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Thermal Activation Cross Sections and Resonance Integrals of In^{115}

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New measurements of the thermal neutron activation cross sections and the resonance activation integrals (14 sec and 54 min activity) of In^{115} are described. The results are discussed and compared with those of other recent determinations.

I. INTRODUCTION

Due to the importance of In^{115} as a neutron detector, its cross sections have been frequently measured. These measurements, however, did not yield clear results in all cases. For instance, Meister (*1*) reports 157.6 ± 4.4 barns for the 54 min activation cross section at 2200 meters sec^{-1}, while a value of 139.2 ± 1.9 barns can be derived from the measured absorption cross section and the branching ratio of the isomers (*2*, *3*). For the resonance activation integral, values ranging from 2140 to 3530 barns have been reported (*4*). Therefore, it was decided to perform repeat measurements of the most relevant quantities.

This paper covers direct measurements of the following parameters for In^{115}:

σ_{act}^{54} (E_0 = 0.0253 ev), the thermal activation cross section for the 54 min activity.

σ_{act}^{14} (E_0 = 0.0253 ev), the thermal activation cross section for the 14 sec activity.

$I_{act}^{54}/\sigma_{act}^{54}(E_0)$, where I_{act}^{54} is the resonance activation integral for the 54 min activity.

$R_{th} = \sigma_{act}^{14}/\sigma_{act}^{54}$ and $R_{epi} = I_{act}^{14}/I_{act}^{54}$.

The half-lives were also redetermined. The measurements are described in Sections II–V. In Section VI, the results are discussed and some other quantities are derived.

II. HALF-LIFE OF In^{116} AND In^{116m1}

To determine the half-lives of the In^{116}-activities, indium foils were irradiated and their activities measured in a $4\pi\beta$-detector. In^{116m1} was excited by irradiating the foils in the thermal column of the Karlsruhe Argonaut Reactor. The excitation of the isomer of In^{115} ($T_{1/2} \approx 4.5$ hr) was negligible. A dead-time unit was included in the counting equipment, defining the dead-time to be 3.26 ± 0.04 μsec. Therefore, counting rates up to 3×10^4 per sec could be tolerated without making the error in the measured counting rates larger than about 0.1 %. The half-life was calculated from

$$T_{1/2} = \frac{(t_2 - t_1)\cdot \ln 2}{\ln (Z_1/Z_2)} \tag{2.1}$$

where Z_1 and Z_2 are the corrected counting rates, measured at times t_1 and t_2, respectively. The result is

$$T_{1/2}(In^{116m1}) = (54.12 \pm 0.05) \text{ min.}$$

The decay of In^{116} was measured after an irradiation of 60 sec. The counting rates were small so that the error in dead-time was negligible. Evaluating the data with Eq. (2.1) yielded

$$T_{1/2}(In^{116}) = (14.10 \pm 0.03) \text{ sec.}$$

III. DIRECT MEASUREMENT OF THE THERMAL ACTIVATION CROSS SECTIONS

The activation cross sections of In^{115} were obtained by a comparison with the activation cross section of Au^{197} $\sigma_{act}(E_0)$ = 98.8 ± 0.3 barns (*5*). The activation rate, $C[cm^{-2}\ sec^{-1}]$, of a circular foil of thickness d irradiated in a thermal flux is

$$C = n\cdot v_0 \Sigma_{act}(E_0)\cdot d \cdot G_0^{th}(\Sigma_{tot}\cdot d, E_T)\cdot 1/(1 + \varkappa_c). \tag{3.1}$$

n is the absolute density of neutrons and v_0 = 2200 meters sec^{-1}, the factor $1/(1 + \varkappa_c)$ describes the pertubation of the foil activation and can be taken from the work of Meister (*7*). The function G_0^{th} includes the self-shielding of the foils and the averaging over the Maxwell spectrum:

$$G_0^{th}(\Sigma_{tot}\, d, E_T) = \frac{2}{\sqrt{\pi}\sigma_a(E_0)} \int_0^\infty \sigma_a(E) \cdot \frac{1 - 2E_3(\Sigma_{tot}\, d)}{2\Sigma_{tot}\, d} \frac{E}{E_T} e^{-E/E_T} \frac{dE}{E_T}. \quad (3.2)$$

σ_a is the absorption cross section and $E_3(\Sigma_{tot}\, d)$ the well-known Placzek-function. For $d \to 0$, that is, for the self-shielding approaching zero, G_0^{th} is identical with the $g(E_T)$-factor given by Westcott (*6*). G_0^{th} for In and Au is shown in Fig. 1. Since the dependency of G_0^{th} on E_T is small, $E_T = E_0 = 0.0253$ ev was assumed.

If Au and In foils are activated in the same thermal flux, then:

$$\frac{C_{In}}{C_{Au}} = \frac{(1 + \varkappa_c)_{Au} \cdot \sigma_{act}^{In} \cdot d_{In} \cdot G_{0\,In}^{th} \cdot N^{In}}{(1 + \varkappa_c)_{In} \cdot \sigma_{act}^{Au} \cdot d_{Au} \cdot G_{0\,Au}^{th} \cdot N^{Au}}. \quad (3.3)$$

N^{Au} and N^{In} is the number of atoms/cm^3 for Au and In^{115}, respectively.

In order to obtain σ_{act}^{In} from Eq. (3.3), C_{In} and C_{Au} must be determined from the activities of the foils.

The gold foils were counted with a $4\pi\beta-\gamma$ coincidence apparatus (*8*) or a $4\pi\beta$-detector. The corrections necessary to obtain the absolute decay rates were taken from a previous work (*9*).

A. The Thermal Activation Cross Section of the 54 min Activity

Indium foils of thicknesses ranging from 8.82 to 37.63 mg/cm^2 together with gold foils were irradiated on a rotating disc in the thermal column of the FR2 reactor. The flux was approximately $3 \times 10^6 cm^{-2} sec^{-1}$. It was established by a cadmium difference measurement that the epithermal portion of the neutron flux could be neglected.

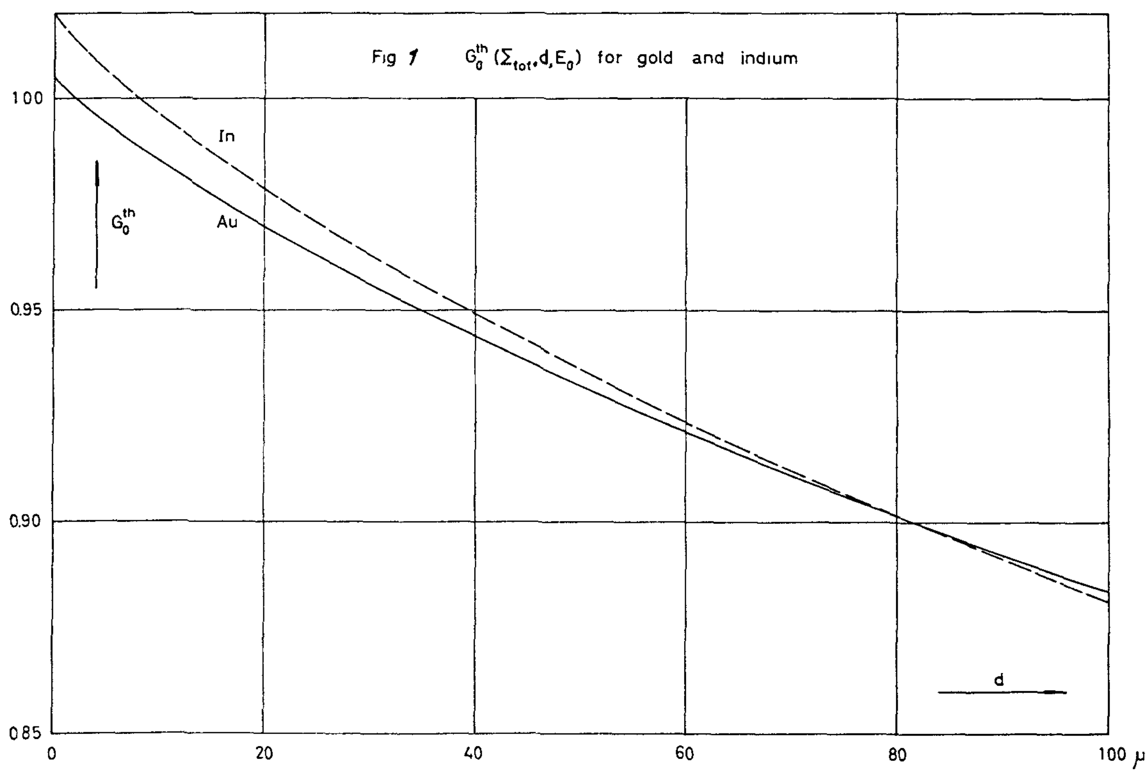
The In^{116m1} activity was measured by the $4\pi\beta-\gamma$ coincidence method. The counting rates were corrected for background, dead-time, and random coincidences. Corrections due to effects depending on foil thickness, i.e., decay scheme and γ-sensitivity of the $4\pi\beta$-detector, were made (*8*).

Measurements on nine indium foils were performed and the cross section evaluated by Eq. (3.3). The average value is

$$\sigma_{act}^{54}(E_0) = 162 \pm 3 \text{ barns}$$

B. Thermal Cross Section for the 14 sec Activity

The ground state of In^{116} decays with 99% by β-transition to the ground state of Sn^{116} so that the $4\pi\beta - \gamma$ coincidence method cannot be used in this



case. Therefore, the activity was measured with a $4\pi\beta$-detector taking into account the self-absorption factor $S_\beta^{th}(d)$ (10). This factor can be determined by an extrapolation method which has good accuracy in this case because of the high β energy of the 14 sec decay.

Indium foils of several thicknesses were activated in a paraffin pile. The H^3 (d, n) He^4 reaction served as the neutron source. The time dependence of the neutron flux was monitored with a BF_3-counter. A cadmium difference measurement eliminated the epithermal activation. Fig. 2 shows the self-absorption factor $S_\beta^{th}(d)$ for the 14 sec activity. Evaluation of the measurements by Eq. (3.3) yields:

$$\sigma_{act}^{14}(E_0) = 42 \pm 1 \text{ barns}$$

IV. BRANCHING RATIO FOR THERMAL AND EPITHERMAL NEUTRON ACTIVATIONS

After irradiation of In foils of different thickness in a paraffin pile, the β-radiation of the 14 sec and 54 min activities were counted in a $4\pi\beta$-detector. The usual corrections for background, dead-time, and the time dependence of the activation were made.

If the foils are activated in a thermal flux, it can be assumed that the neutron self-shielding is the same for both activities. Then, from the ratio of the $4\pi\beta$ counting rates, one obtains:

$$\frac{Z_{th}^{14}(d)}{Z_{th}^{54}(d)} = \frac{S_\beta^{th}(14, d)}{S_\beta^{th}(54, d)} \cdot \frac{\sigma_{act}^{14}}{\sigma_{act}^{54}} \cdot F, \qquad (4.1)$$

where F is a time factor which depends on the irradiation and counting times. For $d \to 0$ the factor $S_\beta^{th}(14, d)/S_\beta^{th}(54, d)$ approaches 1 and one obtains

$$R_{th} = \frac{\sigma_{act}^{14}}{\sigma_{act}^{54}} = \frac{Z_{th}^{14}(0)}{Z_{th}^{54}(0)} \cdot \frac{1}{F}. \qquad (4.2)$$

The extrapolation of $(1/F) \cdot Z_{th}^{14}(d)/Z_{th}^{54}(d)$ to zero thickness yields

$$R_{th} = 0.267 \pm 0.010.$$

Proceeding in a similar way for Cd-covered foils (d_{Cd} = 1mm), one obtains

$$R_{epi} = 0.276 \pm 0.015.$$

V. THE RATIO OF THE RESONANCE INTEGRAL TO THE THERMAL CROSS SECTION FOR THE 54 MIN ACTIVITY

The activation rate of a Cd-covered indium foil in a $1/E$ spectrum, $\phi(E) = \phi_{epi}/E$, is given by

$$C_{Cd} = N^{In} I_{act}^{54}\, d\, \phi_{epi}. \qquad (5.1)$$

If the foil is infinitely thin so that no self-shielding occurs, Eq. (5.1) defines the infinite dilute epicadmium resonance integral. The activation rate

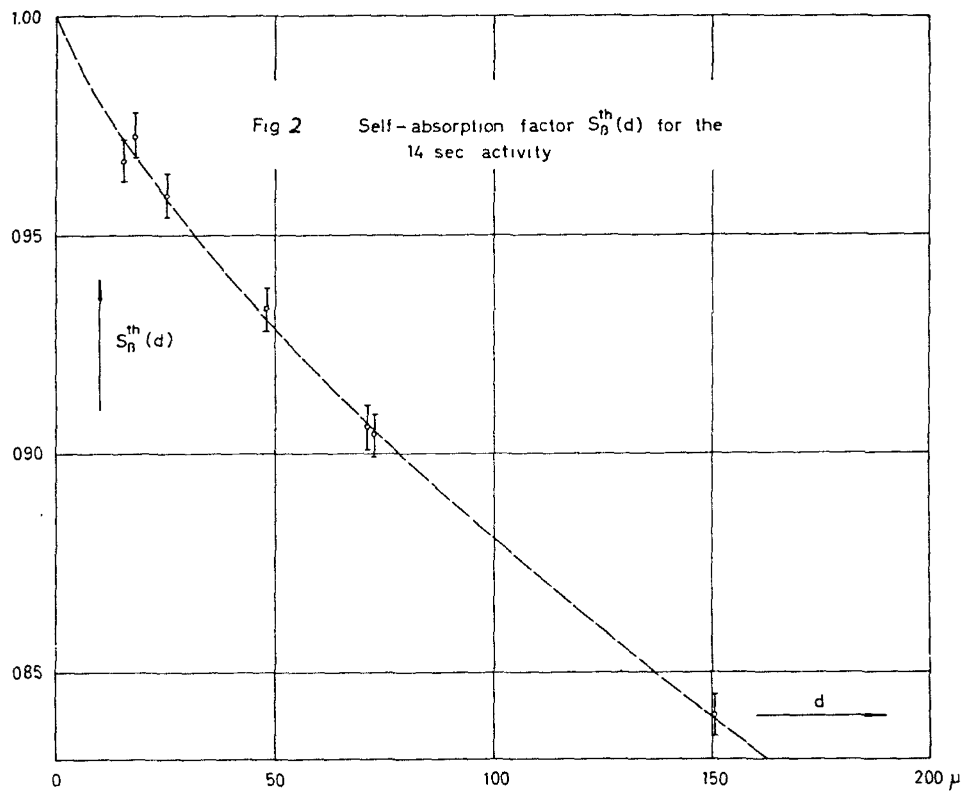
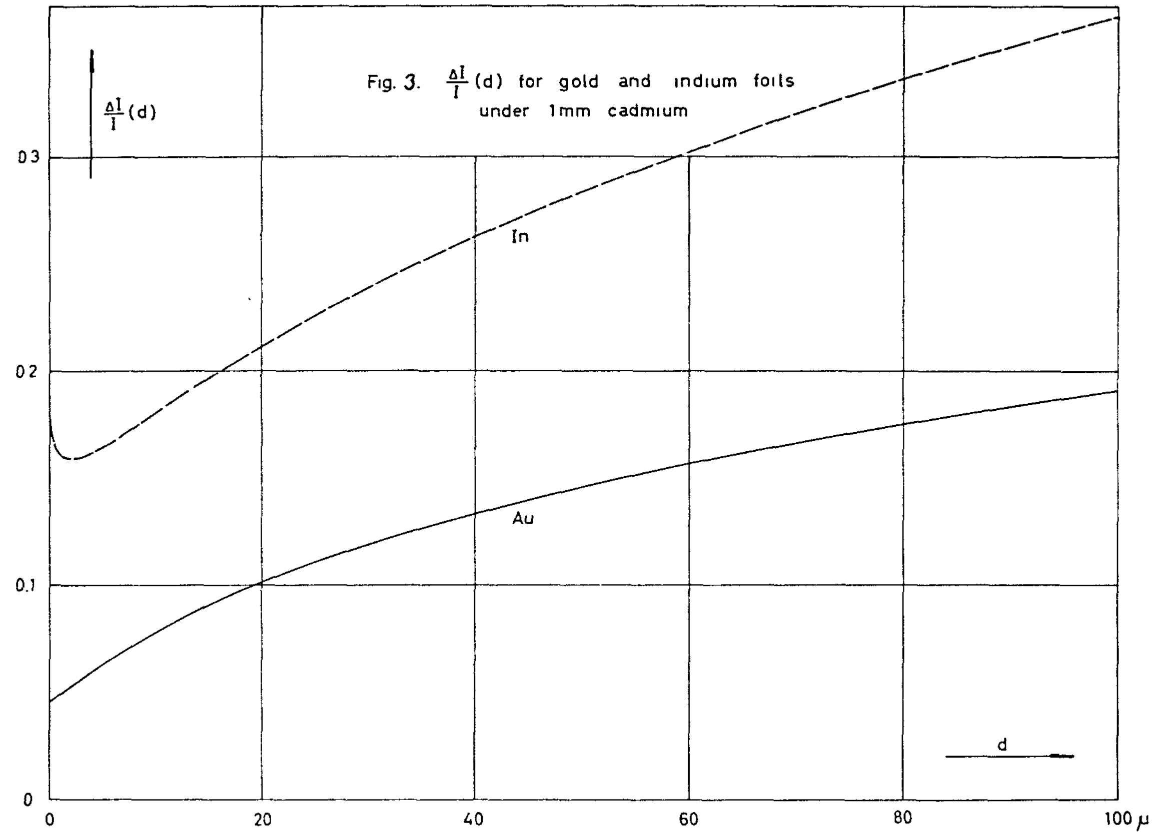


Fig 2 Self-absorption factor $S_\beta^{th}(d)$ for the 14 sec activity



of a bare thin foil is given by

$$C = N^{\mathrm{In}}\sigma_{\mathrm{act}}^{54}(E_0)\, dg(E_T) nv_0 + N^{\mathrm{In}}\bar{I}_{\mathrm{act}}^{54}\, d\phi_{\mathrm{epi}}. \quad (5.2)$$

Here $\bar{I}_{\mathrm{act}}^{54}$ is the total resonance integral, i.e., the resonance integral with the thermal cutoff energy as the lower limit. $\bar{I}_{\mathrm{act}}^{54}$ and I_{act}^{54} are related by

$$\bar{I}_{\mathrm{act}}^{54} = I_{\mathrm{act}}^{54} + \Delta I. \quad (5.3)$$

A measurement of the Cd ratio yields

$$R_{\mathrm{Cd}} = \frac{C}{C_{\mathrm{Cd}}} = 1 + \frac{nv_0}{\phi_{\mathrm{epi}}} \cdot \frac{\sigma_{\mathrm{act}}^{54}(E_0) g(E_T)}{I_{\mathrm{act}}^{54}} + \frac{\Delta I}{I_{\mathrm{act}}^{54}}. \quad (5.4)$$

Equation (5.4) permits the determination of $I_{\mathrm{act}}^{54}/\sigma_{\mathrm{act}}^{54}(E_0)$ from a measured cadmium ratio if nv_0/ϕ_{epi} and $\Delta I/I_{\mathrm{act}}^{54}$ are known. The first of these quantities can be measured quite accurately with gold foils whereas the latter has to be calculated.

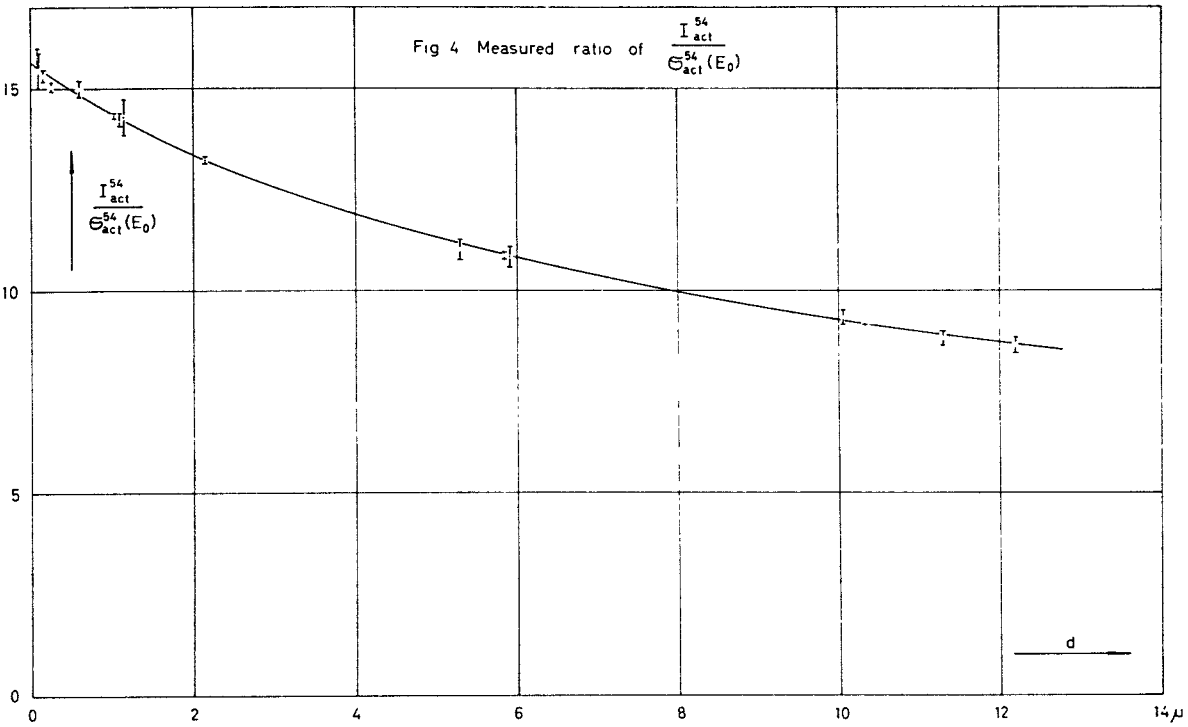
Measurements were performed in the pool of the FRM reactor, where a good $1/E$-spectrum of the epithermal flux exists. Bare and Cd-covered (Cd thickness 1 mm) indium foils ranging from 0.06 to 10 mg/cm^2 In[1] were irradiated and their activity was determined by γ-counting. nv_0/ϕ_{epi} was measured using gold foils *(11)*. $\Delta I/I_{\mathrm{act}}^{54}$ was calculated using the formula

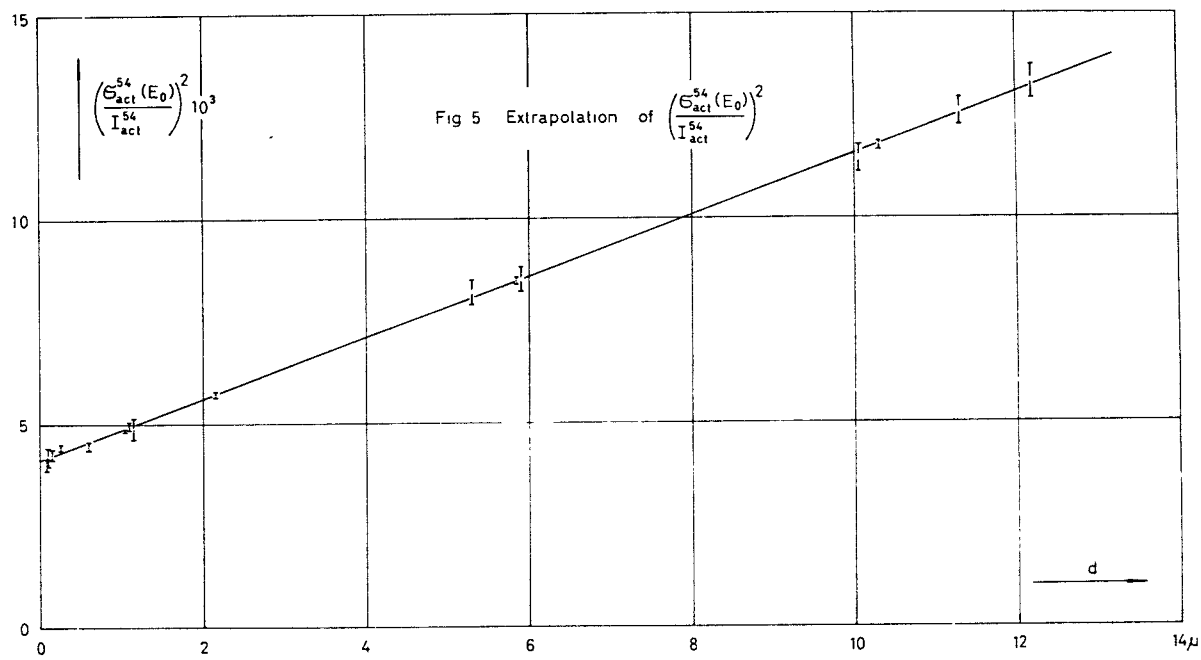
$$\frac{\Delta I}{I_{\mathrm{act}}^{54}} = \frac{\int_0^\infty \sigma_{\mathrm{act}}^{54}(E)\Delta(E)\, dE/E}{\int_0^\infty E_2(\Sigma_{\mathrm{Cd}}(E) d_{\mathrm{Cd}})\sigma_{\mathrm{act}}^{54}(E)\Delta(E)\, dE/E} - 1 \quad (5.5)$$

which applies for foils of zero thickness. In these calculations, the joining function $\Delta(E)$ reported by Johansson *et al.* *(12)* was used; $\sigma_{\mathrm{act}}^{54}(E)$ was approximated by a Breit-Wigner fit of the 1.46 ev resonance. These assumptions may be inaccurate, but since $\Delta I/I_{\mathrm{act}}^{54}$ appears only as a small correction in Eq. (5.4) (the measured Cd ratios were about 7) the resulting error is small. The calculations of $\Delta I/I_{\mathrm{act}}^{54}$ for foils of finite thickness is more cumbersome; it was performed in a similar manner as previous calculations for gold *(11)*. $\Delta I/I$ for indium and gold foils under 1 mm Cd as a function of foil thickness is shown in Fig. 3.

Figure 4 shows the ratios $I_{\mathrm{act}}^{54}/\sigma_{\mathrm{act}}^{54}(E_0)$ which were derived from the measured Cd ratios by use of Eq. (5.4) and the $\Delta I/I$ values in Fig. 3. These

[1] These thin foils were obtained by alloying indium and tin.





ratios increase with decreasing foil thickness due to the self-shielding of resonance neutrons. In Fig. 5, $(\sigma^{54}_{act}/I^{54}_{act})^2$ is plotted vs. foil thickness. For theoretical reasons these values have to follow a straight line which permits extrapolation to zero thickness. This extrapolation yields

$$I^{54}_{act}/\sigma^{54}_{act} = 15.63 \pm 0.47.$$

VI. CONCLUSIONS

A. Thermal Region

The consistency of the experimental results for $\sigma^{54}_{act}(E_0)$, $\sigma^{14}_{act}(E_0)$ and R_{th} is good. The ratio of the measured cross sections is 0.259 ± 0.008, while the measured value for R_{th} was 0.267 ± 0.010. For the absorption cross section, $\sigma_a(E_0)$ =

$\sigma_{act}^{54}(E_0) + \sigma_{act}^{14}(E_0)$, one obtains $\sigma_a(E_0) = 204 \pm 3$ barns. This compares well with a value of $\sigma_a(E_0) = 201 \pm 3$ barns which can be derived from a recently published experiment by Meadows and Whalen (*13*).

Starting from the four directly observed quantities

$$\left.\begin{aligned} \sigma_{act}^{14}(E_0) &= 42 \pm 1 \text{ barns} \\ \sigma_{act}^{54}(E_0) &= 162 \pm 3 \text{ barns} \\ R_{th} &= 0.267 \pm 0.010 \end{aligned}\right\} \text{this paper}$$

$$\sigma_a(E_0) = 201 \pm 3 \text{ barns} \quad (13)$$

and taking into account that only two of them are independent, a least square fitting of the data was performed. This fitting yielded the following consistent set:

$$\sigma_{act}^{14}(E_0) = 42 \pm 1 \text{ barns}$$
$$\sigma_{act}^{54}(E_0) = 160 \pm 2 \text{ barns}$$
$$\sigma_a(E_0) = 202 \pm 2 \text{ barns}$$
$$R_{th} = 0.261 \pm 0.008.$$

This set of parameters is accepted as final. Within the limits of error, $\sigma_{act}^{54}(E_0)$ is consistent with Meister's result which was quoted in Section I. R_{th} is in striking disagreement with the Greenfield-Koontz (*3*) re-evaluation of Sailor's (*14*) experiment which gave $R_{th} \approx 0.415$.

Following Huizenga and Vandenbosch (*15*), it is possible to estimate R_{th} theoretically. Since the thermal cross section is governed by the 1.46 ev resonance, the spin of the capture state is $I = 5$ (*16*). The spins of the In^{116} ground state and first isomeric level are 1 and 5, respectively. Assuming dipole radiation only and a spin cutoff factor $\sigma = 3$,[2] one calculates $R_{th} = 0.205$ for a multiplicity $N_\gamma = 4$, and $R_{th} = 0.298$ for $N_\gamma = 5$. Our result for R_{th} is just between these two values. This is consistent with $N_\gamma = 4.4 \pm 0.2$ which was directly observed by Draper and Springer (*18*).

B. Resonance Region

From $I_{act}^{54}/\sigma_{act}^{54}(E_0) = 15.63 \pm 0.47$ and $\sigma_{act}^{54}(E_0) = 160 \pm 2$ barns we get

$$I_{act}^{54} = 2500 \pm 85 \text{ barns}.$$

Using the measured value $R_{epi} = 0.276 \pm 0.015$ we obtain

$$I_{act}^{14} = 690 \pm 45 \text{ barns}.$$

[2] A higher value of σ is ruled out by the recent experiment of Fettweis (*17*).

This yields

$$I_a = 3190 \pm 120 \text{ barns}.$$

for the resonance absorption integral of In^{115} under 1 mm Cd.

For further considerations, it is necessary to introduce the effective Cd cutoff energy E_{Cd}. This is defined by

$$\int_{E_{Cd}}^{\infty} \sigma_a(E) \frac{dE}{E} = \int_0^{\infty} E_2(\Sigma_{Cd}(E) d_{Cd}) \sigma_a(E) \Delta(E) \frac{dE}{E}. \tag{6.1}$$

Using again Johansson's $\Delta(E)$ function and a Breit-Wigner fit for $\sigma_a(E)$, we computed $E_{Cd} = 1.30$ ev for $d_{Cd} = 1$ mm. Goldstein *et al.* (*19*) have proposed to use 0.55 ev as the lower limit in quoting resonance integrals. Using again the Breit-Wigner fit for $\sigma_a(E)$ one gets

$$\int_{0.55\text{ev}}^{1.3\text{ev}} \sigma_a(E) \frac{dE}{E} = 290 \text{ barns}$$

and therefore

$$I_{a;0.55\text{ev}} = 3480 \pm 120 \text{ barns}.$$

The value calculated from published resonance parameters (*20*) is $I_{a;0.55\text{ev}} \approx 3200$ barns.

Let us finally consider the excess absorption integral. This is defined by

$$\begin{aligned} I_{a;ex} &= \int_0^{\infty} \left(\sigma_a(E) - \sigma_a(E_0) \sqrt{\frac{E_0}{E}}\right) \Delta(E) \frac{dE}{E} \\ &= \bar{I}_a - \sigma_a(E_0) \int_0^{\infty} \sqrt{\frac{E_0}{E}} \Delta(E) \frac{dE}{E}. \end{aligned} \tag{6.2}$$

We get $\bar{I}_a = I_a(1 + (\Delta I/I)_{d=0}) = 3760 \pm 150$ barns and after subtraction of 200 barns for the $1/v$-part

$$I_{a;ex} = 3560 \pm 150 \text{ barns}.$$

TABLE I

Activation Resonance Integrals of In^{115}

Author	Cd thickness	I_{act}^{54}(barns)	I_{act}^{14}(barns)
Walker and Jarvis[a]	0.9 mm	2564 ± 50	—
Baumann	0.76 mm	2550 ± 80	650 ± 30
Brown, Conolly and Foell	0.88 mm	2595	—
This paper	1 mm	2500 ± 85	690 ± 45

[a] These authors report only the ratio $I_{act}^{54}/\sigma_{act}^{54}(E_0)$, I_{act}^{54} was calculated using our $\sigma_{act}^{54}(E_0)$.

Recently, several authors (*21–23*) have performed activation measurements on the In^{115} resonance integrals. Their results are shown in Table I. It is seen that the various determinations agree reasonably well. The agreement in the I_{act}^{54} values becomes even better if one reduces all measurements to a uniform Cadmium filter thickness.

A direct measurement of the absorption integral by the pile oscillator method has been carried out by Tattersall *et al.* (*24*), yielding $I_{a;ex} = 3760 \pm 350$ barns.[3] Within the error limits, this is consistent with our value, 3560 ± 150 barns.

[3] Tattersall *et al.* report 3600 ± 350 barns for natural indium; the above value for In^{115} was derived neglecting the absorption integral of In^{113}.

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