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FAST NEUTRON REACTIONS AND FAST NEUTRON FLUX IN THE NRX REACTOR

CRC-852

by

J C ROY and Mrs D. WUSCHKE

Chalk River, Ontario
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INTRODUCTION

This report deals with fast neutron reactions and fast neutron flux in NRX. By fast neutrons it is meant those neutrons having an energy from ~1 Mev to ~25 Mev.

The report is divided into three parts. In the first part measurements of (n,2n) cross sections in different irradiation positions of NRX are described. It is shown that from these experimental data, any (n,2n) cross section in NRX can be estimated. In the second part, measurements of the fast neutron flux in different irradiation positions of NRX are described. In the third part the values of the fast neutron flux found in Part II are used to estimate a variety of (n,p) and (n,α) cross sections in NRX.

Fast neutron reactions in a reactor have been studied by many different workers. However, this report is not intended to give an exhaustive bibliography on fast neutron research; it will only refer the reader to a few publications where a great deal of information on fast neutron reactions as well as references to earlier work can be found. There is an excellent chapter on fast neutron research in the book of

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Hughes on Pile Neutron Research (Hughes 1953). A tabulation of the published measurements of threshold reactions for fission neutrons has appeared in Nucleonics (Rochlin 1959). Mellish et al. (1958) have discussed at length flux and cross section measurements with fast neutrons.

The reader is also referred to recent work on this subject published in the Canadian Journal of Physics (Roy et al. 1958; Eastwood and Roy 1959; Roy 1959).

PART I. MEASUREMENT OF (n,2n) CROSS SECTIONS

1. Introduction

Since the product of a (n,2n) reaction is isotopic with the target, measurement of (n,2n) cross sections in a reactor by an activation method is feasible when the following conditions are met. First of all the elements where the product of a (n,2n) reaction can also be formed by a (n,γ) reaction on another stable isotope are eliminated. Secondly, the half-life of the radionuclide resulting from a (n,2n) reaction has to be much longer than that of the products of the (n,γ) reactions. Thirdly, the half-life of the radionuclide must be greater than at least 15-20 minutes to permit a good chemical purification of the target material. Finally, the decay scheme of the product of the reaction must be well known. In the measurements described here, the presence of a gamma ray of known intensity was required since the activities were measured by the gamma scintillation method. There are about 15 (n,2n) reactions which meet these conditions; of these, 9 were investigated. In addition one measurement by Betts and Dahlinger (1957) has been included in the compilation.

2. Experimental

(a) Irradiation and Purification - The irradiations were made either in empty fuel rod positions in the core of NRX or in "self serve" positions in the graphite reflector. Trapp (1958) and the NRX Reactor Staff (1955) have described the experimental facilities of NRX.

The amount of target material irradiated varied from a few mg. to several hundred mg. Generally a cobalt wire 0.0127 cm. in diameter and 1 cm. in length was irradiated with the target to monitor the thermal neutron flux (Jervis 1957).

The experimental details, the chemical procedure and the data used to calculate the cross sections are given in Appendix I for each separate reaction.

(b) Counting Techniques - With the exception of thorium, all the activities were measured by the same method. After the chemical purification the final precipitate was deposited as a stoichiometric chemical compound on an aluminum tray, dried and weighed. The activity of the precipitate was measured by placing the sample on the top of a scintillation counter formed by a 1 in. x 1 in. NaI (Tl) crystal coupled to an RCA 5819 photomultipler tube and conventional electronics. The gamma ray spectrum was examined with a multichannel analyzer (Moody et al. 1951). The efficiency of this apparatus for the gamma rays over a range of energies was determined using sources of Au^{198}, Na^{22}, Na^{24}, Cs^{137}, Mn^{56} and Hg^{203} calibrated by 4π β-counting or coincidence techniques (Campion 1959; Merritt et al. 1959).

In the case of thorium, the activity was measured by inserting a small tube containing a solution of the irradiated thorium into the hole of a NaI (Tl) crystal used in conjunction with a single channel analyzer. This spectrometer was calibrated with Th^{231} separated from a known amount of U^{235} (Hasse and Kafalas 1957).

(c) Identification and Counting Rate Determinations - The identification of the product was made by measurement of the energy and half-life of appropriate gamma rays. The radioactive properties of the radionuclide were taken from the compilation of Strominger et al. (1958).

The counting rates were calculated by the summation of the counts at the photopeak. From the counting rates extrapolated to the end of the irradiation, the abundance of the gamma ray and the efficiency of the crystal, the absolute disintegration rate, dN/dt, was obtained.

Although the reproducibility between successive experiments on the same cross section was in general better than 10%, the errors in the values of the cross sections are about 25% and in some cases more, as shown in Table I. The errors arise mainly in the determination of the absolute disintegration rates, errors in the evaluation of the counting rates, errors in the determination of the efficiency of the counter and uncertainties in the half-lives of the radionuclides. Small errors also arise from the weighing of the sample and measurement of the reactor thermal flux. Systematic errors such as the use of incorrect decay schemes were not included in the estimated error.

3. Results

The values of the (n,2n) cross sections are given in Table I. They are expressed as effective cross sections and were calculated in the following manner. From the absolute

TABLE I

Effective (n,2n) Cross Sections

Target	Threshold (Mev)	$\sigma = R/nv_o$ Microbarns Irradiation Positions in the Core of NRX	S-9-5	S-9-1
Th-232	6.3	2600 ± 1000		
Tl-203	8.8	125 ± 50	49	~30
Pb-204	8.9	104 ± 25	42	18
I-127	9.4	54 ± 12	26	7
As-75	10.3	9 ± 3		
Mn-55	10.3	6 ± 2		
Y-89	12.0	4 ± 2		
Ti-46	13.6	0.2 ± 0.03		
Fe-54	13.8	0.1 ± 0.02 (Betts and Dahlinger 1957)		
C-12	20.3	0.0001 ± 0.00005		

disintegration rate at the end of the irradiation, dN/dt, the rate of the reaction, R, was calculated using the equation

$$(1) \quad R = \frac{dN/dt}{N_o(1-e^{-\lambda t})}$$

where N_o is the number of atoms of capturing nuclide, λ is the disintegration constant of the product of the reaction and t is the time of irradiation.

The effective cross section, σ, was obtained by dividing the reaction rate, R, by the reactor thermal flux, nv_o, where n is the total neutron density and v_o = 2200 meters/sec.

$$(2) \quad \sigma = R/nv_o$$

nv_o was calculated from the activities of the cobalt monitor according to the method of Westcott et al. (1958), the application of which to activation measurements was described in detail by Roy and Roy (1959).

The thresholds of the reactions listed in Table I were calculated from the tables of atomic masses of nuclides of Wapstra (1958) except that of the $Pb^{204}(n,2n)Pb^{203}$ reaction which was taken from the semi empirical mass formula of Cameron (1957).

Let us emphasize again that the reactor thermal flux and not the fast flux was used in the calculations of σ. This system has the advantages that the (n,2n) cross sections are expressed in the same convention as the (n,γ) cross sections and that both cross sections are directly comparable.

4. Discussion

1. The experimental values of σ listed in Table I are plotted versus the threshold of the reaction in Figure 1. The factor $25/A^{2/3}$ shown in Fig. 1 converts the observed cross section, σ, to a standard size nucleus for which $A^{2/3} = 25$ ($A = 130$) on the assumption that the cross section varies as $A^{2/3}$ (Hughes 1953). The (n,2n) cross sections vary fairly smoothly with the threshold energy; this plot makes it possible, therefore, to estimate any (n,2n) cross section in NRX within an accuracy of a factor of two. One must know only the threshold energy of the reaction.

2. In the different irradiation positions in the core of NRX a given (n,2n) cross section is substantially constant. This has been found by irradiations in several different tray rod positions in the core of NRX. In the self-serve position, S-9-5, which is located just outside the calandria, there is a decrease of a factor of two with respect to the core in the values of the (n,2n) cross sections. In the self-serve position S-9-1, which is farthest away from the calandria in the S-9 manifold, there is a decrease of about 6 with respect to the core in the values of the (n,2n) cross sections. These decreases of 2 and 6 with respect to the core give a measure of the variation of the fast flux, relative to the thermal flux, in different positions of NRX.

3. One (n,3n) cross section, the $Bi^{209}(n,3n)Bi^{207}$, has been determined experimentally and expressed in the same convention as the (n,2n) cross sections. Since this work has been reported in detail elsewhere (Eastwood and Roy, 1959) no description of the measurement will be given here. The value of this (n,3n) cross section falls on the curve of (n,2n) cross sections given in Fig. 1. Although just one cross section has been measured, this result suggests that Fig. 1 also gives an estimate of any (n,3n) cross section in NRX provided the threshold of the reaction is known. The values of the cross sections of (n,3n) reactions will be very low in all cases due to the high threshold of these reactions. However, prediction of the values

of (n,3n) cross sections is of interest because (n,3n) reactions offer an excellent method to examine the maximum energy of the neutrons emitted in fission.

PART II. FAST NEUTRON FLUX DISTRIBUTION IN NRX

In a paper published in 1952 Watt has shown experimentally that, in the energy range 3.3 - 17 Mev., the energy distribution of fission neutrons emitted from a source of U^{235} placed in the "glory hole" of the Los Alamos Homogeneous reactor can be expressed by the formula

$$(3) \quad f(E) = \sinh \sqrt{2E} \quad \exp^{-E}$$

In similar work done in 1951, but published just in 1959 as a declassified report (LA-2185) Watt reports the observation of neutrons in the energy range 24-25 Mev from the Los Alamos Fast Plutonium Reactor. The energy distribution of the neutron in this energy range had very little deviation from the distribution given by formula (3). The formula is consistent with a model in which the neutrons are emitted from the highly excited fission fragments after they have separated (Erozolimskii 1958). The fraction of neutrons, F(E), having an energy greater than E is given by the formula

$$(4) \quad F(E) = \int_E^\infty f(E)dE / \int_0^\infty f(E)dE$$

which, upon integration (Hanna and Rutledge 1951) gives

$$F(E) = 1 + \left[\left(\sqrt{\frac{2}{\pi e}}\right)\left(\sinh \sqrt{2E}\right) e^{-E}\right] - 1\left[g(\sqrt{2E} - 1) + g(\sqrt{2E} + 1)\right]$$

where $g(x) = \frac{1}{2\sqrt{\pi}} \int_0^x e^{-x^2/2}\, dx$, the so-called error integral which can be readily evaluated from mathematical tables.

Ideally fast neutron reactions in a reactor should be studied in a fission neutron spectrum; in practice however, material irradiated in a reactor is rarely exposed to an uncontaminated fission neutron spectrum. This arises from the fact that the fission neutrons are moderated by collisions with reactor components, coolants and moderators in going from one lattice position to another. This is especially true in NRX where the lattice spacing is 17 cm. (Hurst 1955). Under these conditions the fission neutrons are usually considered to be slowed down to thermal energies and NRX is said to be a well moderated thermal reactor.

One knows that the ratio of the thermal flux to resonance flux per log e interval is about 40 in the empty lattice positions of NRX, but there is very little information on the ratio of fast to thermal flux in NRX (again fast flux refers here to the flux of neutrons having an energy greater than about 1 Mev). The values of (n,2n) and (n,3n) cross sections in Part I show that the fast neutron flux in NRX is significant. In particular the study of the $C^{12}(n,2n)C^{11}$ reaction (Roy 1959) has shown that neutrons with an energy of 20.3 Mev can be detected in NRX. In connection with our studies of fast neutron reactions an attempt was made to determine quantitatively the fast neutron flux in NRX.

For this purpose it is convenient to introduce a term "k" which is defined as the ratio of the cross section of a threshold reaction measured in a reactor neutron spectrum to that measured in a fission neutron spectrum such that

$$(5)\quad \sigma_{reactor} = k\,\bar{\sigma}_{fission}$$

The meaning of k can be derived from the following considerations. In Hughes' notation (Hughes 1953) $\bar{\sigma}$ is an average cross section such that

$$(6)\quad \bar{\sigma}_{fission} = \sigma_o \frac{\int_{E_{eff}}^{\infty} vn(v)dv}{\int_o^{\infty} vn(v)dv}$$

where $\int_o^{\infty} vn(v)dv$ is the flux of fission neutrons having a distribution described by equation (3). The effective cross section called here $\sigma_{reactor}$, which has already been defined by equation (2), becomes in Hughes' notation

$$(7)\quad \sigma_{reactor} = \sigma_o \frac{\int_{E_{eff}}^{\infty} vn(v)dv}{nv_o}$$

If one assumes that the distribution of fission neutrons in a reactor has the same shape as uncontaminated fission neutrons above the energy at which the threshold reactions begin to occur, i.e. at about 1 Mev, then the term $\int_{E_{eff}}^{\infty} vn(v)dv$ in

both equations (6) and (7) is equal. Thus combining these two equations one obtains

$$(8)\quad \sigma_{reactor} = \bar{\sigma} \frac{\int_0^\infty vn(v)dv}{nv_o}$$

which is related to k by equation (5) to give

$$k = \frac{\int_0^\infty vn(v)dv}{nv_o}$$

The term k is therefore the ratio of the total flux in a fission spectrum having the same magnitude above the energy at which the threshold reaction begins to occur as the reactor spectrum to the reactor thermal flux. The validity of the assumption of undistorted fission spectrum in NRX will be discussed as the end of that section.

Thus the term "fast flux" as used throughout the report is defined as: the total flux in a fission spectrum having the same magnitude above the energy at which the threshold reaction begins to occur as the reactor spectrum.

In the nomenclature of Mellish et al. (1958) our definition of fast flux is the same as their "equivalent fission flux", i.e. it is the undisturbed fission flux that would give the observed activities.

In these experiments the threshold reactions used to determine k were:

$S^{32}(n,p)P^{32}$

$Ni^{58}(n,p)Co^{58}$

$Fe^{56}(n,p)Mn^{56}$

$\sigma_{reactor}$ was measured according to equation (2) and $\bar{\sigma}_{fission}$ was taken from published sources.

The experimental details for each reaction are given in Appendix II. The values of k measured from these experiments, the effective cross section measured in NRX and the effective fission cross section used in the calculations are assembled in Table II.

TABLE II

Determination of Fast Flux in NRX

Reaction	E_{eff} Mev	$\bar{\sigma}_{fission}$ mb	$\sigma_{reactor}$ mb	k	References to $\bar{\sigma}_{fission}$
$Ni^{58}(n,p)Co^{58}$	4.1	45	3.0		Mellish et al. (1958)
		45	2.8		
		Mean	2.9	0.0645	
$S^{32}(n,p)P^{32}$	3.5	30	1.6		Hughes (1953)
		30	1.8		
		30	1.7		
		Mean	1.7	0.057	
$Fe^{56}(n,p)Mn^{56}$	7.40	0.44	0.028		Mellish et al. (1958)
		0.44	0.028		
		Mean	0.028	0.064	
Mean of the 3 reactions				0.062 or 1/16	

The value of k, (the average of the three threshold reactions) is 1/16 in an empty lattice position of NRX. Thus the fast neutron flux in an empty rod position in the core of NRX will be 1/16 x 7×10^{13} n/cm^2-sec = 4.4×10^{12} n/cm^2-sec. In other irradiation positions of NRX the fast flux can be derived from the values of the (n,2n) cross sections in different parts of the reactor (cf. Part II). Thus, in an empty rod position anywhere in the reacting vessel the fast flux will be 1/16 of the thermal flux; in S-9-5 it will be ~1/32 of the thermal flux and in S-9-1 ~1/100 of the thermal flux.

Let us point out that, although cross sections for three different (n,p) reactions were measured, the fast flux is in fact determined with reference to the value of 30 mb for the $S^{32}(n,p)P^{32}$ reaction in a fission neutron spectrum. The fission cross section of the $Ni^{58}(n,p)Co^{58}$ and $Fe^{56}(n,p)Mn^{56}$ reactions used in the calculations (Mellish et al. 1958) have been obtained by reference to the value of 30 mb for the $S^{32}(n,p)P^{32}$. If the value of 30 mb happens to be incorrect, the term k in NRX should be changed accordingly. This remark is made necessary because of value of 60 mb for the $S^{32}(n,p)P^{32}$ reaction is also used by some workers (Phillips 1957 ; Richmond 1957).

The three (n,p) reactions were studied to determine if the ratio k will vary with the effective threshold energy, E_{eff}, of the reaction. The meaning of E_{eff} is that the correct reaction rate is obtained on the simple assumption that no neutrons below

E_{eff} contribute to the reaction, but all above it contribute with a penetrability of unity (Hughes 1953). The fact that k is the same for the three reactions shows that below 8 Mev the fast flux in NRX has the same distribution as that for fission neutrons, as given by equation 3. In the range of 7 to 15 Mev, the constancy of the ratio of the (n,2n) to the (n,3n) cross section for Bi^{209} in an empty fuel rod position and in a transformer rod leads to the same conclusion. In a transformer rod the ratio of fast flux to thermal flux will be enhanced and any significant distortion in the fast flux would be accompanied by a change in the value of the ratio of the (n,2n) to the (n,3n) cross section for Bi^{209}.

Having established that the fast flux in NRX is undistorted it is possible with values of k and nv_o using Equation 4 to determine the neutron flux in NRX above a given energy. The results of such a calculation are given in Table III.

TABLE III

Fast Neutron Flux, $\int_E^\infty vn(v)dv$, Above a Given Energy E in NRX

Energy Mev	Pneumatic Carrier	S-9-5	S-9-1
4	4.7×10^{11}		
6	1.1×10^{11}		
8	2.8×10^{10}	$\sim 2.8 \times 10^{9}$	$\sim 1.3 \times 10^{8}$
10	4.3×10^{9}	$\sim 4.3 \times 10^{8}$	$\sim 1.8 \times 10^{7}$
12	1.1×10^{9}		
14	3.6×10^{8}		
16	6.5×10^{7}		
18	1.3×10^{7}		
20	2.6×10^{6}		
24	8×10^{4}		

$$\int_E^\infty vn(v)dv = (nv_o)kF(E)$$

$nv_o \simeq 7.0 \times 10^{13}$ n/cm^2-sec in Pneumatic Carrier

$nv_o \simeq 1.4 \times 10^{13}$ n/cm^2-sec in S-9-5

$nv_o \simeq 2 \times 10^{12}$ n/cm^2-sec in S-9-1

PART III. (n,p) and (n,α) CROSS SECTIONS

Values of (n,p) and (n,α) cross sections for several reactions are important quantities to know in order to determine the activation levels of coolants and reactor components and also because of the implications of such reactions in activation analysis (cf. discussion by Mellish et al. (1958)). However, the measurement of many individual (n,p) and (n,α) cross sections would be a major undertaking. Fortunately those individual measurements do not have to be made if one knows the value of the factor k and if the (n,p) and (n,α) cross sections have already been measured for fission neutrons. This can be easily seen from equation (5). The term k in NRX is known from the measurements described in Part II; many (n,p) and (n,α) fission neutron cross sections have been measured (Rochlin 1959); Mellish et al. 1958). In our compilation, however, only the measurements done by Hughes (1953) and Mellish et al. (1958) will be used. The reason for this choice is that these authors used the same reactions to monitor the fast flux and the same values of the cross sections as those used in the measurements described here which lead to the determination of the term k.

The (n,p) and (n,α) cross sections calculated according to equation (5) are given in Tables IV and V respectively. Again let us emphasize that they must be used with the reactor thermal flux, nv_o. They are expressed in the same system as the (n,γ), (n,2n) and (n,3n) cross sections; hence they are directly

comparable. The values in the Tables are for the core of the reactor; in the S-9-5 and S-9-1 positions outside the core they will be smaller by factors of 2 and 6 respectively.

TABLE IV

(n,p) Cross Sections in Empty Lattice Positions of NRX

Reactions	$\bar{\sigma}$ fission	References*	σ reactor In the irradiation positions in the core of NRX	E_T	E_{eff}
	mb		mb	Mev	Mev
$O^{16}(n,p)N^{16}$	0.014	(H)	0.0009	10.2	11.7
$F^{19}(n,p)O^{19}$	0.5	"	0.031	3.9	5.6
$Na^{23}(n,p)Ne^{23}$	0.7	"	0.043	3.5	5.6
$Al^{27}(n,p)Mg^{27}$	2.8	"	0.17	2.1	4.6
$Mg^{24}(n,p)Na^{24}$	1.0	"	0.062	4.9	7.2
$Mg^{25}(n,p)Na^{25}$	2.0	"	0.12	4.1	6.4
$Si^{28}(n,p)Al^{28}$	4.0	"	0.25	4.0	6.7
$Si^{29}(n,p)Al^{29}$	2.7	"	0.17	3.3	6.0
$P^{31}(n,p)Si^{31}$	19.0	"	1.2	0.7	3.5
$S^{32}(n,p)P^{32}$	30.0	"	1.7 (measured value)	1.0	3.5
$Cl^{37}(n,p)S^{37}$	0.24	"	0.015	3.5	6.7
$Ti^{46}(n,p)Sc^{46}$	4.1	(M)	0.25	1.61	5.5
$Ti^{47}(n,p)Sc^{47}$	0.21	"	0.013	-0.1	3.8
$Ti^{48}(n,p)Sc^{48}$	0.077	"	0.0048	3.3	7.2
$Fe^{54}(n,p)Mn^{54}$	23	"	1.4	-0.16	4.3
$Fe^{56}(n,p)Mn^{56}$	0.44	"	0.028 (measured value)	2.94	7.4
$Ni^{58}(n,p)Co^{58}$	45	"	2.9 (measured value)	-0.64	4.1
$Co^{59}(n,p)Fe^{59}$	5.7	"	0.35	0.8	5.6
$Ni^{60}(n,p)Co^{60}$	3-7	"	0.18 - 0.4	2.3	7.0
$Zn^{64}(n,p)Cu^{64}$	22	"	1.4	-0.22	4.7
$Zn^{67}(n,p)Cu^{67}$	0.27	"	0.017	-0.21	4.7
$Mo^{92}(n,p)Nb^{92}$	1.3	"	0.08	-0.4	6.0
$Mo^{95}(n,p)Nb^{95}$	<0.1	"	<0.0062	0.15	6.6
$Tl^{203}(n,p)Hg^{203}$	0.002	"	0.00012	-0.3	10.1

* (H) refers to Hughes 1953, Pile Neutron Research, page 100

(M) refers to Mellish et al. 1958, AERE 1/R 2630.

TABLE V

(n,α) Cross Sections in Empty Lattice Positions of NRX

Reactions	$\bar{\sigma}$ fission	References*	σ reactor In the irradiation positions in the core of NRX	E_T	E_{eff}
	mb		mb	Mev	Mev
$Be^{9}(n,\alpha)He^{6}$	10.	(H)	0.62	0.3	2.0
$B^{11}(n,\alpha)Li^{8}$	0.085	"	0.0053	7.2	9.0
$F^{19}(n,\alpha)N^{16}$	4.5	"	0.28	1.5	5.1
$Na^{23}(n,\alpha)F^{20}$	0.4	"	0.025	4.0	8.6
$Al^{27}(n,\alpha)Na^{24}$	0.6	"	0.018 (measured value)	3.3	8.7
$P^{31}(n,\alpha)Al^{28}$	1.4	"	0.087	2.0	7.6
$S^{34}(n,\alpha)Si^{31}$	3.0	"	0.19	0.9	7.5
$Cl^{35}(n,\alpha)P^{32}$	16.0	"	1.0	-1.0	6.0
$V^{51}(n,\alpha)Sc^{48}$	0.08	"	0.005	2.4	11.5
$Ti^{48}(n,\alpha)Ca^{47}$	0.0055	(M)	0.00034	2.02	9.6
$Ti^{50}(n,\alpha)Ca^{47}$	0.0002	"	0.00012	3.58	11.2
$Fe^{54}(n,\alpha)Cr^{51}$	0.37	"	0.023	-0.87	9.1
$Ni^{62}(n,\alpha)Fe^{59}$	0.025	"	0.0015	0.88	11.5
$Mo^{96}(n,\alpha)Zr^{89}$	0.017	"	0.0011	-3.0	11.4
$Cs^{133}(n,\alpha)I^{130}$	0.005	"	0.00031	-4.2	13.6

* Cf. Table IV

From the values of (n,p) and (n,α) cross sections listed in Tables IV and V, a few conclusions can be drawn with regard to their use in research. For instance, (n,p) and (n,α) reactions induced in a reactor might be considered as potential routes for producing new radioactive species of nuclides having atomic number greater than 60. Tables IV and V show that in this region the cross sections will have values of the order of 1 to 0.1 microbarn. Such cross sections are very low and make it difficult to detect a product even if its radioactive

properties are known. The possibility is therefore remote of detecting new radioactive species of atomic number greater than 60 by (n,p) or (n,α) reactions in NRX.

SUMMARY

1. Experimental values of ten (n,2n) cross sections and a graph to estimate any (n,2n) cross section are given.

2. The maximum fast neutron flux in NRX as defined in Part II has been determined to be 4.4×10^{12} n/cm^2-sec. The ratio of the fast to thermal flux is constant in the irradiation positions in the core of NRX and is equal to 1/16; in the self-serve position S-9-5 and S-9-1, the ratio is 1/32 and 1/100 respectively.

3. Values of cross sections for 24 (n,p) reactions and 15 (n,α) reactions are given.

4. On multiplication of the values of the (n,2n) cross sections found in Table I or obtained from Fig. 1 by the term 1/k (that is 16), one gets the values of (n,2n) cross sections for fission neutrons. Note that the cross sections will then be given by reference to 30 mb for the $S^{32}(n,p)P^{32}$ reaction.

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APPENDIX I

Experimental Details of (n,2n) Reactions

1. $C^{12}(n,2n)C^{11}$

   Target: anthracene

   E_T = 20.3 Mev

   $t_{1/2}$ = 20.5 minutes

   Gamma-ray: annihilation radiation 100%

   Chemical purification: Anthracene burned in Parr oxygen bomb and CO_2 absorbed on ascarite

   Source: CO_2 on ascarite

2. $Ti^{46}(n,2n)Ti^{45}$

   Target: titanium metal

   E_T = 13.6 Mev

   $t_{1/2}$ = 3.1 hour

   Gamma-ray: annihilation radiation 100%

   Chemical purification: Ti dissolved in HF, Pass on Dowex 1; H_2S scavengings in acid and basic solution. La precipitation, cupferron precipitation; Ignite the cupferrate to TiO_2.

   Source: TiO_2

3. $Mn^{55}(n,2n)Mn^{54}$

   Target MnO_2

   E_T = 10.3

   $t_{1/2}$ = 290 days

   Gamma-ray: 0.842 Mev 100%

   Chemical purification: MnO_2 precipitation in HNO_3 with $KClO_4$; H_2S scavengings.

   Source: MnO_2

4. $Y^{89}(n,2n)Y^{88}$

Target: Y_2O_3

E_T = 12.0 Mev

$t_{1/2}$ = 105 days

Gamma-ray: 1.81 Mev 99.5%

Chemical purification: Ion-exchange resin, Dowex 50, elution with isobutyric acid.

Source: $Y_2(C_2O_4)_3 \cdot 9H_2O$

5. $As^{75}(n,2n)As^{74}$

Target: As_2O_3

E_T = 10.3

$t_{1/2}$ = 17 days

Gamma-rays: annihilation radiation 29%; 0.635 Mev 16%; .596 53%

Chemical purification: Dissolved in HCl, H_2S precipitation followed by Na_2S_x treatment. Precipitation as $MgNH_4AsO_4 \cdot 7H_2O$.

Source: $MgNH_4AsO_4 \cdot 7H_2O$

6. $I^{127}(n,2n)I^{126}$

Target: iodine

E_T = 9.4 Mev

$t_{1/2}$ = 13.3 days

Gamma-ray: 0.65 Mev 33%

Chemical purification: Extraction with bisulphite; oxidation of iodine with nitrous acid followed by extraction with CCl_4.

Source: PdI_2

7. $Tl^{203}(n,2n)Tl^{202}$

Target: thallium metal

E_T = 8.8 Mev

$t_{1/2}$ = 12 days

Gamma-ray: .44 Mev 100%

Chemical purification: Extraction in isopropyl ether from 8N HCl.

Source: TlI

8. $Pb^{204}(n,2n)Pb^{203}$

Target: lead metal

E_T = 8.9 Mev

$t_{1/2}$ = 52 hours

Gamma-ray: 0.279 Mev 100%

Chemical purification: $PbSO_4$ precipitations

Source: $PbSO_4$

9. $Th^{232}(n,2n)Th^{231}$

Target: $Th(CO_3)_2$

E_T = 6.3 Mev

$t_{1/2}$ = 25.6 hours

Gamma-ray: Th^{231} counted in solution inside a well-shaped NaI(Tl) crystal calibrated with Th^{231} from a known amount of U^{235}.

Chemical purification: Dissolve $Th(CO_3)_2$ in conc. HNO_3, change to the chloride and pass on Dowex 1.

APPENDIX II

Experimental Details of Charged Particle Reactions

1. $S^{32}(n,p)P^{32}$

   Target: $PbSO_4$ irradiated under 0.08 cm. of cadmium

   $t_{1/2}$ = 14.3 days

   Beta counting in 2π proportional counter

   No chemical purification

   Source: $PbSO_4$

2. $Ni^{58}(n,p)Co^{58}$

   Target: nickel wire irradiated under 0.08 cm. of cadmium

   $t_{1/2}$ = 71 days

   Gamma-ray: 0.8 Mev 100%

   No chemical purification

   Source: Ni

3. $Fe^{56}(n,p)Mn^{56}$

   Target: iron sponge Irradiated under 0.08 cm of cadmium

   $t_{1/2}$ = 2.58 hours

   Gamma-ray: 0.84 Mev 99.5%

   No chemical purification

   Source: iron

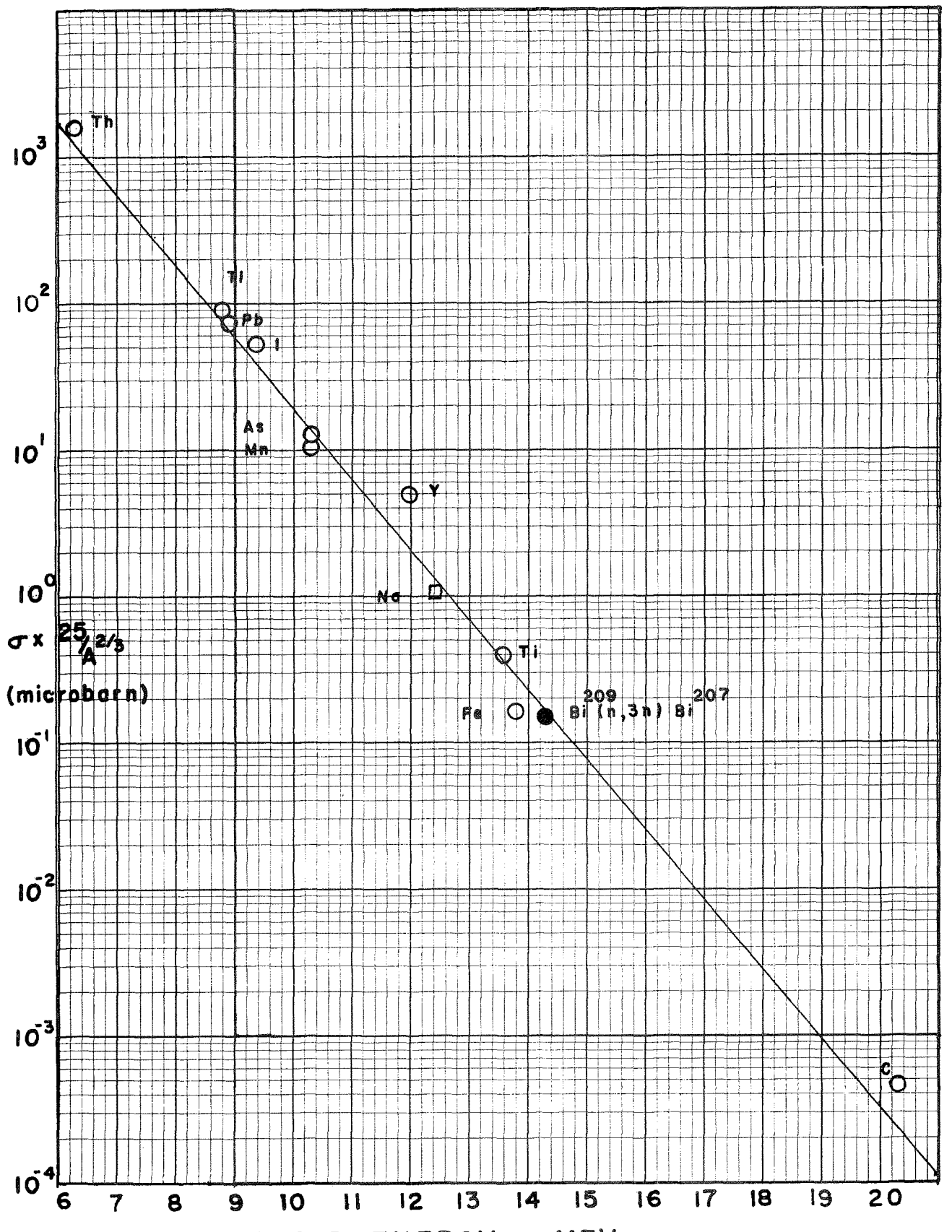
CAPTION FOR FIGURE

Figure 1. Graph of the variation of the (n,2n) cross section versus E_T.

○ (n,2n) cross sections measured in this work.

□ $Na^{23}(n,2n)Na^{22}$ from Hughes 1953 (cf. references).

● (n,3n) cross section from Eastwood and Roy 1959 (cf. references).


Th
Tl
Pb
I
As
Mn
Y
Na
Ti
Fe
^{209}Bi (n, 3n) ^{207}Bi
C
10^3
10^2
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10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
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(microbarn)
6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
THRESHOLD ENERGY - MEV.

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