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ABSOLUTE THERMAL NEUTRON DETERMINATION

PART III:

ABSOLUTE THERMAL NEUTRON FLUX

BY:

MOSES A. GREENFIELD*
ROSCOE L. KOONTZ
ALAN A. JARRETT

*DEPARTMENT OF RADIOLOGY
MEDICAL CENTER
UNIVERSITY OF CALIFORNIA AT LOS ANGELES

ATOMICS INTERNATIONAL

A DIVISION OF NORTH AMERICAN AVIATION, INC.
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ABSTRACT

A method for determining absolute thermal neutron flux is described. The method is based on a determination of the absolute specific disintegration rate in indium foils in a windowless proportional counter with 2π geometry. By combining data on the absolute disintegration rate of activated indium foils with appropriate corrections for neutron effects, the thermal flux is expressed in terms of σ_o, the known thermal absorption cross section of In^{115}.

The method presented has an estimated error of less than 5 per cent, which is a function of the accuracy with which it is possible to determine the various f factors for beta counting. However, it does not include a possible fixed error in the value of σ_o.

The procedure described may be used by laboratories which do not have access to a standard graphite pile or to a standard neutron source.

I. INTRODUCTION

This report describes a method of determining the absolute thermal neutron flux from measurements of activities induced in indium foils. The method is based on a determination of the absolute specific disintegration rate in indium foils in a windowless proportional counter with 2π geometry. By combining data on the absolute disintegration rate of the activated indium foils with appropriate corrections for neutron effects, the thermal flux is expressed in terms of the known thermal absorption cross section of In^{115}.[(1), (2)]

The above method is an alternative to one commonly used by other laboratories in which one measures the activity of foils previously calibrated with reference to a standard radium-beryllium neutron source in a graphite pile. The accuracy of the determination in this way depends on the knowledge of the neutron emission value of the source, and the application of standard diffusion theory.

This report describes a procedure that may be used by laboratories that do not have access to a standard graphite pile or to a known neutron source.

The use of indium as a detector depends on the reaction

$$_{49}In^{115} + {}_{0}n^{1} \longrightarrow {}_{49}In^{116} \longrightarrow {}_{50}Sn^{116} + {}_{-1}\beta^{0}$$

The isotope In^{116} has two periods, one of 13 seconds and one of 54.3 minutes. These periods are excited by thermal neutrons, but there are resonances for 1.44 ev, 3.8 ev, and 8.6 ev neutrons which also gives these periods. The 13-second period is eliminated by waiting several minutes after the neutron activation has ended before beginning to count the activity.

II. NOTATION

The following standard notation will be used. All activities and disintegration rates are assumed to be at saturation.

x = foil thickness in mg/cm^2

A(x) = computed total activity/mg in counts/milligram per minute

M = observed counts per milligram

λ = the decay constant of indium = 0.01276 min^{-1}

t_w = the time interval between end of irradiation and beginning of counting in minutes

t_e = the effective time of irradiation in minutes

t_c = the counting interval in minutes

$R(x)$ = fraction of activity due to thermal neutrons only

$CR(x)$ = cadmium ratio computed as the ratio of bare foil activity to cadmium covered activity

$A_{th}(x)$ = computed thermal activity/mg corresponding to the total activity $A(x)$

$Q(x)$ = absolute disintegration rate/mg in disintegrations/milligram per minute

f_{geom}, f_w, f_{eff}, f_γ, f_{bs}, f_s = correction factors relating disintegration rate to activity for geometry, window, efficiency, gamma counts, backscatter of mounting material, self-absorption, and self-shielding of the indium foil, respectively

σ_o = the microscopic absorption cross section for the 54.3 minute activity of In^{115} at the standard energy E_o = 0.025 ev (standard velocity $v_o = 2.2 \times 10^5$ cm/s) = 145 ± 15 barns;[1] Σ_o is the corresponding macroscopic absorption cross section

ϕ_{th} = standard thermal neutron flux defined as $n_o v_o$; n_o is the thermal neutron density at the standard energy in n/cm^3

ρ = density of indium metal = 7.28 gm/cm^3

k = fractional abundance of In^{115} = 0.9577[3]

A_v = Avogadro's number = 0.6022×10^{24} atoms/mole

$\alpha(x)$ = correction factor arising from the thermal flux depression due to the absorption of the thermal neutrons by the indium foil

$A_{th}^T(x) = xA_{th}(x)$ = computed thermal activity for a foil of thickness x

III. SATURATED SPECIFIC ACTIVITIES AND DISINTEGRATION RATES

The total saturated activity/mg, A(x), of a bare indium foil, and the observed counts/mg, M, are related by a standard formula:

$$A(x) = \frac{\lambda M e^{\lambda t_w}}{\left(1 - e^{-\lambda t_e}\right)\left(1 - e^{-\lambda t_c}\right)} \qquad \text{...(1)}$$

The thermal specific activity is

$$A_{th}(x) = R(x)\, A(x) \quad . \qquad \text{...(2)}$$

The fraction of the bare activity attributable to thermal neutrons, R(x), is ordinarily obtained by using a cadmium ratio correction, CR(x). A detailed discussion of CR(x) and numerical values of R(x) may be found in References (4) and (5).

The saturated disintegration rate/mg, Q(x), is related to the thermal activity/mg, $A_{th}(x)$, via a number of experimentally determined correction factors as follows:

$$Q(x) = \frac{A_{th}(x)}{f_{geom} f_w f_{eff} f_y f_{bs} f_s} \quad . \qquad \text{...(3)}$$

The measurements of the values for the various f's for indium foils are described in Reference (5).

IV. DISINTEGRATION RATES AND THERMAL FLUX

The calculation of the equilibrium rate of production (or disintegration) of In^{116} in atoms/cm^3-sec is made by integrating over the Maxwellian distribution. The rate at which atoms are being activated in atoms/cm^3-sec is

$$\frac{dN}{dt} = \int \Sigma v \, dn \quad , \qquad \ldots(4)$$

where N is the number of activated In^{116} atoms/cm^3 for a Maxwellian distribution of velocities and dn is the number of neutrons/cm^3 with speeds in the interval v to v + dv; thus,

$$dn = \frac{4n_o}{\sqrt{\pi}} \frac{v^2}{v_o^3} e^{-v^2/v_o^2} dv \quad . \qquad \ldots(5)$$

For In^{115}, a good representation of the empirical energy dependence of Σ vs v is given by

$$\Sigma = \Sigma_o \left(\frac{v_o}{v}\right)^c \quad , \qquad \ldots(6)$$

where c is an empirical constant. Then

$$\Sigma v dn = \frac{4n_o}{\sqrt{\pi}} \Sigma_o v_o \left(\frac{v}{v_o}\right)^{3-c} exp\left\{\frac{-v^2}{v_o^2}\right\} \frac{dv}{v_o} \quad . \qquad \ldots(7)$$

The total number of activations per cm^3-sec at equilibrium is obtained by integrating over all velocities from 0 to ∞; the exponential fall-off with velocity will ensure no error at energies above the cadmium cut-off.

Let $x = v/v_o$. The rate of production of In^{116} atoms/cm^3-sec is given by

$$\frac{dN}{dt} = \int \Sigma v dn = \frac{4n_o}{\sqrt{\pi}} v_o \Sigma_o \int_o^\infty x^{3-c} e^{-x^2} dx \quad . \qquad \ldots(8)$$

This may be put in the form of a Γ-function by the substitution of y for x^2.

Then we have

$$\frac{dN}{dt} = \frac{2}{\sqrt{\pi}} n_o v_o \Sigma_o \int_o^\infty y^{1-\frac{c}{2}} e^{-y} dy = \frac{2}{\sqrt{\pi}} n_o v_o \Sigma_o \Gamma\left(2 - \frac{c}{2}\right) \qquad \text{...(9)}$$

or

$$\frac{dN}{dt} = a n_o v_o \Sigma_o \quad ,$$

where

$$a = \frac{2}{\sqrt{\pi}} \Gamma\left(2 - \frac{c}{2}\right) .$$

Some values of a are given below:

c	a
0	1.128
3/4	1.011
1	1.000

For In^{115}, c = 3/4.[3] Thus

$$\frac{dN}{dt} = 1.011 n_o v_o \Sigma_o \text{ atoms/cm}^3\text{-sec} .$$

Since time units in this analysis are all in minutes, and activities (or dis) are per mg, dN/dt is redefined to conform to this notation. The number of atoms formed/mg-min is equal at saturation to Q, the number of disintegrations/mg-min, and is given by

$$Q = 1.011 \phi_{th} \Sigma_o (dis/cm^3\text{–}sec)\ 60 (sec/min)\ \frac{1}{\rho} (cm^3/gm)\ 10^{-3} (gm/mg) \quad .$$

Since

$$\frac{\Sigma_o}{\rho} = \frac{k\sigma_o}{115} A_v ,$$

then

$$Q = 0.06066 \frac{kA_v}{115} \sigma_o \phi_{th} \, dis/mg\text{–}min , \qquad ...(10)$$

or

$$\phi_{th} = \frac{1.896 \times 10^3}{\sigma_o A_v k} Q . \qquad ...(11)$$

Since foils absorb thermal neutrons, there is a depression of the flux which varies as a function of the foil thickness. The ratio of the activity induced by thermal neutrons to that which would have been induced in the foil if there were no neutron flux depression caused by the foil is α (x). Thus

$$Q = \frac{Q(x)}{\alpha(x)}$$

and

$$\phi_{th} = \frac{1.896 \times 10^3 Q(x)}{\sigma_o A_v k \, \alpha(x)} . \qquad ...(12)$$

A detailed discussion and the numerical values of α (x) may be found in References 5 and 6.

By eliminating Q(x) from Equations (3) and (12), one obtains the desired relation between ϕ_{th} and $A_{th}(x)$:

$$\phi_{th} = \frac{1.896 \times 10^3}{\sigma_o A_v k \, \alpha(x) f_{geom} f_w f_{eff} f_y f_{bs} f_s} A_{th}(x) \qquad \ldots(13)$$

Substituting numerical values for σ_o, A_v, and k yields

$$\phi_{th} = \frac{22.67}{\alpha(x) f_{geom} f_w f_{eff} f_y f_{bs} f_s} A_{th}(x) \quad ; \qquad \ldots(14)$$

V. DISCUSSION

Equation (14) gives the desired relation between the thermal flux and the thermal specific activity. The coefficient of $A_{th}(x)$ is a function of the foil thickness or mass, expressed as mg/cm^2, as well as a function of the geometry and the other parameters appearing in Equation (14). However, for the experimental worker in the laboratory, it is convenient to go directly from the saturated total (rather than specific) thermal activity of a foil with a given mass to the thermal neutron flux. The ratio of the flux to the foil activity is often called the "count factor." This ratio is a function only of the specific foil and detector combination that is employed.

In this laboratory, 1 cm by 1 cm indium foils were counted with thick silver backing in a 2π proportional counter. The range of foil weights used is usually between 85 and 100 mg/cm^2. The count factor for these two weights was computed with numerical data from Reference (5).

The count factor for a 100 mg/cm^2 foil is found from:

$$f_w = f_{eff} = 1.00 \; ; \quad f_{geom} = 0.49 \; ; \quad f_{bs} f_y f_s = 0.371 \; ; \quad \alpha(x) = 0.84$$

By combining this data with Equation (14), and replacing the specific thermal activity, $A_{th}(100)$, by its equivalent $A^T_{th}(100)/100$, one obtains

$$\phi_{th} = 1.49 \, A^T_{th}(100) \; . \qquad \ldots(15)$$

The count factor for a 85 mg/cm^2 foil is found from:

$$f_w = f_{eff} = 1.00\ ; \quad f_{geom} = 0.49\ ; \quad f_{bs} f_\gamma f_s = 0.417\ ; \ a(x) = 0.858$$

This gives:

$$\phi_{th} = 1.52\ A_{th}^T\ (85) \qquad \text{...(16)}$$

Note that the count factor for a 85 mg/cm^2 foil is about 2 per cent larger than for a 100 mg/cm^2 foil, as contrasted with the 15 per cent difference in foil weights. Thus it would appear to be pointless to overcontrol foil weights.

It should be emphasized that the flux ϕ_{th} is defined as $n_o v_o$, where v_o is the velocity corresponding to the standard energy 0.025 ev. If one wishes to use the convention that

$$\bar{\phi}_{th} = n_o \bar{v}\ ,$$

where $\bar{v}$ is the average velocity in a Maxwellian distribution, $\bar{\phi}_{th}$ is related to ϕ_{th} by the expression

$$\bar{\phi}_{th} = n_o \bar{v} = 1.128\ n_o v_o = 1.128\ \phi_{th}\ . \qquad \text{...(17)}$$

In this case, the count factors for the above described foils become

$$\bar{\phi}_{th} = 1.68\ A_{th}^T\ (100) \qquad \text{...(18)}$$

and

$$\bar{\phi}_{th} = 1.72\ A_{th}^T (85) \qquad \text{...(19)}$$

VI. CONCLUSION

This report has described a method for computing absolute thermal neutron flux. The short half-life of In^{116} (54.3 minutes) permits rapid and repeated determinations to be made. The method has an estimated error of less than 5 per cent, which is a function of the accuracy with which it is possible to determine the various f factors.[5] However, this does not include a possible fixed error in the value of σ_o which was obtained from the work of Seren, *et. al.*[1] This is the only recent reference available for the thermal neutron activation cross-section for In^{115}. Their value of σ_o is quoted with a standard deviation of 15 per cent of the mean. Seren made a correction, based on external absorption measurements, for self-absorption by the foil on a simple exponential basis. The shapes of the curves shown in References (5) and (7) indicate that: (a) the correction factor is non-monotonic with both a minimum and a maximum in the low-geometry case and (b) the self-absorption and self-scattering correction is not linear in a semilog plot for even the 2π geometry. In fact, for foil thicknesses up to 20 mg/cm^2, the correction may be either positive or negative, depending on the foil thickness. Thus, the reported value of σ_o may be in error because of the impossibility of using a simple exponential type of correction for this complex phenomenon.

A preliminary comparison has been made between flux values based on indium and flux values obtained from the counting of gold foils which had been standardized by exposures to known fluxes at Oak Ridge. This comparison has yielded a difference of approximately 15 per cent to 20 per cent. It is thought that a significant part of this difference may be due to the use of an incorrect value for σ_o.

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