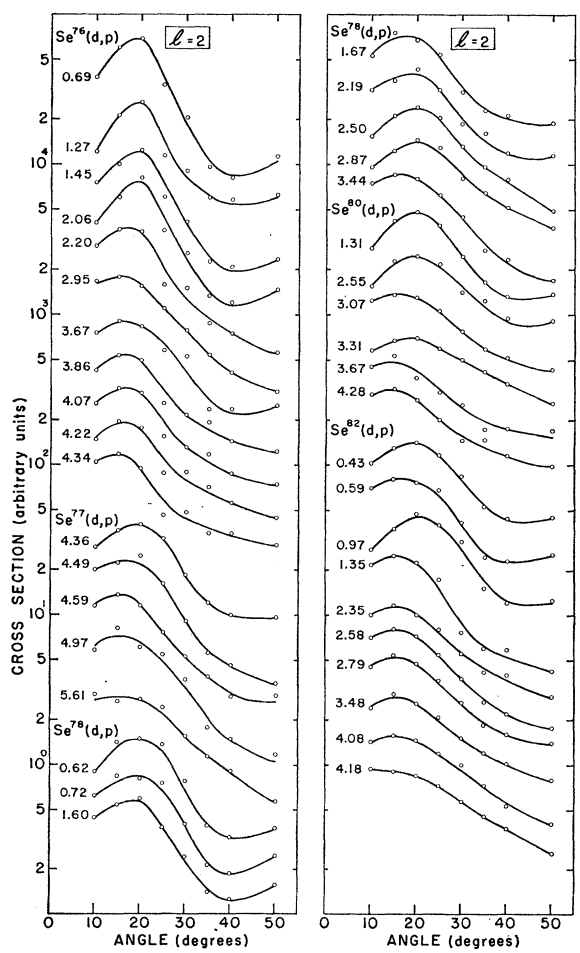

FIG. 6. Measured angular distributions of various peaks assigned to $l=2$ from (d,p) reactions on selenium targets. See caption for Fig. 4.

[16] *Nuclear Data Sheets*, computed by K. Way *et al.*, National Academy of Sciences—National Research Council (U. S. Government Printing Office, Washington, D. C., 1961). NRC-59-3-39.

It was found in the $Se^{78}(d,t)$ reaction that the 0.17-MeV state is also strongly excited. Therefore the (d,p) and (d,t) data suggest it to be a doublet of $\frac{1}{2}^-(\frac{3}{2}^-)$ and $\frac{9}{2}^+$. It was the only $l=4$ state of Se^{77} observed in the (d,p) spectrum. The 0.25-MeV state, which was previously reported[16] as a $\frac{3}{2}^-$ and $\frac{5}{2}^-$ doublet of spacing <10 keV, is weakly excited and not well resolved at some angles. The measured angular distributlon indicates a mixture of $l=1$ and $l=3$, in agreement with previous spin assignments. A similar angular distributlon was also found in the work of Macefield *et al.* This weakly excited state and a very weakly excited state at 0.43 MeV were strongly populated in the $Se^{77}(d,d')$ reaction[17] and by Coulomb excitation.[16] The 0.43-MeV state was previously known[16] to be $\frac{5}{2}^-$, and the present angular distribution indicates $l=3$. The 0.31-MeV state has an $l=2$ angular distributlon; it is weakly excited and was also observed in the $Se^{78}(d,t)$ reaction, so that this state is assigned a spin of $\frac{5}{2}^+$. A weak state at 1.39 MeV seen by Macefield *et al.* was also weakly observed here at some large angles. The uncertainties in data at a few angles make the angular distribution doubtful.

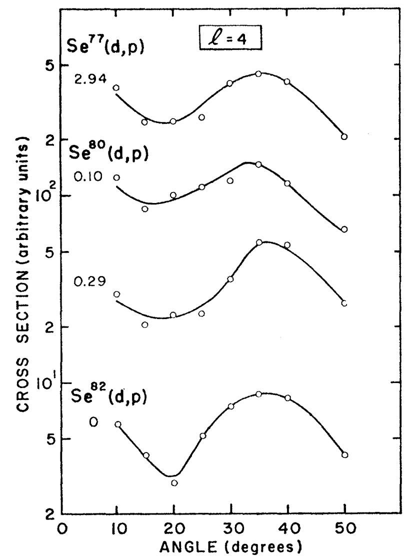

FIG. 8. Measured angular distribution for certain peaks assigned to $l=4$ from (d,p) reactions on selenium targets. See caption for Fig. 4.

B. $Se^{77}(d,p)$ Reactions

Previously information on the nucleus Se^{78} has come from decay-scheme work and (p,p') reactions. No investigation has been reported on the (d,p) reaction. The present analysis of levels of Se^{78} is carred up to 5.61-MeV excitation. The ground and first excited (0.62-MeV) states of Se^{78} are known[16] to be 0^+ and 2^+, respectively. The measured angular distributions for both states are characteristic of an $l=1$ angular

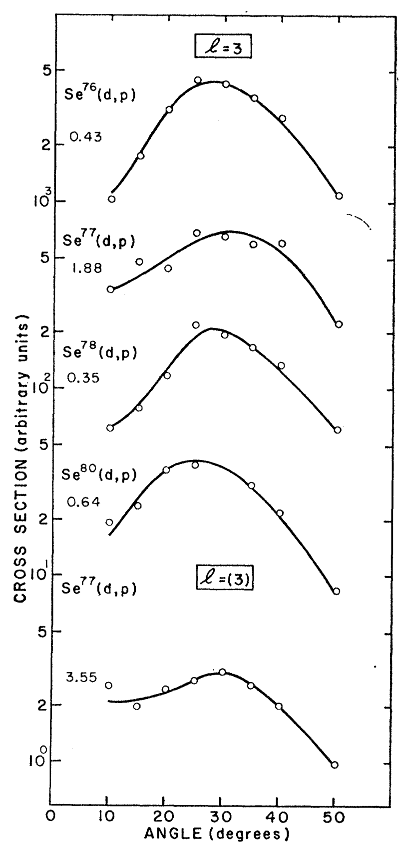

FIG. 7. Measured angular distributions for certain peaks assigned to $l=3$ from (d,p) reactions on selenium targets. See caption for Fig. 4.

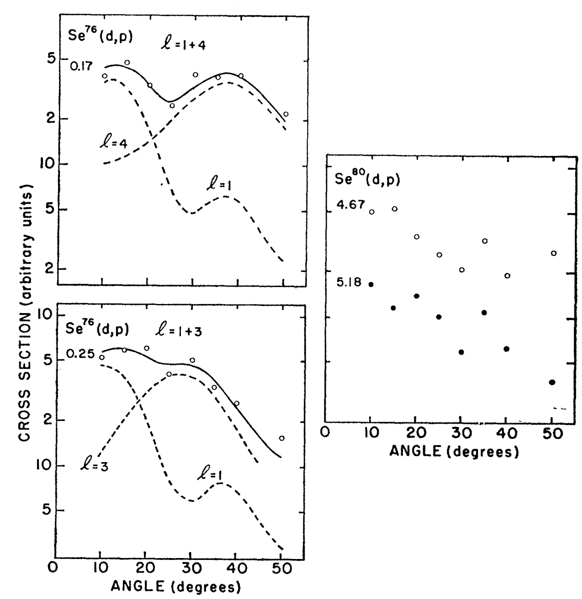

FIG. 9. Examples of fitting experimental data for certain peaks from $Se(d,p)$ reaction to an appropriate mixture of the theoretical angular distributions. The open circles are the experimental, the dashed lines are the individual DWBA curves for a given l value. Angular distributions of the 4.67- and 5.18-MeV states are examples of experimental data which are not fitted with any combination of DWBA curves. No l values can be assigned for these states.

[17] E. K. Lin (to be published).

momentum transfer. The first excited state (2^+) was observed in the spectrum about four times less strongly excited than the ground state. The second 2^+ state at 1.32 MeV is weakly excited, and the experimental accuracy is rather poor in the small-angle region, but beyond 20°, its angular distribution indicates $l=3$. The other one of the two-phonon group at 1.51 MeV is weakly excited. It was presumably considered[18] to be an unresolved doublet (0^+ and 4^+) of spacing $\leqslant 7$ keV in the (p,p') work. The identification of this doublet from the present data seems to be uncertain; the measured angular distribution shows a good stripping pattern of $l=1$, so that it favors the 0^+ assignment as the ground state of Se^{77} is $\frac{1}{2}^-$. Three levels at 1.76, 2.03, and 2.22 MeV which appeared in (p,p') reactions[18] were not observed here. The collective 3^- state is very weakly excited at 2.56 MeV. The angular distribution has an $l=2$ pattern, and the maximum cross section at $\theta=20°$ is about 0.10 mb/sr. Levels above 2.94 MeV have not been previously reported. The I values listed in Table III are from available data for the low-lying states and from various simple couplings between the target spin ($\frac{1}{2}^-$) and the angular momentum of the stripped neutrons.

TABLE II. Summary of results from $Se^{76}(d,p)$ reactious.

E (MeV) This work	E (MeV) Oxford	l This work	l Oxford	σ_{max} (mb/sr)	$(2I+1)S$	I^π This work	I^π Ref. 16	S
0	0	1	1	2.93	0.60	$\frac{1}{2}^-$	$\frac{1}{2}^-$	0.30
0.17	0.177	{1	3, 4	1.24	0.12	$\frac{1}{2}^-(\frac{3}{2}^-)$	$\frac{7}{2}^+$	0.058
		+4			3.60	$\frac{9}{2}^+$		0.36
0.25	0.245	{1	1	0.77	0.13	$\frac{3}{2}^-$	$\frac{3}{2}^-, \frac{5}{2}^-$	0.032
		+3	+3		1.22	$\frac{5}{2}^-$		0.20
0.31	0.306	(2)		1.0	0.28	$\frac{5}{2}^+$		0.046
0.43	0.440	3		~0.12	0.23	$\frac{5}{2}^-$	$\frac{5}{2}^-$	0.038
0.53	0.522	1	1	1.78	0.34	$\frac{1}{2}^-(\frac{3}{2}^-)$	$\frac{1}{2}^-, \frac{3}{2}^-$	0.17
0.69	0.682	2	2	4.63	1.23	$\frac{5}{2}^+$		0.20
0.83	0.826	1	1	0.29	0.27	$\frac{3}{2}^-$	$\frac{3}{2}^-$	0.067
0.97	0.956	0	0	3.68	0.25	$\frac{1}{2}^+$		0.13
1.02	1.013	1	1	1.40	0.17	$\frac{3}{2}^-(\frac{1}{2}^-)$		0.042
1.15	1.134	0	0	10.3	0.76	$\frac{1}{2}^+$		0.38
1.27	1.258	2	2	4.66	1.11	$\frac{5}{2}^+(\frac{3}{2}^+)$		0.19
1.39	1.37	?						
1.45	1.424	2	2	4.30	1.01	$\frac{5}{2}^+(\frac{3}{2}^+)$		0.17
1.76		1		0.35	0.041	$\frac{3}{2}^-(\frac{1}{2}^-)$		0.01
1.83		1		1.97	0.23	$\frac{3}{2}^-(\frac{1}{2}^-)$		0.057
1.97[a]		(0)		0.59	0.041	$\frac{1}{2}^+$		0.02
2.06		2		2.07	0.44	$\frac{5}{2}^+(\frac{3}{2}^+)$		0.073
2.20		2		1.92	0.40	$\frac{5}{2}^+(\frac{3}{2}^+)$		0.067
2.29		2		1.41	0.29	$\frac{5}{2}^+(\frac{3}{2}^+)$		0.048
2.50		(2)		1.86	0.39	$\frac{5}{2}^+(\frac{3}{2}^+)$		0.065
2.57		(2)		2.56	0.50	$\frac{5}{2}^+(\frac{3}{2}^+)$		0.083
2.64		(2)		1.14	0.22	$\frac{5}{2}^+(\frac{3}{2}^+)$		0.036
2.77		?						
2.95		2		1.35	0.25	$\frac{5}{2}^+(\frac{3}{2}^+)$		0.041
3.16		2		2.44	0.51	$\frac{3}{2}^+(\frac{5}{2}^+)$		0.13
3.23		2		2.21	0.46	$\frac{3}{2}^+(\frac{5}{2}^+)$		0.11
3.33		(2)		2.09	0.43	$\frac{3}{2}^+(\frac{5}{2}^+)$		0.11
3.40		2		1.74	0.36	$\frac{3}{2}^+(\frac{5}{2}^+)$		0.09
3.53		2		1.40	0.28	$\frac{3}{2}^+(\frac{5}{2}^+)$		0.07
3.67		2		0.66	0.13	$\frac{3}{2}^+(\frac{5}{2}^+)$		0.033
3.78		2		1.06	0.21	$\frac{3}{2}^+(\frac{5}{2}^+)$		0.05
3.86		2		0.99	0.19	$\frac{3}{2}^+(\frac{5}{2}^+)$		0.048
4.07		2		1.55	0.29	$\frac{3}{2}^+(\frac{5}{2}^+)$		0.072
4.22		2		2.24	0.39	$\frac{3}{2}^+(\frac{5}{2}^+)$		0.10
4.34		2		1.40	0.23	$\frac{3}{2}^+(\frac{5}{2}^+)$		0.058
4.43		2		1.41	0.24	$\frac{3}{2}^+(\frac{5}{2}^+)$		0.06
4.64		(2)		1.32	0.21	$\frac{3}{2}^+(\frac{5}{2}^+)$		0.053
4.75		(2)		0.69	0.10	$\frac{3}{2}^+(\frac{5}{2}^+)$		0.025

[a] Doubtful level.

[18] W. Darcey, D. J. Pullen, and N. W. Tanner, in *Proceedings of the Conference on Direct Interactions and Nuclear Reaction Mechanisms, Padua, 1962* edited by E. Clemental and C. Villi, (Gordon and Breach, Inc., New York, 1963).

C. $Se^{78}(d,p)$ Reactions

In a previous work by Carter[12] on the $Se^{78}(d,p)$ reaction at 7.5-MeV bombarding energy, only the level energies were obtained. The ground-state and 0.09-MeV isomer of Se^{79} and their spins are known[16] from the decays of As^{79} and Br^{79}. The spins were assisted as $\frac{7}{2}^+$ for the ground state, and $\frac{1}{2}^-$ for the 0.09-MeV state. The observed proton spectrum here is similar to the MIT data.[12] However, the first strong peak group is resolved and identified here as the 0.09- and 0.13-MeV states; these were considered as the ground and 0.039-MeV states by the MIT group. The present identification is confirmed by the fact that the measured angular distribution for the strongly excited 0.09-MeV state agrees very well with $l=1$, which is expected for the 0.09-MeV state from the known spin of $\frac{1}{2}^-$. Furthermore, the configuration of the ground state of Se^{79} is known to be $[(g_{9/2})^5]_{7/2^+}$, which is not a

TABLE III. Summary of results from $Se^{77}(d,p)$ reactions.

E (MeV) (d,p)	E (MeV) (d,d)[a]	l	σ_{max} (mb/sr)	$(2j+1)S'$	S'	I^π Known[b]	I^π This work
0	0	1	1.21	0.34	0.17	0^+	0^+
0.62	0.63	1	0.32	0.074	0.019	2^+	2^+
1.32	1.32	(3)	0.12	0.27	0.045	2^+	2^+
1.51	1.51	1	0.15	0.036	0.018	$(0^+,4^+)$	0^+
1.88		3	0.04	0.1	0.02		$2^+, 3^+$
					$\frac{1}{2}^-$ $\frac{3}{2}^-$		
2.36	2.36	1	0.35	0.081	0.041−0.02		0^+–2^+
2.56	2.55	(2)	0.10	0.031	0.006	3^-	3^-
2.94	2.98	4	0.21	0.61	0.061		$4^-, 5^-$
3.13	3.17	1	1.94	0.40	0.20 −0.09		0^+–2^+
3.33	3.37	{1	0.21	0.035	0.018−0.008		0^+–2^+
		+4		0.59	0.059		$4^-, 5^-$
3.46	3.50	(4)	0.59	1.65	0.17		$4^-, 5^-$
3.55	3.56	(3)	0.49	0.88	0.15		$3^+, 3^+$
3.69		2	1.26	0.38	0.064		$2^-, 3^-$
3.83		2	1.12	0.34	0.057		$2^-, 3^-$
4.12		0	1.74	0.68	0.34		$0^-, 1^-$
4.19		0	2.25	0.89	0.44		$0^-, 1^-$
4.36		2	2.38	0.57	0.095		$2^-, 3^-$
4.49		2	3.30	0.76	0.13		$2^-, 3^-$
4.59		2	1.37	0.33	0.055		$2^-, 3^-$
4.78		0	0.87	0.31	0.15		$0^-, 1^-$
4.91		2	1.29	0.28	0.047		$2^-, 3^-$
4.97		2	1.94	0.45	0.075		$2^-, 3^-$
5.12		0	0.80	0.29	0.14		$0^-, 1^-$
5.21		2	2.89	0.60	0.10		$2^-, 3^-$
5.36		(2)	1.31	0.27	0.045		$2^-, 3^-$
5.48		(2)	0.63	0.13	0.021		$2^-, 3^-$
5.61		2	1.49	0.29	0.048		$2^-, 3^-$

[a] Reference 17.
[b] Reference 16.

single-particle state. It would be surprising if this state is strongly excited in the $Se^{78}(d,p)$ reaction. The $Se^{80}(d,t)$ data also show no excitation of the ground state of Se^{79}. There are several $l=1$ levels observed in the (d,p) spectrum. If the first two peaks were 0- and 0.039-MeV states, there would be a peak corresponding to the 0.09-MeV state ($l=1$), which, however, was not seen in the spectrum. If a correction of 0.09 MeV is added to the MIT data, the agreements of observed level energies between the present data and the MIT data are very satisfactory. The angular distribution for the 0.13-MeV state was found to be a mixture of $l=1$ and $l=4$.

TABLE IV. Summary of results from $Se^{78}(d,p)$ reactions.

E (MeV) This work	MIT	l	σ_{max} (mb/sr)	$(2I+1)S$	I^π	S
0.09	0.09	1	2.76	0.44	$\frac{1}{2}^-$	0.22
0.13	0.129	1	2.74	0.38	$\frac{1}{2}^-(\frac{3}{2}^-)$	0.19
		+4		4.10	$\frac{9}{2}^+$	0.41
0.35	0.361	3	0.61	1.04	$\frac{5}{2}^-$	0.17
0.52	0.522	1	2.45	0.33	$\frac{3}{2}^-(\frac{1}{2}^-)$	0.08
0.62	0.626	2	3.23	0.79	$\frac{5}{2}^+$	0.13
0.72	0.721	2	1.69	0.41	$\frac{5}{2}^+$	0.07
0.97	0.970	1	2.32	0.28	$\frac{3}{2}^-(\frac{1}{2}^-)$	0.07
1.16	1.152	0	19.6	1.32	$\frac{1}{2}^+$	0.66
1.25	1.248	2	9.2	2.06	$\frac{5}{2}^+(\frac{3}{2}^+)$	0.34
1.49	1.489	(0)	1.95	0.13	$\frac{1}{2}^+$	0.066
1.60	1.593	2	3.82	0.83	$\frac{5}{2}^+(\frac{3}{2}^+)$	0.14
1.67	1.663	2	0.95	0.21	$\frac{5}{2}^+(\frac{3}{2}^+)$	0.035
1.76	1.746	2	1.38	0.29	$\frac{5}{2}^+(\frac{3}{2}^+)$	0.048
1.87	1.855	(1)	$\sim$0.13	0.014	$\frac{3}{2}^-(\frac{1}{2}^-)$	0.004
1.96	1.953	?				
2.04	2.013	1	0.43	0.048	$\frac{3}{2}^-(\frac{1}{2}^-)$	0.012
2.11	2.079	1	0.43	0.048	$\frac{3}{2}^-(\frac{1}{2}^-)$	0.012
2.19	2.178	2	1.05	0.21	$\frac{5}{2}^+(\frac{3}{2}^+)$	0.035
2.28	2.256	1	0.40	0.04	$\frac{3}{2}^-(\frac{1}{2}^-)$	0.01
2.34	2.325	2	1.03	0.20	$\frac{5}{2}^+(\frac{3}{2}^+)$	0.033
2.40	2.381	2	0.67	0.13	$\frac{5}{2}^+(\frac{3}{2}^+)$	0.022
2.50	2.530	2	0.98	0.18	$\frac{5}{2}^+(\frac{3}{2}^+)$	0.03
2.59	2.588	2	2.73	0.50	$\frac{5}{2}^+(\frac{3}{2}^+)$	0.083
2.73	2.716	(2)	0.44	0.08	$\frac{5}{2}^+(\frac{3}{2}^+)$	0.013
2.78		(2)	0.74	0.13	$\frac{5}{2}^+(\frac{3}{2}^+)$	0.022
2.87		2	1.04	0.21	$\frac{3}{2}^+(\frac{5}{2}^+)$	0.053
2.96	2.922	0	1.70	0.12	$\frac{1}{2}^+$	0.06
3.09		(2)	2.53	0.49	$\frac{3}{2}^+(\frac{5}{2}^+)$	0.12
3.20	3.175	(2)	1.30	0.25	$\frac{3}{2}^+(\frac{5}{2}^+)$	0.063
3.28	3.238	0	1.74	0.12	$\frac{1}{2}^+$	0.06
3.34[a]	3.312	2	0.39	0.077	$\frac{3}{2}^+(\frac{5}{2}^+)$	0.019
3.44	3.473	2	4.18	0.76	$\frac{3}{2}^+(\frac{5}{2}^+)$	0.19
3.59		(2)	1.54	0.42	$\frac{3}{2}^+(\frac{5}{2}^+)$	0.10
3.69	3.668	(0)	3.30	0.26	$\frac{1}{2}^+$	0.13
3.76	3.736	2	0.42	0.076	$\frac{3}{2}^+(\frac{5}{2}^+)$	0.019
3.82	3.790	(2)	0.97	0.17	$\frac{3}{2}^+(\frac{5}{2}^+)$	0.043
3.85	3.835	(2)	1.40	0.25	$\frac{3}{2}^+(\frac{5}{2}^+)$	0.062
3.98	4.004	(2)	1.80	0.31	$\frac{3}{2}^+(\frac{5}{2}^+)$	0.078
4.09		(2)	1.85	0.32	$\frac{3}{2}^+(\frac{5}{2}^+)$	0.08
4.18		(2)	3.30	0.56	$\frac{3}{2}^+(\frac{5}{2}^+)$	0.14
4.36		(2)	1.41	0.23	$\frac{3}{2}^+(\frac{5}{2}^+)$	0.058

[a] Doubtful level.

It is seen in Table IV that there are at least 40 excited states identified up to an excitation energy of 4.36 MeV in Se^{79}. Their spins, except for the 0- and 0.09-MeV states, were not previously known. An $l=3$ state was found here at 0.35 MeV and some $l=1$ states at low energies. The ratio of $\sigma(d,t)$ to $\sigma(d,p)$ at 40° for the known $\frac{1}{2}^-$ state at 0.09 MeV is 0.64. The ratio of $\sigma(d,t)$ to $\sigma(d,p)$ for other $l=1$ states suggests the 0.13-MeV state to be $(\frac{1}{2}^-)$ mixed with $\frac{9}{2}^+$ and the 0.52- and 0.97-MeV states to be $\frac{3}{2}^-$. At energies higher than 2.50 MeV, most levels were found to be $l=0$ and $l=2$ states. Many doubtful levels appear in MIT data; among them the 1.67-, 1.96-, 2.04-, 2.34-, 2.50-, 2.96-, 3.44-, 3.76-, and 3.98-MeV states are confirmed here. The 1.96-, 2.04-, 2.28-, 2.40-, and 3.76-MeV states seen here are all weakly excited, so that the experimental accuracy is rather poor; however, the measured angular distributions suggest $l=1$ for 2.04- and 2.28-MeV states and $l=2$ for the 2.40- and 3.76-MeV states, and no l value can be assigned for the 1.96-MeV state.

TABLE V. Summary of results from $Se^{80}(d,p)$ reactions.

E (MeV) This work	MIT	l	σ_{max} (mb/sr)	$(2I+1)S$	I^π	S
0	0	1	3.96	0.60	$\frac{1}{2}^-$	0.30
0.10	0.103	4	$\sim$0.09	0.25	$\frac{7}{2}^+$	0.03
0.29	0.294	4	1.19	2.83	$\frac{9}{2}^+$	0.28
0.47	0.469	1	1.58	0.20	$\frac{3}{2}^-(\frac{1}{2}^-)$	0.045
0.64	0.627	3	0.28	0.43	$\frac{5}{2}^-$	0.073
0.90		(0)	0.55	0.039	$\frac{1}{2}^+$	0.02
1.06	1.053	2	6.9	1.53	$\frac{5}{2}^+$	0.26
1.25	1.234	0	18.8	1.28	$\frac{1}{2}^+$	0.64
1.31	1.304	2	11.0	2.36	$\frac{5}{2}^+$	0.40
1.42	1.407	1	2.67	0.29	$\frac{3}{2}^-(\frac{1}{2}^-)$	0.075
1.73	1.704	2	1.69	0.35	$\frac{5}{2}^+(\frac{3}{2}^+)$	0.058
1.84	1.829	2	1.88	0.37	$\frac{5}{2}^+(\frac{3}{2}^+)$	0.061
2.06	2.04	?				
2.18	2.179	2	0.36	0.067	$\frac{5}{2}^+(\frac{3}{2}^+)$	0.011
2.26		?				
2.34	2.338	2	1.10	0.12	$\frac{5}{2}^+(\frac{3}{2}^+)$	0.02
		+3		0.38	$\frac{5}{2}^-$	0.06
2.55	2.543	2	1.74	0.31	$\frac{5}{2}^+(\frac{3}{2}^+)$	0.051
2.68	2.663	0	1.42	0.10	$\frac{1}{2}^+$	0.05
2.79	2.773	2	1.65	0.29	$\frac{5}{2}^+(\frac{3}{2}^+)$	0.049
2.93	2.947	(0)	$\sim$0.24	0.02	$\frac{1}{2}^+$	0.01
2.99	2.980	(0)	1.90	0.14	$\frac{1}{2}^+$	0.07
3.07	3.062	2	7.5	1.46	$\frac{3}{2}^+(\frac{5}{2}^+)$	0.36
3.24		(2)	1.60	0.31	$\frac{3}{2}^+(\frac{5}{2}^+)$	0.078
3.31	3.295	2	2.31	0.40	$\frac{3}{2}^+(\frac{5}{2}^+)$	0.10
3.42	3.413	(2)	1.70	0.29	$\frac{3}{2}^+(\frac{5}{2}^+)$	0.07
3.49		2	1.26	0.21	$\frac{3}{2}^+(\frac{5}{2}^+)$	0.05
3.57	3.532	0	2.11	0.16	$\frac{1}{2}^+$	0.08
3.67	3.692	2	2.46	0.40	$\frac{3}{2}^+(\frac{5}{2}^+)$	0.10
3.72	3.774	2	2.22	0.38	$\frac{3}{2}^+(\frac{5}{2}^+)$	0.095
3.84	3.83	(0)	2.52	0.20	$\frac{1}{2}^+$	0.10
3.92		(0)	1.0	0.081	$\frac{1}{2}^+$	0.04
3.97		(0)	1.23	0.10	$\frac{1}{2}^+$	0.05
4.13	4.143	(2)	2.30	0.35	$\frac{3}{2}^+(\frac{5}{2}^+)$	0.088
4.18	4.170	(2)	1.0	0.17	$\frac{3}{2}^+(\frac{5}{2}^+)$	0.042
4.22	4.215	(2)	1.41	0.24	$\frac{3}{2}^+(\frac{5}{2}^+)$	0.06
4.28	4.260	(2)	1.0	0.17	$\frac{3}{2}^+(\frac{5}{2}^+)$	0.042
4.45	4.437	?				
4.56	4.559	?				
4.67	4.656	?				
4.74	4.708	?				
4.86	4.845	?				
4.97	4.958	?				
5.08	5.080	?				
5.18		?				
5.33		?				

TABLE VI. Summary of results from $Se^{82}(d,p)$ reactions.

E (MeV) This work	Known	l	σ_{max} (mb/sr)	$(2I+1)S$	I^π	S
0	0	4	1.06	2.44	$\frac{9}{2}^+$	0.24
0.22		1	1.05	0.13	$\frac{1}{2}^-$	0.065
0.36		(0)	3.56	0.24	$\frac{1}{2}^+$	0.12
0.43		2	0.54	0.11	$\frac{5}{2}^+(\frac{3}{2}^+)$	0.018
0.59		2	17.7	3.73	$\frac{5}{2}^+(\frac{3}{2}^+)$	0.62
0.85		2	0.62	0.13	$\frac{5}{2}^+(\frac{3}{2}^+)$	0.021
0.97		2	0.70	0.14	$\frac{5}{2}^+(\frac{3}{2}^+)$	0.023
1.12		2	5.15	1.01	$\frac{5}{2}^+(\frac{3}{2}^+)$	0.17
1.35		2	2.38	0.44	$\frac{5}{2}^+(\frac{3}{2}^+)$	0.072
1.48		2	0.68	0.12	$\frac{5}{2}^+(\frac{3}{2}^+)$	0.02
1.58[a]		?				
1.70		(2)	1.84	0.32	$\frac{5}{2}^+(\frac{3}{2}^+)$	0.053
1.93[a]		?				
2.12		(3)	0.51	0.42	$\frac{5}{2}^-$	0.07
2.22		(2)	1.20	0.22	$\frac{3}{2}^+(\frac{5}{2}^+)$	0.055
2.35		2	0.79	0.14	$\frac{3}{2}^+(\frac{5}{2}^+)$	0.035
2.58		2	15.7	2.68	$\frac{3}{2}^+(\frac{5}{2}^+)$	0.67
2.79		2	1.46	0.24	$\frac{3}{2}^+(\frac{5}{2}^+)$	0.06
2.88		(2)	1.82	0.30	$\frac{3}{2}^+(\frac{5}{2}^+)$	0.075
3.01		(1)	3.16	0.27	$\frac{3}{2}^-(\frac{1}{2}^-)$	0.067
3.13		?				
3.23		2	1.68	0.26	$\frac{3}{2}^+(\frac{5}{2}^+)$	0.065
3.37		2	1.04	0.17	$\frac{3}{2}^+(\frac{5}{2}^+)$	0.042
3.48		2	2.64	0.39	$\frac{3}{2}^+(\frac{5}{2}^+)$	0.097
3.66		?				
3.79		(0)	1.79	0.17	$\frac{1}{2}^+$	0.08
3.86		(0)	3.03	0.28	$\frac{1}{2}^+$	0.14
4.02		?				
4.08		(2)	0.40	0.054	$\frac{3}{2}^+(\frac{5}{2}^+)$	0.013
4.18		2	0.50	0.066	$\frac{3}{2}^+(\frac{5}{2}^+)$	0.016
4.29		?				
4.42		?				
4.52		?				
4.68		?				
4.77		?				
4.95		?				

[a] Doubtful level.

D. $Se^{80}(d,p)$ Reaction

Carter[12] has also reported many levels of Se^{81} in his (d,p) work. Only spins of the first two states were previously known.[16] The level energies obtained here are listed in Table V. They agree very well with the MIT data.[12] Spins for many levels are properly assigned in Column 6. The observed angular distribution for the ground state fits fairly well with $l=1$ and, therefore, favors spin $\frac{1}{2}^-$, in agreement with the result of the decay scheme work.[16] The lowest excited state, which is known to be a $\frac{7}{2}^+$ isomer, is very weakly excited at 0.10 MeV. The maximum cross section is less than 0.09 mb/sr. It was not found in the $Se^{82}(d,t)$ reaction. Its proton angular distribution indicates $l=4$, but the statistics are rather poor. The 0.29-MeV state also has an $l=4$ angular distribution; it is not weakly excited and was also observed in the $Se^{82}(d,t)$ reaction, so that a $\frac{9}{2}^+$ is assigned to this state. Two $l=1$ states at 0.47 and 1.42 MeV have a larger ratio of $\sigma(d,t)$ to $\sigma(d,p)$ than that of the ground state which is known to be $\frac{1}{2}^-$; both are therefore likely to be $\frac{3}{2}^-$ states. This assignment for the 0.47-MeV state is supported by analogy with the nearest isotone, Kr^{83}, which is known[16] to have a $\frac{3}{2}^-$ state at 0.56 MeV. Three very strongly excited states were seen at 1.06, 1.31, and 3.07 MeV, as shown in Fig. 1. They were all found to be $l=2$ transitions. The strength of the $d_{5/2}$ state seems to be distributed mostly in two levels at 1.06 and 1.31 MeV. The S values for these states were found to be 0.26 and 0.40, respectively. There is only one strong $l=0$ peak appearing at 1.25 MeV. It has about 64% of the strength of the $s_{1/2}$ state. A large fraction of the strength of the $d_{3/2}$ state was found to be contained in a level at 3.07 MeV with $S=0.36$. The only $l=3$ levels were observed at 0.64 MeV and in the mixture of $l=2$ at 2.34 MeV. The doubtful levels found in MIT work at 0.64, 2.06, 2.55, 2.79, 3.31, 4.13, 4.18, 4.28, 4.67, 4.74, 4.86, and 4.97 MeV are confirmed here.

TABLE VII. Summary of results from (d,t) reactions on Se isotopes and comparison with (d,d')[a] and (d,p) reactions.

(a) $Se^{77}(d,t)Se^{76}$

E (MeV) (d,t)	E (MeV) (d,d')	I^π (Ref. 16)	$\sigma(40°)$ (mb/sr) (d,t)	$\sigma(35°)$ (mb/sr) (d,d')
0	0	0^+	0.57	
0.55	0.56	2^+	0.55	6.80
1.21	1.22	2^+	0.49	1.39
1.80	1.80	$(1,2^+)$	0.17	0.33
2.13	2.13	...	0.20	0.13
2.57	2.54	...	0.23	0.34
2.63	2.67	$(1,2^+)$	0.17	0.25
2.86	2.87	...	0.29	0.34
3.00	2.98	...	0.39	0.26

(b) $Se^{78}(d,t)Se^{77}$

E (MeV) (d,t)	E (MeV) (d,p)	I^π	$\sigma(35°)$ (mb/sr) (d,t)	$\sigma(35°)$ (mb/sr) (d,p)
0	0	$\frac{1}{2}^-$[b]	1.55	0.52
0.17	0.17	$\frac{1}{2}^-(\frac{3}{2}^-)$, $\frac{9}{2}^+$	1.51	1.10
0.25	0.25	$\frac{3}{2}^-$[b], $\frac{5}{2}^-$	1.13	0.50
0.31	0.31	$\frac{5}{2}^+$	<0.10	~0.10
0.42	0.43	$\frac{5}{2}^-$	0.31	~0.10
0.70	0.69	$\frac{5}{2}^+$	<0.50	0.63
0.83	0.83	$\frac{3}{2}^-$[b]	1.0	0.24

(c) $Se^{80}(d,t)Se^{79}$

E (MeV) (d,t)	E (MeV) (d,p)	I^π	$\sigma(40°)$ (mb/sr) (d,t)	$\sigma(40°)$ (mb/sr) (d,p)
0.09	0.09	$\frac{1}{2}^-$[b]	0.93	1.45
0.13	0.13	$\frac{1}{2}^-(\frac{3}{2}^-)$, $\frac{9}{2}^+$	0.87	2.00
0.37	0.35	$\frac{5}{2}^-$	0.40	0.48
0.53	0.52	$\frac{3}{2}^-(\frac{1}{2}^-)$	0.96	0.90
0.64	0.62	$\frac{5}{2}^+$	0.23	0.82
0.74	0.72	$\frac{5}{2}^+$	0.37	0.50
0.99	0.97	$\frac{3}{2}^-(\frac{1}{2}^-)$	1.14	0.90

(d) $Se^{82}(d,t)Se^{81}$

E (MeV) (d,t)	E (MeV) (d,p)	I^π	$\sigma(25°)$ (mb/sr) (d,t)	$\sigma(25°)$ (mb/sr) (d,p)
0	0	$\frac{1}{2}^-$[b]	1.53	0.76
0.29	0.29	$\frac{9}{2}^+$	1.06	0.42
0.48	0.47	$\frac{3}{2}^-(\frac{1}{2}^-)$	1.21	0.41
0.63	0.63	$\frac{5}{2}^-$	0.75	0.24
1.06	1.06	$\frac{5}{2}^+$	0.59	4.30
1.32	1.31	$\frac{5}{2}^+$	0.38	6.40
1.42	1.42	$\frac{3}{2}^-(\frac{1}{2}^-)$	1.63	0.57

[a] Reference 17.
[b] From Ref. 16.

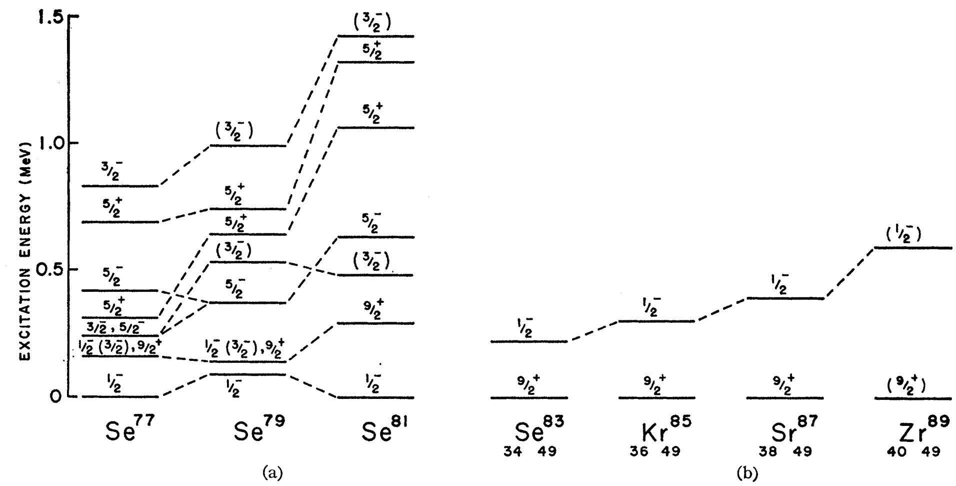

FIG. 10. (a) The location of the low-lying states of Se^{77}, Se^{79}, and Se^{81} excited in both (d,p) and (d,t) reactions. (b) Scheme of first excited states of odd nuclei containing 49 neutrons.

E. $Se^{82}(d,p)$ Reaction

The Q value for this reaction was not previously known in the UCRL report.[19] Recently, Yamada and Matumoto[20] estimated the proton and neutron separation energies and found $Q=3.75$ MeV for $Se^{82}(d,p)$ reaction to be consistent with the result of Everling *et al.*,[21] who also found the same Q value from mass-excess measurements. In the present experiment, the Q value is determined to be 3.75 ± 0.05 MeV, which agrees well with their data.

The Se^{82} target is not as highly enriched as Se^{78} and Se^{80} targets used in the present work. The isotopic enrichment of Se^{82} is $\sim75\%$. Some peaks from isotopic impurities found in the low-energy region of the $Se^{82}(d,p)$ spectra are carefully identified by taking into account the strengths of the peaks of known isotopic impurities. Except for the ground state, all excited states of Se^{83} were previously unknown. The ground state was previously assigned[16] as $(\frac{9}{2}^+)$. The measured angular distribution here, as shown in Fig. 8, indicates $l=4$ in favor of the assignment $\frac{9}{2}^+$. Two weak peaks were observed at positions corresponding to 0.16- and 0.22-MeV states of Se^{83}, respectively. The former is from the impurity of Se^{78} at the energy corresponding to 1.25-MeV state of Se^{79}. It has $l=2$ angular distribution, as expected from the 1.25-MeV state of Se^{79}. As Se^{83} was previously known[16] from beta-decay work to have a 69-sec isomer of spin $\frac{1}{2}^-$ at low energy, it is expected to exist at energy less than 0.3 MeV by analogy with the other odd mass nuclei with 49 neutrons (see Sec. IV). The observed 0.22-MeV state is weakly excited, which would be expected for $\frac{1}{2}^-$ state, as it is mostly full in Se^{83}. The fact that the measured angular distribution for this state was found to be $l=1$ indicates that the 0.22-MeV state is the isomer (see Fig. 10). Further support to this comes from other data of $E3$ isomers given by Mayer and Jensen,[22] who have plotted experimental half-life for $E3$ isomers against energy of isomeric transition; the present data in energy is consistent with their plot.

The observed levels up to an excitation energy of 4.95 MeV are listed in Table VI. An $l=0$ level was found at 0.36 MeV with $S=0.12$. Levels at 0.59 and 2.58 MeV are very strongly excited with $l=2$ angular-momentum transfer. The former is the strongest $d_{5/2}$ peak with $S=0.62$, while the latter is the strongest $d_{3/2}$ peak with $S=0.67$. These two and other strongly excited states can be identified as a coupling of the ground state of Se^{82} with the various single-particle states in the 50-82 shell.

F. $Se(d,t)$ Reactions

Measurements with the enriched Se^{77}, Se^{78}, Se^{80}, and Se^{82} targets have been made on (d,t) reactions. The results are presented in Table VII. Column 1 lists the observed energy levels which are then compared with (d,p) or (d,d') data[17] in the next column. In general, the agreement between energies is within the experimental error.

Several firmly established energy levels of Se^{76} have been reported from inelastic scattering.[18] In the present $Se^{77}(d,t)$ experiment, three strong triton groups observed correspond to the transitions to the ground, first, and second 2^+ states of Se^{76}, respectively. The first strong triton group, resulting from $\frac{1}{2}^-$ pickup, is expected from the known spin of the ground state of Se^{77} which has a hole in the $p_{1/2}$ shell. The second and third triton groups were observed at excitation energies 0.55 and 1.21 MeV, respectively. The former corresponding to the first 2^+ state has slightly larger intensity than the latter which corresponds to the second 2^+ state. The other two members of the two-phonon triplet were not

[19] V. J. Ashby and H. C. Catron, UCRL Report No. 5419 (unpublished).

[20] Yamada and Z. Matumota, J. Phys. Soc. Japan **16**, 1497 (1961).

[21] F. Everling, L. A. Koneg, and J. H. E. Mattauch, Nucl. Phys. **18**, 529 (1960).

[22] M. G. Mayer and J. H. D. Jensen, *Elementary Theory of Nuclear Shell Structure* (John Wiley & Sons., Inc., New York, 1955).

observed here. The collective 3^- state strongly excited in the (d,d') reaction[17] at 2.45 MeV was also not seen in the $Se^{77}(d,t)$ reaction.

For $Se^{78}(d,t)$ reactions, the Q value is more negative; only six triton peaks are identified as due to energy levels of Se^{77}. The region of excitation energies above 0.83 MeV is obscured by scattered deuterons. The ground state corresponds to a transition resulting from $\frac{1}{2}^-$ pickup. It is strongly excited at the observed angle, 35°, with cross sections decreasing at other angles. This agrees with the evidence that the $l=1$ angular distribution for Q value (-4 MeV) in the $Ni^{64}(d,t)Ni^{63}$ reaction[23] has a maximum at 35°. The 0.17- and 0.25-MeV states are clearly resolved; both are strongly excited. An $l=1$ state at 0.53 MeV which appeared in the $Se^{76}(d,p)$ spectrum is obscured by the elastic deuterons.

For $Se^{80}(d,t)$ reactions, the excitation energies are given in Table VII. Two groups which contributed to the first strong peak are clearly resolved to be the 0.09- and 0.13-MeV states. These and two other groups at 0.53 and 0.99 MeV were all observed in the $Se^{78}(d,p)$ reaction to be p states. The 0.09-MeV isomeric state was known to be $p_{1/2}$. The spin assignments to other p states, as discussed above, are in agreement with the systematics of levels in the selenium isotopes found both in (d,p) and (d,t) reactions as shown in Fig. 10(a).

For $Se^{82}(d,t)$ reactions, the strongest peak observed corresponds to the ground state ($\frac{1}{2}^-$) of Se^{81}. A known $\frac{7}{2}^+$ state at 0.10 MeV is not excited in the present pickup reaction. The 0.19- ($\frac{9}{2}^+$) and 0.48- ($\frac{3}{2}^-$)-MeV states are strongly excited here. An $s_{1/2}$ state at 0.90 MeV, found in the (d,p) reaction, was not observed.

It is notable that in the above three (d,t) reactions, two $d_{5/2}$ states were observed and very weakly excited at 0.31 and 0.70 MeV in Se^{77}, 0.64 and 0.74 MeV in Se^{79}, and 1.06 and 1.32 MeV in Se^{81}. Their V_j^2 values, in each case, are approximately 0.10, corresponding to 0.6 particles filled in the $d_{5/2}$ subshell. Therefore, the present (d,t) data shows an evidence that the beginning of the next (50-82) major shell is starting to fill in the selenium nuclei even though the lower major 28-50 shell is not completely full. The higher states, $l=0$ levels, were not found in the (d,t) reactions; however, from the present (d,t) data, the upper limit for this excitation is estimated here to be $\sum S(d,t)\leqslant 0.04$.

IV. DISCUSSION

A. (d,p) Reactions on Selenium Targets

The results of the sum-rule analysis for $\sum S$ of the spectroscopic factors of all nuclear levels belonging to the shell-model state j, and the single-quasiparticle energy E_j are summarized in Tables VIII and IX. A comparison is made with pairing-theory predictions, calculated with parameters ϵ, taken from Refs. 5 and 24, and Δ obtained from the relationship

$$2\Delta\simeq\tfrac{1}{2}[|\mathrm{S.E.}(n)-\mathrm{S.E.}(n-1)| + |\mathrm{S.E.}(n)-\mathrm{S.E.}(n+1)|], \quad (3)$$

where the values for the separation energies (S.E.) were taken from a UCRL report.[18]

The striking feature for the results shown in Table VIII is that the experimental $\sum S$ for $f_{5/2}$, $p_{3/2}$, and $p_{1/2}$ states are unexpectedly large. The $p_{3/2}$ and $f_{5/2}$ states are deeply bound in the selenium isotopes; however, both are found to be less full than the pairing-theory prediction. The same is also seen to be true for the $p_{1/2}$ state. The fact that many p and d states were found excited in the (d,p) reaction indicates a considerable residual interaction which disturbs the single-particle neutron state appreciably. It is seen in Tables II–VI that the strength of $l=1$ and $l=2$ levels are spread widely over about 2 and 4 MeV, respectively. It is apparent that some $g_{9/2}$ states in Se^{76} are missed in the analysis of data, and also some $s_{1/2}$ states are missed in Se^{76} and Se^{82}, since the $s_{1/2}$ state should be completely empty and has $\sum S=1$. The $d_{3/2}$ state should also be completely empty, while the $d_{5/2}$ state should not be as some $d_{5/2}$ levels were observed at low energies in the (d,t) reaction. Because the $d_{3/2}$ and $d_{5/2}$ states were not well distinguished in the intermediate energy region, the $U_{5/2^+}{}^2$ values obtained from (d,p) reactions are not very accurate.

For purposes of comparing the experimental results with pairing theory, we made three separate calculations according to pairing theory; namely, Theory a, Theory b, and Theory c, as shown in Table VIII. They were calculated with different parameters from Refs. 5 and 24, as given in the footnote of Table VIII. First, it was calculated with the parameters "set b" ($\epsilon_{9/2^+}=3.60$ MeV, $\epsilon_{1/2^-}=2.50$ MeV, $\epsilon_{5/2^-}=1.0$ MeV, $\epsilon_{3/2^-}=0$, and $\Delta=1.65$ MeV); it is readily seen that there exists the quantitative discrepancy in the $\sum S$ for $f_{5/2}$, $p_{3/2}$, and $p_{1/2}$ states. The experimental values for $f_{5/2}$, $p_{3/2}$, and $p_{1/2}$ states are larger, and for the $g_{9/2}$ state is smaller than the predictions. It is apparently due to an overly high $g_{9/2}$ single-particle energy used in the calculations. The calculation with the parameters "set a," using a lower $g_{9/2}$ single-particle energy[23] ($\epsilon_{9/2^+}=3.0$ MeV) was then made, and it was found that the agreement is considerably improved in the $\sum S$ for $p_{3/2}$, $p_{1/2}$, $f_{5/2}$, and $g_{9/2}$ states. The third calculation was made with the parameters "set c" which were taken from Kisslinger and Sorensen.[5] It is seen here that the agreement between the experimental data and the theoretical calculations is worse in this case. The quantitative discrepancy between two calculations using parameters "set b" and "set c" arises basically from the values of $\epsilon_{5/2}$ and $\epsilon_{3/2}$ and Δ which were chosen; in Ref. 5, the single-particle energy $\epsilon_{5/2^-}$ (-0.18 MeV) was chosen lower than the single-particle energy $\epsilon_{3/2^-}$ (0.09 MeV), and the Δ($\sim$1.10 MeV) was chosen smaller than the

[23] R. H. Fulmer, Ph.D. thesis, University of Pittsburgh (unpublished).

TABLE VIII. Comparison of experimental data from (d,p) reactions for even Se isotopes with pairing theory. The experimental ΣS values are not normalized.

(a) ΣS

Nucleus \ State	Exptl.	Theory[a]	Theory[b]	Theory[c]	Exptl.	Theory[a]	Theory[b]	Theory[c]
	$\frac{3}{2}-$				$\frac{5}{2}-$			
Se^{76}	0.21	0.073	0.06	0.03	0.24	0.15	0.11	0.024
Se^{78}	0.19	0.056	0.045	0.022	0.17	0.11	0.07	0.02
Se^{80}	0.12	0.043	0.036	0.02	0.13	0.072	0.032	0.032
Se^{82}	0.067	0.028	0.02	0.013	0.062	0.044	0.02	0.012
	$\frac{1}{2}-$				$\frac{9}{2}+$			
Se^{76}	0.53	0.44	0.33	0.24	>0.36	0.59	0.64	0.72
Se^{78}	0.41	0.31	0.22	0.15	0.41	0.46	0.50	0.56
Se^{80}	0.30	0.20	0.18	0.09	0.28	0.30	0.35	0.37
Se^{82}	0.065	0.10	0.08	0.055	0.24	0.15	0.17	0.18

Nucleus \ State	$\Sigma(2j+1)U_j^2$ Exptl.	Theory	$\frac{5}{2}+$ Exptl.	$\frac{1}{2}+$ Exptl.	$\frac{3}{2}+$ Exptl.
Se^{76}	>6.94	8	1.02	>0.53	1.01
Se^{78}	6.62	6	1.0	0.98	1.03
Se^{80}	4.66	4	0.94	1.06	1.09
Se^{82}	3.17	2	1.0	>0.34	1.13

(b) E_j (MeV)

Nucleus \ State	$\frac{3}{2}-$ Exptl.	$\frac{3}{2}-$ Theory[a]	$\frac{5}{2}-$ Exptl.	$\frac{5}{2}-$ Theory[a]	$\frac{1}{2}-$ Exptl.	$\frac{1}{2}-$ Theory[a]	$\frac{9}{2}+$ Exptl.	$\frac{9}{2}+$ Theory[a]
Se^{77}	1.10	1.50	0.32	0.71	0.19	0	0.19	0
Se^{79}	1.12	1.90	0.35	0.10	0.11	0.11	0.13	0
Se^{81}	0.48–1.42	2.26	0.64–1.39	1.37	0	0.25	0.29	0
Se^{83}	3.01	2.60	2.12	1.67	0.22	0.38	0	0

Nucleus \ State	$\frac{5}{2}+$ Exptl.	$\frac{1}{2}+$ Exptl.	$\frac{3}{2}+$ Exptl.
Se^{77}	1.61	>1.23	>3.75
Se^{79}	1.52	1.76	3.72
Se^{81}	1.48	1.71	3.48
Se^{83}	0.82	0.36–2.60	2.76

[a] Calculated with parameters ϵ taken from Ref. 24 except the smaller $\epsilon_{9/2+}$ value (3.0 MeV) is used here, and $\Delta=1.65$ MeV from odd-even mass difference.
[b] Calculated according to Ref. 24 with parameters: $\epsilon_{9/2+}=3.6$ MeV, $\epsilon_{1/2-}=2.5$ MeV, $\epsilon_{5/2-}=1.0$ MeV, $\epsilon_{3/2-}=0$, and $\Delta=1.65$ MeV.
[c] Calculated according to Ref. 5 with parameters: $\epsilon_{9/2+}=3.76$ MeV, $\epsilon_{1/2-}=2.51$ MeV, $\epsilon_{5/2-}=-0.18$ MeV, $\epsilon_{3/2-}=0.09$ MeV, and $\Delta=1.10$ MeV.

Δ ($\sim$1.65 MeV) obtained from the odd-even mass difference. It is cited in Ref. 5 that their chosen parameters in the region $28\leqslant Z\leqslant 50$, $28\leqslant N\leqslant 50$, on the whole, are generally good for nuclei in this region, but not for particular isotopes with $N\sim 42$, $32\leqslant Z\leqslant 36$. This is clearly seen for Se isotopes from the results shown in Table VIII.

The numbers of neutron holes in the 28-50 shell are also calculated and listed in Table VIII. It is seen that although the measured emptiness of individual subshells does not agree very well with pairing theory, the total numbers of neutron holes (except in Se^{76}) are in rather good agreement, perhaps about as good as one might expect from the experimental errors and errors inherent in the DWBA analysis. The smaller value of $\sum(2j+1)V_j^2$ in Se^{76} is attributed to some experimentally missing $g_{9/2}$ levels in Se^{76}.

As far as the single-quasiparticle energy, E_j, is concerned, the calculation with the parameter "set a" also gives a better fit to the experimental data, and in Table VIII only this calculation is given for comparison with experiment. It is seen that there still exists the quantitative discrepancy between experimental data and pairing theory. The experimental E_j's, taken from the excitation energy of the center of gravity of levels for a given shell-model state j weighted by the spectroscopic factor S, are almost all lower than the predictions. This may be explained by the effect of the additional long-range quadrupole interaction which is well known to have an important effect on the single-quasiparticle energy for the spherical nucleus. In Kisslinger and

TABLE IX. Comparison of experimental $\Sigma S'$ from $Se^{77}(d,p)Se^{78}$ with pairing theory. The theories a, b, and c are described in the text.

State	Experimental	Theory(a)	Theory(b)	Theory(c)
$\frac{3}{2}-$	0.02–0.14	0.065	0.031	0.025
$\frac{5}{2}-$	0.21	0.12	0.027	0.02
$\frac{1}{2}-$	0.19–0.45	0.38	0.21	0.18
$\frac{9}{2}+$	0.39	0.53	0.63	0.65
$\frac{5}{2}+$	>0.74	0.96	0.97	0.98
$\frac{1}{2}+$	1.09	0.97	0.97	0.98

Sorensen calculations,[5] the $\frac{1}{2}^-$ state was found to be depressed much more than the $\frac{9}{2}^+$ state by the quasiparticle-phonon interaction. Experimentally, for the $\frac{9}{2}^+$ state, there is always only one level observed at energy close to the single-quasiparticle energy of the $\frac{1}{2}^-$ state; and it seems that the residual interactions have about the same important effect on these two states.

For (d,p) reactions on the odd nucleus Se^{77}, the results for U_j^2 and a comparison with the pairing theory prediction are presented in Table IX. The agreements between experiment and theory are somewhat better than those in the case of (d,p) reactions on the even selenium nuclei. Since the ground state of Se^{77} is $\frac{1}{2}^-$, the observed $l=1$ angular distributions for the lowest 2^+ and 0^+ states at 0.62 and 1.32 MeV, respectively, indicate that the first 2^+ and 0^+ states contain $(p_{1/2}p_{3/2})_2$ and $(p_{1/2})_0^2$ in the configuration, respectively. The experimental U_j^2 for the $f_{5/2}$ state is apparently too large, but the measured value is consistent with the data from even Se isotopes. This would indicate that, if the cross sections predicted in DWBA with the chosen set of optical-model parameters are of correct magnitude, the value of $U_{5/2}^{-2}$ in Table VIII is probably correct. The (d,t) data also support this statement.

The pairing theory can be applied to the $Se^{77}(d,p)Se^{78}$ ground-state reaction for determining the lower limit on the emptiness U_j^2 of the $p_{1/2}$ state in Se^{78} from the relationship as given by

$$d\sigma/d\Omega \leqslant (1-U_j^2)\sigma_{\mathrm{DW}}, \tag{4}$$

which gives $U_{1/2}^2 \leqslant 0.66$ for Se^{78}, if the ground state is the only important $p_{1/2}$ state in Se^{77}. Taking into account crudely from Table II the excited states of Se^{77} at 0.17 and 0.53 MeV, this is reduced to 0.43 as compared to 0.41 determined directly from the $Se^{78}(d,p)$ reaction. The agreement is seen to be very good.

All $g_{9/2}$ states observed in (d,p) reactions are very close to the ground state. No appreciable configuration mixing in $\frac{9}{2}^+$ levels was found. The theoretical prediction[2] of the range of mixing, i.e., the energy over which a state may be spread, is given by

$$W \simeq \tfrac{1}{3}E^*, \tag{4}$$

where W is the depth of the imaginary potential in the optical model, and E^* is the excitation energy. There are some experimental evidences for this from previous work[2] in which the $\frac{1}{3}E^*$ rule has been tested and found to work quite successfully in the nickel region. In the selenium isotopes, as for example, the $\frac{9}{2}^+$ state, the possible configurations leading to the $\frac{9}{2}^+$ state are $[(0^+)(g_{9/2})]_{9/2^+}$, $[(2^+)(d_{5/2})]_{9/2^+}$, $[(2^+)(g_{9/2})]_{9/2^+}$, and $[(3^-)(f_{5/2})]_{9/2^+}$. The first one is the single-particle configuration; the second and third are formed by adding a $d_{5/2}$ and a $g_{9/2}$ particle, respectively, to the lowest 2^+ state of the target nucleus; the fourth, by adding an $f_{5/2}$ particle to the 3^- state. The $\frac{9}{2}^+$ single-particle state corresponding to the first configuration is excited in the present (d,p) stripping reactions at $\sim$0.2 MeV. From Eq. (5), $W=0.07$ MeV. Taking into account the known 2^+ and 3^- states at $\sim$0.6 and $\sim$3.0 MeV, respectively, the $[(2^+)(g_{3/2})]_{9/2^+}$, $[(2^+)(d_{5/2})]_{9/2^+}$, and $[(3^-)(f_{5/2})]_{9/2^+}$ states with which the $\frac{9}{2}^+$ single-particle state could mix, have the excitation energies $\sim$0.8, $\sim$2.2, and $\sim$3.5MeV, respectively, which differ from 0.2 by much more than 0.07. Thus only little mixing is expected in these energy regions. Experimentally, no mixing was found. It might be possible that there are some weakly excited $g_{9/2}$ states which mixed with the strongly excited $l=1$ and $l=2$ states and are not resolved

It is noticeable in Tables II–VI that the strength of d states seems to be uniformly distributed over many $l=2$ levels in Se^{77} and begins to concentrate in a few levels as the number of neutrons increases. This can also be seen from the distribution of components of a given single-particle state. As the number of neutrons increases near a closed shell (from Se^{77} to Se^{83}), the width W for d states becomes smaller, and their strengths therefore distribute only in a few levels. When Se^{83} is reached by adding the 49th neutron to Se^{82}, experimentally there is only one strong $d_{5/2}$ and one strong $d_{3/2}$ state found to contain large amounts of single-particle strength at 0.59 and 2.58 MeV, respectively. The energy separation of these two levels indicates that the spin-orbit splitting for d states is approximately $\sim$2.0 MeV, which is about as expected in this mass region ($\Delta E=2.50$ MeV in Zr^{90}).

It is interesting to compare the present results with information from isotonic nuclei such as Kr isotopes. Unfortunately, no experimental results from (d,p) and (d,t) reactions on Kr^{82} and Kr^{84} are available. An extensive study on Kr isotopes with stripping and pickup reactions is now in progress in this laboratory. A comparison can be made here for the excitation energy of the first excited state in Se^{83} with the neighboring nuclei containing the same number of neutrons but differing by the number of proton pairs. The first excited states of Kr^{85}, Sr^{87}, and Zr^{89} are all known[16] to be $\frac{1}{2}^-$. As shown in Fig. 10(b), the excitation energy decreases with decreasing number of even protons away from a closed shell. It is also notable that the $\frac{1}{2}^-$ state becomes the ground state in Se^{81}. The small change of energy indicates the small effect of adding a few proton pairs on a single-particle neutron state in this one particular case. This agrees with the usual assumption of the shell-model theory.

B. (d,t) Reactions on Selenium Isotopes

The agreement between the excitation energies measured in (d,t) and (d,p) reactions as shown in Table VII indicates that the same levels are being observed in two reactions. This enables one to assign some $p_{1/2}$ and $p_{3/2}$ states at low energies by comparing (d,t) and (d,p) cross sections for exciting the level as described above.

TABLE X. Summary of results for U_j^2 (averaging over two or three angles) found in (d,t) reactions. The DWBA calculations used here were for Ni^{64} (d,t) reactions.[a] The U_j^2 values found in (d,p) reactions are also given for comparison.

State	Se^{78} (d,t)	Se^{78} (d,p)	Se^{80} (d,t)	Se^{80} (d,p)	Se^{82} (d,t)	Se^{82} (d,p)
$\frac{3}{2}^-$	<0.27	0.19	<0.11	0.12	<0.01	0.067
$\frac{5}{2}^-$	<0.10	0.17	0.27	0.13	0.09	0.062
$\frac{1}{2}^-$	0.24	0.41	0.20	0.30	<0.01	0.065

[a] Reference 23.

The scheme of low-lying excited states and I assignments of odd Se nuclei, except Se^{83}, found both in (d,t) and (d,p) reactions is illustrated in Fig. 10(a). The excitation energies show a tendency to increase with increasing number of neutrons. This behavior of $\frac{3}{2}^-$, $\frac{5}{2}^-$, and $\frac{1}{2}^-$ levels is expected from pairing theory, as these orbits are below the Fermi surface. The two low-lying components of the $\frac{5}{2}^+$ level are seen to lie lower in Se^{77} than in Se^{79} and Se^{81}. This arises basically from considerable effects of residual interaction other than pairing, which splits the $l=2$ multiplets appreciably. Most probably it is due to the quadrupole interaction which seems to be larger as increasing the number of neutrons outside of a closed shell, and therefore lowers the first two $d_{5/2}$ levels more in Se^{77} than in Se^{79} and Se^{81}. However, the excitation energy of the center of gravity of $d_{5/2}$ levels as shown in Table VIII does behave in a normal manner from Se^{76} to Se^{82}, as expected from pairing theory.

The $\sum S$ values for $p_{3/2}$, $f_{5/2}$, and $p_{1/2}$ states are obtained in (d,t) reactions, from which the $U_j^2(d,t)$ values are determined and listed in Table X. The present methods of obtaining $U_j^2(d,t)$ are not highly quantitative, because no angular distribution was obtained in (d,t) reactions and there is a large uncertainty in extracting data from DWBA calculations at two or three observed angles which are not usually at the peak of the angular distribution. The fact that $U_j^2(d,t)$ values agree reasonably with $\sum S(d,p)$ values, which are more reliable than the $U_j^2(d,t)$, gives some support to this procedure.

A remarkable result of (d,t) reactions in this study is that a small admixture of $d_{5/2}$ states was found in the ground states of Se^{78}, Se^{80}, and Se^{82}. All the observed $d_{5/2}$ states in the (d,t) reactions are weakly excited. The excitation of these states in (d,t) reactions would indicate that the next major (50-82) shell is starting to fill in the selenium isotopes, even though the filling major shell is not completely full, and the ground states of these nuclei contain $d_{5/2}$ particles in their configuration. Therefore, the total strength in these nuclei should be all $\sum S_{5/2^+}<1$. It was found from the present (d,t) data that they have $V_j^2=0.10$, corresponding to about 0.6 particles filling in the $d_{5/2}$ subshell. A similar situation was observed in the tellurium isotopes,[24,25] in which the $2f_{7/2}$ states from the next major shell are excited in the $Te^{130}(d,t)$ and $Te^{128}(d,t)$ reactions, and was also observed in the calcium isotopes,[26] in which the $1f_{7/2}$ states from the 20-28 shell are excited in the $Ca^{40}(p,d)$ and Ca^{40}-(He^3,α) reactions.

C. Conclusion

The accuracy of experimental data on $\sum S$ and E_j depends primarily on the energy levels of a given shell-model state being observed. Insufficient energy resolution makes the experimental data somewhat incomplete as unresolved doublets lead naturally to misassignments of levels and wrong interpretation of data. The present energy resolution ($\sim$40 keV) seems to be about good enough for this study. To get better quantitative results would require improved energy resolutions.

It can be concluded that not only does the pairing approximation give an adequate and plausible picture of the occupation numbers and levels structure in Ni and Zr nuclei,[2,3] but also applied to the intermediate region between Ni and Zr nuclei, like Se isotopes, it can give an understandable over-all picture. As neutrons and protons in the Se isotopes are filling in the same major 28-50 shell, and neither neutrons nor protons form a closed shell; there is a tendency for neutrons and protons to be in same j levels, so that the neutron-proton interaction is considerably important. Furthermore, in Se nuclei, the one-phonon states lie quite low in energy ($\sim$0.6 MeV), which is in the same energy region as the one-quasiparticle states; thus the quasiparticle-phonon interaction is also expected to be important. It is notable that in Kisslinger and Sorensen calculations including proton-neutron interactions in the long-range part of the force, the $\frac{9}{2}^+$ state in Se^{77} and Se^{79} was found to lie higher than the $\frac{1}{2}^-$ state by $\sim$1 MeV. Experimentally, they were observed to be very close together at low energies. Kisslinger and Sorensen[5] have pointed out that the simple pairing-plus-quadrupole approximation is not adequate for nuclei in the region, $N\sim40$, $32\leqslant Z\leqslant36$, and suggested that both the consideration of the neutron-proton short-range interaction and a better treatment of the phonon-quasiparticle coupling are needed for a truly quantitative treatment.

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