Neutron Resonances in the kev Region: Heavy Even Elements*

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Neutron cross-section curves as a function of neutron energy have been measured for Se(1–80), Sr(6–102), Zr(2–80), Mo(1–80), Ba(15–102), Ce(5–55), and Pb(2–80); the energy range in kev of each curve is shown in parentheses. The number of peaks observed are 8, 4, 11, 9(?), 5, 12, and 10, respectively. Isotopic assignments of a few of the observed resonance peaks are Se^{80}; 3 and 7 kev; Sr^{88}; 15 and 95 kev; Zr^{90}; 43 kev; and Ce^{140}; 24 kev. No doubt many peaks, particularly those due to minor isotopes, have been missed completely. It is concluded that many of the nuclides which make up these complicated isotropic mixtures would be found to have strong, well-separated resonances if they were measured in an isotopically pure state with a neutron energy spread of the order of a few kev.

INTRODUCTION

THE general experimental conditions were about the same as those described in the preceding paper,[1] which will be called I hereafter. Sample thicknesses were, on the whole, thicker than optimum for bringing out peaks; this thickness is usually about $1\text{–}2\times10^{22}$ atoms/cm^2. Table I gives sample thickness in terms of the isotopes which probably are responsible for most of the peaks, as well as minor isotopes which may contribute to some extent. It should be pointed out that, in all of the cross section curves, atomic cross sections have been plotted. Certainly many of the resonances due to minor isotopes have been missed, but it is impossible to tell how many of them have been counted. In separated isotope work now in progress, well marked peaks have been found in a sample with an effective thickness of only 0.3×10^{22} atoms/cm^2.

SELENIUM

The total cross section of selenium appears in Fig. 1. This spectrum was measured principally to assist in the interpretation of selenium activation cross sections which were measured at the same time. Strong activation[2] of Se^{81} in the region from 2 to 8 kev makes it very likely that peaks at 3 and 7 kev are due to Se^{80} which is twice as abundant as Se^{78} and about five times as abundant as Se^{76}, Se^{77}, and Se^{82}. Bollinger[3] has found resonances at energies lower than 3 kev; these are probably to be attributed to the less abundant isotopes, since Rohrer *et al.*[2] showed that the lowest energy resonance of Se^{80} was in the neighborhood of 3 kev. However, it seems most likely that nearly all the resonances observable in Fig. 1 are due to Se^{80}.

STRONTIUM

Natural strontium is 83% Sr^{88}; there are two minor components, Sr^{86} and Sr^{87}, with abundances somewhat less than 10% and one with an abundance less than 1%. The small number of resonant peaks observed (Fig. 2) are probably all due to the predominant isotope; in this case the two minor isotopes have slightly less than a "magic" number of neutrons and resolvable resonant spectra should be expected. Strong interference dips appear below the peaks at 15 and 95 kev; these peaks are noticeably asymmetric and give every indication of being due to *s*-neutrons. In this case, the theoretical peak-to-valley difference should be about 185 barns at 15 kev and 30 at 95 kev. A 10 percent isotope would, therefore, show maximum changes of 3 barns at 95 kev as compared to an observed 6 barns; this rules out the assignment of the 95-kev peak to any isotope but Sr^{88}. Similarly, a 10% isotope could show a maximum difference of 18.5 barns at 15 kev compared to an observed value of about 12; this represents almost impossible resolving power for the experimental arrangement, and this resonance may be safely assigned to Sr^{88}. It will be seen, however, that there is evidence in the Ce cross section that a 10 percent isotope gave rise to observable resonances. Hence, the peaks at 27 and 31 kev may possibly be due to one of the weak isotopes but it will be noticed that in Sr the thickness of the minor isotope is very small. Some cases of apparent point scatter are probably weak resonances which might be established by more detailed measurements, but there seemed to be little point to going into such detail where definite isotopic assignment is impossible.

MOLYBDENUM

Such elements as samarium, niobium, and krypton which contain minor isotopes of neutron number 82 have been omitted from our list because of the difficulties anticipated in these complicated isotopic

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[1] J. H. Gibbons, preceding paper [Phys. Rev. **102**, 1574 (1956)].

[2] Rohrer, Newson, Gibbons, and Cap, Phys. Rev. **95**, 302(A) (1954).

[3] L. M. Bollinger (private communication) and Brookhaven National Laboratory Report BNL-325 (unpublished).

TABLE I. Data on samples.

	Magic or predominant isotope			Other isotopes (>3 percent)			Whole sample	
	Neutron number	Abundance %	Atoms/cm² $\times 10^{-22}$	Range of percent abundance	Number	Range of atoms/cm² $\times 10^{-22}$	Av. transmission[a] %	Atoms/cm² $\times 10^{-22}$
Se^{80}	46	50	2.66	7–24	4	0.37–1.3	...	5.32
Se^{80}	46	50	4.42	7–24	4	0.62–2.1	45	8.85
Sr^{88}	50	83	1.85	7–10	2	0.16–0.23	80[a]	2.27
Zr^{90}	50	52	3.45	11–18	3	0.76–1.28	55[a]	6.9
Mo^{92}	50	16	2.47	9–24	6	1.4–3.8	33	15.7
Ba^{138}	82	72	1.40	6–12	3	0.12–0.23	85	1.95
Ce^{140}	82	89	4.9	11	1	0.6	52[a]	5.5
Pb^{208}	126	52	5.1	21–26	2	2.0–2.5	38	9.82

[a] In curves where there are large resonant peaks, these peaks are not included in estimates of average transmission.

mixtures. However, it seemed wise to measure one such mixture. In molybdenum the "magic" isotope, Mo^{92}, is 16 percent abundant while the six other isotopes are all heavier and vary in abundance from 9 to 23%. The sample used was much too thick for optimum resolving power of an element consisting of a single isotope but the effective thickness of Mo^{92} was not far from optimum (2.47×10^{22} atoms/cm²). It is seen in Fig. 2 that no prominent resonances appear. If we notice that peak-to-valley difference in the 14-kev resonance in Sr (83% Sr^{88}) is only about 12 barns, we might expect peaks of only about 2 barns in the Mo atomic cross section.

ZIRCONIUM

Zirconium is 50% Zr^{90} which contains fifty neutrons and is intermediate between Mo and Sr in this respect. The resonance spectrum is shown in Fig. 3 and contains a large number of well-marked resonances. Other isotopes are not present to much more than a third of the abundance of Zr^{90}. The larger peaks may be definitely assigned to Zr^{90} by the same arguments that were used for similar peaks in the Sr curve. It will be noted that the minor isotopes of Zr are present in rather favorable thickness; some of these isotopes may well be contributing some of the smaller peaks. This greater likelihood of observing minor isotope peaks in Zr as compared to Sr may be responsible for the fact that more peaks are observed in Zr than in Sr.

CERIUM

Resonances have already been found in natural cerium by Miller *et al.*[4] These authors found peaks at

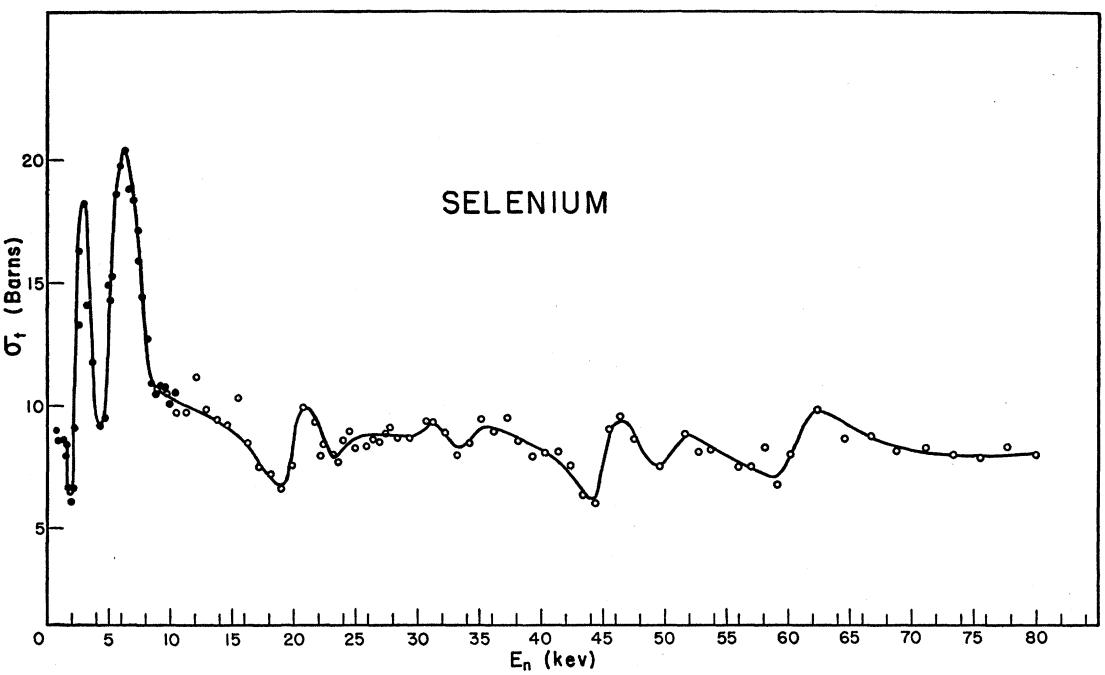

FIG. 1. The total atomic cross section (σ_t) of natural selenium as a function of neutron energy. The solid dots were points measured with a thinner sample (Table I) than those shown as open circles.

[4] Miller, Adair, Bockelman, and Darden, Phys. Rev. 88, 83 (1952).

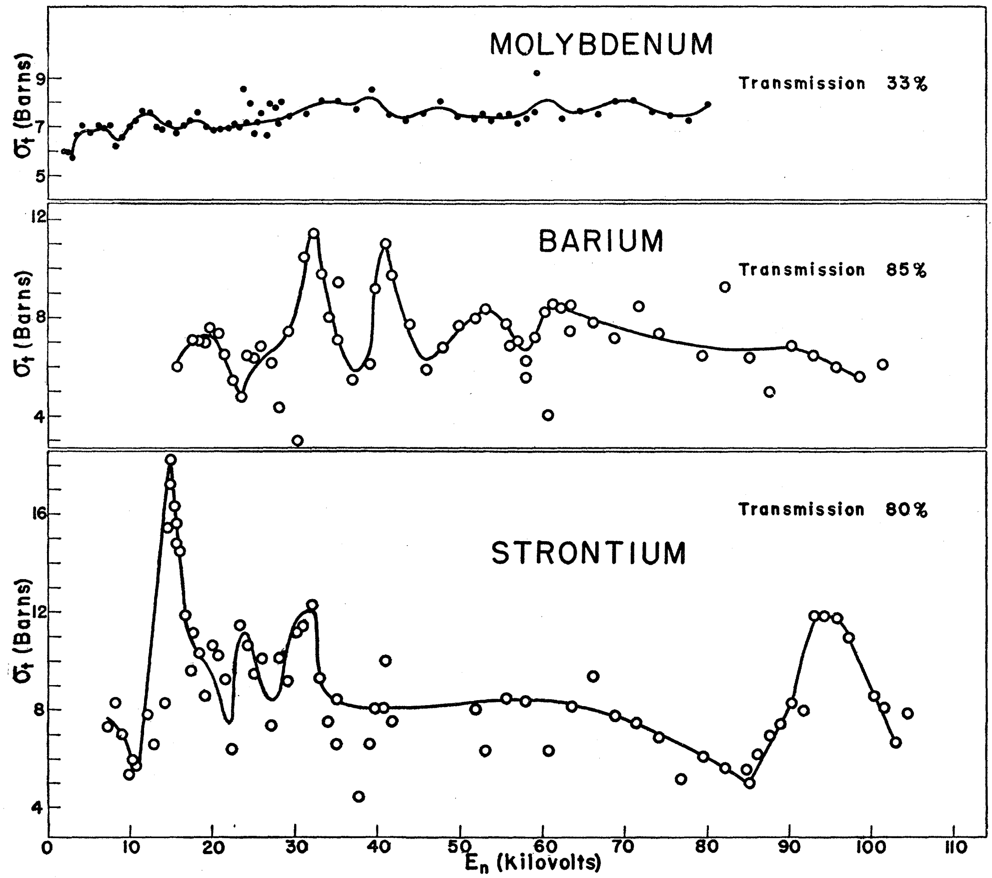

FIG. 2. The total atomic cross section (σ_t) of natural Sr, Mo, and Ba as a function of neutron energy (E_n).

25 and 100 kev with a resolving power of about 10 kev. In Fig. 4, the results of our measurements between 10 and 60 kev are shown. The magnetic analyzer and a stainless steel proton tube with a silver soldered tantalum end cap was used for this early measurement. The strong resonance at 24 kev, which exhibits a

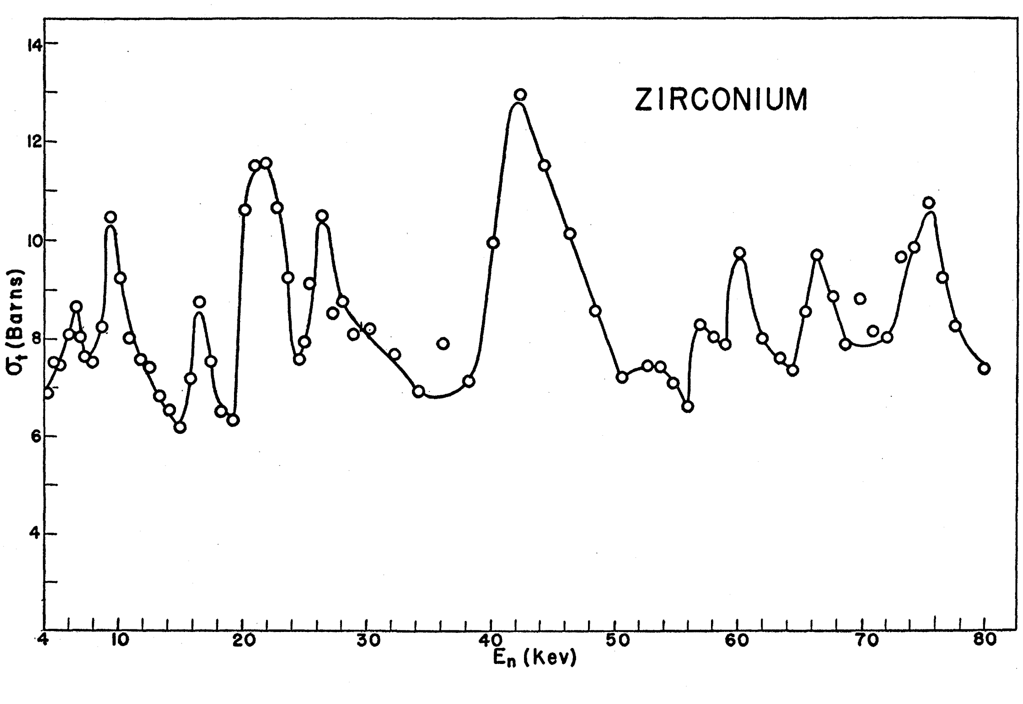

FIG. 3. The total atomic cross section (σ_t) of natural zirconium as a function of neutron energy (E_n).

marked interference dip is evidently the same as that reported at 25 kev by Miller *et al.* In addition, there are at least six much weaker resonances some of which are superimposed on the large resonance at 24 kev. Since natural cerium is 89% Ce^{140}, it is practically certain that the resonance at 25 kev is due to this nuclide. By the same token, the smaller resonances which are superimposed on it are more likely to be due to Ce^{142} (11%) since this is the only other important isotope of Ce and superposition of resonances due to the same even-even nuclide is very unlikely.

BARIUM

Natural barium is 72% Ba^{138} and strong resonances similar to those in Ce^{140} were expected to occur. As will be seen in Fig. 2, no such very strong resonances appeared even though the measurements were extended to much higher energies than are usually profitable by our method. There are, however, some relatively minor resonances which may be due to any of three relatively prominent isotopes in addition to Ba^{138}.

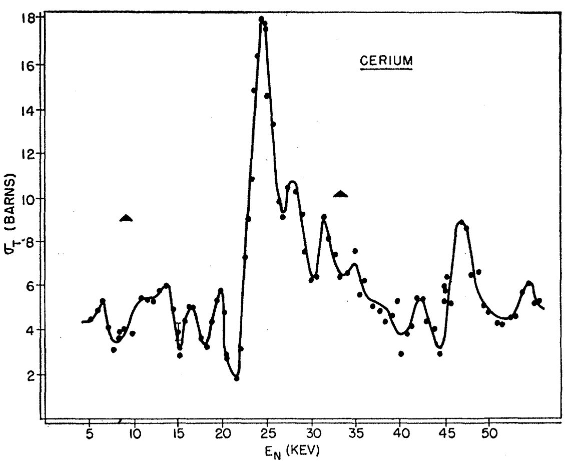

FIG. 4. The total atomic cross section (σ_t) of cerium as a function of neutron energy (E_n). The energy scale was normalized against the Li(p,n) threshold and the strong resonance in sulfur which was assumed to be at 110 kev.

LEAD

A thick sample of natural lead was measured between 5 and 80 kev under the same experimental conditions as the cerium measurements (Fig. 5). An obvious s-wave resonance was observed at 46 kev. The small fluctuations in cross section appear to be reproducible but may possibly arise from instrumental difficulties.

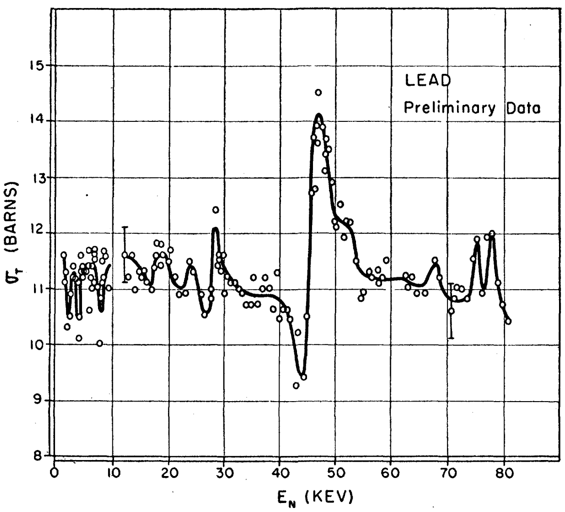

FIG. 5. The total atomic cross section (σ_t) of lead as a function of neutron energy (E_n). The energy scale was normalized against the Li(p,n) threshold and the strong resonance in sulfur which was assumed to be at 110 kev.

DISCUSSION

The heavy even-even nuclei at the magic numbers appear to have distinctly wider spacings than similar odd elements of about the same mass.[5] The isotopic complexity of the even elements makes their study a formidable problem. However, in view of the results on Fe (see reference 1), Pb, Ce, Zr, and Sr it appears that at least some intermediate and heavy even-even nuclei have resonance structures which we can resolve easily. It appears that the spectrograph is most suitable for studies of even-even nuclei where separated isotopes are available in suitable quantity and quality.

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[5] Block, Gibbons, Bilpuch, and Herring, Phys. Rev. **94**, 774(A) (1954).