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Neutron Resonances of Selenium*

R. E. Coté, L. M. Bollinger, and G. E. Thomas
Argonne National Laboratory, Argonne, Illinois

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The neutron resonances of selenium have been studied by a wide variety of methods over the energy range from a few electron volts to several keV. The measured values of the total cross section are presented for the range from 100 eV to about 5 keV. Information from transmission measurements on enriched samples and from capture gamma-ray spectra are used to make isotopic assignments of resonances. The capture gamma-ray data are also used for spin assignments. Complete sets of parameters are determined for most of the many resonances below 2 keV assigned to Se^{77} and for the resonances below 5.5 keV assigned to the even-even targets. Average values of spacings and strength functions are deduced. The strength functions for Se^{76} and Se^{77} are $(1.6_{-0.7}^{+3.2})\times10^{-4}$ and $(1.7_{-0.4}^{+1.8})\times10^{-4}$, respectively. These relatively large values reinforce the previously reported observation of an intermediate structure in the dependence of strength function on nuclear size, an effect that has been interpreted as evidence for the influence of two-particle one-hole states. The question of a possible spin dependence of the strength function is discussed.

I. INTRODUCTION

THE low-energy neutron resonances of the isotopes of selenium have been of special interest for two reasons during the past eight years or so. The first interest arose in connection with an apparent splitting[1] in the established maximum[2] of the *s*-wave strength function near nucleon number 55, an effect that now takes on renewed interest because of its recent interpretation[3] in terms of an excitation of two-particle one-hole states. Second, selenium, particularly Se^{77}, has been of interest because it is one of the few most useful targets for the study of the fluctuations of partial radiation widths.[4] Se^{77} was chosen for the study because (1) it was known to have at least three resonances below 1 keV and (2) the capture of neutrons in Se^{77} leads to compound states with negative parity and an angular momentum of 0 or 1. Thus the resonances with angular momentum $J=1$ may be selected from an observation of a transition to the 0^+ ground state.

The results reported in this paper are a byproduct of our study[4] of partial radiation widths, in which a need arose for reliable information about the low-energy resonances of Se^{77}. In the early stages of this study, it became clear that selenium presented some unexpected experimental problems. First, the detection of gamma rays rapidly demonstrated that there were many more resonances below 1 keV than had been detected in the earlier transmission measurements.[1] Second, the summing of coincident gamma rays in the large scintillator used as the gamma-ray spectrometer was found to be much greater for Se^{77} than for the other nuclides studied; as a consequence, the assignments of angular momenta from observations on single gamma-ray spectra were subject to more than the usual degree of doubt.

To eliminate the uncertainties about the energies, the isotopic assignments, and the angular momenta of the low-energy resonances in selenium, it was necessary to make an exhaustive study with all of the experimental techniques at our disposal. The quantities measured include: (a) the transmissions of a complete set of samples of normal selenium, (b) the transmissions of samples enriched in Se^{76} and Se^{77}, (c) the high-energy spectra of single gamma rays, (d) sum-coincidence spectra, and (e) low-energy gamma-ray spectra. The results of these measurements were supplemented by a reexamination of our previously reported[1] transmission data for isotopically enriched samples of the selenium isotopes and by a comparison with the results of high-resolution measurements on normal selenium recently reported by the Saclay group.[5]

II. METHOD

All of the measurements were made with the Argonne fast-chopper time-of-flight neutron spectrometer.[6] In the transmission measurements, the high-resolution rotor (rotor No. II) was used; the flight path was either 60 or 120 m; the neutrons were detected with a boron-loaded liquid scintillator[7]; and the data were recorded in a 1024-channel time analyzer.[8] The over-all resolution of this system was 25 nsec/m for the 60-m flight path and 12 nsec/m for the 120-m flight path.

In the capture gamma-ray measurements, the high-intensity rotor (rotor No. III)[9] was used, the flight path

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[1] J. M. LeBlanc, R. E. Coté, and L. M. Bollinger, Nucl. Phys. **14**, 120 (1959).

[2] R. E. Coté, L. M. Bollinger, and J. M. LeBlanc, Phys. Rev. **111**, 288 (1958).

[3] B. Block and H. Feshbach, Ann. Phys. (N. Y.) **23**, 47 (1963).

[4] L. M. Bollinger, R. E. Coté, R. T. Carpenter, and J. P. Marion, Phys. Rev. **132**, 1640 (1963).

[5] J. Julien, C. Corge, V. Huynh, J. Morgenstern, and F. Netter, Compt. Rend. **256**, 4009 (1962); Phys. Letters **3**, 67 (1962).

[6] L. M. Bollinger, R. E. Coté, and G. E. Thomas, in *Proceedings of the Second International Conference on Peaceful Uses of Atomic Energy, Geneva, 1958* (United Nations, Geneva, 1958), Vol. 14, p. 239.

[7] L. M. Bollinger and G. E. Thomas, Rev. Sci. Instr. **28**, 489 (1957).

[8] R. W. Schumann, Rev. Sci. Instr. **28**, 489 (1957).

[9] L. M. Bollinger, R. E. Coté, and G. E. Thomas, Argonne National Laboratory Report ANL-6169, p. 1, 1960 (unpublished).

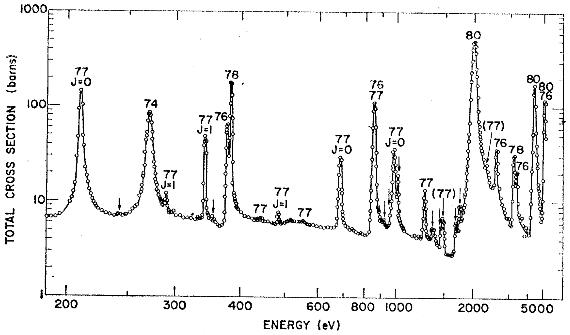

FIG. 1. The total neutron cross section of selenium for neutrons with energies between 190 eV and 5 keV.

was 25 m, and the spectra were recorded in the 3-parameter analyzer.[10] The sample of normal selenium metal was 8 in. square and 5.0 g/cm^2 thick. The over-all time-of-flight resolution of the system was about 100 nsec/m in the region of interest. The gamma-ray spectrometer consisted of various NaI(Tl) scintillators, depending on the nature of the measurement. For the detection of single high-energy gamma rays, the crystal was 8 in. in diameter and 6 in. thick. Measurements on the low-energy gamma rays were made with a 4×4-in. crystal in coincidence with the 6×8-in. crystal. Sum-coincidence measurements were made with two of the 6×8-in. crystals. The ways in which the spectra obtained with these various detection systems are used will be described below.

III. RESULTS

One of the principal difficulties in the study of the resonance structure of selenium arises from the rather large number of isotopes that are present in the normal element. The problem is to detect and assign the resonances of these many isotopes in a range of energy in which our time-of-flight resolution is not entirely adequate. To do this, we must take advantage of the various physical properties that characterize each isotope. Some of these properties are listed in Table I.

TABLE I. Some characteristics of the selenium isotopes.

Characteristic	Isotope 74	76	77	78	80	82
Abundance (%) in normal sample	0.9	9.0	7.6	23.5	49.8	9.2
Abundance (%) in Se^{76} sample	0.6	54.8	6.9	12.5	21.5	3.7
Abundance (%) in Se^{77} sample	0.4	6.1	49.4	21.4	19.6	3.0
Binding energy (MeV)	8.0	7.4	10.5	7.0	6.8	6.0
γ-ray energies (keV)	285	246	615 695			

A. Energies of Resonances

The basic source of information about the energies of the resonances comes from transmission measurements, with the best resolution available, on samples of normal selenium. The samples were formed of selenium metal in thicknesses of 29.2, 7.32, 2.67, and 0.119 g/cm^2. The variation of the total cross section (uncorrected for resolution effects) as a function of neutron energy is shown in Figs. 1 and 2. The position and isotopic assignment of most resonances detected are shown on the figures. It will be observed that some of these resonances are not resolved in the transmission measurements on the normal samples of selenium. In such cases, the evidence for the existence of the resonances comes either from the measurements on the separated isotopes or from the study of the capture gamma-ray spectra.

The energies E_0 of all of the resonances detected are listed in Table II, along with the experimental technique used in the observation. For comparison, the results from previously reported measurements[1,5] are also given. An interesting aspect of this comparison is the demonstration that, although the time-of-flight resolution used in the measurements reported in Ref. 5 was an order of magnitude better than that in our measurements, the greater variety of experimental techniques used in our measurements allowed us to observe several resonances that were not detected previously. On the other hand, when the resolution width becomes wide in comparison with the level spacing, our techniques fail. Consequently, the results of Ref. 5 on Se^{77} would be expected to be more reliable than ours at energies greater than, say, 1200 eV. Aside from differences of this kind, the agreement between the results of the various measurements is good.

The resonances in several regions of energy require special comment. The tiny resonances at very low energy are too weak to be studied quantitatively. However, their existence is well established by detec-

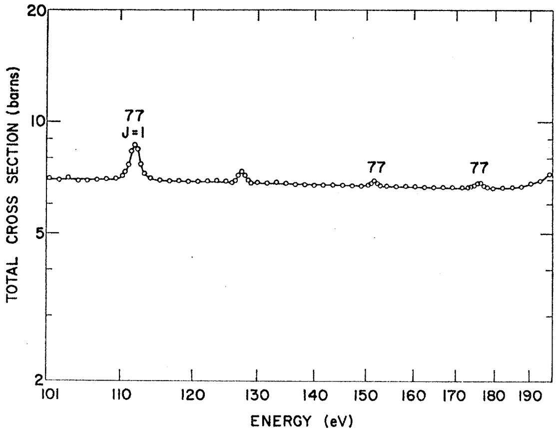

FIG. 2. The total neutron cross section of selenium for neutrons with energies between 101 and 200 eV.

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[10] C. C. Rockwood and M. G. Strauss, Rev. Sci. Instr. **32**, 1211 (1961).

TABLE II. The detection and isotopic assignment of neutron resonances in selenium. The letter E indicates that a resonance was observed at the indicated energy for the experimental conditions listed, but the information could not be used to make the isotopic assignment.

	Present experiment					
E_0 (eV)	Trans- mission	Low- energy γ rays	Binding energy	Ref. 1	Ref. 5	Isotopic assign- ment
5.15	E	E				
27.0	E	74	74	74		74
46.8	E	E	E			
56.7	E	E	E			
112.0	E	E	77		77	77
127.5	E	E	E			not 77
151.6	E	E	77			77
176.4	E	E	77			77
209	77	77	77	77	77	77
240	E					
270	E	74	74	74		74
289	77	E	77		77	77
340	77	E	77		77	77
355	E					
376	76	76	76	{(78)}		76
381	78	E	78			78
440	E	E	77			77
481	E	E	77		77	77
555	E	E	(77)			(77)
688	77	77	77	77	77	77
855	76	E	E	76		76
855	77	E	77			77
915	E					
962	E				E	
991	77	E	E	77	77	77
1013	E				E	
1259	77	E	77		77	77
1360	E					
1462	E				E	
1480	E				77	(77)[a]
1670					E	
1719					E	
1980	80			80	80	80
2250	(77)				E	(77)
2550	76			76		76
3190	78					78
3315	76					76
4265	80					80
5080	80					80
5350	76					76
6150	E					
7140	E					

[a] This assignment is considered uncertain because the resonance does not appear in the transmission of the Se^{77} sample [see Fig. 3(b)].

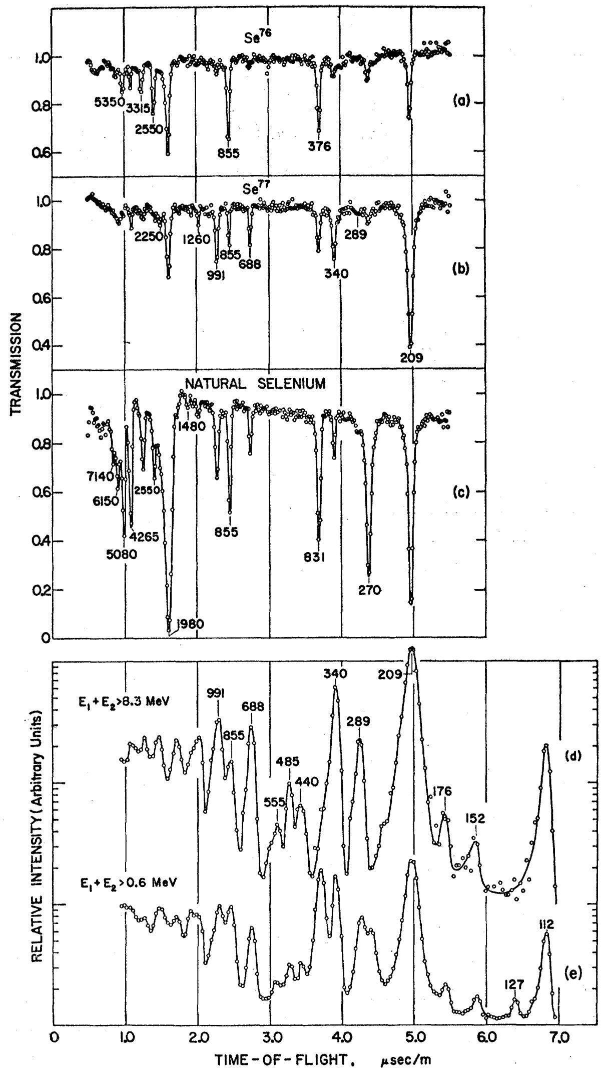

FIG. 3. Data from which most of the isotopic assignments were made. The numbers associated with transmission dips and peaks in counting rate are resonance energies in eV. The results shown in (a), (b), and (c) are the transmissions of samples of Se^{76}, Se^{77}, and natural selenium, respectively. The results shown in (d) and (e) are the neutron time-of-flight spectra corresponding to sum-coincidence capture gamma rays for which the bias on the sum was set at 8.3 and 0.6 MeV, respectively. The former requirement on the sum excludes detection of all resonances except those in Se^{77}.

tion in both transmission and capture gamma-ray studies. The chance that any of these resonances are associated with impurities is slight, since they do not correspond in energy to any known strong resonances. At higher energy, although we list a single resonance at 555 eV, the general appearance of the variation of the cross section (Fig. 1) suggests the existence of several small resonances rather than a single resonance at about this energy. In the neighborhood of 1000 eV, the resonance structure appears to be especially complex; the experimental evidence is presented in Sec. III.C. Finally, it is probable that most of the resonances in Se^{77} at energies greater than 1 keV have not yet been detected. On the other hand, because of their greater widths and spacings, most of the resonances in the even-even targets Se^{76}, Se^{78}, Se^{80}, and Se^{82} are probably detected up to about 5 keV.

B. Isotopic Assignments

Isotopic assignments were made on the basis of the results obtained in transmission measurements on isotopically enriched samples and in various kinds of gamma-ray measurements with normal samples. The transmission measurements are those reported previously in Ref. 1 and new ones on samples of Se^{76} and Se^{77}. For the new measurements, the samples were

TABLE III. Summary of results upon which the spin assignments were made.

		Relative partial radiation widths			
E_0 (eV)	g	$\Gamma_{\gamma 0}$ (to ground state) (10.48 MeV)	$\Gamma_{\gamma 1}$ (to 1st excited state) (9.88 MeV)	Relative strengths of sum coincidences to ground state	J
112		44 ± 17	44 ± 27	4.1 ± 1.9	1
209	0.248 ± 0.10	-6 ± 11	-3 ± 14	21.5 ± 1.3	0
289		174 ± 31	678 ± 59	9.6 ± 2.3	1
340		102 ± 17	2801 ± 49	8.4 ± 1.4	1
481		462 ± 100	1387 ± 188	$-13\ \pm 10$	1
688	0.236 ± 0.075	7 ± 36	-1 ± 53	20.0 ± 4.5	0
991	0.186 ± 0.075	434 ± 35	90 ± 41	13.6 ± 3.0	0, 1

formed of the material used in the earlier study; the composition of the sample materials is given in Table I. The thicknesses were 0.395 and 0.366 g/cm^2 of selenium for the Se^{76} and Se^{77} samples, respectively. The time-of-flight resolution used in the new measurements was 25 nsec/m.

Of the various kinds of gamma-ray spectra observed (high-energy singles, high-energy/low-energy coincidences, sum coincidences), the most useful kinds of information for isotopic identification are the characteristic low-energy gamma rays and the high-energy limits of the spectra; the latter quantity, especially for a sum-coincidence spectrum, is closely related to the neutron binding energy. These two characteristic properties of the gamma-ray spectra were used for isotopic identification in much the same way as has been described previously[11] in some detail.

Examples of the data used for isotopic identification are given in Fig. 3. Because of the very large difference between the binding energy of Se$^{77}+n$ and that of the even-even isotopes, the easiest way to locate the resonances of Se^{77} is to study the time-of-flight spectra obtained with different restrictions on the sum (E_1+E_2) of the pulse heights of two coincident gamma rays from neutron capture. This is demonstrated in the figure. Since the condition $(E_1+E_2)>8.3$ MeV excludes detection of all resonances except those in Se^{77}, curve *d* in Fig. 3 is sufficient to locate resonances in Se^{77} at about 112, 152, 176, 209, 289, 340, 440, 481, 555, 687, 991, and 1259 eV. The identification of the tiny resonances at 152 and 176 eV is an especially impressive demonstration of the power of the gamma-ray method. A surprising feature of curve *d* is the appearance of a well-defined peak at 855 eV, the position of a resonance previously assigned to Se^{76}. An examination of the transmission data given in curves *a*, *b*, and *c* confirms the conclusion that both Se^{76} and Se^{77} have resonances at about 855 eV.

The isotopic assignment of the unresolved pair of resonances in the neighborhood of 380 eV requires a careful analysis of all of the data obtained. The combination of the new and the previously reported transmission measurements on separated samples shows conclusively that one of the resonances is in Se^{76} and the other in Se^{78}. The assignment of the resonance at 376 eV to Se^{76} and the one at 381 eV to Se^{78} rests on three pieces of evidence. First, the transmission dip for the Se^{76} sample falls at a slightly lower energy than does the dip for the sample of normal selenium. Second, a study of the spectrum of sum pulses as a function of channel number shows that the apparent binding energy changes from a value like that for Se^{78} on the high-energy side to a value close to that for Se^{76} on the low-energy side. Finally, the 246-keV gamma ray that is characteristic of Se^{76} is stronger on the low-energy side of the observed time-of-flight peak.

The isotopic assignments obtained on the basis of all of the available evidence are summarized in Table II.

C. Spin Assignments

Under the assumption that all of the resonances with which we are concerned are excited by *s*-wave neutrons, the total-angular-momentum quantum number J is known for all except the resonances of the even-Z/odd-N target Se^{77}. For it, three kinds of data are used to distinguish between the two possibilities of $J=0$ and $J=1$. These data are the observed peak cross section, the intensities of radiative transitions directly from the initial state to the ground state or the first excited state, and the intensity of two-step gamma-ray cascades to the ground state. The experimental data and the assignments obtained from these data are summarized in Table III.

The information obtained from the observed peak cross section is summarized in Table III by listing experimental values of the statistical factor $g= 2J+1)$ $(2I+1)^{-1}$, where I is the spin of the target nucleus. For the wider resonances, these experimental values of g are seen to be consistent with one and only one of the allowed values $g=\frac{1}{4}$ or $g=\frac{3}{4}$.

The use of high-energy gamma rays for spin assignments, a method introduced by Landon and Rae,[12] is by now too well known to require description. For the compound nucleus Se^{78}, the observation of a nonzero intensity for a transition to either the 0^+ ground state or the 2^+ first excited state is almost definite evidence that the initial state has $J=1$. However, a reliable measurement of the intensities of the high-energy gamma rays of Se^{78} is not completely straightforward because of a relatively high probability for the summing of two pulses in a single detector. The magnitude of the summing effect was determined by measuring the spectra of the sum of coincident pulses in two scintillators of equal size mounted on opposite sides of the target. To a high degree of accuracy, this spectrum is equal to twice the contribution of sum pulses

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[11] H. E. Jackson and L. M. Bollinger, Phys. Rev. **124**, 1142 (1961).

in a single scintillator. Details of the methods used in the analysis of spectra are given in Ref. 4.

From the nonzero intensities observed (Table III), one is immediately able to assign $J=1$ to a number of the resonances. (The spectra for the 209- and 340-eV resonances are shown in Fig. 8 of Ref. 4.) On the other hand, for the resonances at 209 and 688 eV, where the observed intensities are 0 within the experimental errors, we may only say that the assignment $J=0$ is probably correct. The probability that assignments based only on these intensities are wrong is only about 3% for the 209-eV resonance and 10% for the 688 eV.

The observation of a relatively strong ground-state transition for capture in the neighborhood of 991 eV raises a difficulty, since this ground-state transition implies a resonance with $J=1$, whereas the transmission data show unambiguously (as first reported in Ref. 5) that the wide resonance at this energy has $J=0$. Since each of these conflicting experimental observations is believed to be completely reliable, we interpret the data as implying that there are two resonances in Se^{77} at about 991 eV, one resonance with $J=0$ and the other with $J=1$. This hypothesis is quantitatively consistent with all the evidence. If the resonance with $J=1$ is assumed to have a neutron width of roughly 0.2 eV, the resonance would have little influence on the Doppler-broadened total cross section but would capture roughly as many neutrons as the much wider resonance with $J=0$.

The spin assignments derived from the transmission data and the intensities of single gamma rays were compared with assignments obtained from the intensities of two-step cascades to the ground state, as observed in the sum-coincidence measurements with two large scintillators. The basic idea of this method, which has been outlined previously,[13] is that the sum of the intensities of all two-step cascades through many intermediate states is proportional to the level spacing at the initial state. Hence, the two-step cascades from states with $J=0$ are expected to be three times as intense as from states with $J=1$. The only difficulty expected is that the observed intensity for individual resonances might fluctuate significantly from the expected mean value. To limit fluctuations of this kind (i.e., to minimize the influence of particular pairs of transitions), pulse-height conditions were imposed in such a way as to require that the intermediate states lie in the interval 4.5—6 MeV.

The experimental values of intensity for two-step cascades are given in Table III. The values are observed to fall into two classes for which the mean values differ by the expected ratio 3. Moreover, the fluctuations about the mean values are not large enough to raise serious doubts as to the applicability of the method to the target Se^{77}. Thus, it is gratifying to observe that the assignments based on the intensities of two-step cascades are in all cases the same as those obtained in other ways.

Returning to the hypothesis of two resonances at about 991 eV, we see that the intensity of two-step cascades at this energy tends to confirm that the two resonances do indeed exist. The observed relative intensity of 13.6 ± 3.0 is the only value that is clearly greater than the mean for the resonances with $J=1$ and less than the mean for the resonances with $J=0$. An intermediate value of this kind is, of course, expected under our hypothesis of two resonances.

D. Resonance Parameters

Once the isotopic identification and spin assignment were made, the remainder of the parameters were obtained by standard methods of area analysis. The results obtained are given in Table IV. A comparison of these results with those obtained by the Saclay group[5] shows excellent agreement except for the resonances at 112 and 289 eV. The factor-of-ten difference in the values of Γ_n for the 112-eV resonance suggests a typographical error in Ref. 5; the factor-of-two difference for the 289-eV resonance has no obvious explanation.

The very small widths of some of the resonances at low energy suggest that they are excited by p waves. It had been hoped that a way could be found to use the gamma-ray spectra to make a positive identification of p-wave resonances. However, the intensities were so weak that we could not even identify the isotopes responsible for the small resonances below 100 eV, and no definite parity assignments could be made for either the resonance at 152 or that at 176 eV, both of which have been assigned to Se^{77}.

IV. AVERAGE VALUES OF PARAMETERS

From the detailed knowledge of resonance parameters, as given in Table IV, one can deduce various average values that are of interest for comparison with theory. The results obtained are summarized in Table V.

Most of the observed resonances are excited by s-wave neutrons. However, a few of the extremely narrow resonances at low energy could well be excited by p-wave neutrons. These p-wave resonances must be identified if one is to obtain meaningful average values of the spacings. Our only available evidence for such an identification is the observation of an exceptionally small value of $g\Gamma_n$. In the low-energy range of interest, the average value of $g\Gamma_n$ for p-wave resonances is given[14] by

$$(\langle g\Gamma_n\rangle_{\mathrm{av}}/E_0^{\frac{1}{2}})\approx0.6\times10^{-6}D_0S_1E_0\,,$$

where S_1 is the neutron strength function (as defined

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[12] H. H. Landon and E. R. Rae, Phys. Rev. **107**, 1333 (1957).

[13] L. M. Bollinger and R. E. Coté, Argonne National Laboratory Report ANL-6146, p. 1, 1960 (unpublished).

[14] See for example the discussion of the potential barrier in J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley & Sons, Inc., New York, 1952), Chap. 8.

TABLE IV. Parameters of neutron resonances in selenium.

E_0 (eV)	Isotope	J	σ_0 (b)	Γ (eV)	Γ_n (eV)	Γ (eV)	Γ_n^0 (10^{-3} eV)
5.15					$\sim2.3\times10^{-8}$[a]		
27.0	74[b]		45 000±4800[b]	0.355±0.025[b]	0.166±0.008[b]	0.189±0.030[b]	
46.8	...				1.25×10^{-6}[a]		
56.7	...				$1.4\ \times10^{-6}$[a]		
112	77	1	37± 15	0.7 ±0.2	$(1.5\pm0.2)\times10^{-3}$	0.7 ±0.2	0.14± 0.02
127.5	not 77				$\sim0.018\times10^{-3}$[a]		
151.6	77				$\sim0.16\ \times10^{-3}$[c]		0.013[c]
176.4	77				$\sim0.32\ \times10^{-3}$[c]		0.024[c]
209	77	0	2350± 900	2.0 ±0.5	1.5±0.2	0.5[d]	104 ±15
240	...				0.4×10^{-4}[a]		
270	74		8800±3800	4.6 ±1.1	4.2±0.8	0.5[d]	256 ±50
289	77	1	200± 50	0.5 ±0.15	$(1.2\pm0.1)\times10^{-2}$	0.5[d]	0.7 ± 0.1
340	77	1	1350± 540	0.54 ±0.13	0.13±0.02	0.41 ±0.15	7.0 ± 1.1
354	...				0.8×10^{-4}[a]		
376	76		2500± 520	0.79 ±0.2	0.29±0.07	0.5[d]	15 ± 3.6
381	78		2550± 520	0.8 ±0.2	0.30±0.07	0.5[d]	15.5 ± 3.9
440	77				0.003±0.0015[c]		0.15± 0.07[c]
481	77	1	78± 15	0.51 ±0.1	0.01 ±0.001	0.5[d]	0.46± 0.05
555	(77)						
688	77	0	770± 230	2.9 ±0.6	2.36 ±0.24	0.54 ±0.5	90 ±10
855	76		2650± 60	3.15 ±0.25	2.75 ±0.25	0.5[d]	94 ±10
855	77	(1)			~0.46[c]		~16[c]
915	...						
962	...						
991	77	0	625± 10	7.5 ±0.7	7.1±0.7	0.5[d]	226 ±23
1013	...				$\sim0.6\times10^{-2}$[a]		
1259	77	(1)	1260± 390	1.40 ±0.25	1.13±0.16	0.27 ±0.4	32 ± 3
1360	...						
1462	...						
1480	(77)	1[e]	800± 500	1.25 ±0.5	0.75±0.25	0.5[d]	20 ± 6
1670	...				$\sim1.4\times10^{-2}$[a]		
1719	...				$\sim5.1\times10^{-2}$[a]		
1980	80[b]				48 ±2[b]		
2250	(77)						
2550	76				15.5±2		307 ±40
3190	78						
3315	76				15.4±2		268 ±35
4265	80						
5080	80						
5350	76				11.8±2		162 ±27
6150	...						
7140	...						

[a] These are values of $ag\Gamma_n$. The isotopic fraction is denoted by a.
[b] These values are from Ref. 1.
[c] These values correspond to values of $g\Gamma_n$.
[d] The magnitude of the radiation width Γ_γ was assumed to be 0.5 eV.
[e] This assignment was taken from Ref. 5.

in Ref. 15), D_0 is the average level spacing for states with $J=0$, and the energy is in eV. Thus, for Se^{77} in the range 100–200 eV (the only range and target for which the p waves cause a significant uncertainty in this study) the average value of $g\Gamma_nE_0^{-\frac{1}{2}}$ for p waves would be expected to be roughly 6×10^{-6} eV, under the assumption that the p-wave strength function is of the same order of magnitude as that for s waves. One sees in Table IV that the neutron widths of the resonances at 152 and 176 eV are of roughly this size. On the other hand, they are improbably narrow for s-wave neutrons, for which the mean value of $g\Gamma_nE_0^{-\frac{1}{2}}$ is about 2.5×10^{-2} eV. Thus, there is a high degree of probability that the 152- and 176-eV resonances are excited by p waves. Similar arguments can be used to show that all of the other resonances below 200 eV, except those at 27 and 112 eV, probably result from p-wave excitation. The average values summarized in Table V were obtained under this assumption.

TABLE V. The s-wave neutron strength function, the average radiation width, and the average level spacing for Se^{74}, Se^{76}, Se^{77}, and Se^{80}.

Isotope	$\bar{S}$ (eV)	E_{n+1} (eV)	D_0 (eV)	$\bar{\Gamma}_n^0/D$	$\bar{\Gamma}_\gamma$ (eV)
Se^{74}					0.19±0.03[a]
Se^{76}	1244	5350	2490_{-1200}^{+1800}	$1.6_{-0.7}^{+3.2}\times10^{-4}$	
Se^{77}	100	991	400_{-100}^{+160}	$1.7_{-0.4}^{+1.8}\times10^{-4}$	0.5 ±0.15
Se^{80}				$2.4_{-1.0}^{+2.5}\times10^{-4}$	

[a] This value, obtained from Ref. 1, represents the value of Γ_γ for only one resonance, namely the resonance at 27 eV.

To obtain average values of spacings from the data

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[15] A. Saplakoglu, L. M. Bollinger, and R. E. Coté, Phys. Rev. **109**, 1258 (1958).

of Table IV, the observed spacing $\bar{S}$ was calculated from the relationship $\bar{S}=(E_1-E_{n+1})/n$, where E_1 is the energy of the first resonance and E_{n+1} is the energy of the $(n+1)$th resonance in an interval in which all the s-wave resonances of a given isotope are believed to have been detected. In the table, the energy range used to determine a value of $\bar{S}$ is specified by listing the corresponding value of E_{n+1}. The errors are calculated from the Wigner distribution[16] of spacings under the assumption that the effect of correlations may be neglected; thus, if no resonances are missed, the errors listed are overestimates of the true uncertainties.

For the target Se^{77}, the average spacing was calculated under the assumption that the resonances at 152, 176, 240, and 355 eV are excited by p-wave neutrons. The average value obtained clears up a minor anomaly in our previous data.[1] These data had seemed to indicate that the spacing $D_0\equiv 2\bar{S}(2I+1)$ is much greater for Se^{77} than for the neighboring nuclides As^{75} and Br^{79}. It is now clear, of course, that many resonances were missed in the earlier study and the new value of D_0 for Se^{77} is approximately the same as that for the neighboring odd-Z/even-N targets.

Although a substantial number of resonances are observed in Se^{76}, the uncertainty in the average spacing is large because narrow resonances could have been missed. To deduce the most complete statement of the probable range of $\bar{S}$, the upper limit (as specified by the positive error) was determined from all four of the observed spacings whereas the lower limit was determined from just the first two spacings.

When the data of Table IV are used to deduce values of the strength function, the error from missing small levels becomes much less significant. Thus, a much wider range of energy can be used. The s-wave strength function is deduced from the relationship

$$\frac{\bar{\Gamma}_n{}^0}{D}=\frac{1}{\Delta E}\sum_i (g\Gamma_n{}^0)_i\,,$$

where ΔE is the energy interval that contains just the resonances appearing in the sum. For Se^{77} the interval is 0 to 1200 eV and for Se^{76} it is 0 to 5500 eV. The errors associated with the values of $\bar{\Gamma}_n{}^0/D$ are standard statistical uncertainties calculated under the assumption that the reduced widths obey the Porter-Thomas distribution[17] and the spacings the Wigner distribution. In this calculation, the estimated size of the statistical samples was five resonances for Se^{76} and twelve resonances for Se^{77}.

The values of $\bar{\Gamma}_n{}^0/D$ for Se^{76} and Se^{77} are of interest mainly for the additional evidence they provide for structure in the dependence of $\bar{\Gamma}_n{}^0/D$ on A in the range $40\leqslant A\leqslant 90$. As discussed previously,[1] the experimental values of $\bar{\Gamma}_n{}^0/D$ exhibit a strong maximum at $A=52$, a shallow minimum at about 70, a hump at about 80, and a deep minimum at about 93. The relatively high values of $\bar{\Gamma}_n{}^0/D$ for Se^{76} and Se^{77} fit in well with this description. Two explanations have been offered for this clear-cut deviation from the less-structured curve obtained in calculations based on the most simple assumptions about the optical-model potential well—an undeformed square well or a well with diffuse edges. First (as discussed previously[1]), the experimental data are consistent with the values calculated by Chase, Wilets, and Edmonds[18] for a deformed well. Second, Bloch and Feshbach[3] have recently shown that the observed structure in $\bar{\Gamma}_n{}^0/D$ may be interpreted as resulting from the excitation of two-particle, one-hole states. This latter explanation in terms of the so-called "doorway" states is currently of considerable interest because of its implication for a wide variety of nuclear-structure experiments.

The Saclay group has recently devoted considerable attention[5,19] to a possible spin dependence of the average reduced neutron width $\bar{\Gamma}_n{}^0$. In the case of Se^{77}, the evidence for the effect is that the sum of $\Gamma_n{}^0$ for the resonances with $J=0$ is seven times the sum for the resonances with $J=1$, an effect brought about mainly by the dominant contribution of the 991-eV resonance with $J=0$. According to Refs. 5 and 19, there is only a 1% probability for the observed ratio of sums to occur by chance if the strength functions of the two spin states are equal.

Since we have detected several resonances in Se^{77} that have not been reported previously, it seems worth while to reexamine the evidence for a possible spin dependence in $\bar{\Gamma}_n{}^0/D$. Let us treat the data by enquiring whether the ratio

$$\rho=\sum_{J=0}\Gamma_n{}^0\Big/\sum_{J=1}\Gamma_n{}^0$$

differs significantly from unity, the mean value when the strength functions of the two spin states are equal and the statistical samples are large. The experimental value of ρ is found to be 7 is we use the resonances at energies less than 1500 eV, a range that includes three resonances with $J=0$ and seven with $J=1$. The distribution of the random variable ρ corresponding to these resonances was calculated under the hypothesis that the individual reduced widths are governed by the Porter-Thomas distributions and that the strength functions are equal for the two spin states. We find, under these conditions, that there is a

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[16] E. P. Wigner, in Proceedings of the International Conference on the Neutron Interactions with the Nucleus, Columbia University, New York, 1957, TID-7547, p. 49 (unpublished).

[17] C. E. Porter and R. G. Thomas, Phys. Rev. **104**, 483 (1956).

[18] D. M. Chase, L. Wilets, and E. R. Edmonds, Phys. Rev. **110**, 1080 (1958).

[19] J. Julian, G. Bianchi, C. Corge, V.-D. Huynh, G. LePoittevin, J. Morgenstern, F. Netter, and C. Samour, Phys. Letters **10**, 86 (1964).

2% chance for ρ to be greater than the experimental value of 7 and that there is a 7% probability[20] that $\rho<1/7$. Thus there is a significant probability that a single measurement of the ratio could result in a value very different from unity. This leads us to conclude that although the measured value $\rho=7$ is somewhat surprising, it does not in any way establish the existence of a dependence of the strength function on spin; it merely suggests an area for further investigation.

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[20] The probability pr[$\rho>\alpha$] is different from pr[$\rho<1/\alpha$] because of the difference in the skewness of the probability density functions for the two sums of reduced neutron widths that determine ρ. If both sums are governed by the same density function, or if these functions are different but symmetrical, pr[$\rho>\alpha$] is equal to pr[$\rho<1/\alpha$], of course.

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Can a Scalar Meson "Bootstrap" Itself?

P. D. B. Collins[*]
Lawrence Radiation Laboratory, University of California, Berkeley, California

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It is shown that although a scalar meson can be described by a renormalizable field theory, it is not possible for such a particle to "bootstrap" itself, because the force arising from the crossed channels is too great. This result is in accordance with the "bootstrap" philosophy that there should be only one solution of the S-matrix equations consistent with maximal analyticity of the second kind, and also indicates the need for symmetries in strong interactions.

INTRODUCTION

It has been proposed that there should be only one solution for the scattering matrix in strong interactions which is consistent with unitarity and maximal analyticity of the second kind.[1] All the poles should be continuable in angular momentum. This would mean that no experimental information need be included to derive the properties of all the observed particles, whether bound states or resonances. Alternatively it may be that it is necessary to know the masses and coupling constants of a certain number of "elementary" particles before the properties of the other particles can be derived from purely dynamical considerations.

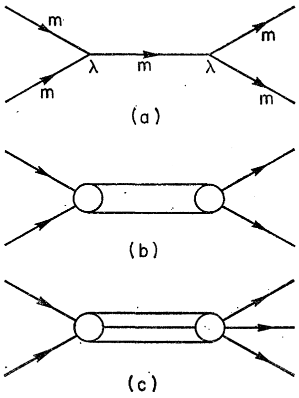

FIG. 1. The unitarity diagrams.

As yet we are unable to perform calculations that encompass all the known particles, and so no decision can be made in the matter, but one might be able to show that a set of particles other than those which have been observed can give rise to a self-consistent S matrix, i.e., can "bootstrap" themselves, and thus demonstrate the need for the inclusion of at least some experimental information in order to arrive at the solution corresponding to the real world.

Of course if the hypothetical set of particles is too complicated one is again unable to solve the S-matrix equations, but if only a single type of particle is considered the problem is quite tractable. The neutral scalar meson is a likely candidate, because it obeys the renormalizable Hurst-Thirring[2] field theory with an interaction Lagrangian

$$\mathcal{L}_I=\lambda\phi^3\,, \tag{1}$$

and thus is viable as an independent particle. Other renormalizable field theories involve the interaction of two different types of particles. It is certainly not obvious that a "bootstrap" solution can exist because, as we shall show, there are fewer free parameters than conditions to be satisfied, but of course this is also true of the hypothetical solution involving all the strongly interacting particles. In this article we shall try to

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[1] See, for example, G. F. Chew and S. C. Frautschi, Phys. Rev. Letters **7**, 395 (1961); F. Zachariasen and C. Zemach, Phys. Rev. **128**, 849 (1962); E. Abers and C. Zemach, *ibid.* **131**, 2305 (1963).

[2] N. N. Bogoliubov and D. V. Shirkov, *Introduction to the Theory of Quantized Fields* (Interscience Publishers, Inc., New York. 1959), p. 352.