NEUTRON CROSS SECTIONS OF PRASEODYMIUM, YTTERBIUM AND LUTETIUM

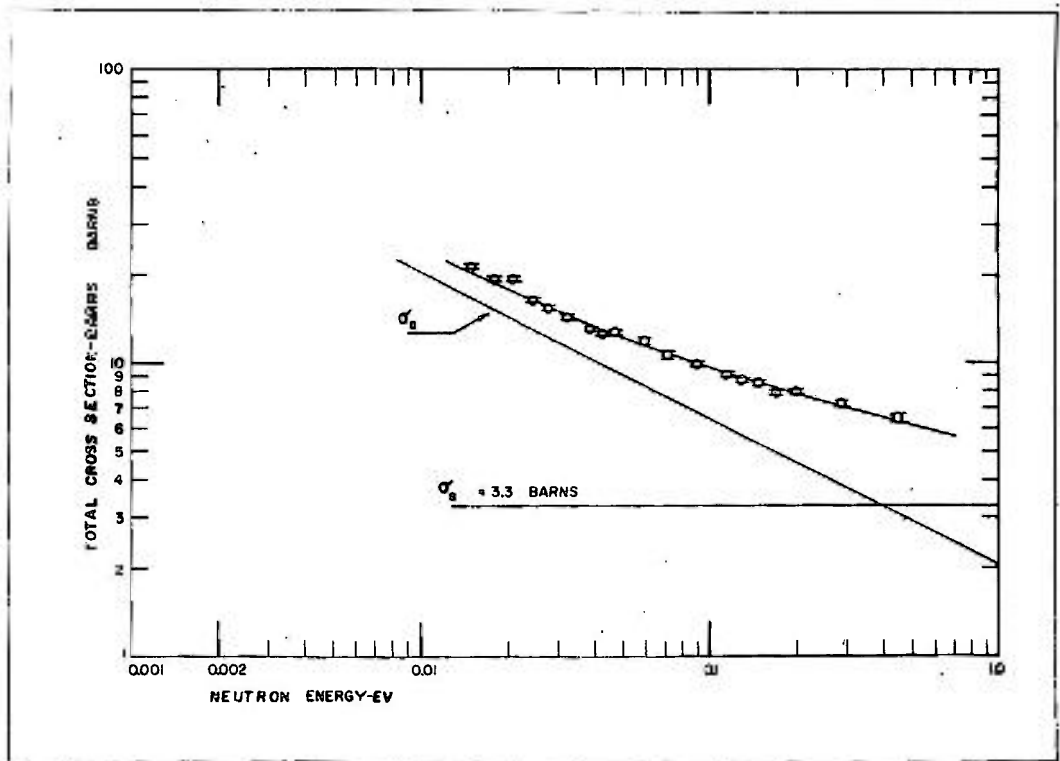*R. ZIMMERMAN, O. MARTINS, M. ABREU and M. C. MATTOS*

FIGURE 5

Total cross section of praseodymium. The statistical errors are shown on the experimental points. The solid curve through the experimental points is theoretically obtained assuming no nearby resonances. The two straight lines show the contribution of scattering $\widetilde{\sigma}_s$, and of absorption $\widetilde{\sigma}_a$.

NEUTRON CROSS SECTIONS OF PRASEODYMIUM, YTTERBIUM AND LUTETIUM*

by

R. Zimmerman**, O. Martins, M. Abreu and M. C. Mattos

NUCLEAR PHYSICS DIVISION
INSTITUTO DE ENERGIA ATÔMICA
São Paulo - Brasil

Presented at the 4th Inter-American Symposium on the Peaceful Application of Nuclear Energy, Mexico City, April 1962.

Comissão Nacional de Energia Nuclear

    Presidente: Prof. Luiz Cintra do Prado

Universidade de São Paulo

    Reitor: Prof. Luiz Antonio da Gama e Silva

Instituto de Energia Atômica

    Diretor: Prof. Rômulo Ribeiro Pieroni

Conselho Técnico-Científico do IEA

    Prof. José Moura Gonçalves   )
) pela USP
    Prof. Francisco João Humberto Maffei)

    Prof. Rui Ribeiro Franco   )
) pela CNEN
    Prof. Theodoreto H.I. de Arruda Souto)

Divisões Didático-Científicas:

    Div. de Física Nuclear: Prof. Marcello D.S. Santos

    Div. de Engenharia de Reatores: Prof. Paulo Saraiva de Toledo

    Div. de Ensino e Formação: Prof. Luiz Cintra do Prado

    Div. de Radioquímica: Prof. Fausto Walter de Lima

    Div. de Radiobiologia: Prof. Rômulo Ribeiro Pieroni

    Div. de Metalurgia Nuclear: Prof. Tharcisio D.Souza Santos

    Div. de Engenharia Química: Prof. Pawel Krumholz

NEUTRON CROSS SECTIONS OF PRASEODYMIUM,

YTTERBIUM AND LUTETIUM

R. Zimmerman , O. Martins, M. Abreu and M.C. Mattos.

Instituto de Energia Atômica, São Paulo, SP, Brasil.

SUMÁRIO

A secção de choque total foi medida para os óxidos das
terras raras praseodímio, itérbio e lutécio para a energia dos
neutrons variando de 0,015 a 0,3 electron volts com especial aten
ção para conseguir valores na energia térmica 0,025 ev. Para es-
sas medidas, usou-se no reator do I.E.A. um monocromador de neu-
trons a cristal de calcita natural. As amostras dos óxidos foram
fornecidas pelos laboratórios de pesquisa da Orquima S.A.. Veri-
ficou-se, experimentalmente, a pureza do praseodímio cuja secção
de choque é a mais sensível a impurezas de alta secção de choque,
fazendo-se a medida destas antes e depois de um processo de puri
ficação que deveria diminuir a concentração do gadolíneo de   um
fator superior a cem. A concordância dos resultados obtidos indi
ca que as amostras de óxidos usadas no presente trabalho conti-
nham quantidades desprezíveis de gadolíneo e samário. A correção
das secções de choque, devida à presença da reflexão de segunda
ordem dos cristais, foi feita experimentalmente medindo-se a sec
ção de choque conhecida do ouro no intervalo conveniente de ener
gia. Em um dêstes elementos, o lutécio, existe uma ressonância
nuclear dentro do intervalo estudado. Os parâmetros encontrados
para essa ressonância coincidem com os valores publicados,   mas
com uma melhor aproximação. Cálculos com a fórmula de   Breit-
-Wigner para essa ressonância no lutécio e para a secção de cho-
que do praseodímio mostram que nenhum estado ligado, na vizinhan
ça, é necessário para explicar a grandeza e forma dos resultados
experimentais. Provas de um estado ligado existem no caso do itér
bio.

SOMMAIRE

La section efficace totale des oxides des terres rares
praseodymium, ytterbium et lutetium a été mesurée dans l'inter -
valle d'énergie de neutrons 0,015 à 0,3 electron volts, en fai-
sant spéciale attention quant à obtenir des valeurs à l'énergie
thermique 0,025 ev. Pour ces mesures, on a utilisé au réacteur

de l'IEA un monochromateur de neutrons à crystal de calcite naturel. Les échantillons des oxides ont été fournis par les labo ratoires de l'Orquima S.A.. On a verifié, expérimentalement, la pureté du praseodymium dont la section efficace est la plus sen sible à des impuretés de haute section efficace, en mesurant la section efficace de l'échantillon avant et après un procédé de purification qui devait diminuer la concentration du praseody - mium d'un facteur supérieur à cent. L'accord des résultats obte nus indique que l'échantillon employé à notre expérience conte- nait des quantités négligeables de gadolinium et samarium. La correction des sections efficaces, due à la présence de la re- flection de deuxième ordre des cristaux, a été faite, expérimen talement, en mesurant la section efficace connue de l'or dans l'intervalle convenable d'énergie. Quant à l'un de ces éléments, le lutetium, il y a une résonance nucléaire dans l'intervalle étudié. Les paramètres trouvés pour cette résonance coincident avec les valeurs publiées, mais avec une meilleure approxima - tion. Des calculs avec la formule de Breit-Wigner pour étudier cette résonance du lutetium et la section efficace du praseody- mium montrent qu'il n'y a pas besoin d'un état lié, ou voisina- ge, pour expliquer la grandeur et la forme des résultats expéri mentaux. Des preuves d'un état lié existent dans le cas de l' ytterbium.

ABSTRACT

The total neutron cross section of oxides of the rare earths praseodymium, ytterbium and lutetium has been measured within the neutron energy range from 0.015 to 0.3 electron volts, very special attention having been given to obtain values at the thermal energy 0.025 ev. For these measurements, a crystal neutron monochromator with natural calcite crystals was used at the IEA reactor. The oxide samples were supplied by the Orquima Industries S/A. The purity of the praseodymium, which is most sensitive to high cross section impurities, was checked experimentally by measuring the cross section of the sample before and after a purification process which reduces the gadolinium concentration by more than a factor of 100. The consistency of the results indicates that the sample used in these experiments contains a negligible amount of gadolinium and samarium. The correction to the cross sections due to the presence of second order reflection from the monochromator crystal was made experimentally by measuring the well-known gold cross section in an appropriate energy interval. In one of the elements, lutetium, a nuclear resonance exists within the energy range studied. The parameters found for this resonance agree with the published values but with improved accuracy. Calcul- ations with the Breit-Wigner formula for this resonance in lutetium, and for the cross section of praseodymium, show that no nearby bound state is necessary to explain the magnitude and shape of the experimental results. Evidence of a bound state exists in the case of ytterbium.

NEUTRON CROSS SECTIONS OF PRASEODYMIUM,

YTTERBIUM AND LUTETIUM

INTRODUCTION

The neutron cross sections of the rare earth nuclei have received very special attention. Because these rare earths are present in the fragments of nuclear fission, their cross sections play an important part in the calculations of reactor physicists who must predict the effects of neutron absorbers in a nuclear reactor. In addition, the rare earth nuclei are among those which have a higher than the average absorption cross section below 1 Mev because their radius has a size, relative to the neutron wavelength, which greatly augments the effective penetrability of the nuclear surface [1]. Finally, mos of the rare earth nuclei possess a number of nucleons intermediate between the numbers required to close the nuclear shells. This last fact explains why the rare earth nuclei have a large number of nuclear levels available for studying with thermal and fast neutrons. The parameters of these levels often enter into reactor design calculation, and are of great importance to theoretical nuclear physics as well.

While these reasons have prompted experimental physicists to collect a large amount of data [2], a few elements still exist whose cross sections have never been measured in the thermal neutron energy range, or for which existing measurements show discrepancies relative to the methods used for their determination.

Although the measurements themselves are in principle very simple, the materials are often very rare and difficult to

purify sufficiently.

We are fortunate in Brazil to have a large source of rare earth materials in the mineral monazite, and a local industry well equipped to separate and purify the individual rare earths. One of these industries has isolated many of these materials in quantities and degrees of purification unknown elsewhere in the world.

We have chosen to concentrate our efforts on the total cross sections of praseodymium, lutetium, and ytterbium in the thermal neutron energy range because no measurements exist, and because for lutetium and ytterbium reasonable extrapolations of the existing measurements of the total cross sections at higher energy, together with reasonable assumptions of the potential scattering, do not agree with the absorption cross section obtained with pile oscillators.

This paper is identical to Publicação IEA nº 51, in Portuguese version, except for minor tipographical corrections.

EXPERIMENTAL APPARATUS

The neutrons for this work were produced in the Instituto de Energia Atômica reactor, a Babcock Wilcox swimming pool research reactor designed to operate at a maximum power of 5 Mw. During most of this experiment the reactor was operated eight hours each week at 2 Mw for the purpose of this experiment, for the production of radioisotopes, and other purposes as well. Recently, when increased radioisotopes demand and additional experiments required it, the reactor schedule was enlarged to two such irradiations each week routinely, and with low-power irradiations the other days of the week. The policy always has been to operate the

reactor on a schedule and at power levels to accommodate every coordinated request by the various divisions requiring irradiation facilities.

The neutron crystal spectrometer was located close to the reactor on one of the fourteen horizontal experimental ports. The neutron beam was allowed to pass from the moderator close to the edge of the core through an air-filled tube and collimator to the spectrometer outside the shielding. The thermal flux, at the neutron radiator, measured with gold foils, near the core of the reactor is $2.4 \cdot 10^{12}$ $n/cm^2/$ second with the reactor at 2 Mw. A lead gate was provided to close the beam port.

The mechanical apparatus that constitutes the crystal spectrometer was constructed in the shops of the Instituto de Energia Atômica and consists of a steel column which supports both the crystal mount and the moveable arm of the detector. The detector arm may move through an arc of 90° in the horizontal plane starting from the direction of the main beam. Angles may be read on a vernier scale with a precision of 0.01 degree.

The spectrometer design and the detection system are similar to what has been described in the literature published some time ago [3,4,5,6].

The supporting mount of the crystal has six degrees of freedom and may be adjusted manually to optimize the alignment.

The crude alignment of the spectrometer was made periodically by exposing photographic plates to the residual gamma beam of the reactor. The BF_3 neutron detectors were used for final alignment. The latter was used in its normal position on the spectrometer arm to establish accurately the position of the undeflected beam of neutrons from the reactor. Later, with the detector arm at some larger angle,

the crystal was mounted and adjusted to optimize the counting rate.

An auxiliary experiment was performed with the spectrometer apparatus with a theodolite and a mirror in place of the crystal. It was verified that the Bragg angle could be reproduced to less than one minute of arc. In addition, this experiment confirmed that, although a relatively large backlash existed in the two-for-one spectrometer gearing, the two-for-one condition could be maintained within less than three minutes during an operation that involved many changes in the spectrometer angle.

In the cross section measurements, no difficulty was encountered either in reproducing an angle, or in maintaining the two-for-one condition over a large range of angles.

The cross section measurements were taken with a natural crystal of calcite whose interplanary distance was $3.03 \cdot 10^{-8}$ cm.

Commercial boron trifluoride detectors, enriched to 90% in the isotope B^{10} and filled to a pressure of 120 cm Hg, were used for the main detection; shielding of boric and paraffin was coaxially arranged with the detector. The monitor system in the direct beam used a counter of the same type but with lower efficiency owing to the high flux in the direct beam. A system of three independent channels was used, two for the main system and one for the monitoring system. The components of the main system were as follows:

1. Stabilized high voltage supply.
2. Pre-amplifier with cathode follower.
3. Linear amplifier.
4. Pulse-height discriminator.

5. Scalers, recorder, and ratemeter.
6. Remote controls for spectrometer.
7. Electronic voltage stabilizer.

(See figure 1.)

A large fraction of the electronics, including essential components, was manufactured by local industry from advanced modern designs.

A beam-catcher of concentric layers of boric acid and paraffin has been built thinking of the biological protection of the spectrometer staff. Behind the beam-catcher, a wall was built of barium concrete bricks with about half a meter thickness.

The control of the neutron flux, from the exit of the first collimator to its entrance into the beam catcher, has been done by three different processes:

1. Theoretical calculation, considering only the beam opening.
2. Gold foil method.
3. With a BF_3 counter.

Some of the results, normalized for 2 Mw, can be seen in Table I. We adopted as standard position in every experiment the angle formed by the detector and the direct beam equal to 25 degrees, which corresponds for the calcite to a 0.0470 electron volts energy; at this energy the number of neutrons counted by the detector is 2,440 n/sec.

The samples, prepared as described in the next section, were placed in aluminium holders and introduced into the beam in an accurately reproducible position. The transmission through the sample was obtained by measuring the counting rate with the

. 7 .

sample in the beam, and the rate obtained with an identical empty sample holder in the beam. A small background was subtracted from each counting; this background was obtained by rotating the crystal away from the Bragg angle enough to remove all coherently scattered neutrons. The sample holders were changed manually and the counting rates recorded manually.

To avoid the influence on the transmission of the variations of the reactor power and the instability of the electronics, we took the following precautions:

1. The transmission measurements were repeated several times in cycles of about five minutes, according to a routine designed to cancel linear drifts in the counting rate.

2. The flux of the reactor was monitored during the measurements with an independent detector and electronic system.

3. The main detector pulses were amplified, analyzed and counted by two independent electronic systems. In this way, the stability of the systems could be tested continuously by the relation between the two counting rates.

4. The high-voltage sources, amplifiers and analyzer were connected to electronic stabilizers of the alternating current power.

SAMPLE PREPARATION

The oxides of praseodymium, lutetium, and ytterbium were placed in containers designed to give the best transmission[7] in the energy range from 0.01 to 0.4 electron volts, taking for

the cross sections in these intervals averages extrapolated from the values already known.

The samples used were supplied by the Orquima S/A. laboratories; the method employed, using ionic resins, assured us of the degree of purification necessary for these experiments.

The effects of sample contamination by water were noticed in the first measurements by the increase of the measured cross section with time. To avoid this contamination, the samples were calcinated for one hour at 900° C and stored in a dessicator during the measurement interval. Next, the sample weight was checked during the experiment and the cross section, measured for an energy of 0.0470 electron volts, was presented graphically against the date of the experiment; no variations larger than the experimental errors were observed.

The absence of gadolinium in a quantity that could affect the value of the measured cross section was checked by measuring the cross section before and after a purification process which would reduce the gadolinium concentration by more than a factor of 100; no variations of the measured cross sections larger than the experimental error have been noticed.

The stoichiometric formulae used for the oxides were [8]:

$$Lu_2O_3, \quad Yb_2O_3 \quad \text{and} \quad Pr_6O_{11}.$$
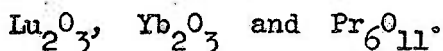
On the two former oxides small differences from these formulae do not affect the measurements, because lutetium and ytterbium have cross sections much higher than oxygen. For the praseodymium oxide the assumed formula was Pr_6O_{11}; this formula has been determined after the one-hour calcination at

900° C, by dissolving the oxide in hydrochloric acid, in the presence of potassium iodide. The free iodine corresponds to the active oxygen, not stoichiometric, existing in the Pr_2O_3. This iodine is titrated with sodium thiosulfate (appendix I).

CROSS SECTION CALCULATIONS

For the cross section measurements, the counts were taken in cycles of about five minutes. In the calculations the corresponding counts and the respective times were added; calculations were made for the two channels, independently, using the formula

$$\sigma = \frac{1}{n} \ln \left(\frac{I - Bg}{I_o - Bg_o} \right) - B,$$

where σ is the cross section of the element, I is the total counting rate with sample, I_o is the total counting rate without sample, Bg is the total background counting rate with sample, Bg_o is the total background counting rate without sample, B is a constant that depends on the chemical composition of the sample, and

$$n = c \cdot \frac{N_o \, m}{A \cdot (\text{perpendicular area})} \, ;$$

in this formula, A is the molecular mass of the compound, c depends on the sample stoichiometry and m is the sample mass.

The conventional formula has been used for the error.

Calculations were made twice for each one of the two channels, independently, by different computors and the four results have been compared, in order to eliminate calculation errors.

For ytterbium and praseodymium there is only the correction due to oxygen. For lutetium, in addition to the correction due to oxygen, a correction due to 8.5% of ytterbium oxide has to be made.

The second order correction was made by using as standard sample gold, whose microscopic cross section, for a certain energy (first order), is know with precision. The formula used for the second order correction was:

$$\sigma = \sigma_m - \frac{1}{n} \ln \left[1 + k \left(1 - e^{n(\sigma_m - \sigma_2')}\right)\right] \quad (A.1)$$

(see appendix II).

COMPARISON WITH THE BREIT-WIGNER FORMULA

The Breit-Wigner formula, as is shown in formula (A.3), appendix III, has been compared with the experimental values of ytterbium. We did not measure experimentally the cross section near the closest resonance peak, which we know is due to the Yb^{168} isotope, but we worked in a region where its influence can be felt. In the calculation of the cross section due to this resonance at $E_0 = 0.597$ ev, we assumed the values[2,9] $\sigma_0 \Gamma^2 = 1.28$ barns. ev^2, $\Gamma_\gamma = 0.073$ ev, where σ_0 is the cross section value at energy E_0.

The Breit-Wigner formula becomes

$$\sigma = \frac{4.28 \sqrt{\dfrac{E_0}{E}}}{4(E - 0.597)^2 + 0.0053} + \sigma_s + \frac{a}{\sqrt{E}}, \quad (2)$$

where a is a parameter that can be adjusted and that depends on distant resonance absorptions. In order to adjust this

theoretical formula to the experimental curve, we determined the constants $\sigma_s = 18$ barns and a = 8.0 barns $\text{ev}^{1/2}$; it can be seen in figure 2 that $\dfrac{a}{\sqrt{E}} = \sigma_{a_o}$

The formula used for the lutetium data was the formula (A.2) that is shown in appendix III. It is known that lutetium has a very high spin, equal to 9 or 10, and so g is very close to 1/2.

For Lu^{176} we assumed
$$f = 0.0264$$
$$g = 0.5$$
$$\sigma_s = 10 ,$$

where σ_s was assumed by comparison with values for nearby nuclei.

Comparing the theoretical and experimental curves, the parameters Γ_n^o and Γ_γ were determined, and the following values were obtained: $\Gamma_\gamma = 0.0584 \pm 0.003$ ev, $\Gamma_n^o = 0.000201 \pm 0.000004$ ev, and for the constant a = 10 barns. $\text{ev}^{1/2}$. For the resonance energy the value obtained was $E_o = 0.141 \pm 0.002$ ev. The results obtained are compared with the experimental points in figures 3 and 4.

For praseodymium the experimental points are for energies much lower than the one of the nearest resonance peak, that is for $E_o = 85.5$ ev. In the region where we work, that is, in the range from 0.015 to 0.5 ev, the first term of the formula (A.2), that is shown in appendix III, becomes negligible and the cross section varies as a function of energy according to the formula

$$\sigma = \sigma_s + \frac{a}{\sqrt{E}} ;$$

the constants σ_s and a are determined in order to adjust the

theoretical curve to the experimental one; we obtained the
values

$$\sigma_s' = 3,3 \quad \text{barns}$$
$$a = 2,05 \quad \text{barns. ev}^{1/2}.$$

The results can be seen in figure 5.

RESOLUTION

The energy resolution of a neutron crystal mono-
chromator is determined to some extent by the initial
collimation, the collimation on the arm of the spectrometer, and
by the mosaic structure of the crystal. It is seldom determined
wholly by one or two of these as may be observed in the
literature.

It is commom practise to optimize the counting rate by
perfoming an auxiliary experiment with the spectrometer arm fixed
and varying the angle of the crystal. The well-known "rocking
curve" is the result. The half width, $\Delta\Theta_R$, of this nearly
symmetrical curve is determined in general by the geometry of both
collimators and by the mosaic structure of the crystal, and it may
be approximately given by

$$\Delta\Theta_R = \sqrt{\left(\frac{\Delta\Theta_1}{2}\right)^2 + \left(\frac{\Delta\Theta_2}{2}\right)^2 + \left(\Delta\Theta_m\right)^2} \quad , \qquad (3)$$

where $\Delta\Theta_1$, $\Delta\Theta_2$ and $\Delta\Theta_m$ are, respectively, the half
widths of the angular divergences of the two collimators, and of
the angular distribution of the micro-crystals in the mono-
chromator. Each has been well approximated to have a Gaussian
shape, here assumed to be equal in both vertical and horizontal
directions.

. 13 .

In the cross section experiment it is clear that neither the spectrometer arm nor the crystal is moved and the resolution, or half-width of the probability distribution of the Bragg angles experienced by the neutrons detected, is a complicated function of the three parameters $\Delta\theta_1$, $\Delta\theta_2$, and $\Delta\theta_m$. In particular it is not always simply related to the rocking curve, $\Delta\theta_R$.

If the collimation angle on the spectrometer arm, $\Delta\theta_2$, is larger than $\Delta\theta_1 + 2\Delta\theta_m$, the resolution, R, is given approximately by

$$R = \sqrt{\left(\Delta\theta_m\right)^2 + \left(\frac{\Delta\theta_1}{2}\right)^2} \quad . \quad\quad (4)$$

The resolution is thus mostly determined by the larger of the two angles under the radical, and is not related in a sensitive way to the results of the "rocking curve" experiment.

If $\Delta\theta_2$ is much smaller than both $\Delta\theta_1$ and $2\Delta\theta_m$, the resolution is

$$R = \Delta\theta_m \qquad \text{if } \Delta\theta_1 > 2\Delta\theta_m$$

or

$$R = \frac{\Delta\theta_1}{2} \qquad \text{if } \Delta\theta_1 < 2\Delta\theta_m \quad\quad (5)$$

Thus the resolution is determined by the smaller of the two angles considered before, and it is more readily related to the width of the rocking curve by allowing $\Delta\theta_2$ go to zero in equation (3).

Only for the values of the spectrometer arm collimator intermediate between the two extreme values considered above does $\Delta\theta_2$ affect the resolution and may be used as a convenient way of changing it.

With the natural calcite crystal used throughout our experiments the rocking curve was observed to have a half width of 22 minutes. The angular divergence of the collimators was measured to be 19 minutes for the first, and 15 minutes for the second, or spectrometer arm collimator. Equation (3) then gives the mosaic structure of the crystal to be about 18 minutes. In practise, the second collimator was designed to have 15 minutes of angular divergence, in order to leave the resolution almost entirely determined by the crystal structure, in this case.

The collimators were constructed of steel, and the effect of reflection from their walls may be neglected.

With $R = \triangle \Theta_m$ = 18 minutes, as in equation (5), there is no resolution correction to our results, except for the case of lutetium. The peak cross section of lutetium requires a 2% resolution correction and the effect on the other parameters is of the same order.

CONCLUSION

Our experimental results, calculated as has been described in the preceding section, are shown in table II.

In each case, our results may be used for determining the value of the total cross section at thermal energy. By using the theoretically calculated behaviour of the cross section at low energy, many points may help to determine the value of the thermal cross section and the partial cross sections σ_s and σ_a may be determined as well, although with less accuracy. The results of this analysis appear in Table III, together with previously published results. Comparison only may be made for the partial cross sections, since no previous measurements of the total cross section at thermal

energy exist.

Table III shows that our measurements of the
praseodymium total cross section agree with the previously
published results. We must place a relatively large experimental
error on our partial cross sections because of the uncertainty
in finding the correct division of the total cross section into
the two components.

Similarly with lutetium, the previously published
absorption cross section agrees with our total cross section
considering the uncertainty in estimating the scattering cross
section.

In contrast, our ytterbium results conflict with the
existing absorption cross section. In addition, the large
activation cross section previously observed [2] for the isotope
168 accounts for 15 barns absorption in normal ytterbium, only
about 5 barns of which come from the level observed at .597 ev.
A bound state in the isotope 168 near zero neutron energy would,
of course, explain this discrepancy and could explain our
observation that the scattering cross section is higher than is
expected from potential scattering alone. When the resonance
parameter and isotopic assignments of higher energy resonances
are known, the possible parameters and position of this bound
state can be calculated.

Another group at the Instituto de Energia Atômica will
measure the absorption cross section of some of the important
rare earth elements by comparing the neutron age in a solution
containing the unknown material with that obtained with a
solution containing a standard material. Moderated neutrons will
be provided by a Van de Graaf. The results of this work will check
the previous measurements with pile oscillators, and perhaps

eliminate the discrepancy between our total cross section of
ytterbium and the previously published absorption cross
section (see Table II).

DETERMINATION OF ACTIVE OXYGEN IN
## PRASEODYMIUM OXIDE

The principle of this determination is the following: the oxide is dissolved in hydrochloric acid in the presence of potassium iodide and the free iodine is titrated with thiosuphate. The free iodine corresponds to the active oxygen [8].

The reagents used were

a) Starch solution: 2,5 g/l - Dissolve in hot water, boil, cool, and dilute. Use solution recently prepared.

b) Sodium thiosulphate, $Na_2S_2O_3 \cdot 5H_2O$, 0.1 M (24,82 g/l) - Weigh 25g of the Salt, dissolve in hot water, add 0.1g of Na_2CO_3, cool and complete the volume in a 1 litre volumetric flask.

c) Sodium thiosulphate 0.01 M. Dilute solution b ten times. For standardization of thiosulphate[10]: iodine - Put in a weighing bottle 2-3g of KI and dissolve in a minimum of water (1 to 2ml). Weigh . Add 0.4 or 0.5g of re--sublimated C.P. iodine and weigh again analitically. For titration - Transfer to an Erlenmeyer containing 200 ml 1% KI solution (2g of KI in 200 ml of water) and titrate with sodium thiosulphate, using 5 ml of the starch solution. The correspondent reaction is

$$2\ Na_2S_2O_3 + I_2 = 2\ NaI + Na_2S_4O_6;\ thus,$$
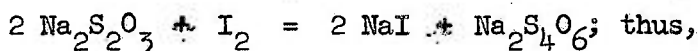
thiosulphate title = iodine mass/thiosulphate volume x 126.92.

d) hydrochloric acid 1 + 1. One volume of C.P. hydro-

chloric acid + one volume of water.

      e) KI solution - Dissolve 100g of KI in one litre of
water. Keep it in a brown bottle.

The dissolution of oxide was made in one 125 ml
Erlenmeyer, with a ground joint, a ground covering and reflux
with ground adaptation for the Erlenmeyer flask.

For the dissolution, weigh (analytically) about 100 mg
of oxide, transfer to the Erlenmeyer with a minimum of water, add
10 ml of the KI solution (100 mg/l) and adapt the reflux vertical
ly. Add, through the reflux, 5ml of HCl 1+1 and heat during
5-10 minutes, until complete dissolution of the oxide, maintaining
a good circulation of water through the reflux. Take out the heat-
ing mantle. Add, through the reflux, 20 ml of iced water, to wash
the walls. Cool the Erlenmeyer with iced water, but maintaining
the reflux adapted. Take out the Erlenmeyer, titrate immediately
with thiosulphate 0.01 M, by using 5 ml of the starch solution. If
it is impossible immediately to titrate, or if it is necessary to
transfer the Erlenmeyer, close it with the ground covering.

Blank.

Repeat the procedure using only 10 ml of KI 100g/l and
5 ml of HCl and titrate the free iodine.

The formula for the calculation was

$$W = \frac{V. \; 1.6492}{m - 0.08 \, . \, V} \qquad , \text{ where } \underline{V} \text{ is the}$$

volume of thiosulphate 0.01 M (already corrected by factor and
discounted the blank), in millilitres, $\underline{m}$ is the mass of
praseodymium oxide in milligrams, and $\underline{W}$ is the number of atoms
of active oxygen per weight-gram Pr_2O_3. The atomic mass and
weight-grams used were:

$$O = 16.00,$$
$$I = 126.92,$$
$$Pr = 140.92,$$
$$Pr_2O_3 = 329.84 \text{ and } Na_2S_2O_3 \cdot 5H_2O = 248.21$$

APPENDIX II

SECOND ORDER CORRECTION

Being σ^* the measured cross section of the standard sample, with second order contamination, I_1 and I_2 direct beam intensities, i_1 and i_2 beam intensities transmitted through the sample, σ_1 and σ_2 standard sample cross sections, N standard sample constant, the direct beam intensity measured is $I = I_1 + I_2$, the intensity of the transmitted beam is $i = i_1 + i_2$; if we call k the ratio

$$k = \frac{I_2}{I_1}, \quad \text{we have} \quad \frac{I}{i} = \frac{I_1 + I_2}{i_1 + i_2} \; ;$$

we arrive at $k = -\dfrac{1-e^{N(\sigma^* - \sigma_1)}}{1-e^{N(\sigma^* - \sigma_2)}}$; let us

call now σ = cross section at the energy E_1 of the material studied; σ_m = measured cross section at the energy E_1 ; σ_2' = = cross section at the energy $E_2 = 4 E_1$, n = sample constant. Then,

$$e^{n\sigma_m} = \frac{1 + k}{1 + k \, e^{n(\sigma - \sigma_2')}} \, e^{n\sigma}$$

and we arrive at

$$\sigma = \sigma_m - \frac{1}{n} \ln\left[1 + k\left(1 - e^{n(\sigma_m - \sigma_2')}\right)\right] . \quad (A.1)$$

APPENDIX III

BREIT-WIGNER FORMULA.

The Breit-Wigner formula determines the cross section, σ, as a function of energy, E, for one level at E_o.

We define Γ_n^o as reduced width for emission of neutrons; it gives a partial probability for emission of neutrons, reduced for the value relative to 1 ev.

$$\Gamma_n = \Gamma_n^o \sqrt{E} ,$$

where Γ_n^o is the disintegration probability for emission of neutrons; it is a partial width. Γ_γ is the disintegration probability for emission of gamma rays. Γ gives the total disintegration probability. It is approximately the width of the level at half height.

$$\Gamma = \Gamma_n^o + \Gamma_\gamma .$$

We substitute for these values in the Breit-Wigner formula, which becomes

$$\sigma = \frac{\lambda^2}{4\pi} \frac{fg \; \Gamma_n^o \left(\Gamma_n^o + \frac{\Gamma_\gamma^o}{\sqrt{E}} \right)}{(E-E_o)^2 + \frac{1}{4}\left(\Gamma_n^o \sqrt{E} + \Gamma_\gamma \right)^2} + \sigma_{pot} + \frac{a}{\sqrt{E}}$$

f is defined as the isotopic abudance; g is a statistical factor depending on the spin.

$$g = \frac{1}{2} \frac{2J+1}{2I+1}$$

$$J = I \pm \frac{1}{2} .$$

I is the spin of the target nucleus, J is the spin of the compound nucleus and σ_{pot} is the potential scattering cross section. $a = \sigma_a \sqrt{E}$, where σ_a is the absorption cross section due to other resonances.

The Breit-Wigner formula becomes, then,

$$\sigma = \frac{fg \quad .6511 \times 10^6 \; \Gamma_n^o \left(\Gamma_n^o + \frac{\Gamma_\gamma}{\sqrt{E}} \right)}{(E-E_o)^2 + \frac{1}{4} \left(\Gamma_n^o \sqrt{E} + \Gamma_\gamma \right)^2} + \sigma_s + \frac{a}{\sqrt{E}}, \quad (A.2)$$

Calculations have shown, in our case, that the term due to the interference between the potential scattering and the resonance scattering is negligible. Interference between potential scattering and scattering from distant resonances is slowly varying and for our purposes simply adds to σ_{pot} to give scatter ing cross section σ_s.

For calculating $\frac{\lambda^2}{4\pi}$, where λ is the neutron wavelength, we assumed in the de Broglie expression $\lambda^2 = \frac{h^2}{2m\,E}$ the following values for Planck's constant h, for the mass of the neutron m and for the conversion of units:

$$h = 6.625 \times 10^{-27} \text{ erg. seg}$$
$$m = 1.675 \times 10^{-24} \text{ g}$$
$$1 \text{ ev} = 1.602 \times 10^{-12} \text{ erg}$$
$$1 \text{ barn} = 10^{-24} \text{ cm}^2 .$$

The result is

$$\frac{\lambda^2}{4\pi} = \frac{.6511 \times 10^6}{E} \text{ barns.}$$

The Breit-Wigner formula may be written, then, as follows:

. 22 .

$$\sigma = \frac{\sigma_0}{4} \Gamma'^2 \frac{\sqrt{\dfrac{E_0}{E}}}{(E-E_0)^2 + \dfrac{\Gamma'^2}{4}} + \sigma_s + \frac{a}{\sqrt{E}} \qquad (A.3)$$

. . . .

ACKNOWLEDGEMENTS

REFERENCES:

1 - Feshback, H., Porter C.E. and Weisskopf, V.F., Phys. Rev. 96, 448 (1954).

2 - Hughes, D.J. and Schwartz, R.B., Neutron Cross Section, U.S. Government Printing Office (1958) - BNL 325.

3 - Hurst, D.G., Pressesky, A.J. and Tunnicliffe, P.R., Rev. Sci. Instr. 21, 705 (1950).

4 - Sturm, W.J., Phys. Rev. 71, 757 (1947).

5 - Zinn, W.H., Phys. Rev. 71, 752 (1947).

6 - Borst, L.B. and Sailor, V.L., Rev. Sci. Instr. 24, 141 (1953).

7 - Rose, M.E. and Shapiro, M.M., Phys. Rev. 74, 1853 (1948).

8 - Vickery, R.C., Chemistry of the Lanthanons 247, Academic Press Incorporated, (1953).

9 - Sailor, V.L., Landon, H.H. and Foote, H.L., Phys. Rev. 96, 1014 (1954)

10 - Scott's Standard Methods of Chemical Analysis, vol. 1.

o o o o o o o o o o o o

REACTOR SHIELDING · SAMPLE · COLLIMATOR No.2 · AMPLIFIERS · DISCRIMINATORS · SCALERS · HIGH VOLTAGE SUPPLY · PRE AMP · COLLIMATOR No. 1 · CRYSTAL · BF_3 DETECTOR AND SHIELDING · BEAM CATCHER · 2θ
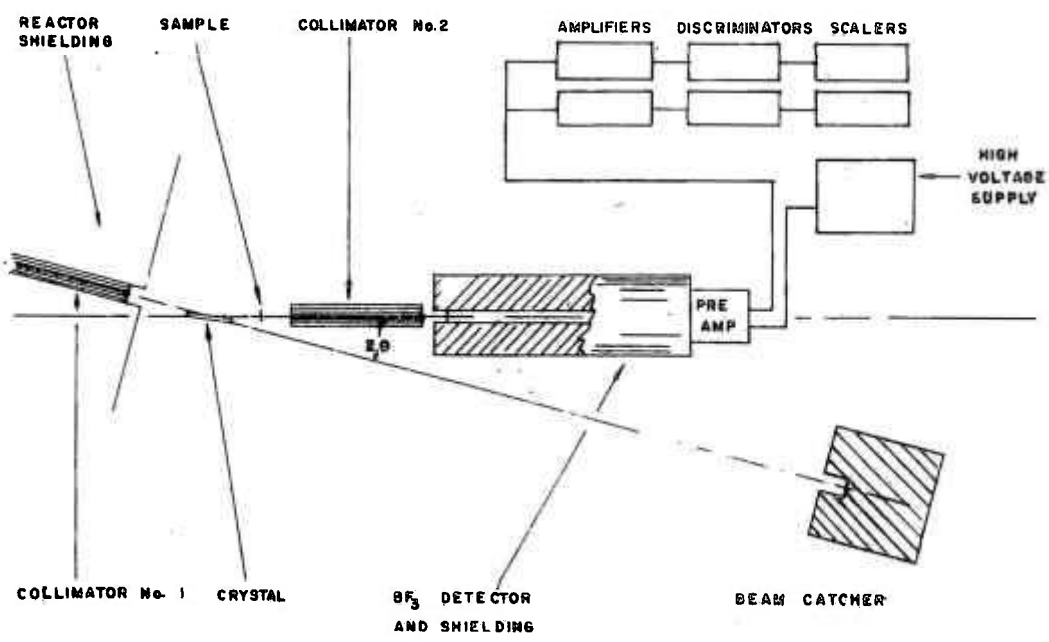
FIGURE 1

Schematic diagram of the apparatus and the electronic equipment. Not shown is the monitor counter, placed near the direct beam, and its electronics, which were similar to those of the principal detector.
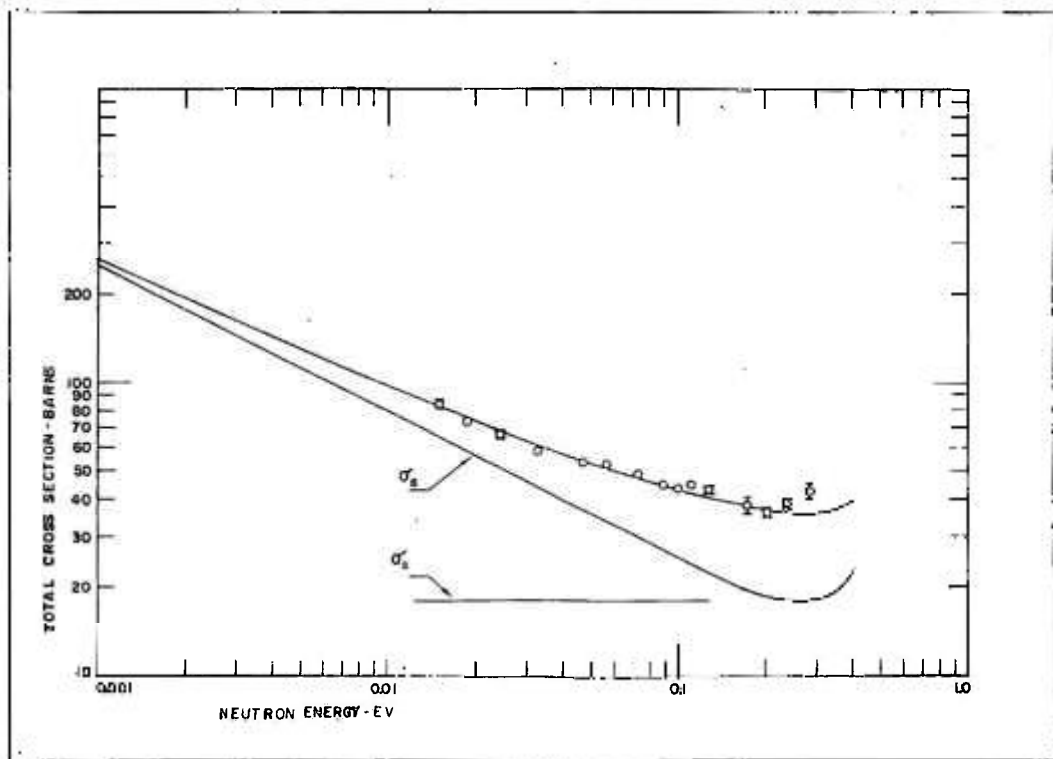
NEUTRON ENERGY - EV

TOTAL CROSS SECTION - BARNS

σ_s

σ_a

FIGURE 2

Total cross section of ytterbium. $\sigma_s = 18$ barns and σ_s from absorption due to other resonances in addition to the Yb^{168} resonance at energy .597 ev were used to obtain agreement with the experimental data. The published values for the parameters were used in calculating the contribution of this resonance. Statistical errors are smaller than the experimental points, except where they are indicated.
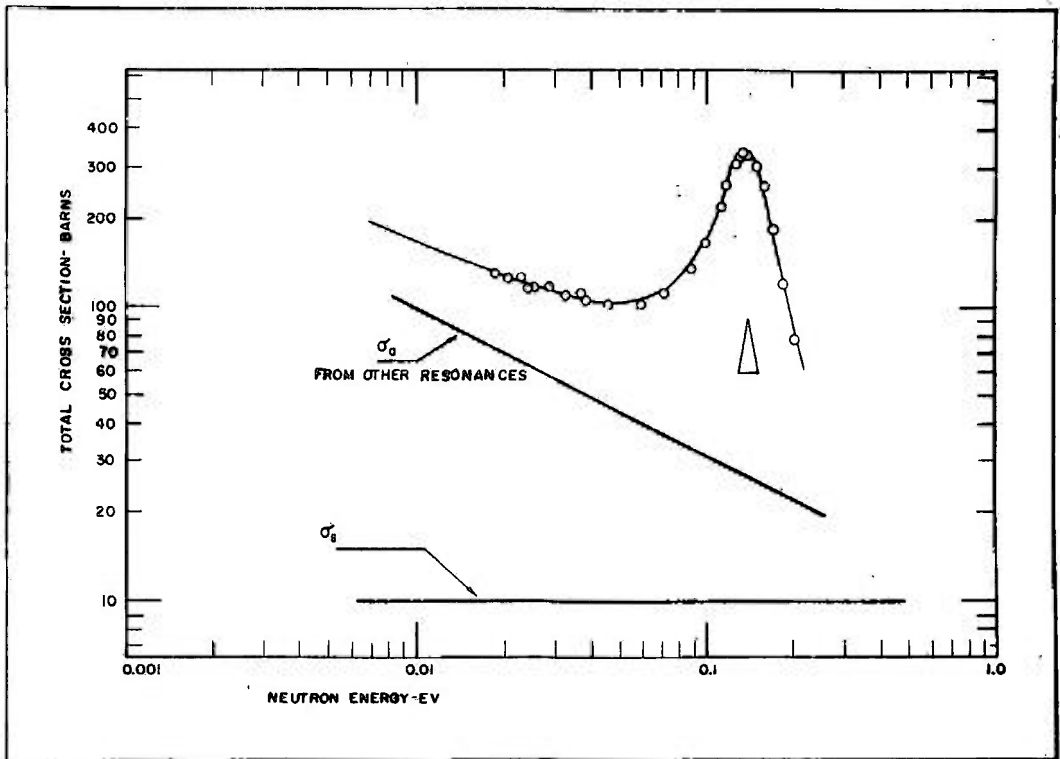
FIGURE 3

Total cross section of lutetium. The solid curve through the experimental points shows the results obtained using the Breit-Wigner formula that determined the constants $E_o = .141 \pm .002$ ev, $\Gamma_f = .058 \pm .003$ ev and $\Gamma_n^o = .000201 - .000004$ ev. $\sigma_s = 10$ barns has been assumed. No nearby bound state is needed, but the usual contribution from far-away resonances and from scattering are included and are shown by the straight lines. Statistical errors are smaller than experimental points.
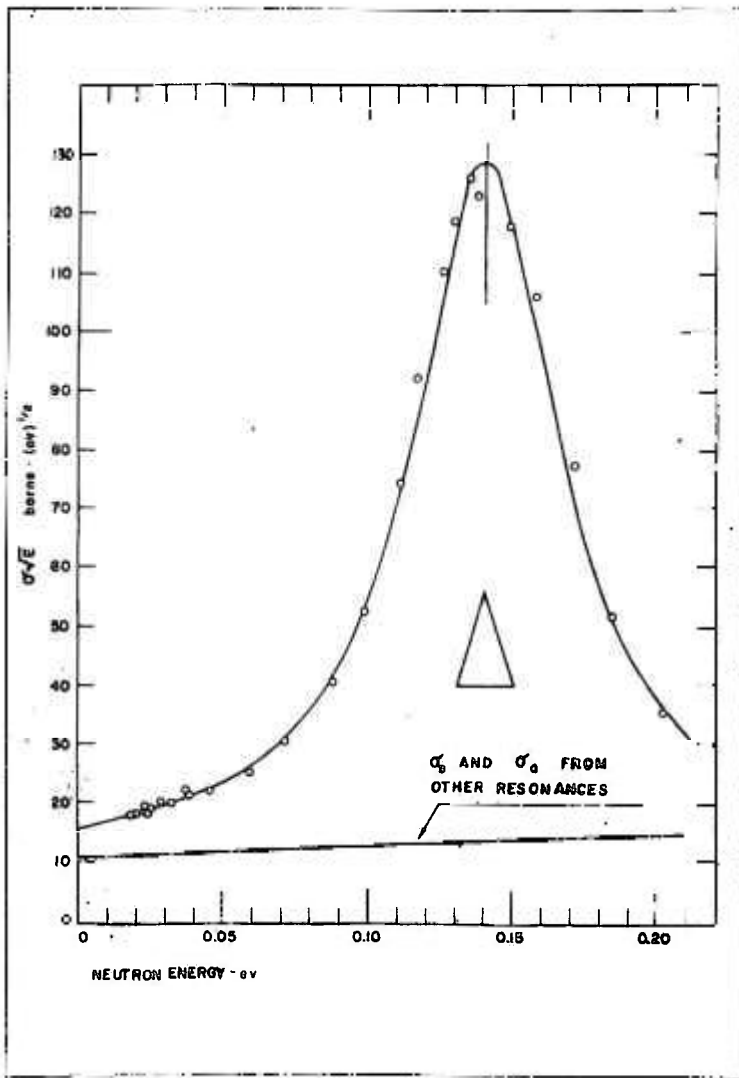
FIGURE 4

Experimental results of the total cross section measurements of lutetium plotted as $\sigma\sqrt{E}$ versus E. The solid curve through the experimental points is obtained using the Breit--Wigner formula with the parameters shown with figure 3. The line below shows the contribution from other resonances. The triangle represents schematically the resolution at the peak energy.

TABLE I

Method Location	Geometrical calculation	Gold Foil Calculation	BF_3 counter calculations
First Collimator exit	3.9×10^6	4.2×10^6	2.9×10^6
Crystal	3.1×10^6	4.1×10^6	-

Values for the flux of thermal neutrons, in $n/cm^2/seg$ normalized for 2 Mw.

TABLE II*

Neutron energy in ev.	Ytterbium	Lutetium	Praseodymium
0.456			6.5±2.5
0.290	43±2		7.3±0.4
0.240	39±1		
0.203	37±1	79±1	8.1±0.2
0.185		121±3	
0.172	39±2	187±2	7.9±0.4
0.159		266±2	
0.149		305±1	8.5±0.5
0.139		331±2	
0.136		342±1	
0.131		329±2	
0.127	43.9±0.7	310±1	8.8±0.2
0.118		268±1	
0.112	45.4±0.9	222±1	9.2±0.2
0.0994	44.2±0.5	168±1	
0.0888	45.5±0.9	136±1	10.0±0.2
0.0724	48.7±0.3	113.6±0.9	10.8±0.2
0.0595	54 ±1	102.9±0.7	12.1±0.2
0.0470	54.2±0.3	102.5±0.4	12.89±0.05
0.0434			12.8±0.2
0.0390		108±1	13.2±0.1
0.0378		114±2	
0.0328	59.4±0.7	110±2	14.6±0.3
0.0290		118±2	15.4±0.2
0.0259		118±4	
0.0244	68 ±1	116±2	16.5±0.2
0.0232		128±3	
0.0210		126±3	19.6±0.4
0.0185	73 ±1	131±2	19.5±0.3
0.0150	86 ±1		21.6±0.6

*Total neutron cross section in barns; statistical errors are shown, also.

TABLE III *

	The present experimental			Previously published results	
	σ_{total}	σ_a	σ_s	σ_a	σ_s
Praseodymium	$16.3 \pm .3$	$13.0 \pm .5$	$3.3 \pm .5$	$11.6 \pm .6$	$4.0 \pm .4$
Lutetium	118 ± 1	108 ± 5	(10 ± 5)	122 ± 5	
Ytterbium	69 ± 1	51 ± 2	18 ± 2	37 ± 4	12 ± 5

* Cross sections for thermal neutrons. The previously published results are all taken from D.J. Hughes and R.B. Schwartz, Neutron Cross Sections, U.S. Government Printing Office, (1958). Most of the previously measured values of the absorption cross section were measured with a pile oscillator, but the values are expressed for a neutron energy of .0253 ev, correcting for the effect of the Maxwellian distribution of energies used in the experiment. The scattering cross section of lutetium (in parentheses) has been assumed for the purpose of calculations.