

Isotopic Identification of Neutron Resonances of Cd, Sb, Os, and Pt from Capture Gamma-Ray Spectra*

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The Argonne fast chopper has been used in conjunction with a 3-variable magnetic-tape recording system to demonstrate the high efficiency and sensitivity of isotopic identification of neutron resonances by observation of capture γ rays. A discussion of features of capture spectra which can be useful in isotopic assignment is presented as well as results for resonances in natural Cd, Sb, Os, and Pt. The experimental study reported emphasizes primarily the observation of coincident γ rays as a means of measuring binding energies and characteristic low-energy lines of nuclides giving rise to resonant capture. The isotopic assignments include 23 resonances in Cd between 18 ev and 235 ev, 6 of which were previously unassigned; 20 resonances in Sb between 5 and 200 ev; 23 resonances in Os in the region between 6 ev and 61 ev; and two previously unresolved resonances at 67 ev assigned to Pt¹⁹⁶. The data lead to observed level spacings of 33 ev in Cd¹¹¹, 80 ev in Cd¹¹², 27 ev in Cd¹¹³, 27 ev in Sb¹²¹, 12 ev in Sb¹²³, and 5.1 ev in Os¹⁸⁹. Strength functions for Cd¹¹¹ and Cd¹¹³ based on the identifications are in agreement with previous reported values. For Os¹⁸⁹, from transmission data previously unreported, the value $\bar{\Gamma}_n/D = (2.0^{+2.2}_{-0.7}) \times 10^{-4}$ is obtained.

I. INTRODUCTION

IN the past a substantial fraction of the time and effort of workers in slow-neutron spectroscopy has gone into the isotopic identification of the hundreds of neutron resonances that have been studied. Generally, this identification is done by comparing the results of a series of transmission measurements on samples of "separated" isotopes of the element.¹ Although this approach to isotopic identification of resonances is thoroughly tested and reliable, it does have several serious defects; it is very time consuming, since the transmission of each sample of separated isotope must be measured; the samples of separated isotopes are not always available; even when samples are available, they are often of such a small size that the identification of narrow resonances may be impossible because the transmission dip is unobservably small.

In the light of the weaknesses of the transmission method, one considers with interest a method that shows promise of giving an isotopic identification from a relatively short measurement on a single sample of the *normal* element. We refer to the identification of a neutron resonance by the observation of a capture gamma-ray spectrum that is characteristic of the isotope responsible for the resonance. This idea stems from the results of the group working with the neutron time-of-flight spectrometer at Yale,² who studied the low-energy spectra of gamma rays from capture in several resonances in each of several target nuclides. They found that, although the spectra of resonances in a single nuclide are not identical, the spectra are qualitatively similar in that they all exhibit the same gamma-ray lines formed by transitions between the low-energy

states of the compound nucleus. This regularity in the spectra implies that an observation of the characteristic lines can be used to identify the isotope responsible for a resonance. This idea has been used by Bird *et al.*³ in a study of the resonances of mercury. They found the spectra of single gamma rays useful for the identification of resonances in the even-odd target nuclides Hg¹⁹⁹ and Hg²⁰¹ and were able to identify a resonance of Hg²⁰¹ which was too narrow to be identified in a series of transmission measurements on separated isotopes. However, no gamma-ray lines could be resolved in the more complex spectra resulting from capture in the even-even nuclides. In a further study of the resonances of Hg, Carpenter and Bollinger¹ showed that the characteristic line structure of the spectra could be enhanced by a large factor by observing the pulse-height spectra associated with coincidence counts in two crystals rather than the spectra of single gamma rays. In this way they were able to observe a prominent line structure in the spectra associated with resonances of the even-even target nuclide Hg¹⁹⁸.

The experiments reviewed above suggest strongly that, as the experimental techniques are advanced still further, the observation of neutron-capture gamma-ray spectra may replace transmission measurements on separated isotopes as the most useful method of isotopic assignment of resonances. The experiments described in the present paper were undertaken in an effort to help realize this objective by using the most advanced equipment now available in a study of the resonances of cadmium, antimony, osmium, and platinum. These elements were chosen for study because they are typical cases, in rather different regions of the periodic table, of elements with many isotopes, and because the isotopic identification of the resonances of some of these isotopes, when combined with the results of transmission meas-

* Work performed under the auspices of the U. S. Atomic Energy Commission.

¹ For example, see R. T. Carpenter and L. M. Bollinger, *Nuclear Phys.* **21**, 66 (1960).

² C. A. Fenstermacher, R. G. Bennett, A. E. Walters, C. K. Bockelman, and H. L. Schultz, *Phys. Rev.* **107**, 1650 (1957); J. A. Draper, C. A. Fenstermacher, and H. L. Schultz, *ibid.* **111**, 906 (1958).

³ J. R. Bird, M. C. Moxon, and F. W. K. Firk, *Nuclear Phys.* **13**, 525 (1959).

urements already on hand, lead to a significant set of new resonance parameters.

II. METHODS OF IDENTIFICATION

For the capture gamma-ray techniques of isotopic identification of resonances to be effective, the measurements must emphasize features of the spectra that are distinctively associated with the various isotopes under study. Some nuclear properties one might attempt to use are (a) characteristic low-energy gamma-ray lines, (b) characteristic high-energy gamma-ray lines, (c) neutron binding energy, (d) characteristic lifetimes of low-energy states, and (e) gamma-ray multiplicity. In the present section, the applicability of these nuclear properties to isotopic identification is considered in a general way. Discussions of applications to particular nuclides are deferred until Sec. IV.

The usefulness of low-energy capture gamma rays for the isotopic identification of neutron resonances has already been demonstrated by the experiments cited in Sec. I. In our work, several aspects of the technique have received further investigation. First, a systematic study was made of the relative merits of observing single low-energy gamma rays as compared to observing coincident gamma rays in the two NaI(Tl) scintillators. Single gamma rays from resonant capture were detected with scintillators having thicknesses of 0.1, 1.0, 10, and 15 cm. Similarly, coincidence spectra were recorded with various combinations of the same crystals. For the coincidence measurements, it was immediately apparent that the best combination was the two largest crystals (10×10 cm and 15×20 cm), of which the smaller one was used to detect the characteristic low-energy lines. On comparing the spectra for this pair of crystals with the spectra for the various single crystals, the coincidence spectra were found, without exception, to give a more sensitive indication of the isotope responsible. That is, the lower background that results from the coincidence requirement was found to be more advantageous than the higher counting rate that can be achieved with a single crystal. Thus the coincidence mode of measurement was used throughout the experiments described in Sec. IV.

One might hope to enhance the sensitivity of the coincidence measurements by placing restrictive conditions on the pulse height of one of the scintillators. Restrictions of this kind do, of course, tend to result in spectra that are more distinctively characteristic of the radiating nuclide. However, in general it was found that the improvement in the spectral shape is not great enough to offset the loss of statistical accuracy which is necessary to achieve it. The one condition that is sometimes worthwhile is to require the pulse in the second crystal to be greater than the pulse for an annihilation quantum. As shown previously,¹ this condition often results in a reduction of the relative background from annihilation and backscattered quanta without an important loss of counting rate.

As mentioned in Sec. I, the usefulness of the low-energy spectra for isotopic identification depends on a strong tendency for the relative intensity for particular low-energy lines to be the same at all resonances. This regularity is not unexpected, since the low-energy states (the decay of which results in the low-energy lines) are generally reached from the capture state by way of many intermediate states. Thus the low-energy lines are related to the *average* intensity for many primary transitions. In contrast, the characteristic high-energy gamma rays are themselves primary transitions and their intensities are not expected to exhibit much uniformity. Recent measurements at this laboratory⁴ and elsewhere indicate that the widths for radiative transitions from initial states to particular low-lying final states differ markedly between different initial states at nearly the same energy, even when the initial states are of the same spin and parity. Moreover, the high-energy transitions may be strongly dependent on the spin and parity of the capture state. Therefore, the absence of a high-energy line that is characteristic of a particular nuclide is not convincing evidence that a resonance should not be assigned to that nuclide. We must conclude, then, that the high-energy capture gamma-ray spectra are not as generally useful for the isotopic identification of resonances as are the low-energy spectra. However, the fluctuations in the high-energy end of the spectrum, which are objectionable for isotopic identification, may be used to advantage to improve the effective time-of-flight resolution of the measurement. Thus, as is demonstrated in Sec. IV, changes in the gamma-ray spectra over a single time-of-flight peak may be an indication that more than one resonance contributes to the peak.

Detection of single high-energy γ rays is also an elementary way of making use of the binding energy for isotopic identification. Measurements of this kind have given useful results at several laboratories.^{5,6} However, the random fluctuations of the partial widths for primary transitions and the dependence of the widths on the spin and parity of the initial state limit the usefulness of the measurement, since it can only lead with certainty to a lower limit on the binding energy. To make the most effective use of the binding energy, it is desirable to devise a method of measurement that minimizes the influence of the characteristics of the initial state. To some extent this objective is achieved by recording the spectra of the *sum* of heights of coincident pulses in two scintillators, in the same way as was done by Bollinger and Coté⁷ for a determination of the spins of resonances. From the sum spectra one can determine the energy of the cascades that proceed in ex-

⁴ L. M. Bollinger, R. E. Coté, and T. J. Kennett, *Phys. Rev. Letters* **3**, 376 (1959).

⁵ J. D. Fox, R. L. Zimmerman, D. J. Hughes, H. Palevsky, M. K. Brussel, and R. E. Chrien, *Phys. Rev.* **110**, 1472 (1958).

⁶ C. Corge, V. Hugnh, J. Julien, S. Mirza, F. Netter, and J. Simic, *Compt. rend.* **249**, 413 (1959).

⁷ L. M. Bollinger and R. E. Coté, *Bull. Am. Phys. Soc.* **5**, 294 (1961).

actly two steps from the initial state to some low-energy state. One often has enough information about the spins and parities of the low-energy states of the compound nucleus to relate the upper energy limit of the sum spectrum to the binding energy. Indeed, for a large class of nuclides the upper limit is the binding energy itself; and for another large class the upper limit, although not equal to the binding energy, is at least independent of the spin of the initial state. Moreover, the relative intensities of the two-step cascades are expected to be, and for some nuclides have been experimentally demonstrated to be, largely free of random fluctuations. Thus, the shape of the sum spectrum is relatively insensitive to the characteristics of the initial state and for many nuclides, as will be seen in Sec. IV, the upper energy limit of the spectrum gives a reliable measure of the binding energy.

The utilization of the lifetime of a low-energy isomeric state in the compound nucleus, which could be detected by observing delayed coincidences in two NaI scintillators, would appear to be a very sensitive means for the isotopic identification of resonances in the few special nuclides that form states with lifetimes in the range from about 10^{-5} to 10^{-8} sec. However, since a systematic application of this idea would require equipment that was not readily available, no attempt was made to use the method.

The use of the multiplicity of gamma rays as a means of isotopic identification is not expected to be very profitable. From what little is known about the dependence of the multiplicity on the nuclear species, it would seem that a knowledge of the multiplicity could only be used to separate out major classes of isotopes (such as even-even ones). What appears in effect to have been a measure of the multiplicity has been used by Desjardins⁸ to give worthwhile information of this kind. However, we have made no effort to make use of the method, since the same kind of classification of resonances can be made so easily on the basis of the neutron binding energy.

III. APPARATUS

As was shown above, the most sensitive methods of isotopic assignment are based on the observation of capture events in which de-excitation of the compound state results in the emission of more than one cascade photon, two of which are detected. Such coincident events are observed with low detection efficiency because of the limited solid angles subtended by the detectors. In addition, the distinct features of interest in the photon spectra comprise only a small fraction of the total amount of data; consequently a large number of capture events per resonance must be measured to make an identification. In view of the large number of resonances to be studied in the typical element and in view of the limited intensity of the source of radiation, the

methods outlined are generally attractive only when many pulse-height spectra can be accumulated simultaneously over a broad range in time-of-flight.

In the present work, the simultaneous recording of a large number of spectra was achieved by use of a 3-variable magnetic-tape recording system developed by the Argonne Electronics Division.⁹ The system consists of two major units, a recording station and a search station. At the recording station, the three parameters characterizing each event are recorded in digital form on magnetic tape. At the end of the experiment the tape is taken to the search station to be analyzed. The two pulse heights and the time-of-flight are encoded as 8-bit numbers. The 3×8 bits of each event are recorded on a 24-track magnetic tape that is $1\frac{1}{4}$ in. wide. Thus there are $(256)^3$ possible combinations or channels available in the recorder. The data are recorded with a uniform density of 100 events per in., for a total capacity of about 4.5×10^6 events on a 3600-ft tape. The maximum rate of recording is 170 events per sec, with a pair-resolving time of 300 μ sec.

The analysis of the recorded tape yields the spectrum of one variable when arbitrary conditions on the other two variables are satisfied. Four sets of restrictions can be imposed simultaneously, so that four independent spectra are obtained in each pass of the tape through the search unit. The data are sorted into the four spectra and stored in four independent quadrants of a 1024-word core memory at the rate of about 10^6 events per minute. At the end of a pass of the tape, the four spectra may be viewed on a cathode-ray tube or read out simultaneously by a typewriter, a punch paper tape, and an x - y recorder at the rate of one spectrum per 5 min. The entire system is made of solid-state devices, including 2100 transistors and 3300 diodes.

The record station was incorporated into the basic experimental arrangement as shown schematically in Fig. 1. The Argonne fast chopper¹⁰ was used to select neutrons of known energy on the basis of their time of flight. The samples consisted of thin plates of the material under study, placed at a large angle with respect to the beam in order to be effectively thick to the incoming neutron beam and thin for capture photons. The sample was placed 25 m from the chopper and the over-all time-of-flight resolution varied from 0.08 μ sec/m to 0.06 μ sec/m, depending on the chopper rotor used. Capture photons were observed in a 4 in. \times 4 in. NaI(Tl) crystal in coincidence with photons observed in a 6 in. \times 8 in. NaI(Tl) crystal. The amplified scintillation pulses were fed directly into gated analog-to-digital converter sections of the record station. The arrival of a time-of-flight signal in the form of an output pulse from the coincidence circuit signalled an event to be recorded,

⁹ M. G. Strauss and C. C. Rockwood, *Bull. Am. Phys. Soc.* **6**, 241 (1961).

¹⁰ L. M. Bollinger, R. E. Coté, and G. E. Thomas, *Proceedings of the Second International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1958* (United Nations, Geneva, 1958), Vol. 14, p. 239.

⁸ Scott Desjardins, Columbia University Report CU-189, 1959 (unpublished).

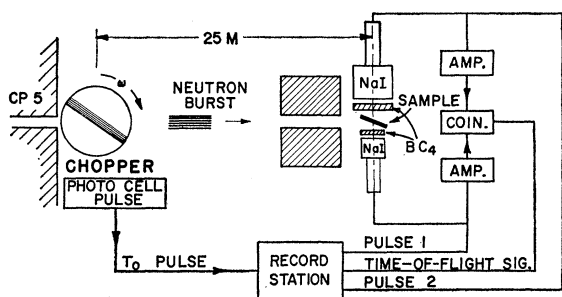


FIG. 1. Block diagram of the experimental arrangement. The resolving time of the coincidence circuit was about 80 nsec.

and the time between the photocell pulse and the coincidence signal was registered as the time of flight.

IV. RESULTS

In Sec. II it was shown that three kinds of spectra are especially well suited to a systematic use of capture gamma rays for the isotopic identification of resonances. The three kinds of data are (a) the spectra of single high-energy gamma rays (primarily useful for the location of resonances), (b) the spectra of low-energy gamma rays in coincidence with any specified type of event in a second crystal (from which isotopic identification is made by observation of characteristic low-energy lines), and (c) the spectra of the sum of the heights of coincident pulses from two crystals (measures of the binding energy).

The primary objective of this section is to discuss isotopic identifications that have been made from these kinds of γ -ray spectra. However, where necessary to complete the discussion, we also present γ -ray spectra that may be of interest as an indication of nuclear structure and some previously unpublished data on neutron transmission. Typically, the data presented were obtained in runs that were 24 hr long.

Cadmium

The prominent low-energy resonances of cadmium had previously been isotopically assigned on the basis of the results of transmission measurements¹¹⁻¹³ on samples of "separated" isotopes. More recently, Desjardins⁸ used the Nevis time-of-flight spectrometer to study the resonances of normal cadmium by means of the self-indication method. Because of the high resolution used (5 nsec/m), these latter measurements revealed the presence of many narrow resonances which had not been detected in the earlier work. The purpose of our measurements on cadmium was to identify the isotopes responsible for these narrow resonances.

¹¹ R. R. Palmer and L. M. Bollinger, *Phys. Rev.* **102**, 228 (1956).

¹² F. B. Simpson and R. G. Fluharty, *Phys. Rev.* **105**, 616 (1957).

¹³ R. B. Schwartz, V. E. Pilcher, and R. M. Schectman, *Bull. Am. Phys. Soc.* **1**, 187 (1956).

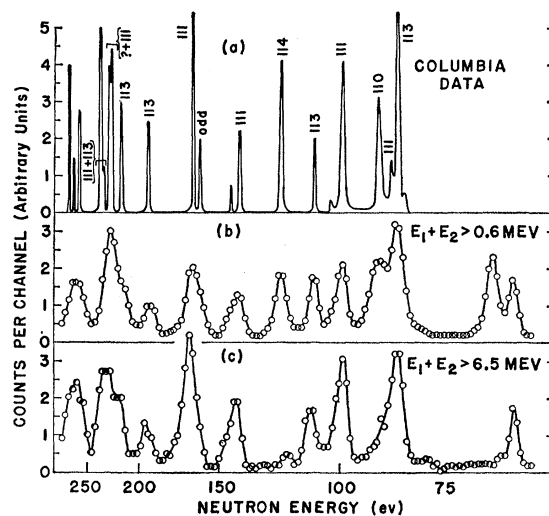


FIG. 2. Time-of-flight spectra for cadmium. For the Columbia data, the background counts have been subtracted.

The time-of-flight spectrum obtained by the Columbia group (with a sample in the detector position only) and the isotopic assignments obtained from the transmission data are shown in Fig. 2(a). In our experiment, a spectrum that should be roughly equivalent to Fig. 2(a) is one in which we place very loose conditions on the pulses accepted for analysis. Figure 2(b) gives a spectrum of this kind. For these data, it is only required that there be coincident counts in two scintillators and that the sum of the heights of the two pulses be greater than 0.6 Mev. It should be noted that many of the resonances for which it is hoped to obtain an isotopic identification are not resolved with the 80 nsec/m resolution used in the neutron time-of-flight measurement. In the range of energy below that shown in Fig. 2, resonances had previously been observed at 0.2, 18.5, 27.7, and 29.1 ev. In addition to these, we have detected narrow resonances at 22.1 and 58.7 ev which had been missed in the transmission measurements. The energies of all of the low-energy resonances of cadmium are listed in Table I, along with the isotopic assignments from the transmission data. For most of the resonances, the energies given are those that appear in previous publications.

As a first step in an attempt to obtain isotopic assignments from the gamma-ray spectra, let us make use of the difference in the neutron binding energies to separate the even-even from the even-odd targets. For cadmium this technique is very effective since the binding energies¹⁴ for the two classes of isotopes (Table II) differ by at least 1.5 Mev. When the sum of pulse heights is required to be greater than 6.5 Mev, the spectrum given in Fig. 2(c) is obtained. The peaks at 67.8, 89.6, and 120.2 ev, which have been attributed to

¹⁴ *Nuclear Data Sheets*, National Academy of Sciences, National Research Council, 1960 (U. S. Government Printing Office, Washington, D. C.).

TABLE I. Isotopic assignment of resonances of cadmium.

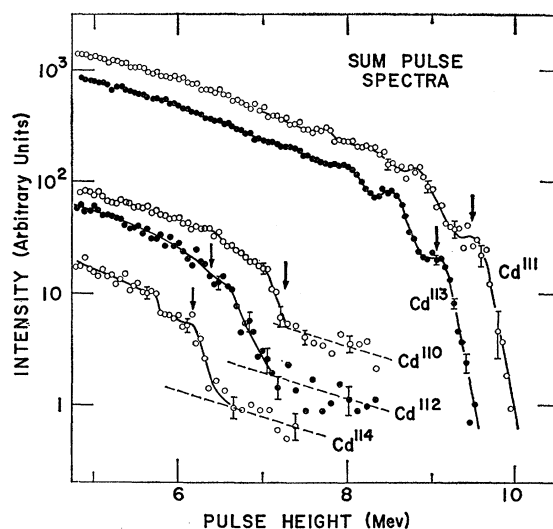
Energy (ev)	Method of assignment			Isotopic assignment
	Transmission	Binding energy	Characteristic γ rays	
0.2	113	113	113	113
18.5	113	113	113	113
22.1		even	even	even
27.7	111	111	111	111
29.1			111	111
58.7		114	114	114
64.0	113	113	113	113
67.8	111, 112	112	112	112
83.4		112	112	112
84.9	113	113	113	113
86.3	111	111	111	111
89.6	110	110	110	110
99.6	111	111	111	111
103.1				
108.5	113	113	113	113
120.2	114	114	114	114
138.3	111	111	111	111
143.2		odd	113	113
159.1	odd	odd	113	113
164.3	111	111	111	111
193.2	113	113	113	113
215.4	113		113	113
225.4	{111		{111	{111
226.8	{...		{112	{112
231.0	{113			
233.6	{111		111	111

even-even target nuclides, are observed to have almost disappeared from the spectrum. If the pulse-height window is raised still further to the range from 9.3 to 9.5 Mev, the resonances at 18.5, 64.0, 108.5, and 193.2 ev also drop out. This indicates that they must be assigned to Cd^{113} , which has a lower binding energy than Cd^{111} .

An alternative, and perhaps more sensitive, way of using the sum-coincidence data is to examine the pulse-height spectra for fixed intervals of flight time. Spectra of this kind are given in Fig. 3 for resonances that are known to be in Cd^{114} , Cd^{112} , Cd^{110} , Cd^{113} , and Cd^{111} . The high-energy limits of these spectra are seen to be quite different. Thus, except for the difficulty that we have no direct information about the spectra from capture in Cd^{106} , Cd^{108} , and Cd^{116} , the sum spectra can give an

TABLE II. Neutron binding energies of the cadmium isotopes. The sum-pulse data are normalized to a value of 9.046 ± 0.008 for Cd^{113} .

Nucleon number	Binding energy (Mev)	
	Nuclear data sheets ^a	Sum-pulse spectra
106	7.7 ± 0.1	
108	7.25 ± 0.06	
110	7.25 ± 0.15	6.98 ± 0.1
111	9.48 ± 0.08	9.46 ± 0.05
112	6.38 ± 0.07	6.55 ± 0.1
113	9.046 ± 0.008	
114	6.16 ± 0.04	6.16 ± 0.1
116	~ 6.2	

^a See reference 14.FIG. 3. Sum-coincidence spectra for various isotopes of cadmium. In the spectra for Cd^{114} , Cd^{112} , and Cd^{110} , the dashed curves indicate the magnitude of the contribution from background radiations.

immediate isotopic assignment for most of the cadmium resonances which are resolved in time-of-flight. However, when the resonances are not resolved in time-of-flight, the sum-coincidence spectra are of limited usefulness because the spectrum of the isotope with the highest binding energy tends to obscure the distinctive features of the spectra for the other isotopes. For example, with the poor statistics available and in view of the known dependence of the shape of the spectra on the spin of the initial state,⁷ one cannot be sure about the assignments of the unresolved pair of resonances at 138.3 and 143.2 ev, although it is certain that at least one of them must be attributed to Cd^{111} .

Although it is of secondary importance for this paper, it is of interest to inquire whether the sum-coincidence spectra give useful information about the neutron binding energies of the Cd isotopes. The location of each arrow is intended to correspond to the center of the distribution that would be formed by events in which the full binding energy is dissipated in the crystals. Thus, in the case of the even-odd targets, for which we are certain that the upper end of the spectrum is dominated by two-step cascades to the ground state, the arrow is seen to be located at the maximum of what appears to be a partially resolved peak. The spectrum for the resonance in Cd^{114} is also consistent with this interpretation. However, the upper limits of the spectra of Cd^{110} and Cd^{112} appear to be significantly different from the reported binding energies. Yet from the known characteristics of the low-energy states of Cd^{111} (Fig. 4) one would expect the high-energy end of the Cd^{110} spectrum to be dominated by events in which the full binding energy is detected. To check the possibility that this expectation failed because the sum spectrum for the particular resonance was dominated by a few

exceptionally strong cascades, we recorded the spectrum of one of the crystals when the sum of the pulse heights satisfied the condition that the sum be in a narrow interval near the upper energy limit. The fact that the spectrum of the single crystal was found to extend approximately uniformly over the full range of energy less than the binding energy indicates that many transitions are involved in the formation of the upper energy limit. Thus the upper limit of the spectrum for Cd^{110} should give a valid measure of the binding energy. The result obtained is 6.98 ± 0.1 Mev, where the error given is in the nature of a limit of uncertainty. This result appears to be almost inconsistent with the previously reported value of 7.25 ± 0.15 Mev.^{14a} In a similar way one can show that the upper energy limit of all of the spectra of Fig. 3 would be expected to give a direct measure of the binding energy for the isotope involved. The results obtained under this assumption are given in Table II. For all of the even-even isotopes, the errors given are merely estimates of limits of uncertainty. For Cd^{111} , on the other hand, our greater knowledge about the nature of the spectrum made it worthwhile to obtain a standard statistical error by a least-squares comparison of the data for Cd^{111} and Cd^{113} . The apparent discrepancy between the two values of binding energy for Cd^{112} is even more significant than is the corresponding discrepancy for Cd^{110} , since there is no way in which the pulse-height spectra can have a limit that is greater than the binding energy.

Turning now to a consideration of the use of characteristic low-energy gamma rays for isotopic identification, let us examine the spectra for the various isotopes of cadmium. These spectra, which are given in Fig. 4, are distinctive enough to provide a sensitive means of identification. Aside from the problem of statistical fluctuations, the only uncertainty involved is the possibility that the spectra for capture in Cd^{106} , Cd^{108} , and Cd^{116} , about which little is known, could be similar to the spectra for one of the other even-even targets. Note that almost all of the strong gamma-ray lines in the spectra of Fig. 4 appear to be the same as the transitions observed in beta decay.

The power of the gamma-ray spectra for the isotopic assignment of the cadmium resonances is graphically demonstrated by the ease with which one can identify the four resonances that contribute to the unresolved time-of-flight peak around 85 ev. The spectra corresponding to four time-of-flight intervals within this peak are shown in Fig. 5. One sees that the spectra are all different and a qualitative comparison with the spectra of Fig. 4 shows immediately that the resonances at 83.4, 84.9, 86.3, and 89.6 ev should be attributed to Cd^{112} , Cd^{113} , Cd^{111} , and Cd^{110} , respectively. These and the

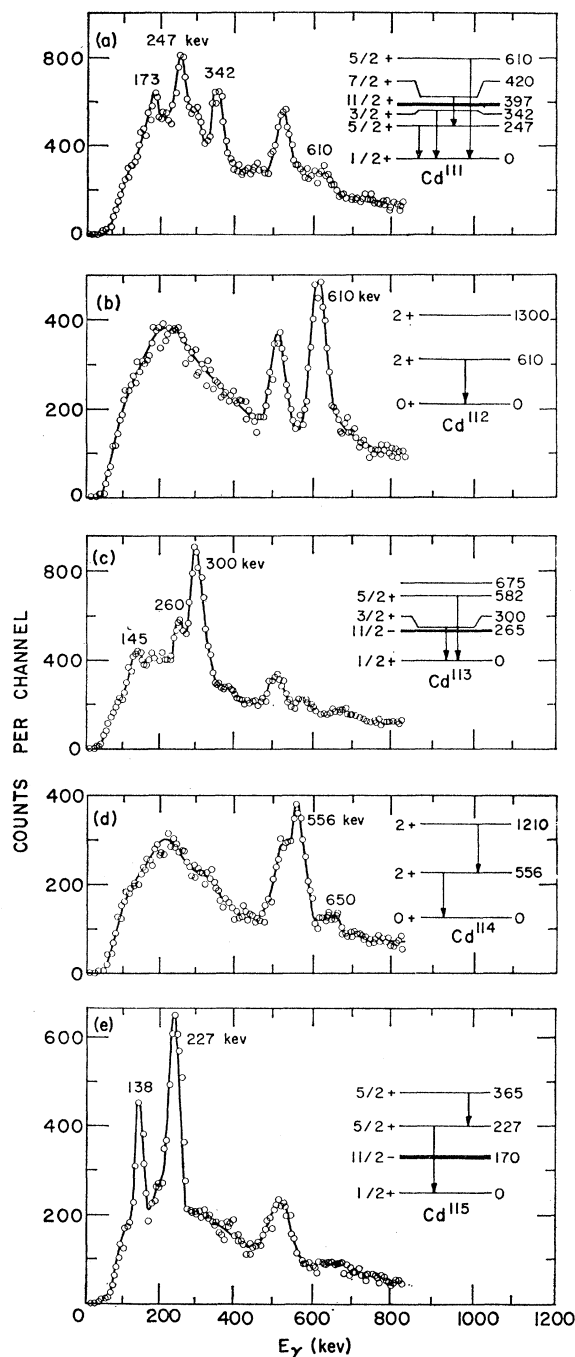


FIG. 4. Characteristic low-energy spectra of the cadmium isotopes. Spectra (a), (b), (c), (d), and (e) are for capture in Cd^{110} , Cd^{111} , Cd^{112} , Cd^{113} , and Cd^{114} , respectively. The decay schemes given on the right of the figure are taken from the Nuclear Data Sheets (reference 14). The energies associated with the γ -ray lines are taken from the decay scheme when the line is present there. States with long lives are indicated in the level schemes by heavy lines. The line at 511 keV present in all spectra is due to annihilation radiation.

other assignments that are made from the observation of characteristic gamma rays are listed in Table I.

A special measurement was required for the identifica-

^{14a} Note added in proof. A more recent value of 6.97 ± 0.19 Mev which is in excellent agreement with the above result is given by L. A. Koenig, J. H. E. Mattauch, and A. H. Wapstra, 1960 *Nuclear Data Tables, Part II* (U. S. Government Printing Office, Washington 25, D. C.).

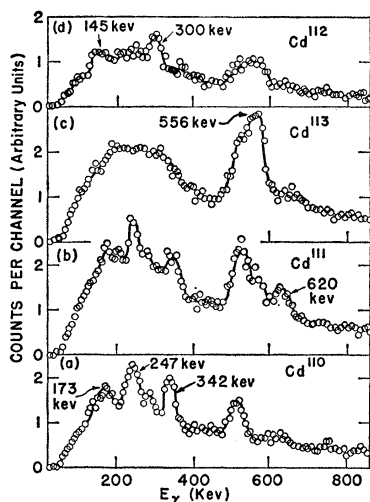


FIG. 5. Gamma-ray spectra from capture of neutrons in cadmium resonances. Curves (a), (b), (c), and (d) were obtained when the time-of-flight was required to be in an interval around the resonances at 89.6, 86.3, 84.9, and 83.4 ev, respectively. The γ -ray lines that are labeled are the lines that permit one to assign these resonances to the isotopes given on the figure.

tion of the resonance at 29.3 ev, a resonance which was normally obscured by the much more prominent one at 27.7 ev. A definite assignment could be made only when the relative contribution from the 27.7 ev resonance was diminished by passing the neutron beam through a cadmium filter $\frac{3}{16}$ in. thick.

The final isotopic assignments of the cadmium resonances, as determined from both the transmission and gamma-ray measurements, is given in the last column of Table I. Several weak resonances require individual comment. Our failure to observe a 620-keV line in the spectra for the two peaks near 67 ev leads us to support the assignments of Simpson *et al.* and to conclude that the 66.8-ev resonance listed for Cd^{111} in BNL-325 (see reference 17) does not exist. At higher energy, we do not accept the evidence from the transmission measurements of Simpson for the assignment of a resonance near 232 ev to Cd^{113} . From the gamma-ray spectra it is now clear that this resonance would have to be the very narrow one observed by the Columbia group at 231.0 ev. Thus, in view of the failure of the transmission measurements to give a complete assignment for the much simpler case of the pair of levels at 159 and 165 ev, the evidence for a resonance in Cd^{113} near 232 ev is felt to be unconvincing. Finally, the Columbia data suggest the presence of small resonances at 111 ev, 116 ev, and 141 ev, although the evidence for their existence is tenuous. Since there seems to be some possibility that the small peaks observed could result from neutron scattering of the kind discussed by Kennett *et al.*,¹⁵ we have omitted these resonances from our tabulation.

¹⁵ T. J. Kennett and L. M. Bollinger, Nuclear Phys. **12**, 249 (1959).

Antimony

The most recent previous study of resonances in antimony was made in 1956 by Palmer and Bollinger.¹¹ Because of the limited resolution available at that time (120 nsec/m), they were not able to resolve the resonance structure above 100 ev. Isotopic identification was accomplished by comparison of transmission data on a normal sample with data obtained with a sample enriched in Sb^{123} . In the present experiment the observation of characteristic low-energy gamma rays was used exclusively in making assignments. Because the available information concerning the level structure of Sb^{122} and Sb^{124} is so meager, it was necessary to determine the characteristics of the coincidence spectra entirely from neutron capture in resonances which had previously been assigned to Sb^{121} and Sb^{123} , the resonances at 6.2 and 21.6 ev, respectively. The spectra are shown in Fig. 6. The energies of the most prominent gamma-ray lines are given on the figure. It is clear that capture in the two isotopes produces gamma-ray spectra that are sufficiently different to be useful for isotopic identification. The spectrum for the 6.2-ev resonance is similar to that observed by Draper¹⁶ for the capture of thermal neutrons in normal antimony, although the energies of the lines differ somewhat.

The intensity of the 80-keV line associated with Sb^{121} and the 90-keV line associated with Sb^{123} was observed to fluctuate greatly from resonance to resonance. This fluctuation is consistent with the expectation that these lines should be strongly absorbed in the target and hence that their intensity should be dependent on the param-

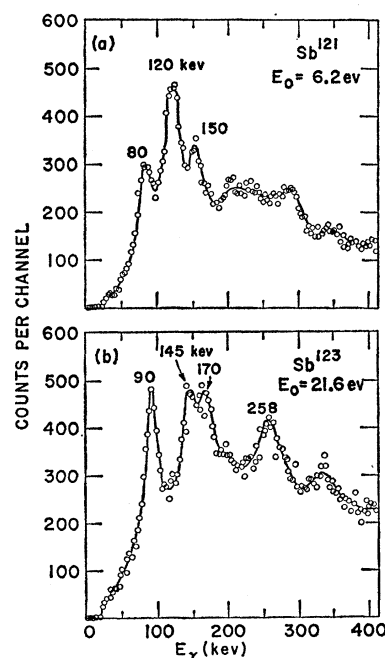


FIG. 6. Gamma-ray spectra from capture of neutrons in resonances of antimony.

¹⁶ J. E. Draper, Phys. Rev. **114**, 268 (1959).

TABLE III. Isotopic assignment of resonances of antimony.

Energy (ev)	Method of assignment		Isotopic assignment
	Transmission	Characteristic γ rays	
6.24 \pm 0.04	121	121	121
15.5 \pm 0.1	121	121	121
21.6 \pm 0.2	123	123	123
29.7 \pm 0.3	121	121	121
47.3 \pm 0.5		123	123
50.5 \pm 0.9	123	123	123
53.5 \pm 0.9	121	121	121
64.0 \pm 0.1	121	121	121
74.0 \pm 0.1	121	121	121
76.5 \pm 1.5	123	123	123
90.0 \pm 2	121	121	121
105.0 \pm 2	123	123	123
113.0 \pm 2	121	121	121
127 \pm 2	unresolved	121	121
132 \pm 2		121	121
145 \pm 2	unresolved	121	121
150 \pm 2		121	121
162 \pm 2	unresolved	121	121
167 \pm 2		121	121
193 \pm 2	123	123	123

ters of the resonances. Because of this effect, for the sample used (3.8×10^{20} atoms/cm²) the 80- and 90-kev lines were not very useful for isotopic identification. However, the line at 120 kev and the pair at 145 ± 5 and 170 ± 5 kev proved reliable indications of capture in Sb¹²¹ and Sb¹²³, respectively.

Because of our inadequate information about the cross sections of normal antimony, a special run was made to locate the resonances by making the measurements on antimony with the high-resolution rotor II in the chopper.¹⁰ The resolution width of the system was about 60 nsec/m. The resonances observed and their isotopic assignments are given in Table III. Although we are confident that the assignments given in Table III are correct, we cannot be sure that some narrow resonances have not been missed in the region above about 100 ev. Unlike the spectra from neutron capture in nuclides of cadmium, the spectra from capture in the isotopes of antimony are not distinctive enough to provide a sensitive indication of capture.

Osmium

In the absence of separated isotopes of osmium, no prior attempt had been made to identify its resonances. Moreover, the available cross section data for the element are unusually incomplete, being limited to unpublished results of transmission measurements¹⁷ made with the Brookhaven fast chopper. As a result, it seems worthwhile to present some transmission data obtained with the Argonne fast chopper in an experiment in which the shape of the 6.7-ev resonance of Os¹⁸⁹ was the

primary point of interest.¹⁸ The measurements were made in the energy range from 4 to 40 ev with a resolution width of 35 nsec/m. The sample was osmium metal with a thickness of 0.00025×10^{24} atoms/cm². The energies of the resonances observed are shown in Table IV.

An isotopic identification of the resonances of Os was attempted by an observation of the low-energy gamma rays. The spectra of the compound nuclides of even A , which lie in a nonspherical region, show strong transitions characteristic of a ground-state rotational band. Transitions from the first-excited states of Os¹⁸⁸ and Os¹⁹⁰ at 155 and 187 kev, respectively, are particularly strong and provide a sensitive means of detecting capture in Os¹⁸⁷ and Os¹⁸⁹. In addition to these lines, weaker lines were observed at 478 ± 20 and 633 ± 15 kev for capture in Os¹⁸⁷ and at 370 ± 5 and 558 ± 15 kev for capture in Os¹⁸⁹. These energies are in good agreement with the energies of lines observed in the spectra¹⁴ from beta decay. In contrast to the clear-cut spectra observed for the compound nuclides of even A , both the predictions of the collective model of nuclear excitation and the experimental results indicate that the nuclides of odd A would be expected to have level structure of much greater complexity. As a result, for only one of the five resonances detected in the even nuclides was the energy resolution width of the NaI(Tl) scintillator small enough to permit observation of line structure; hence no isotopic

TABLE IV. Isotopic assignment of resonances of osmium.

E_0 (ev)	Isotopic assignment	Relative intensity of 187-kev line in Os ¹⁸⁹
6.71 \pm 0.01 ^a	189	1.10
8.96 \pm 0.02 ^a	189	0.99
9.5 \pm 0.5 ^b	187	...
10.30 \pm 0.05 ^a	189	1.08
11.8 \pm 0.2 ^b	even-even	...
12.6 ^c	{ 187 even-even	...
12.6 ^c		...
13.8 \pm 0.2 ^b	189	...
18.7 \pm 0.1 ^a	189	0.93
20.4 \pm 0.3 ^b	even-even	...
22.0 \pm 0.1 ^a	189	1.04
22.3 \pm 0.2 ^a	even-even	...
27.4 \pm 0.1 ^a	189	1.06
28.3 \pm 0.1 ^a	189	0.95
30.8 \pm 0.4 ^b	189	1.03
38.7 \pm 0.5 ^c	even-even	...
41 \pm 0.5 ^b	187	...
43.5 \pm 0.5 ^b	189	...
44.5 \pm 0.5 ^b	even-even	...
47.5 \pm 0.5 ^b	187	...
50.8 \pm 0.5 ^b	189	0.94
56.0 \pm 0.5 ^b	189	1.01
61.0 \pm 0.5 ^b	189	0.93

^a Resonance energy determined from transmission measurement reported herein.

^b Resonance energy determined from measurements of capture γ -ray spectra.

^c Taken from *Neutron Cross Sections*, compiled by D. J. Hughes and R. B. Schwartz, Brookhaven National Laboratory Report BNL-325 (U. S. Government Printing Office, Washington, D. C., 1955).

¹⁸ H. E. Jackson, L. M. Bollinger, and R. E. Coté, *Bull. Am. Phys. Soc.* **5**, 295 (1960).

¹⁷ *Neutron Cross Sections*, compiled by D. J. Hughes and R. B. Schwartz, Brookhaven National Laboratory Report BNL-325 (U. S. Government Printing Office, Washington, D. C., 1960), Suppl. No. 1.

TABLE V. Resonance parameters of osmium.

Resonance energy	Isotope	Γ	$g\Gamma_n^0$ (mev)	Γ_γ
6.71 ± 0.01	189	84 ± 3	0.62 ± 0.02	81.5 ± 5
8.96 ± 0.02	189	110 ± 10	1.74 ± 0.16	99 ± 10
10.30 ± 0.05	189	102 ± 10	0.64 ± 0.07	97 ± 10
$12.6 \left. \begin{array}{l} \} \\ \} \end{array} \right\}$	187, —	two unresolved resonances		
18.7 ± 0.1	189	...	1.2 ± 0.2	...
22.0 ± 0.1	189	...	0.92 ± 0.15	...
22.3 ± 0.2	even-even
27.4 ± 0.1	189	...	0.68 ± 0.07	...
28.3 ± 0.1	189	...	1.40 ± 0.10	...

identification could be made. In the one case in which line structure was observed (the spectrum for the resonance at 11.9 ev) a single line was observed at 320 ± 5 kev. However, not enough is known about the level schemes of the osmium isotopes to permit the use of this line for isotopic identification.

Because of the high density of resonances in osmium, the range of measurements was limited to the region below 61 ev. The resonances observed in the γ -ray measurements are given in Table IV. The high efficiency of the gamma-ray technique for observing small resonances is demonstrated by the detection of resonances at 9.5, 11.8, 13.8, and 20.4 ev, resonances which had been missed in the transmission data. It should be noted that the time-of-flight resolution width used to obtain both the transmission data and the gamma-ray data were wide enough that many of the resonances present above about 40 ev probably have not been detected. The isotopic assignments obtained from the observation of characteristic low-energy gamma rays are given in the second column of Table IV.

As was pointed out in Sec. II, the observation of characteristic low-energy lines is a reliable technique only in the absence of large fluctuations of their relative intensity from resonance to resonance. The target nuclide Os^{189} provides an excellent case in which to obtain a quantitative measure of the magnitude of such fluctuations, since ten resonances of Os^{189} were sufficiently well resolved to make it possible to deduce the relative intensity of the 187-kev line. If the total number of coincident events is assumed to be proportional to the rate of capture, the relative intensity of the 187-kev line is equal to the area (corrected for background) of the line divided by the total number of coincidences. For the latter quantity, the relatively unimportant background counting rate is assumed to be the same as that observed in off-resonance regions of energy. Under these assumptions we determined the intensities with an uncertainty of roughly $\pm 5\%$. The relative intensities of the 187-kev gamma ray for the various resonances in Os^{189} are listed in the last column of Table IV. It is observed that not one of the values deviates from the mean value by more than 10%. This high degree of uniformity may be used to establish the

presence of two or more unresolved resonances in a single time-of-flight peak. For example, on the high-energy side of the time-of-flight peak observed at about 22 ev, the observation that the relative intensity of the 187-kev line drops by about 40% demonstrates the presence of at least one resonance in addition to the one which must be assigned to Os^{189} .

On the basis of isotopic identifications of Table IV, our transmission data may now be used to obtain resonance parameters. The results obtained are given in Table V.

Platinum

In contrast to our finding for Os^{189} , Bird and Waters¹⁹ have reported large fluctuations in the combined intensities of the 354- and 331-kev lines resulting from resonant capture in Pt^{195} ; the relative intensities measured at the various resonances are reported to range from 0.5 to 1.7. Because these lines represent transitions from the second to the first excited state and from the first excited state to the ground state, transitions of the same character as that observed in Os^{190} , their relative intensities might have been expected to exhibit a comparable degree of uniformity. To check on the apparent contradiction, we have studied the Pt^{195} resonances in the energy range from 60 to 160 ev. This range includes resonances at 112, 120, 140, 151, and 155 ev that are known⁶ to be in Pt^{195} . In addition, there is an unresolved pair²⁰ of resonances at 66.9 and 67.4 ev, at least one of which is known¹⁷ to be in Pt^{195} . The relative intensities of the pair of gamma-ray lines observed by Bird and Waters¹⁹ was measured at the five time-of-flight peaks formed by these resonances, namely, the peaks formed by the 112-, 120-, and 140-ev resonances and by the unresolved pairs of resonances at about 67 ev and 153 ev. All values of the relative intensities were found to be the same within 10%. Since the experimental uncertainty was also 5 or 10%, there is no experimental evidence for any fluctuation in the relative intensity. Thus our result is in sharp contradiction to that of reference 19.

If our finding of uniformity in the relative intensity of the low-energy lines formed by capture in resonance of Pt^{195} is accepted, we may use the value of the relative intensity to give information about the unresolved pair of resonances at 66.9 and 67.4 ev. The experimental value of 1.0 ± 0.1 for the relative intensity for the pair of γ -ray lines at 354 and 331 kev shows that most of the capture in these resonances is in the isotope Pt^{195} . Two possibilities are consistent with this statement: Both resonances are in Pt^{195} or, if only one is in 195, the other does not capture much. To make a choice between these alternatives, one may make use of the marked differences, from resonance to resonance, in the intensity of

¹⁹ J. R. Bird and J. R. Waters, Nuclear Phys. 14, 212 (1959).

²⁰ L. M. Bollinger, R. T. Carpenter, R. E. Coté, and G. E. Thomas, Argonne National Laboratory Report ANL-6072, 1959 (unpublished), p. 4.

TABLE VI. Average level spacings for isotopes of cadmium, antimony, and osmium.

Isotope	I	B_n (Mev)	\bar{S} (ev)	Number of levels	$2(2I+1)\bar{S}$
Cd ¹¹¹	$\frac{1}{2}$	9.48	33 \pm 10	8	132 \pm 40
Cd ¹¹²	0	6.38	80 ⁺⁵⁵ ₋₂₀	3	160 ⁺¹¹⁰ ₋₄₀
Cd ¹¹³	$\frac{1}{2}$	9.05	27 \pm 7	9	108 \pm 28
Sb ¹²¹	$\frac{5}{2}$	6.80	12 \pm 3	12	144 \pm 36
Sb ¹²³	$\frac{7}{2}$	6.15	29 ⁺¹⁷ ₋₁₁	6	464 ⁺²⁷² ₋₁₇₆
Os ¹⁸⁹	$\frac{3}{2}$	7.88	5.1 \pm 1.2	13	40.8 \pm 9.6

the high-energy gamma rays for resonances of a given nuclide. In another experiment performed at this laboratory, the spectra for single high-energy gamma rays were recorded for all time-of-flight channels in the neighborhood of the pair of resonances under discussion.²¹ It was observed that the relative intensity of gamma rays in the range from 7 to 8 Mev is about four times as great for the time channel about half-way up the high-energy side of the time-of-flight peak as is the same intensity for the corresponding time channel on the low-energy side of the peak. This great difference implies that both resonances play an important role in the capture. Thus both resonances must be assigned to Pt¹⁹⁵.

V. AVERAGE VALUES OF RESONANCE PARAMETERS

The data of Tables I, III, and IV have been used to calculate mean values for the spacings of resonances in Cd¹¹¹, Cd¹¹², Cd¹¹³, Sb¹²¹, Sb¹²³, and Os¹⁸⁹. The results obtained are given in Table VI. The value given for the average observed spacing \bar{S} is simply the mean for the sample. In the calculation of the uncertainties associated with these values, the spacings for states of a given spin and parity were assumed to be distributed according to the Wigner distribution

$$\rho(x) = \frac{1}{2}\pi x \exp(-\frac{1}{4}\pi x^2),$$

where x is the ratio of an individual spacing to the mean spacing. The distribution of spacings for target nuclides of odd A is a superposition of the two Wigner distributions corresponding to the two possible values of angular momentum for the compound state. Under these assumptions, one may deduce the distribution law for the mean spacing and from this distribution calculate confidence limits for the true mean spacing. The limits given in Table VI specify the range of values of \bar{S} within which the true value lies with a probability of 0.683. No attempt was made to correct the data for the possible presence of p -wave resonances. However, the number of p -wave resonances detected is believed to be small because (1) the nuclides under study are sufficiently far

from the peak in the p -wave strength function near $A=90$, and (2) the energy region has been restricted to the range from 0 to 200 ev. Also given in Table V are values of $2(2I+1)\bar{S}$, a quantity which is independent of the spin J of the initial state if, as expected, the density of states is proportional to $(2J+1)$. The factor 2 is introduced to obtain a quantity that will be equal to the spacing of states with $J=0$ for even-even compound nuclides. In general, the results of Table VI tend to be somewhat smaller than the values that have appeared previously in the literature, a not unexpected effect in view of our detection and identification of narrow resonances which had previously been missed.

The data presented in Sec. IV may also be used to obtain values of strength functions for the target nuclides Cd¹¹¹, Cd¹¹³, and Os¹⁸⁹. For the cadmium nuclides we make use of the parameters of Simpson and Fluharty¹² for resonances at energies less than 70 ev and the parameters of Desjardins⁸ for parameters of resonances at energies greater than 70 ev. As is customary, the strength function $\bar{\Gamma}_n^0/D$ was calculated as the ratio $\bar{\Gamma}_n^0/2\bar{S}$, where $\bar{\Gamma}_n^0$ and \bar{S} are the sample means of the reduced width and the observed level spacing, respectively. The results obtained are $(0.26_{-0.12}^{+0.28}) \times 10^{-4}$ and $(0.39_{-0.16}^{+0.33}) \times 10^{-4}$ for the strength functions of Cd¹¹¹ and Cd¹¹³, respectively. Again the uncertainties given are the limits within which the true value is expected to fall with 0.683 probability, as determined from the number of resonances involved. For this calculation it is assumed that the reduced widths obey the Porter-Thomas distribution. Our values of $\bar{\Gamma}_n^0/D$ for Cd¹¹¹ and Cd¹¹³ do not differ significantly from those obtained previously by Simpson and Fluharty,¹² since the reduced widths of most of the resonances identified in the present study are too small to have much influence. However, the uncertainties associated with our values should be more realistic, partly because of a more accurate knowledge of the number of resonances involved and partly because we now have a better appreciation of the importance of taking into account the great fluctuations that are characteristic of the Porter-Thomas distribution.

In the absence of separated isotopes of osmium, no previous measurement of the strength function of an individual isotope has been reported. Using the resonance parameters listed in Table V, we proceed to obtain a value of $\bar{\Gamma}_n^0/D$ for Os¹⁸⁹ in the same way that was described above for the isotopes of cadmium. The result obtained is $(2.0_{-0.7}^{+2.2}) \times 10^{-4}$. This result is consistent with the previously published value of 1.9×10^{-4} for the average strength function of the normal element, a value which was determined by Hughes *et al.*²² from an average cross-section measurement.

²¹ L. M. Bollinger, R. E. Coté, R. T. Carpenter, and J. P. Marion (to be published).

²² D. J. Hughes, R. L. Zimmerman, and R. E. Chrien, Phys. Rev. Letters **1**, 461 (1958).

VI. CONCLUSIONS

The measurement of average values of resonance parameters such as mean level spacings and strength functions is one of the central problems of slow-neutron spectroscopy. To date the statistical significance of such results has been limited by the intensity and resolution of neutron spectrometers. Consequently, quantitative studies of the systematics of level spacings, particularly the presence of shell effects and local fluctuations, have been seriously limited. The accuracy with which strength functions are known also leaves much to be desired. The greatly improved resolution that is now becoming available with pulsed accelerators provides a means of obtaining more refined results by determining parameters for a much greater number of resonances in those cases in which the isotopic assignments are known. However, because of the large samples required for study by the accelerators, transmission measurements on separated isotopes will not be generally useful. Therefore, the demonstration in the present paper of the power of gamma-ray measurements for isotopic identi-

fication is currently of special interest since it is expected that the pulsed accelerators will be able to make effective use of the techniques described. It is well to keep in mind, however, the weaknesses as well as the strengths of the gamma-ray methods. On the basis of the experiments described above, we draw the following conclusions about the effectiveness of the methods: (1) the gamma-ray method is much faster and more sensitive than is the transmission method for most of the even-odd target nuclides, (2) it is a competitive technique for other nuclides if the spacings between low-lying levels of the compound nucleus are sufficiently large or if the binding energies of the several isotopes are sufficiently different, and (3) it is inferior to the transmission method when the low-energy levels of the compound nuclides are too close together and when, simultaneously, the binding energies of the various isotopes are not sufficiently different. Also, even when the nuclear characteristics are favorable for isotopic identification, ignorance about these characteristics may make it difficult to utilize the γ -ray data.