isotope in each of the three spectra. The states of Sc^{45}, thus deduced, are shown in the energy level diagram of Fig. 5. For the states shown by solid lines, the evidence is conclusive; groups yielding this Q value were observed in two or more spectra, and could not be ascribed to contaminants. The two dashed lines indicate possible states. The proton groups which could be interpreted as due to such states showed better consistency if considered as due to N^{14} and C^{13} surface contaminants.

The work of Temmer and Heydenburg[13] indicated a level in Sc^{45} at 388 kev, which is in reasonable agreement with the 377-kev level found in the present experiment. Since their work was concerned with levels below 500 kev, they did not observe the 541-kev level, which the present results indicate to be the second excited state of this nucleus.

The β^- decay of Ca^{45} has an end point of 0.254 Mev[14] and thus produces no information on the level structure of Sc^{45}. The β decay of Ti^{45} has a maximum energy of 1.02 Mev; however, various observers[15] do not agree on the presence of γ rays in this process. The only reported γ-ray energy, 0.450 Mev, does not agree with the first excited state energy found here.

[13] G. M. Temmer and N. P. Heydenburg, Phys. Rev. **93**, 351 (1954).

[14] B. H. Ketelle, Phys. Rev. **80**, 758 (1950); Macklin, Feldman, Lidofsky, and Wu, Phys. Rev. **77**, 137 (1950); L. Marquez, Phys. Rev. **92**, 1511 (1953).

CROSS SECTIONS

Cross sections were estimated for all of the reactions studied. The values obtained are probably only accurate within a factor of two or three. For these measurements target thicknesses were determined as described previously. The yield was determined by direct count of the proton tracks that appeared in a given line on the photographic plate, while the incident beam was measured by means of a current integrator. The solid angle subtended by the spectrometer detection system was calculated from geometric considerations of the spectrometer dimensions, but was more accurately determined empirically by measuring the yield of reactions of known cross sections. The cross sections for the individual reactions are given in Table I along with the energy level information.

[15] H. E. Kubitschek, Phys. Rev. **79**, 23 (1950); Ter-Pogossian, Cook, Porter, Morganstern, and Hudis, Phys. Rev. **80**, 360 (1950); Naussbaum, Van Leishout, and Wapstra, Phys. Rev. **92**, 207 (1953).

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Total Neutron Cross Section of Thulium in the Energy Region 0.038 to 1.56 ev*

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Measurements of the total cross section of thulium as a function of neutron energy have been made with the Materials Testing Reactor crystal spectrometer. Twelve cylindrical pellets which contained a total of 2.414 grams of metallic thulium were used as a sample. The low-energy data can be described by the expression $\sigma(E)=6.5+20.1E_{ev}^{-\frac{1}{2}}$ (barns). The extrapolated value for the total cross section at 0.0253 ev is 134±3 barns.

I. INTRODUCTION

PRECISE values of the neutron cross section of thulium are of importance in the production of high specific activity thulium x-ray sources. Measurements of the resonance structure of thulium have been made by Foote, Landon, and Sailor[1] and Harvey, Hughes, Carter, and Pilcher.[2] When metallic thulium became available to the cross-section group at the Materials Testing Reactor (MTR), measurements were undertaken to increase the statistical accuracy of the data below 1 ev and to extend the measurements to 0.03 ev.

* Work carried out under contract with the U. S. Atomic Energy Commission.

[1] Foote, Landon, and Sailor, Phys. Rev. **92**, 656 (1953).

[2] Harvey, Hughes, Carter, and Pilcher, Phys. Rev. **99**, 10 (1955).

II. EXPERIMENTAL DETAILS

The cross-section measurements were made on the MTR crystal spectrometer at 5-minute increments in glancing angle with the 240 planes of a sodium chloride monochromating crystal. The over-all instrument resolution was 0.9 μsec/meter or 2.5% in energy at 1 ev.

The sample consisted of 12 cylindrical metal pellets that were sent to the MTR for irradiation. These were made available for cross-section measurements prior to irradiation. The pellets were 0.422 cm in diameter, 0.160 cm high and had a measured density of 9.00±0.05 g/cm^3. The thulium was purified and fabricated into pellets by Dr. F. H. Spedding and his colleagues at the U. S. Atomic Energy Commission's Ames Laboratory. The pellets, made by powder metallurgy techniques, contained small voids which were visible under low

magnification. A spectrographic analysis, supplied with the sample, listed the following impurities: Si<0.02%, Ca<0.04%, Mg<0.02%, Ta<0.05%, and Y<0.03%.

To use the pellets in transmission measurements, two sample containers were made of 2 in. thick pieces of borated Lucite containing about 2% by weight of boron. Holes 0.366 cm in diameter were counter-bored to a diameter of 0.430 cm and a depth of 0.320 cm. Since the plastic had poor dimensional stability, it was clamped tightly between $\frac{1}{4}$ in. plates of brass. The two assemblies were made as alike as possible by doing all surfacing and boring operations on a milling machine. One of the containers held the thulium pellets, and the other was used in the "open beam" position to correct, approximately, for the effects of the container material and geometry upon the Bragg beam. Both containers were mounted with the collimating holes in a vertical plane on a circular turn table which placed them alternately in the Bragg beam of the spectrometer. Since the transmission of this thickness of plastic is of the order of 0.05%, the Bragg beam was limited to passing through the circular openings. A single pellet would have had a high transmission in the low cross-section region so two pellets were placed in each of the bottom six holes of one container, and the top five holes of both were covered with pieces of borated plastic 2 in. thick. The resulting sample thickness was 0.3199±0.0021 cm or 2.88±0.02 g/cm². Prior to loading the pellets, the containers were translated and rotated in the Bragg beam to obtain a maximum counting rate. Because of the difficulty of alignment and possible dissimilarity of the containers, their counting rates differed by about 3%. Corrections for these differences were made as described in the next paragraph.

For the purpose of this discussion designate the empty container "container A" and the one containing the thulium "container B." If T_1 is the transmission of thulium, T_2 the ratio of the transmitted intensities for unloaded container B and container A, and $T_{1,2}$, the ratio of intensities for the loaded container B and empty container A (the observed transmission), then $T_{1,2}=T_1T_2$. Converting T_1 to cross section, we obtain $\sigma_{Tm}=-(\ln T_1)/n$, which reduces to

$$\sigma_{Tm}=-(\ln T_{1,2})/n+(\ln T_2)/n=\sigma(\text{obs})-\Delta\sigma,$$

where n is the number of thulium atoms/cm². The term $\Delta\sigma$ varies slowly with neutron energy and is essentially constant for energy increments large compared to the separation between individual points. The quantity T_2 was measured at several energies during the course of the experiment and corresponding correction factors were applied.

III. RESULTS AND DISCUSSION

Figure 1 shows a plot of the total cross section of thulium as a function of energy. For comparison, data

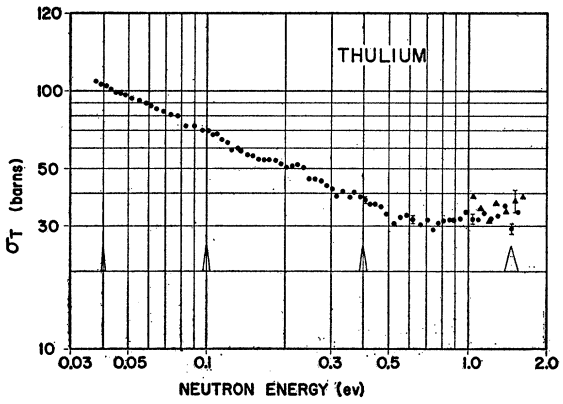

FIG. 1. Total neutron cross section of thulium as a function of energy. For convenient plotting several adjacent energy points were averaged. The number of individual observations averaged for one plotted point varies from ten at 0.04 ev to two at 1.5 ev. The triangular points are those obtained by Foote, Landon, and Sailor.[1] The vertical bars indicate standard deviations of the averaged points due to counting statistics. The full width at half-maximum of the triangles below the data represent energy spreads due to averaging of adjacent energy data and to instrument resolution.

obtained by Foote, Landon, and Sailor[1] between 1 and 1.7 ev are included. The MTR data were plotted as a function of $E^{-\frac{1}{2}}$ and were found to fit the empirical relationship, $\sigma=20.1E_{\text{ev}}^{-\frac{1}{2}}+6.5$ barns from 0.04 ev to 0.7 ev, with a root-mean square deviation of 1.4 barns for the individual points from the fitted line. Extrapolations to infinite and thermal ($E=0.0253$ ev) energies give values of 6.5±3 barns and 134±3 barns, respectively. The difference gives a value of 127±4 barns for the thermal absorption cross section. (The standard deviation includes the precision of fitting the data, uncertainty in sample thickness, and an estimate of the errors resulting from the use of the collimating sample holder.) This value is to be compared with the values of 118±6 barns obtained by Pomerance[3] and 106±20 barns obtained by Seren, Friedlander, and Turkel.[4] The relation for the potential scattering cross section,

$$\sigma_{sc}=4\pi(1.45\times10^{-13}A^{\frac{1}{3}})^2 \text{ cm}^2,$$

gives a value of 8.0 barns for thulium which agrees with the observed intercept.

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[3] H. Pomerance, Phys. Rev. 83, 641 (1951).
[4] Seren, Friedlander, and Turkel, Phys. Rev. 72, 888 (1949).