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THE THERMAL NEUTRON CAPTURE CROSS-SECTION AND THE RESONANCE CAPTURE INTEGRAL OF ^{124}Xe

by

M. BRESESTI, F. CAPPELLANI,
A. M. DEL TURCO and E. ORVINI

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Joint Nuclear Research Centre
Ispra Establishment - Italy
Materials Department
Nuclear Chemistry Laboratory

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These values have been determined by irradiating natural Xenon and measuring the activity of ^{125}I, the decay product of ^{125}Xe.

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THE THERMAL NEUTRON CAPTURE CROSS-SECTION AND THE RESONANCE CAPTURE INTEGRAL OF ^{124}Xe

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(*Received* 13 *May* 1963)

Abstract—The thermal neutron capture cross-section of ^{124}Xe, its resonance capture integral (from 0·5 eV to ∞) and its effective capture cross-section in a reflector position of the Ispra 1 reactor have been found to be 111 ± 11 barns, 3600 ± 500 barns and 135 ± 13 barns respectively.

These values have been determined by irradiating natural Xenon and measuring the activity of ^{125}I, the decay product of ^{125}Xe.

ALTHOUGH the nuclear reaction ^{124}Xe(n,γ)^{125}Xe is used for the preparation of ^{125}I, decay product of ^{125}Xe, the capture cross-section of ^{124}Xe is known only imprecisely.

TOBIN and SAKO[1] evaluated this neutron capture cross-section by the measurement of the intensity of the 0·190 MeV γ-ray of ^{125}Xe. They obtained a value of 74 barns in a reactor spectrum of unspecified epithermal content. Moreover the incertainty in the value of the neutron flux was about 25 per cent. HARPER[2] found in preliminary measurements that the cross-section may even be a factor of 2 or 3 higher than the value previously reported. MANN *et al.*[3] have measured the total neutron cross-section of xenon from about 1 eV to about 200 eV. Irradiating various isotopic mixtures of xenon, they attributed to ^{124}Xe a resonance peak at 5·16 ± 0·06 eV. For the resonance analysis a radiation width of 90 ± 20 meV was assumed.

In the present work the neutron capture cross-section is determined from the activity of ^{125}I formed through the following nuclear reactions:

$$^{124}\mathrm{Xe}(n,\gamma)^{125}\mathrm{Xe} \xrightarrow[18\ \mathrm{hr}]{\mathrm{EC}} {}^{125}\mathrm{I} \xrightarrow[60\ \mathrm{days}]{\mathrm{EC}} {}^{125}\mathrm{Te} \quad \text{(stable)}$$

The neutron capture reaction can also produce ^{125m}Xe. This isotope, never observed in the neutron irradiation of ^{124}Xe, has been studied only as a decay product of ^{125}Cs.[4] Since ^{125m}Xe decays to ^{125}Xe by isomeric transition with a 55 sec half-life it is correct to evaluate the neutron capture cross-section of ^{124}Xe, without taking into account the production of ^{125m}Xe.

* Student from Nuclear Chemistry Institute of Pavia University.

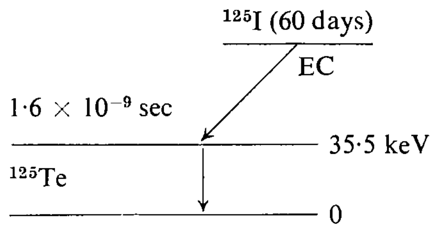
(1) J. M. TOBIN and J. H. SAKO, *J. Appl. Phys.* **29**, 1373 (1958).

(2) P. V. HARPER, Proc. 5th C.N.R.N. Nuclear Congress—Vol. II, 245 ROME (1960).

(3) D. P. MANN, W. W. WATSON, R. E. CHRIEN, R. L. ZIMMERMAN and R. B. SCHWARTZ, *Phys. Rev.* **116**, 1516 (1959).

(4) H. B. MATHUR and E. K. HYDE, *Phys. Rev.* **95**, 708 (1954).

The decay scheme of ^{125}I is the following:



The data reported in literature on the electron capture and the internal conversion of the 35·5 keV transition, are summarized in Table 1.

TABLE 1.—DATA ON ELECTRON CAPTURE AND INTERNAL CONVERSION IN ^{125}I PER 100 DISINTEGRATIONS.

Type of decay	Ref. (5)	Ref. (6)	Ref. (7)
K electron capture	77 ± 8	81 ± 2	
L electron capture	23 ± 8	19 ± 2	
K internal conversion			80 ± 5
L internal conversion			11 ± 2
M internal conversion			2 ± 0·4
Unconverted γ-ray			7 ± 2

On the basis of the data of Table 1, using the intensity ratio and the fluorescent yield reported in the *Nuclear Spectroscopy Tables*(8) the number of $X_{K\alpha}$, $X_{K\beta}$ and unconverted γ-rays has been calculated (Table 2).

TABLE 2.—NUMBER OF 27·4, 31·2 AND 35·5 keV PHOTONS PER 100 DISINTEGRATIONS OF ^{125}I.

Electron capture		
K capture 80%	$X_{K\alpha}$	56·3
	$X_{K\beta}$	12·1
35·5 keV transition		
Unconverted γ-ray		7
K conversion 80%	$X_{K\alpha}$	56·3
	$X_{K\beta}$	12·1
$X_{K\alpha}$ total number		112·6
$X_{K\beta}$ total number		24·2
Unconverted γ-ray		7
Total number of photons per 100 disintegrations		143·8

(5) G. FRIEDLANDER and W. C. ORR, *Phys. Rev.* **84**, 484 (1951).
(6) E. DER MATEOSIAN, *Phys. Rev.* **92**, 938 (1953).
(7) J. C. BOWE and P. AXEL, *Phys. Rev.* **85**, 858 (1952).
(8) A. H. WAPSTRA, G. J. NIJGH and R. VAN LIESHOUT—*Nuclear Spectroscopy Tables*—North-Holland Publishing Company, Amsterdam (1959).

The ^{125}I activity was evaluated by measuring the intensity of the 35·5 keV γ-ray, 27·4 keV $X_{K\alpha}$ and 31·2 keV $X_{K\beta}$.

EXPERIMENTAL

(a) *Irradiations*

High purity natural xenon, containing 0·096 per cent of ^{124}Xe, supplied by "Air Liquide", was sealed in silica ampoules. Each ampoule was filled at a pressure of about 1 atm with an amount of xenon exactly measured in a high vacuum line. The samples, closed in rubber capsules, were irradiated by a pneumatic carrier in the graphite reflector, close to the heavy water tank, of the Ispra 1 reactor. The irradiation time was about 2 hr.

To evaluate the epithermal activation some xenon ampoules were enclosed in 1 mm thick cadmium boxes. In the irradiations under the cadmium silica ampoules had a volume of about 2 ml, in the other ones the volume was about 4 ml.

In all the irradiations a 1 mm in diameter wire of Al/Co alloy (1 per cent Cobalt) was added to the sample to evaluate exactly the neutron flux.

(b) *Chemical separation*

The ampoules were opened in a glove-box 10 days after the end of the irradiation, when ^{125}Xe had totally decayed to ^{125}I.

About 80 per cent of ^{125}I activity was recovered from the walls of the ampoule by washing with CCl_4. This fraction of ^{125}I is presumably present in the elementary form. The remaining 20 per cent was recovered by a NaI aqueous solution.

The main impurity present on the walls of the ampoule was ^{137}Cs, daughter of ^{137}Xe produced by ^{136}Xe neutron capture. The whole ^{137}Cs activity was found in the aqueous solution. To eliminate ^{137}Cs and to obtain ^{125}I in iodide form, suitable for the preparation of the sources, the following procedure was adopted: a few milligrams of $NaNO_2$ and one drop of concentrated HNO_3, added to the aqueous solution, oxidize the iodide to iodine that is separated by repeated extractions with 1 ml fractions of CCl_4. The whole ^{137}Cs activity remains in the aqueous fraction. The CCl_4 fractions are added to the carbon tetrachloride used for washing the capsule. By adding to the whole solution 1 ml of alkaline solution of Na_2SO_3, obtained by dissolving 30 mg of Na_2SO_3 and 10 mg of NaOH in 10 ml of water, elementary iodine is reduced to iodide that is separated by repeated extractions with 2 ml fractions of water. The aqueous solution is utilized for the preparation of the sources on aluminium discs.

Losses of ^{125}I in the purification process have been controlled and corrections have been introduced.

(c) *Counting methods*

The chemical separation of ^{137}Cs and the purity of the final solution of ^{125}I were tested by γ-spectroscopy using a 3 in $\times$ 3 in NaI(Tl) crystal and a multichannel pulse analyser.

Due to the short irradiation periods (2 hr) no trace of ^{126}I, produced by (n, γ) reaction on ^{125}I, was found, although the neutron capture cross section of ^{125}I seems to be of several hundred barns from measurements in progress.

The quantitative analysis of ^{125}I was performed by a proportional counter filled with an argon + 10 per cent methane mixture. The efficiency curve of the proportional counter was previously determined in the energy range of our interest. A typical spectrum of ^{125}I is shown in Fig. 1. By assuming the total number of $X_{K\alpha}$, $X_{K\beta}$ and 35·5 keV γ-rays equal to 143·8 for 100 disintegrations as reported in Table 2 the following values were obtained: $X_{K\alpha} = 114{\cdot}8$; $X_{K\beta} = 24{\cdot}0$; $\gamma = 5{\cdot}0$.

The data for the $X_{K\alpha}$ and $X_{K\beta}$ intensities agree very well with those of Table 1 while the value for the 35·5 keV γ-ray is quite different. However, this value which is within the experimental error indicated by BOWE,[7] seems to be more reliable for the better resolution of the proportional counter.

The ^{60}Co intensity of the flux monitors was determined by a 3 in $\times$ 3 in NaI(Tl) crystal which had been calibrated previously.

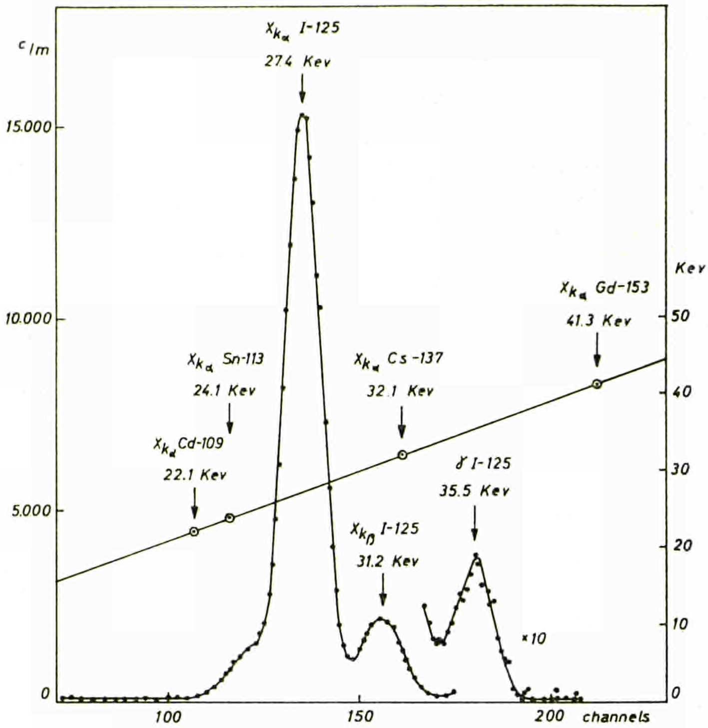


FIG. 1—^{125}I photon spectrum by the proportional counter.

CROSS-SECTION AND RESONANCE INTEGRAL CALCULATION

The results were calculated following the procedure of EASTWOOD *et al.*,[(9)] based on the convention described by WESTCOTT *et al.*[(10)]

The data for ^{59}Co used in the calculation of the conventional flux were taken from WESTCOTT[(11)] and are the following:

$$\sigma_0 = 37{\cdot}3 \text{ barns}$$
$$RI = 75 \quad \text{barns}$$
$$s_0 = 1{\cdot}736$$

No self-shielding correction had to be applied to the thermal and epithermal activities induced in ^{59}Co.

The general expression for calculating the effective cross-section from the ^{125}I activity is the following:

$$A_t = \frac{Nnv_0\hat{\sigma}}{\lambda_1 - \lambda_2}\left[\lambda_1 e^{-\lambda_2 t}(1 - e^{-\lambda_2 t_0}) - \lambda_2 e^{-\lambda_1 t}(1 - e^{-\lambda_1 t_0})\right]$$

(9) T. A. EASTWOOD, A. P. BAERG, C. B. BIGHAM, F. BROWN, M. J. CABELL, W. E. GRUMMITT, J. C. ROY, L. P. ROY and R. P. SCHUMAN, *Proceedings of the Second International Conference on the Peaceful Uses of Atomic Energy, Geneva*, 1958 Vol. 16, p. 54. United Nations (1959).

(10) C. H. WESTCOTT, W. H. WALKER and T. K. ALEXANDER, *Proceedings of the Second International Conference on the Peaceful Uses of Atomic Energy, Geneva*, 1958 Vol. 16, p. 70 United Nations (1959).

(11) C. H. WESTCOTT, Report, AECL-1101 (1960).

where

A_t = ^{125}I activity at time t after the end of the irradiation
N = number of ^{124}Xe atoms
nv_0 = conventional flux
$\hat{\sigma}$ = effective cross-section
λ_1 = decay constant of ^{125}Xe
λ_2 = decay constant of ^{125}I
t_0 = irradiation time
t = time after the end of the irradiation

In the present experiment, the irradiation time was 2 hr and the ^{125}I activity was measured about 10 days after the end of the irradiation. Under these conditions the term $\lambda_2 e^{-\lambda_1 t}(1 - e^{-\lambda_1 t_0})$ can be neglected and the expression simplifies to

$$A_t = Nnv_0\hat{\sigma}\,\frac{\lambda_1}{\lambda_1 - \lambda_2}\,e^{-\lambda_2 t}(1 - e^{-\lambda_2 t_0})$$

The reaction rates for ^{124}Xe and ^{59}Co measured without cadmium cover are reported in Table 3. These reaction rates are conventionally defined[9,10] as $R = nv_0\hat{\sigma}$.

The data utilized for the calculation of the conventional flux nv_0 and the results obtained have been assembled in Table 4. The average value for $R_{^{59}Co}$ reported in

TABLE 3.—REACTION RATES OF ^{124}Xe AND ^{59}Co WITHOUT CADMIUM COVER

Experiment	$R_{^{124}Xe}$ (sec^{-1})	$R_{^{59}Co}$ (sec^{-1})
1	$2\cdot93 \times 10^{-9}$	$8\cdot18 \times 10^{-10}$
2	$2\cdot98 \times 10^{-9}$	$8\cdot24 \times 10^{-10}$
3	$2\cdot98 \times 10^{-9}$	$8\cdot35 \times 10^{-10}$
Average value	$2\cdot96 \times 10^{-9}$	$8\cdot26 \times 10^{-10}$

TABLE 4.—CONVENTIONAL NEUTRON FLUX MEASURED WITH COBALT MONITORS

Experiment under cadmium	$R_{^{59}Co}$(Cd) (sec^{-1})	$CR_{^{59}Co}$	$r\sqrt{\left(\frac{T}{T_0}\right)}$	$\hat{\sigma}_{^{59}Co}$ (barns)	nv_0 (neutron cm^{-2} sec^{-1})
4	$1\cdot17 \times 10^{-11}$	70·6	0·0066	37·73	$2\cdot19 \times 10^{13}$
5	$1\cdot17 \times 10^{-11}$	70·6	0·0066	37·73	$2\cdot19 \times 10^{13}$
6	$1\cdot16 \times 10^{-11}$	71·2	0·0065	37·72	$2\cdot19 \times 10^{13}$
7	$1\cdot04 \times 10^{-11}$	79·4	0·0059	37·68	$2\cdot19 \times 10^{13}$
8	$1\cdot09 \times 10^{-11}$	75·8	0·0061	37·70	$2\cdot19 \times 10^{13}$

Table 3 has been utilized in the calculation of the Cadmium Ratio $CR_{^{59}\text{Co}}$. $R_{^{59}\text{Co}}$ (Cd) is the reaction rate of ^{59}Co under cadmium, $\hat{\sigma}_{^{59}\text{Co}}$ the effective cross-section.

The calculated values of the effective cross-section $\hat{\sigma}_{^{124}\text{Xe}}$, of the thermal cross-section σ_0 and of the resonance integral *RI* are assembled in Table 5. The average

TABLE 5.—CAPTURE CROSS-SECTION AND RESONANCE CAPTURE INTEGRAL OF ^{124}Xe

Experiment under cadmium	$\hat{\sigma}_{^{124}\text{Xe}}$ (barns)	$R_{^{124}\text{Xe}}$(Cd) (sec^{-1})	$CR_{^{124}\text{Xe}}$	$s_{0\,^{124}\text{Xe}}$	σ_0 (barns)	*RI* (barns)
4	135·2	$5{\cdot}95 \times 10^{-10}$	4·97	37·6	108	3810
5	135·2	$5{\cdot}40 \times 10^{-10}$	5·48	33·3	111	3470
6	135·2	$4{\cdot}73 \times 10^{-10}$	6·26	28·7	114	3060
7	135·2	$4{\cdot}96 \times 10^{-10}$	5·97	33·6	113	3590
8	135·2	$5{\cdot}87 \times 10^{-10}$	5·04	40·2	109	4050

value of $R_{^{124}\text{Xe}}$ reported in Table 3 has been utilized in the calculation of the Cadmium Ratio $CR_{^{124}\text{Xe}}$ and the effective cross-section $\hat{\sigma}_{^{124}\text{Xe}}$.

We have made a liberal estimate of possible errors, mainly systematic errors in the evaluation of the ^{125}I activity and of the neutron flux, as ± 10 per cent for $\hat{\sigma}$ and σ_0 and as ± 15 per cent for the resonance integral *RI*. This error does not take into account the uncertainties in the decay scheme of ^{125}I and in the values of σ_0 and *RI* for ^{59}Co.

The average of the five determinations, including the estimated errors, gives values of $\hat{\sigma} = 135 \pm 13$, $\sigma_0 = 111 \pm 11$ and $RI = 3600 \pm 500$ barns.

The value obtained for the resonance integral is in good agreement with the value calculated from the expression

$$RI = 2\pi\sigma_0 E_0^{1/2} E_r^{1/2}/\Gamma$$

where σ_0 = thermal cross section (111 barns)

$E_0 = 0{\cdot}0253$ eV

E_r = resonance energy of ^{124}Xe (5·16 eV)

Γ = radiation width (90 meV)

Taking into account the uncertainty of the radiation width, the value obtained is $RI = 2800 \pm 600$ barns.

The expression reported above is valid when the epithermal activation is almost exclusively due to a single resonance with the following parameters: $\Gamma \ll E_r$; $E_r \gg E_{\text{Cd}}$. This enables us to conclude that the epithermal activation of ^{124}Xe is mainly due to the resonance at 5·16 eV.

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