Neutron Resonances in the kev Region: Heavier Odd Elements*

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(Received August 20, 1956)

The neutron total cross sections have been measured as functions of energy for thallium (0.1–80), yttrium (6–80), rubidium (5–25), copper (1–80), and chlorine (6–200); peaks are observed which appear to be due to single resonances. The energy range of the measurements in kev is indicated in parentheses. Lanthanum (1–10) and yttrium (0.5–10) show peaks which may be due to single resonances. Lanthanum (10–100), praseodymium (0.5–150), gallium (1–60), gold (1–40), tantalum (1–6), silver (2.5–11), niobium (0.5–10.5), cesium (1–4.5), and iodine (1–15) show flat or wavy cross-section curves which are typical of spectra so poorly resolved that no single resonances are observed. Our failure to observe even the strongest single resonance in any of these elements is consistent with a roughly exponential distribution of reduced widths. Useful averaged cross sections are tabulated for some of the latter elements.

INTRODUCTION

THIS paper presents the results of a survey on the total cross sections of heavy odd elements. The apparatus is described in paper I of this series.[1] We were interested principally in the question of whether or not an element had a resonance structure which was resolvable with our apparatus; it was also important to determine to what extent certain elements, used as construction materials in the experiments, could be considered to have a constant cross section at our resolution. Average cross sections are reported in some of the cases where the resonance spectrum was not resolved. We have not included cross sections for a natural element where more detailed later work included remeasurement over the same energy range. However, these later studies usually involved enriched isotopic mixtures rather than the natural elements.

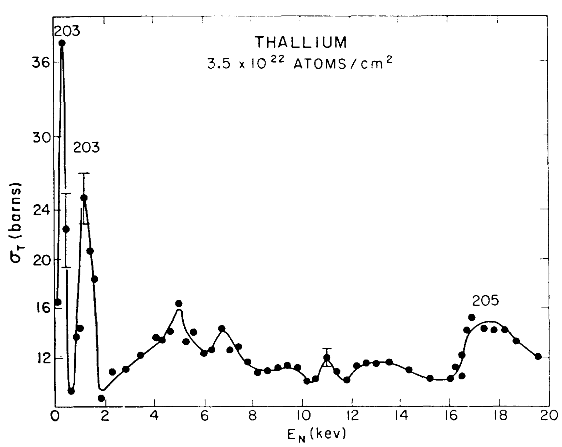

FIG. 1. Total neutron cross section of natural thallium *vs* energy. Isotopic assignments are listed above some of the peaks. Errors indicated are derived from counting statistics.

THALLIUM

Figure 1 shows the cross-section curve for thallium metal between 100 ev and 20 kev. This cross section was measured with a tantalum-backed lithium target and an aluminum proton tube (see reference 1) so that large background corrections had to be made in the lower energy regions. However, the peaks below 2 kev show up very clearly: these two peaks have been attributed to Tl^{203} by Newson and Rohrer on the basis of activation measurements.[2] The peak at about 18 kev may be assigned to Tl^{205} on the basis of both separated isotope measurements[3] and activation cross sections which will be reported later. Many small peaks below 15 kev have been shown to be due to Tl^{203}. Figure 2 shows a transmission curve for a thicker sample of thallium at higher energies.

COPPER, GALLIUM, ARSENIC, AND BROMINE

Figure 3 shows cross-section curves for gallium and copper. The two elements differ in charge by two units and both consist of two isotopes with an abundance ratio of about 2:1 in favor of the lighter isotope. Nevertheless, the two cross-section curves illustrate an im-

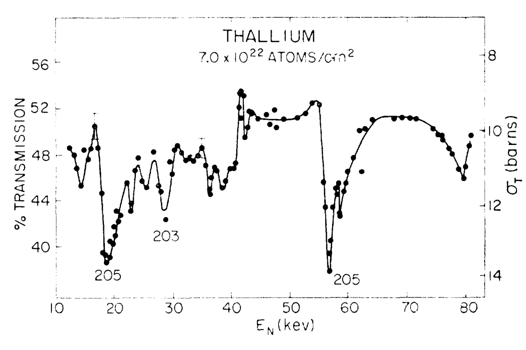

FIG. 2. Thallium transmission *vs* energy. This was an early measurement performed with a magnetic analyzer alone (see reference 1). Isotopic assignments are listed below some of the minima.

* This work was supported by the U. S. Atomic Energy Commission.
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[1] J. H. Gibbons, Phys. Rev. **102**, 1574 (1956).

[2] H. W. Newson and R. H. Rohrer, Phys. Rev. **94**, 654 (1954).
[3] J. H. Gibbons and H. W. Newson, Phys. Rev. **95**, 644(A) (1954).

portant difference in spectra. The widths at half-maxima in the gallium peaks are in general much wider than the energy spread of the neutron beam (see reference 1). Furthermore, we know from the low-energy measurements of the Argonne Group[4] that the level spacing of gallium (all isotopes and open channels) is about 200 ev. Thus, each maximum (which probably contains only about 10 individual resonances) is due to statistical fluctuations in the strength function[5] averaged over a small number of levels. Hence, a very large number of resonances must be averaged by the energy spread of a cross-section measurement in order to obtain a monotonic cross-section curve. The wavy pattern is typical of poorly resolved spectra. The gallium curve was obtained with a slightly hydrated sample of Ga_2O_3; a rather large correction for the hydrogen scattering is responsible for an unusually large uncertainty in the absolute cross section (±2 barns).

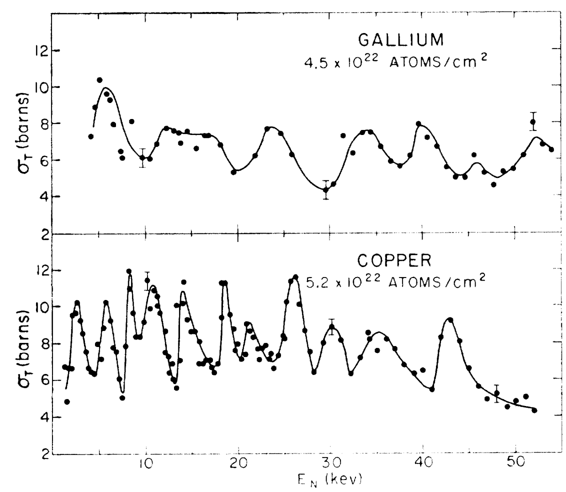

FIG. 3. Total neutron cross section of natural copper and gallium. In addition to the statistical errors indicated for gallium, there is a ±2 barns error due to H_2O uncertainty.

On the other hand, the copper curve shows many peaks which are approximately as wide as the neutron energy spread and considerably higher than the amplitude of the fluctuations in gallium. By comparing with separated isotope data, it appears that while these peaks are not necessarily due to single resonances, they probably correspond to the stronger resonances in Cu^{63} since the peaks observed in Fig. 3 are nearly the same as those observed in pure Cu^{63}.[6] The Cu^{65}, because of its low abundance (31%), is responsible for maxima too weak to be observed in the presence of the stronger peaks due to Cu^{63} (69%). With a few exceptions near magic numbers, copper appears to be the heaviest odd element where individual resonances may be found by

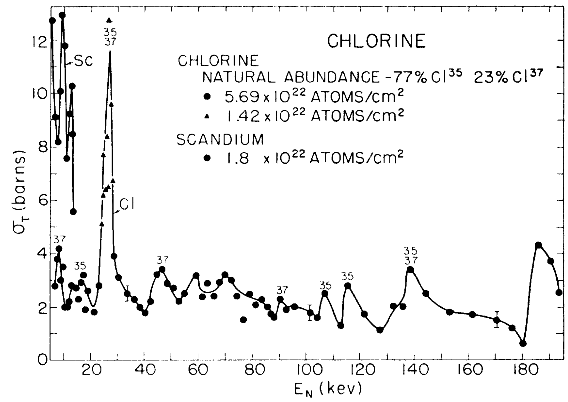

FIG. 4. Total neutron cross section of chlorine and scandium. Chlorine isotopic assignments from later measurements are indicated above the curve.

our technique. As^{75} and $Br^{79,81}$ show only fluctuations like those observed in gallium.

CHLORINE AND SCANDIUM

Figure 4 shows the total cross section of chlorine as measured with a sample of AgCl. The data have been corrected for the cross section of the silver using our own data at lower energies and that of Bockelman *et al.*[7] at higher energies. Chlorine isotopic assignments based on separate isotope measurements[8] are also shown in the figure. The peaks at 140 and 190 kev have been observed by Kiehn *et al.*[9] The separated isotope measurements have shown that these peaks are complex. Any resonances between 50 and 90 kev are too weak to be observed clearly even in the separated isotope runs. Natural chlorine has been investigated with the Material Testing Reactor fast chopper and no resonances were found between 1 and 8 kev.[10] It is evident that the resonance spectra of both isotopes of chlorine consist of rather widely spaced and unusually narrow levels.

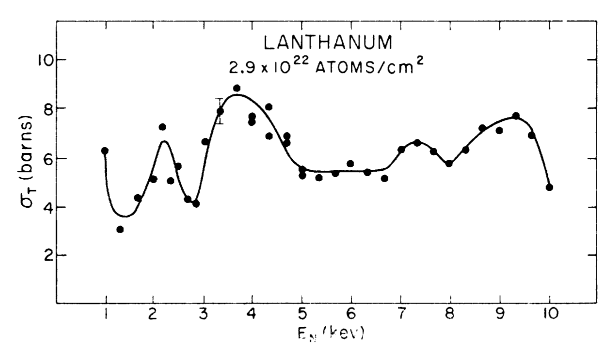

FIG. 5. Total neutron cross section of lanthanum *vs* energy.

[4] L. W. Bollinger (unpublished data).
[5] This is defined as the ratio of the average reduced neutron half width to the average level spacing.
[6] H. Marshak, Phys. Rev. 94, 774(A) (1954).
[7] Bockelman, Peterson, Adair, and Barschall, Phys. Rev. **76**, 277 (1949).
[8] Toller, Patterson, and Newson, Phys. Rev. **99**, 620(A) (1955).
[9] Kiehn, Goodman, and Hansen, Phys. Rev. **91**, 66 (1953).
[10] Brugger, Evans, Joki, and Shankland, Bull. Am. Phys. Soc. Ser. II, **1**, 176 (1956).

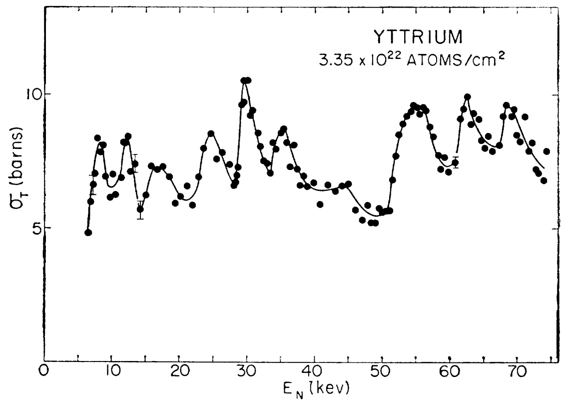

FIG. 6. Total neutron cross section of yttrium *vs* energy.

As is evident from inspection of the curve, the shape elastic scattering is $\ll 4\pi R^2$ and the strength function of the resonances $\ll 10^{-4}$. These low values are in agreement with the predictions of the cloudy crystal ball model of Feshbach, Porter, and Weisskopf.[11] The transmission data from which the curve in Fig. 4 was calculated have been analyzed to estimate the strength function.[12]

As a contrast to chlorine a small portion of a total cross-section curve of scandium is also shown in Fig. 4. This nuclide is close to the $3s$ giant resonance at approximately $A=47$. It is quite evident that the strength function is much stronger for Sc^{45} than for either of the isotopes of chlorine. The sample was Sc_2O_3; the curve was corrected for the oxygen on the assumption that $\sigma_T = 3.6$ barns. A more thorough study of scandium will appear in a later paper.[12]

LANTHANUM AND PRASEODYMIUM

These two nuclides have the same number of neutrons (82) and differ in charge by only two. One would, therefore, expect very similar spectra. However, the Brookhaven Fast Chopper Group has found evidence for at least 5 resonances in praseodymium below 0.6 kev,[13] but over the same energy range found only one very weak one (at 73.5 ev) in lanthanum.[14] If the level spacing is approximately the same for the two nuclides, the strength function for lanthanum must be exceedingly low and at higher energies one should observe an average cross section practically constant and equal to the shape elastic scattering. Hence, no statistical variations should appear. Figure 5 shows the cross-section curve for lanthanum which was measured with a metallic lanthanum sample under our most favorable conditions. The observed peaks are narrow enough to be resonant peaks but the general appearance of the curve does not preclude statistical peaks. However, no peaks at all should be observable if the strength function of lanthanum is very low. Thus, it seems most likely that the level spacing of lanthanum is much greater than that of praseodymium. Preliminary experiments on La_2O_3 and Pr_2O_3 above 10 kev showed only statistical fluctuations.

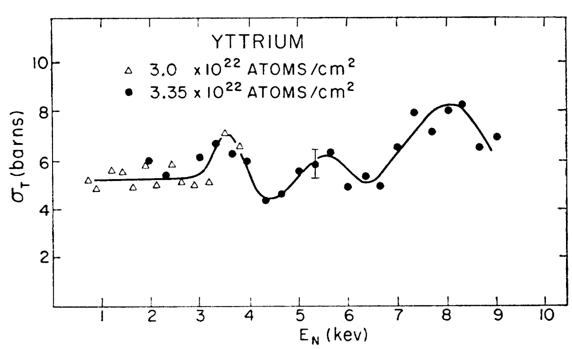

FIG. 7. Total neutron cross section of yttrium *vs* energy. Circled points were taken with a metallic sample. Data marked by triangles were taken with a Y_2O_3 sample and corrected for oxygen assuming $\sigma_T = 3.6$ barns.

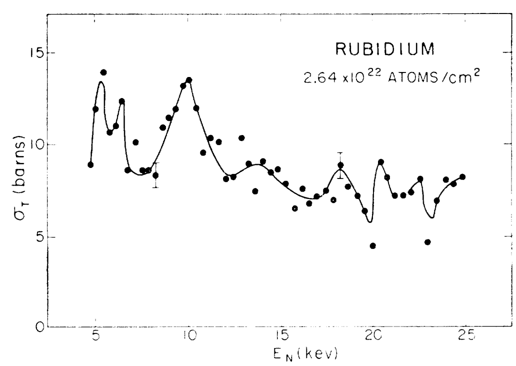

FIG. 8. Total neutron cross section of natural rubidium *vs* energy.

YTTRIUM

A sample of Y_2O_3 was studied with neutron energies up to about 80 kev. A number of definite peaks were observed, but the oxide sample was found to be slightly hydrated. Yttrium was remeasured (Fig. 6) with a sample of the pure metal loaned by the Ames Laboratories of the Atomic Energy Commission. The same resonance structure was found as before but the average cross section was now in agreement with results of Miller *et al.*[15] The earlier measurements, however, had slightly better resolving power and the double peak indicated in Fig. 6 at about 56 kev showed up much more clearly. A third measurement on metallic yttrium is shown in Fig. 7 (circles). These data were taken under

[11] Feshbach, Porter, and Weisskopf, Phys. Rev. **96**, 448 (1954).
[12] H. Marshak and H. W. Newson (to be published).
[13] Unpublished data from this group. This curve can be found in BNL 325 [D. J. Hughes and J. A. Harvey, *Neutron Cross Sections*, Brookhaven National Laboratory Report BNL-325 (Superintendent of Documents, U. S. Government Printing Office, Washington, D. C., 1955)].
[14] A. Stolovy and J. A. Harvey (to be published).
[15] Miller, Adair, Bockelman, and Darden, Phys. Rev. **88**, 83 (1952).

the best conditions as outlined in reference 1. The lower energy points (triangles) were measured with Y_2O_3 and corrected for the effects of oxygen and water. The first measurement on Y_2O_3 indicated two weak peaks at about 3 and 5 kev and later measurements (Fig. 7) confirmed this observation.

The spectrum of yttrium is difficult to interpret, because of its nearness to the $3p$ giant resonance at about $A=100$. The importance of p resonances in this spectrum is shown by the gradual increase of σ with energy in Fig. 6. An interpretation will be attempted in a later paper where other nuclides near $A=100$ will be discussed.

RUBIDIUM

RbI was pressed and sealed in a brass tube with 0.005-in. silver end windows. The cross-section curve (Fig. 8) was corrected for iodine and silver using the previously measured cross sections (see next section). Natural rubidium is 72% Rb^{85} and 28% Rb^{87} (50 neutrons). However, preliminary experiments with separated isotopes[3] indicate that both isotopes contribute to the lower energy peaks.

TABLE I. Averaged cross sections for gold, cesium, and iodine.

Element	Energy range (kev)	Sample thickness (10^{22} atoms/cm^2)	$\bar{\sigma}_T$ (barns)
Au	12–21 36–38	6.2	12.0
Cs	2–4.5	2.1	10.2
I	2–4.5	2.1	8.3

CLOSELY SPACED SPECTRA

Figure 9 shows three cross-section curves (measured with rather thick samples) for elements where the levels are so closely spaced that the apparent cross sections are essentially flat. Au, Cs, and I also showed no prominent maxima (see Table I). It is now known[16,17] that the resonance parameters and the distribution of neutron widths (approximately exponential) are such that there was practically no chance of observing even the strongest resonance in any of these elements.

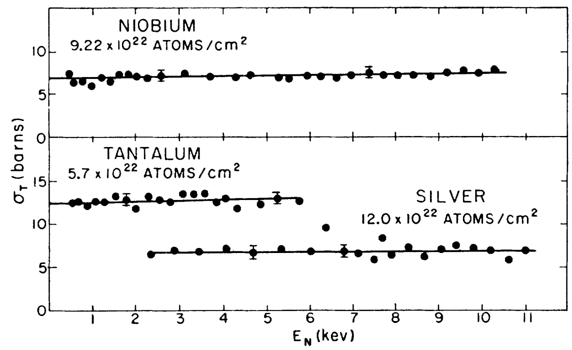

FIG. 9. Total cross sections of niobium, tantalum, and silver *vs* energy.

It may be noted that the average cross section of Cs is greater than that of I as might be expected from the nuclear model of Feshbach, Porter, and Weisskopf,[11] but appears to be contrary to the strength functions reported by the Brookhaven Group.[16,17] However, the observations are reasonably consistent if we take into account the rather large estimated uncertainties of the Brookhaven results for iodine.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge the help of P. Cap, T. E. Gilmer, E. Bilpuch, D. Herring, R. Smith, J. Vorona, O. Meier, A. L. Toller, and R. Block at various phases of this investigation. The Van de Graaff, which was of course indispensable, was purchased by the U. S. Atomic Energy Commission from the High Voltage Engineering Corporation. We are particularly grateful to Professor Spedding and the staff of the Ames AEC Laboratory for the loan of a sample of metallic yttrium.

[16] Seidl, Hughes, Palevsky, Levin, Kato, and Sjöstrand, Phys. Rev. **95**, 476 (1954).
[17] Harvey, Hughes, Carter, and Pilcher, Phys. Rev. **99**, 10 (1955).