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CHAPTER 6

FISSION PRODUCT ABSORPTION CROSS-SECTION AT 2200 M/sec.

Thermal neutron absorption and resonance integrals

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CHAPTER 6

FISSION PRODUCT ABSORPTION CROSS-SECTIONS

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ABSTRACT

This memorandum is to be published as one chapter (6) of a book entitled "Nuclear Data for Reactor Design, Vol I'' by N. G. Sjostrand and J. S. Story. (publish Pergamnon Press) and is a critical assessment of experimental data relating to the 2200 m/s. absorption cross-section of fission product isotopes.

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A.E.E.,
Winfrith.

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Table

6.1 Introduction

Knowledge of the absorption cross-sections of fission-products is needed for calculating the long-term reactivity changes in nuclear reactors. Because they absorb neutrons, fission-products act as "poisons" by reducing the reactivity. The best known fission-product poisons are Xe^{135} and Sm^{149}, for these have very large absorption cross-sections and their effects are observable quite soon after start-up. However with continued irradiation of the fuel many other fission-products accumulate sufficiently to cause appreciable "poisoning".

Generally speaking only the stable or relatively long-lived fission-products accumulate sufficiently. To exemplify this statement consider the effects of a fission-product formed directly in fission during operation of a reactor at a steady flux ϕ. Admittedly the primary fission fragments are not usually significant poisons; however precursor nuclei are often sufficiently short-lived that a poison can be treated as if formed directly in fission. The saturation concentration of the fission product would be

$$N = \frac{y.\ \Sigma_F.\ \phi}{\lambda + \sigma_\gamma \phi}, \qquad (6.1)$$

where

y is the yield per fission of the fission product
λ is its decay constant
σ_γ is its capture cross-section
Σ_F is the macroscopic fission cross-section of the fuel.

The poisoning P by a given nuclide may be defined as the ratio of the neutron absorption rate in the nuclide and the fission rate in the fuel, per unit volume. At saturation

$$P = \frac{y\sigma_\gamma \phi}{\lambda + \sigma_\gamma \phi} \qquad (6.2)$$

P attains its maximum value at saturation concentration,

$$P = y,$$

if the nuclide is stable or long-lived ($\lambda \ll \sigma_\gamma \phi$). Short-lived nuclei decay before they have time to absorb a neutron, and so have a smaller poisoning effect. For a numerical example suppose $\sigma_\gamma = 100$ barns, and $\phi = 10^{14}$ neutrons/cm^{2}sec. Then the product $\sigma_\gamma\ \phi$ is 10^8 sec^{-1} which corresponds to a half-life of about 3 years. Thus if the nuclide has a half-life of 1 month or less it has only a small chance of neutron capture before it decays.

Detailed assessments of the relative importance in thermal reactors of the various fission-product poisons have been given by PATTENDEN & ROSE (1958), PATTENDEN (1959), SHAFTMAN (1959), NEPHEW (1960), and WALKER (1960).

6.2 Experimental Methods

Several of the methods for cross-section measurement have been discussed in detail in chapter 3 (A.E.E. W-M57), and for the present chapter a brief outline will suffice. The following methods have been used to determine the capture cross-sections of fission products:

A. Transmission measurements with neutron choppers and crystal spectrometers. The total cross-section is determined absolutely as a function of neutron energy in the low energy region. The absorption cross-section is obtained by subtracting the scattering cross-section. Since the latter is usually not known very accurately the method gives its best results when σ_A is much larger than σ_S. The method has been used by PATTENDEN (1958), and by SMITH et al. (1959).

B. Pile oscillators The measurements are made by comparison with a standard absorber, and are most easily interpreted if the neutron spectrum has only a very small epithermal component. POMERANCE (1951, 1952) used a local oscillator in the reflector of a neutron reactor, and ROSE et al. (1958) used a reactivity oscillator in an internal thermal column or "thermal well". Gold and boron respectively were used as standard absorbers.

It should be noted that in the local oscillator used by POMERANCE, the neutron counter has approximately a 1/v response to the absorbed neutrons. There are two consequences:

(i) The oscillator operates in a region where the epithermal neutron flux is very small, and the counter response practically annuls any residual epithermal effect.

(ii) None-the-less the average cross-section measured is not strictly $g\ \sigma_0$ unless $g = 1$. It is more nearly σ_0, unless there is a resonance in the thermal region.

C. Activation. This method is of great value when the samples available are very small. The samples are usually irradiated in a thermal column or inside a reactor, and cadmium-difference techniques may be employed to simplify the interpretation. The measurements are made in comparison with an activation standard used to monitor the neutron flux. For reliable results it is necessary to have a fairly detailed understanding of the decay characteristics of the various activities observed, and particularly for isomeric activities. Many of the older measurements are unreliable in these respects. A classical survey by this method was made by SEREN et al. (1947) who give an admirable description of the difficulties encountered. An example of more recent applications is the work of EASTWOOD et al. (1958).

D. Mass spectrometry. If the cross-sections are fairly large, prolonged irradiation may cause observable changes in the mass spectrum. Usually the sample is irradiated in a reactor. Since a large capture cross-section almost always implies that there is a resonance at low neutron energies the measurements cannot always be interpreted in a very satisfactory way. However the method does permit the identification of strong "poisons", and has the added virtue that only small samples are needed. Recent work has been reported by ANIKINA et al. (1958) and by BIDINOSTI et al. (1958).

Broadly speaking one expects the most reliable data from the pile oscillator method, or from the transmission method if σ_A is large; however errors may ensue if the samples contain impurities. For small cross-sections (<0.5 barn) activation methods may be more reliable, and pure samples are usually not necessary. The mass spectrometer method has permitted the identification of many strong absorbers, particularly among those leading to stable product nuclides; but it seems that very careful work is needed for reliable results.

6.3 Cross-section tables

Description and notation

In Tables 6.1, 6.2 and 6.3 following, are given the cross-sections for all those fission-products listed by KATCOFF (1958) for which the data are available, and for a few additional nuclei also, which may be formed through neutron capture in fission-product nuclie.

The elements are listed in table 6.1 in order of increasing atomic number, except for Xe^{135}. This important nuclide is treated separately in section 6.5 and in tables 6.2 and 6.3, which follow table 6.1. The following notation is used:

σ_o denotes an absorption or activation cross-section for 2200m/sec neutrons.

$\hat{\sigma}$ denotes the effective cross-section in the experimental spectrum,

$$\hat{\sigma} = (g + rs)\sigma_o$$

in the terminology of WESTCOTT (1958), see chapter 1.

Σ'_r denotes the resonance absorption integral for dilute material, excluding the $^1/v$ contribution.

$$\Sigma'_r = \int_{\mu kT}^{\infty} \{\sigma(E) - \sigma_o\sqrt{(E_o/E)}\}dE/E$$

$$= \sigma_o\{\frac{\sqrt{\pi}}{2} s + 2\ (g - 1)\sqrt{\mu}\}\sqrt{(T_o/T)},$$

the notations of WESTCOTT (1958) being used on the right.

* denotes that probably the cross-section obeys the $^1/v$ law approximately in the thermal region, so that $g \simeq 1.00$

⁂ denotes that g and s coefficients have been tabulated, the cross-section having been measured as a function of neutron energy.

The column headed "Reaction" shows whether the data are for total neutron absorption by the nuclide, or it gives the half-life of the product activity if an activation measurement was made.

Recommended values are underlined or are mentioned explicitly.

r_o denotes $r\sqrt{(T_o/T)}$, in the terminology of WESTCOTT (1958).

Most of the data listed in table 6.1 were measured in broad neutron spectra, by methods B, C, or D, of section 6.2. Values for $_o$, the 2200m/sec cross-section, cannot be derived unless the neutron spectrum and the energy variation of the cross-section are known. However for many nuclides it is reasonable to presume that the capture cross-sections obey the $^1/v$ law in the thermal region at least approximately ⁄; then

$$g \simeq 1.00$$

and for measurements in thermal spectra with $r \approx 0$, or in sub-cadmium spectra,

$$\sigma_o \simeq \hat{\sigma}$$

Corrections to experimental data

It may be noticed that many of the data differ slightly from the values given in the references cited. It has been possible to revise a good many of the comparative measurements, using the values recommended in chapter 3 for the standard cross-sections at 2200m/sec. For example, the data of SMITH & REEDER (1955, 1956), ROY and co-workers (1956-1958), BAERG et al. (1958), BIDINOSTI et al. (1958), KENNETT & THODE (1958), FICKEL & TOMLINSON (1959), have been revised using a half-life of 5.23 years for Co^{60} and σ_{act} [Co] = 37.7 barns at 2200m/sec. The data of BOTHE (1946) have been ammended using $\hat{\sigma}_{act}$ [Ho] = 59.6 barns.

It is not generally feasible to amend activation data for improved half-life values, unless it can be assumed that the irradiation and cooling periods were much shorter than the half-life. However some of the activation cross-sections reported by SEREN et al. (1947) have been revised by using more up-to-date values for the relative isotopic abundances in natural samples

Resonance integrals

Resonance integrals have been included for convenience. We have not attempted to present all resonance integral data for each nuclide, but have aimed to give representative values. The data of HARRIS et al. (1950a) appear to be too low in general, presumably because the samples were not sufficiently dilute. TATTERSALL et al. (1960) on the other hand may have over-compensated for resonance self-shielding. We tend to prefer the values calculated from resonance parameters. WALKER (1960) seems usually to have used the most recent data.

⁄ For example, transmission measurements with a sample of natural isotopic composition may show $^1/v$ behaviour in the thermal region (see BNL 325). Then it is reasonable to guess that the individual isotopes would give similar results. This inference is weakened when applied to an isotope of low relative abundance.

The resonance integral data also have been revised as described in the preceding paragraph. For example the data of KLIMENTOV & GRYAZEV (1957) have been renormalised so that they give approximately the expected results for both boron and uranium.

6.4 Short-lived fission-products

Besides the information given in tables 6.1, 6.2 and 6.3, qualitive information has been obtained by mass-spectrometry for several fission-product chains. BIDINOSTI et al. (1958) pointed out that the effect of neutron caputre by the short-lived fission-products will be most apparent if the fissile sample is irradiated in a very high neutron flux, and would result in unexpected changes in the yields of the stable and long-lived end products. Using this principle they were able to show that there is no significant neutron absorption amongst the short-lived precursors of the 23 chains with the following mass-numbers

88 - 90
92 - 96
133 - 137
142
144 - 152

6.5 The absorption cross-section of Xe^{135}

In thermal reactors Xe^{135} is the most important of the fission-product poisons, because of both the extremely large thermal neutron cross-section ~ 3×10^6 barns and the short half-life of 9.18 hours. The thermal cross-section has nearly the maximum possible value $\pi g^* \lambda^2$, in consequence of a low energy resonance with an unusually large neutron reduced-width; E_{res} = 0.084 eV and $g^* T_n^o \simeq 0.013$ eV. The existance of this resonance is the more noteworthy in that the compound nucleus Xe^{136} is a "closed shell" nucleus with 82 neutrons. Consequently the resonance spacing is particularly wide, ~600 eV in the low energy region.

With a radioactive nuclide of such a short half-life it is a formidable task to accrete, extract, and handle a sample large enough for measurements with a neutron spectrometer. In spite of these difficulties the total cross-section has been measured as a function of neutron energy, first by BERNSTEIN et al. (1956)* who used a bent-crystal focussing spectrometer, and more recently by SMITH et al. (1959)* with a fast neutron-chopper. A more copious supply of fission-product Xe was available to SMITH et al., so they had the benefits of a much larger sample.

The cross-section determined by BERNSTEIN et al. is systematically lower than the data of SMITH et al. At thermal energies the difference is of the order of 12%. This is significantly greater than would be expected from the uncertainties assigned to the data, but is not very surprising for so difficult a measurement.

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* The work was carried out in 1948 and 1954, respectively.

TABLE 6.1

Fission-product absorption of thermal and resonance neutrons

$_{32}Ge$

Reference	Mass no.	Half -life	$\hat{\sigma}$ barns	σ_o barns	Σ'_r barns	Reaction	Method and comments
POMERANCE (1952)	72	Stable		0.97 ± 0.10		Absorption	Local oscillator, r ≈ 0
				*	Small	Absorption	No resonance known below 4 keV
POMERANCE (1952)	73	Stable		14 ± 1			Local oscillator, r ≈ 0
				*	Small		No resonance known below 100 eV
SEREN et al (1947)	74	Stable	0.38 ± 0.08	*		-> 82 min	Activation in reactor
REYNOLDS (1950a)			0.53 ± 0.10			-> 82 min	Activation with sub-Cd neutrons
POMERANCE (1952)				0.62 ± 0.06		Absorption	Local oscillator, r ≈ 0
FLAMMERSFELD (1952)			0.43 x $\hat{\sigma}$ [-> 82 m]	*		-> 48 sec	Activation
der MATEOSIAN & GOLDHABER (1957)			0.042 ± 0.008	*		-> 48 sec	Activation with sub-Cd neutrons
			0.22 ± 0.04	*		-> 82 min	
SUNYAR & GOLDHABER (1949)					≲ 10	?	Probably from activation cadmium-ratio
					Small	Absorption	No resonance known below 370 eV

The 48 sec isomeric state of Ge^{75} decays by isomeric transition to the ground state. The values given for $\hat{\sigma}_{act}$ [->82 min] are for production of the ground state both directly, and by complete decay of the short-lived isomer.

Table 6.1 $_{32}Ge$ continued

References	Mass no.	Half -life	$\hat{\sigma}$ barns	σ_0 barns	Σ'_r barns	Reaction	Method and Comments
SEREN et al. (1947)	76	Stable	0.071 ± 0.014	*		->11 hr	Activation in reactor
ARNOLD & SUGARMAN (1947)			1.1 x $\hat{\sigma}$[->11 h]	*		->54 sec	Activation in reactor
REYNOLDS (1950a)			(0.015 ± 0.006 (0.30 ± 0.06	* *		-> 54 sec β^- ->11 hr	) Activation with sub-Cd) neutrons
POMERANCE (1952)				0.36 ± 0.07		Absorption	Local oscillator; r ≈ 0
LYON & ELDRIDGE (1957)			(0.10 ± 0.01 (0.043 ± 0.002	* *		->54 sec β^- ->11 hr	) Activation in reactor)
der MATEOSIAN & GOLDHABER (1957)			(0.076 ± 0.015 (0.089 ± 0.015	* *		->54 sec β^- ->11 hr	) Activation in sub-Cd) neutrons
					Small	Absorption	No resonance known below 550 eV

The 54 sec isomeric of Ge^{77} decays ~ 30% by isomeric transitions to the ground state, and the rest by beta emission to As^{77}. The values given here for $\hat{\sigma}_{act}$[->54 sec β^-] are for production of the ~ 70% beta activity only. The values for $\hat{\sigma}_{act}$[-> 11 hr] are for production of the ground state both directly and by decay of the short-lived isomer.

Table 6.1

33^{As}

References	Mass no.	Half -life	$\hat{\sigma}$ barns	σ_0 barns	Σ'_r barns	Reaction	Method and comments
SEREN et al. (1947)	75	Stable	4.2 ± 0.8	*		->26.4 hr	Activation in thermal column
COLLER & LITTLER (1950)			5.2 ± 0.3	*		Absorption	Reactivity oscillator in reactor spectrum
HARRIS er al. (1950b)			5.8	*		Absorption	Reactivity oscillator; $r_0 = 0.046$
POMERANCE (1951)				4.29 ± 0.22		Absorption	Local oscillator; $r \approx 0$
HARRIS et al. (1950a)					36	→ 26.4 hr	Activation Cd ratio. Revised

Table 6.1

$_{34}Se$

Reference	Mass no.	Half -life	$\hat{\sigma}$ barns	σ_0 barns	Σ'_r barns	Reaction	Method and comments
ARNOLD & SUGARMAN (1947)	76	Stable	≈ 6	*		→ 17 sec	Activation of isomeric state, in reactor
POMERANCE (1952)				85 ± 7		Absorption	Local oscillator; r ≈ 0
					Small		No resonance known below 860 eV
POMERANCE (1952)	77	Stable		41 ± 4		Absorption	Local oscillator; r ≈ 0
WALKER (1960)				*	≈ 12	Absorption	Calculated from resonance parameters
POMERANCE (1952	78	Stable		0.4 ± 0.4		Absorption	Local oscillator; r ≈ 0
				*	Small		No resonance known below 380 eV
SEREN et al. (1947)	80	Stable	0.034 ± 0.007 0.46 ± 0.09	* *		→ 57 min → 18 min	Activation in reactor Activation in thermal column
POMERANCE (1952)				0.61 ± 0.06		Absorption	Local oscillator; r ≈ 0
WALKER (1960)					≈ 0.6	Absorption	Calculated from resonance parameters
SEREN et al. (1947)	82	Stable	0.063 ± 0.013	*		→ 70 sec + 26 min	Activation in reactor. Activity of Br^{83} daughter observed
ARNOLD & SUGARMAN (1947)			0.044 0.0041	* *		→ 70 sec → 26 min	) Activation in reactor. Based) on σ[nat. Se → 18 min Se^{81}] = 0.23 barns
POMERANCE (1952)				2.1 ± 1.5		Absorption	Local oscillator; r ≈ 0
				- -	Small		No resonance known below 3 keV

Table 6.1

$_{35}Br$

Reference	Mass no.	Half -life	$\hat{\sigma}$ barns	σ_0 barns	Σ'_r barns	Reaction	Method and comments
SEREN et al. (1947)	79	Stable	2.9 ± 0.6 8.5 ± 1.7	* *		->4.4 hr ->18 min	Activation in thermal column. Corrected for 5% decay for Br^{80} ground state by orbital electron capture
REYNOLDS (1950b)			10.3 ± 0.8	*		Absorption	Mass spectrometry with isotope dilution. Result is for thermal neutrons see footnote
HARRIS et al. (1950a)					132	-> ?	Activation Cd-ratios. Recalculated
KLIMENTOV & GRYAZEV (1957)					223 ± 30	Absorption	Reactivity measurements with natural Br under Cd. Recalculated, and Br^{81} contribution subtracted
Authors (1960)					242	Absorption	Calculated from resonance parameters
SEREN et al. (1947)	81	Stable	2.3 ± 0.5	*		->36 hr	Activation in reactor
REYNOLDS (1950b)			2.8 ± 0.2	*		Absorption	As for Br^{79}, above
ORNL unpublished work quoted in BNL 325 (1960)			3.3 ± 0.4	*		->36 hr	Activation
WALKER (1960)					≈ 60	Absorption	Calculated from resonance parameters

Note: REYNOLDS (1950b) measured the ratio $\sigma_A\,[Br^{79}]\,/\,\sigma_A\,[Br^{81}] = 3.86 \pm 0.05$ in a reactor spectrum. We have combined this with σ_A [natural Br] = 6.6 ± 0.1 barns at 2200 m/sec from the work of POMERANCE (1951) and EGELSTAFF (1953), and with the resonance integrals. Both isotopes have nearly the same value for Σ'_r/σ_0 so that $\hat{\sigma}$ for thermal neutrons can be calculated with little uncertainty.

Table 6.1

$_{36}Kr$

Reference	Mass no.	Half -life	$\hat{\sigma}$ barns	σ_0 barns	Σ'_r barns	Reaction	Method and comments
MACNAMARA & THODE (1950)	82	Stable	45 ± 15	*		(n, γ)	Mass spectrometry. Reactor spectrum
WALKER (1960)					~180	Absorption	Calculated from resonance parameters
MACNAMARA & THODE (1950)	83	Stable	205 ± 30	*		(n, γ)	Mass spectrometry. Reactor spectrum. Revised uncertainty from BNL 325 (1960)
KENNETT & THODE (1958)			227 ± 45	*		(n, γ)	Mass spectrometry. Reactor spectrum. Recalculated
WALKER (1960)					~140	Absorption	Calculated from resonance parameters
HOAGLAND & SUGARMAN (1945)	84	Stable	0.10 ± 0.03 0.06 ± 0.02	* *		→4.4 hr β^- - 10 yr	Activation in reactor
MACNAMARA & THODE (1950)			<2			(n, γ)	Mass spectrometry. Reactor spectrum
					~3.3		Calculated from resonance parameters
MACNAMARA & THODE (1950)	85	10.5 yr	<15			(n, γ)	Mass spectrometry. Reactor spectrum
SUGARMAN & TURKEVICH (1944)	86	Stable	0.08	*		→76 min	Activation in reactor
HOAGLAND & SUGARMAN (1945)			0.06 ± 0.02	*		→ 76 min	Activation in reactor
MACNAMARA & THODE (1950)			<2	*		(n, γ)	Mass spectrometry. Reactor spectrum
SUGARMAN & TURKEVICH (1944)	87	76 min	<600			→2.3 hr	Activation in reactor. Original value ≤ 470 barns, revised in BNL 325 (1958)

The 4.4 hr isomeric state of Kr^{85} decays ~23% by isomeric transitions to the 10 yr ground state, and the remainder transforms to Rb^{87} by beta emission. The value given for σ_{act} [→4.4 hr β^-] is for production of the ~77% beta activity alone. The value for σ_{act} [→10 yr] is for production of the 10 yr ground state, both directly and by decay of the short-lived isomer

Table 6.1

$_{37}Rb$

Reference	Mass no.	Half -life	$\hat{\sigma}$ barns	σ_o barns	Σ'_r barns	Reaction	Method and comments
SEREN et al. (1947)	85	Stable	0.72 ± 0.15	*		-> 18.7 day	Activation in reactor
POMERANCE (1951)				0.96 ± 0.10		Absorption	Local oscillator; $r \approx 0$. Subtraction of σ_{act} [Rb^{87}] from σ_A [natural Rb]
ORNL unpublished work quoted in BNL 325 (1960)			0.91 ± 0.08	*		-> 18.7 day	Activation
WALKER (1960)					≈0.12		Calculated from resonance parameters
		Recommended value		0.93 ± 0.08			
SEREN et al. (1947)	87	5×10^{10} yr	0.118 ± 0.024	*		-> 18 min	Activation in thermal column
WALKER (1960)					≈0.11		Calculated from resonance parameters
ROY et al. (1958)	88	18 min	1.08 ± 0.32			-> 15 min	Activation in reactor; $r_o \approx 0.02$. Revised

Table 6.1

$_{38}Sr$

Reference	Mass no.	Half -life	$\hat{\sigma}$ barns	σ_0 barns	Σ'_r barns	Reaction	Method and comments
SEREN et al. (1947)	86	Stable	1.31 ± 0.26	*		→ 2.8 hr	Activation of isomer in thermal column
ORNL unpublished work quoted in BNL 325 (1960)			1.65 ± 0.16	*		→ 2.8 hr	Activation of isomer
POMERANCE (1951				≤10		Absorption	Local oscillator; $r \approx 0$ Subtraction of known activation cross-sections from σ_A [natural Sr]
KLIMENTOV & GRYAZEV (1957)					≤ 50	Absorption	Reactivity measurements with natural Sr under Cd. Recalculated and contributions of Sr^{87} and Sr^{88} subtracted
POMERANCE (1951)	87	Stable		≤15		Absorption	As above
WALKER (1960)				≥ 3.3	~100		Calculated from resonance parameters
SEREN et al. (1947)	88	Stable	5 ± 1 mb	*		→ 50 day	Activation in reactor
ROY et al. (1958)			6.2 ± 0.4 mb	*		→ 50 day	Activation in reactor with $r_0 \approx 0.02$. Recalculated with revised input data
POMERANCE (1951)				≤1.0		Absorption	As for Sr^{86} above
WALKER (1960)				≥ 0.016	~0.0045	Absorption	Calculated from resonance parameters
There is evidence for an isomeric state of Sr^{89} of 10 days half-life decaying by isomeric transition to the 50 day ground state. The values given for σ_{act} [→ 50 day] are for production of the 50 day activity and probably include the production via the isomeric state.							
ROY & ROY (1957)	89	50 day	0.43 ± 0.04			→ 28 day	Activation in reactor with $r_0 \approx 0.02$. Recalculated, using revised input data for Co and Sr^{88}
ANL unpublished work quoted in BNL 325 (1955)	90	28 yr	1.0 ± 0.6			→ 9.7 hr	Activation

For Sr^{86} and Sr^{87} only upper limits have been given for σ_A, but these values are correlated. If the maximum value holds for one of the two isotopes, then the other can have only a small cross-section.

Table 6.1

$_{39}Y$

Reference	Mass no.	Half -life	$\hat{\sigma}$ barns	σ_o barns	$\Sigma' r$ barns	Reaction	Method and comment
BOTHE (1946)	89	Stable	1.2 ± 0.3	*		→ 64 hr	Activation
SEREN et al. (1947)			1.24 ± 0.25	*		→ 64 hr	Activation in reactor
POMERANCE (1951)				1.43 ± 0.14		Absorption	Local oscillator; $r \approx 0$
BENOIST et al. (1951)			1.33 ± 0.19	*		Absorption	Reactivity oscillator in reactor spectrum. $r_o = 0.03$
ORNL unpublished work quoted in BNL 325 (1957, 1958)			1.31 ± 0.08	*		Absorption	
- ditto -			1.26 ± 0.08	*		→ 64 hr	Activation
HARRIS et al. (1950a)					0.27	→ 64 hr	Activation Cd ratio
WALKER (1960)					≈0.1	Absorption	Calculated from resonance parameters
		Recommended value		1.3 ± 0.1			
SMITH & REEDER (1955)	90	64 hr	<7.3			→ 58 day	Activation; r = 0 assumed. Includes the production of 58 day Y^{91} by decay of the 50 min. isomer. Revised
EASTWOOD et al. (1958)	91	58 day	<10			→ 3.6 hr	Activation in reactor; $r_o \approx 0.02$
Chalk River unpublished work quoted in BNL 325 (1960)			1.07 ± 0.09			→ 3.6 hr	Activation

Table 6.1

$_{40}Zr$

References	Mass no.	Half -life	$\hat{\sigma}$ barns	σ_0 barns	Σ'_r barns	Reaction	Method and comments
POMERANCE (1952)	90	Stable		0.11 ± 0.02		Absorption	Local oscillator; r ≈ 0
				*	Small		No resonance known below 300 eV
POMERANCE (1952)	91	Stable		1.57 ± 0.13		Absorption	Local oscillator; r ≈ 0
WALKER (1960)				*	~4.8	Absorption	Calculated from resonance parameters
POMERANCE (1952)	92	Stable		0.26 ± 0.08		Absorption	Local oscillator; r ≈ 0
				*	Small		No resonance known below 300 eV
POMERANCE (1955)	93	1.1×10^6 y		<4 *		Absorption	Local oscillator; r ≈ 0. No thermal resonance assumed
SEREN et al. (1947)	94	Stable	0.42 ± 0.18	*		→ 65 day	Activation in reactor
LEDDICOTTE & REYNOLDS (1949)			0.060 ± 0.01	*		→ 65 day	Activation with sub-Cd neutrons
POMERANCE (1952)				0.080 ± 0.040		Absorption	Local oscillator; r ≈ 0
ORNL unpublished work quoted in BNL 325 (1960)			0.076 ± 0.008	*		→ 65 day	Activation
					Small	Absorption	No resonance known below 300

Reference	Mass no.	Half -life	$\hat{\sigma}$ barns	σ_0 barns	Σ'_r barns	Reaction	Method and comments
SEREN et al. (1947)	96	Stable	0.32 ± 0.06			→ 17 hr	Activation in reactor
LEDDICOTTE (1949)			0.045			→ 17 hr	Activation
POMERANCE (1952)				0.10 ± 0.10		Absorption	Local oscillator; $r \approx 0$
ORNL unpublished work quoted in BNL 325 (1960)			0.053 ± 0.005			→ 17 hr	Activation
SUNYAR & GOLDHABER (1949)					$\lesssim 10$	?	Probably from activation cadmium-ratio

Revised values of σ_{act} [Zr^{94}] and σ_{act} [Zr^{96}], obtained by re-evaluation of the early data, have been listed without explanation in BNL 325 (1955, 1957 and 1958). Presumably these revisions were necessitated by discovery of the complex decay schemes of Zr^{95} and Zr^{97} with their Nb daughters in equilibrium. This serves but to emphasise the unreliability of the early activation data, and the need for new measurements.

Table 6.1

$_{41}Nb$

Reference	Mass no.	Half -life	$\hat{\sigma}$ barns	σ_o barns	Σ'_r barns	Reaction	Method and comments
SEREN et al (1947)	93	Stable	1.0 ± 0.4	*		→ 6.6 min	Activation in thermal column of short lived isomer of Nb^{94}
ANDERSON et al (1944)			1.55			Absorption	Reactivity; reactor spectrum
COLMER & LITTLER (1950)			1.35 ± 0.15	*		Absorption	Reactivity oscillator; in reactor spectrum
HARRIS et al (1950b)			1.61	*		Absorption	Ditto, with r_c = 0.046
POMERANCE (1951)				1.1 ± 0.1		Absorption	Local oscillator; $r \approx 0$, ($g \approx 1.0$ assumed)
ROSE et al (1959)			1.17 ± 0.02	1.17 ± 0.02		Absorption	Reactivity oscillator in thermal well; $r \approx 0$, (g = 1.000 assumed)
TATTERSAL et al (1960)					13 ± 5	Absorption	Reactivity oscillator in thermal well and lattice spectra
- ditto -					15 ± 5	Absorption	Calculated from resonance parameters

Table 6.1

$_{42}Mo$

Reference	Mass no.	Half -life	$\hat{\sigma}$ barns	σ_o barns	$\Sigma r'$ barns	Reaction	Method and comments
POMERANCE (1952)	95	Stable		13.9 ± 1.1		Absorption	Local oscillator; r ≈ 0
TATTERSALL et al. (1960)			14.7 ± 0.5	*		Absorption	Reactivity oscillator in thermal well; r ≈ 0
- ditto -					100 ± 20	Absorption	Ditto, with lattice spectrum also
- ditto -					100 ± 15	Absorption	Calculated from resonance parameters
			Recommended value	14.5 ± 0.5			
POMERANCE (1952)	96	Stable		1.2 ± 0.6		Absorption	Local oscillator; r ≈ 0
WALKER (1960)					~ 26	Absorption	Calculated from resonance parameters
POMERANCE (1952)	97	Stable		2.2 ± 0.7		Absorption	Local oscillator; r ≈ 0
WALKER (1960)					14 ± 3	Absorption	Calculated from resonance parameters
SEREN et al. (1947)	98	Stable	0.42 ± 0.08	*		→ 67 hr	Activation in reactor
POMERANCE (1952)				0.4 ± 0.4		Absorption	Local oscillator; r ≈ 0
ANDERS (1958)			0.21 ± 0.03	*		→ 67 hr	Activation; r ≈ 0
ORNL unpublished work quoted in BNL 325 (1960)			0.51 ± 0.06	*		→ 67 hr	Activation
ANDERS (1958)					13 ± 5	→ 67 hr	Activation in different spectra with Cd-ratios for Au
WALKER (1960)					~ 3.4	Absorption	Calculated from resonance parameters
SEREN et al. (1947)	100	Stable	0.46 ± 0.09			→ 14.6 min	Activation in reactor
POMERANCE (1952)				0.5 ± 0.5		Absorption	Local oscillator; r ≈ 0
Unpublished work quoted in BNL 325 (1955)			0.22 ± 0.05			→ 14.6 min	Activation
CABELL (1960)			0.197 ± 0.008			→ 14.6 min	Activation with sub-Cd neutrons
- ditto -					3.1 ± 0.2	→ 14.6 min	Activation Cd-ratios
WALKER (1960)				≳ 0.4	~ 6.2		Calculated from resonance parameters

Table 6.1

$_{43}Tc$

Reference	Mass no.	Half -life	$\hat{\sigma}$ barns	σ_o barns	Σ'_r barns	Reaction	Method and comments
POMERANCE (1955b)	99	2.1×10^5y		19 ± 2		Absorption	Local oscillator; $r \approx 0$
PATTENDEN (1958)				25 ± 2		Absorption	Transmission, using a crystal spectrometer
- ditto -					※		Tables of g and s coefficients are given
TATTERSALL et al. (1960)			16 ± 7			Absorption	Reactivity oscillators in reactor spectra
				16 ± 7			Results given here are for $\hat{\sigma}$ (thermal),
					60 ± 20	Absorption	σ_o, and Σ'_r g = 1.009 is assumed.
WALKER (1960)				≳ 18	200 ± 20	Absorption	Calculated from resonance parameters
		Recommended value		22 ± 3			

Table 6.1

$_{44}Ru$

Reference	Mass no.	Half -life	$\hat{\sigma}$ barns	σ_o barns	Σ'_r barns	Reaction	Method and comments
POMERANCE (1951)	99	Stable		$\leqslant$ 15 *		Absorption	Local oscillator, with natural Ru, and subtraction of known activation cross-sections. $r \approx 0$
NEPHEW (1960)					$\leqslant$350	Absorption	Calculated from resonance parameters of natural Ru
POMERANCE (1951)	100	Stable		$\leqslant$15 *		Absorption	As for Ru^{99}
NEPHEW (1960)					$\leqslant$ 350	Absorption	As for Ru^{99}
POMERANCE (1951)	101	Stable		$\leqslant$12		Absorption	As for Ru^{99}
NEPHEW (1960)					$\leqslant$ 260	Absorption	As for Ru^{99}
SEREN et al. (1947)	102	Stable	1.17 ± 0.23	*		$\rightarrow$ 39.8 day	Activation in reactor
KATCOFF & WILLIAMS (1951)			1.44 ± 0.16	*		$\rightarrow$ 39.8 day	Activation with sub-Cd neutrons
- ditto -					4.0	$\rightarrow$ 39.8 day	Calculated from Cd-ratios
SEREN et al (1947)	104	Stable	0.74 ± 0.15	*		$\rightarrow$ 4.5 Hr	Activation in reactor. Includes data from activation of daughter, 37 hr Rh^{105}
SUNYAR & GOLDHABER (1949)					$\lesssim$10	?	Probably from activation Cd-ratio
SHARMA & POOL (1959)	105	4.5 hr	0.20 ± 0.06			$\rightarrow$ 1.0 yr	Activation, probably in reactor spectrum

The upper limits given for σ_o of Ru^{99} are correlated. If σ_o has its maximum value for one of these isotopes then it must be very small for the other two. Similar remarks apply to the values for Σ'_r for these isotopes, (but not for Ru^{104})

Table 6.1

$_{45}Rh$

Reference	Mass no.	Half -life	$\hat{\sigma}$ barns	σ_a barns	$\Sigma' r$ barns	Reaction	Method and comments
SEREN et al. (1947)	103	Stable	11.6 ± 1.2 137 ± 14			→ 4.4 min → 44 sec	Activation in thermal column
MEIJER (1949)				140 ± 3		Absorption	Transmission using slow chopper
HARRIS et al. (1950b)			185			Absorption	Reactivity oscillator in reactor spectrum; r_o = 0.046
POMERANCE (1951)				156 ± 8		Absorption	Local oscillator; r ≈ 0
SAILOR (1953)				142 ± 10		Absorption	Transmission using crystal spectrometer in range 0.18 to 30 eV. Value given is contribution of 1.26 eV level only
ROSE et al. (1958)			146 ± 5	143 ± 5		Absorption	Reactivity oscillator in thermal well; r ≈ 0, g = 1.023 at 20°C
HARRIS et al. (1950a)					582	→ ?	Activation Cd-ratios. Revised
WALKER (1960)					1020 ± 20	Absorption	Calculated from resonance parameters
WESTCOTT (1960)							Tables of g and s coefficient
			Recommended value	143 ± 5	1020 ± 100		
The 4.4 min isomeric state of Rh^{104} decays almost entirely by isomeric transition to the 44 sec ground state. The activation cross-sections given are for the independent direct production of the two isomers through neutron capture in Rh^{103}.							
Chalk River unpublished work quoted in BNL 325 (1960)	104	4.4 min	800 ± 100			→ 36 hr	Activation in reactor
		44 sec	40 ± 30			→ 36 hr	- ditto -

Table 6.1

$_{46}Pd$

Reference	Mass no.	Half -life	$\hat{\sigma}$ barns	σ_0 barns	$\Sigma' r$ barns	Reaction	Method and comments
POMERANCE (1951)	104	Stable		$\leqslant 40$		Absorption	Local oscillator; $r \approx 0$. Subtraction of known activation cross-sections from σ_A [natural Pd]
WALKER (1960)				$\gtrsim 0.5$	~14	Absorption	Calculated from resonance parameters
POMERANCE (1951)	105	Stable		$\leqslant 17$		Absorption	As for Pa^{104} above
WALKER (1960)				$\gtrsim 1.35$	≈ 67	Absorption	Calculated from resonance parameters
POMERANCE (1951)	106	Stable		$\leqslant 14$		Absorption	As for Pa^{104} above
WALKER (1960)				$\gtrsim 0.2$	~ 5.5	Absorption	Calculated from resonance parameters
SEREN et al. (1947)	108	Stable	11.2 ± 2.2			→ 13.5 hr	Activation in thermal column
MEISTER (1958)			9.3 ± 0.7			→ 13.5 hr	Activation; $r \approx 0$ assumed
SEHGAL et al. (1959)			0.26 ± 0.04 14.4 ± 2.1			→ 4.8 min → 13.5 hr	)Activation in thermal column)Recalculated with $\hat{\sigma}$ [Au] = 99.0 b
WALKER (1960)				$\gtrsim 4.7$	≈ 150		Calculated from resonance parameters
The 4.8 min isomeric state of Pd^{109} decays by isomeric transition to the ground state. The values given here for σ_{act} [→ 13.5 hr] are for production of the 13.5 hr ground state both directly and by decay of the short-lived isomer.							
SEREN et al. (1947)	110	Stable	0.39 ± 0.08			→ 23.6 min	Activation in thermal column
SEHGAL et al. (1959)			< 0.05 0.19 ± 0.03			→ 5.5 hr → 23.6 min	)Activation in thermal column)
WALKER (1960)					~ 6.0		Calculated from resonance parameters

Upper limits are given for the thermal cross-sections of Pd^{104}, Pd^{105} and Pd^{106}. These values are correlated, so that if the maximum value holds for one isotope then the cross-sections of the other two must be close to zero.

Table 6.1

$_{47}Ag$

Reference	Mass no.	Half -life	$\hat{\sigma}$ barns	σ_o barns	Σ'_r barns	Reaction	Method and results
See chapter 3	107	Stable		34.9 ± 2.5			
HARRIS et al. (1950a)					69	→ 2.3 min.	Activation Cd ratio. Recalculated
TATTERSAL et al. (1960)					95	Absorption	Calculated from resonance parameters
See chapter 3	109	Stable		92.4 ± 2.7		Absorption	
- ditto -				0.9 ± 0.6		→ 253 day	)Activation
- ditto -				91.5 ± 2.8		→ 24 sec.	)
HARRIS et al. (1950a)					1240	→ ?	Activation Cd ratios. Recalculated
TATTERSALL et al. (1960)					1870 ± 200	Absorption	Reactivity oscillator in thermal well and lattice spectra
- ditto -					1400 ± 65	Absorption	Calculated from resonance parameters. Mainly due to resonance at 5.2 eV
WESTCOTT (1960)					※		Table of g-coefficients for natural Ag. The deviation from unity is due to Ag^{109}

Reference	Mass no.	Half -life	$\hat{\sigma}$ barns	σ_o barns	Σ'_r barns	Reaction	Method and comments
Unpublished work (1948) quoted in BNL 325	110	Stable	0.2 ± 0.1	*		→ 49 min.	Activation of Cd^{111} isomer
WALKER (1960)					~ 30	Absorption	Calculated from resonance parameters
WALKER (1960)	111	Stable		≳ 0.5	≈ 44	Absorption	Calculated from resonance parameters
BELL et al. (1950)	112	Stable	80 ± 40 mb	*		→ 14 yr	Activation of Cd^{113} isomer. Revised for half-life
WAHL (1959)			43 ± 10 mb	*		→ 14 yr	Activation of Cd^{113} isomer with thermal neutrons
WALKER (1960)				≳ 0.06	~ 5	Absorption	Calculated from resonance parameters
Both the data for σ act [→ 14 yr] are proportional to the value assumed for σ act [Cd^{114} → 44 day], namely 0.14 ± 0.03 barns.							
MESERVEY (1951)	113	Stable		20040		(n, γ)	Time-of-flight using pulsed cyclotron; capture radiation detection
BROCKHOUSE (1951)				19790 ± 450		Absorption	Transmission and scattering using crystal spectrometer
BNL 325 (1958) graphs				20830		Absorption	Apparently renormalisation of old transmission data by RAINWATER et al. (1947)
ROSE et al (1958)			21620 ± 300	19640 ± 240		Absorption	Reactivity oscillator in thermal well; r ≈ 0. We assume g = 1.330 ± 0.008
WESTCOTT (1960)				✗		Absorption	Tables of g and s coefficients for natural Cd, but the absorption is due to Cd^{113} almost completely. The g values may be ~ 1% low
		Recommended value		19740 ± 260			
SEREN et al. (1947)	114	Stable	0.14 ± 0.03 1.04 ± 0.21	*		→ 44 day → 53 hr	Activation in reactor
OVERMAN et al. (1948)			0.064 0.64	*		→ 44 day → 53 hr	- ditto -
WALKER (1960)					≈ 10	Absorption	Calculated from resonance parameters
SEREN et al. (1947)	116	Stable	1.3 ± 0.26	*		→ 3.0 hr	Activation of Cd^{117} isomer in reactor spectrum
SUNYAR & GOLDHABER (1949)					≲ 10	?	Probably from activation Cd-ratio of some isomer

Table 6.1

$_{49}In$

References	Mass no.	Half -life	$\hat{\sigma}$ barns	σ_o barns	Σ'_r barns	Reaction	Method and comments
See chapter 3	113	Stable		41 ± 19 2 ± 0.3 *		→ 49 day → 72 sec	Activation
HARRIS et al. (1950 a)					740	→ ?	Activation Cd-ratios. Recalculated
WALKER (1960)					200	Absorption	Calculated from resonance parameters
See chapter 3	115	6×10^{14}y		146 ± 9 50 ± 5		→ 54 min → 13 sec	Activation
HARRIS et al. (1950 a)					2650	→ ?	Activation Cd-ratios. Recalculated
TATTERSALL et al. (1960)					3580 ± 100	Absorption	Reactivity oscillators with natural In
WALKER (1960)					3230 ± 90	Absorption	Calculated from resonance parameters
WESTCOTT (1960)							Tables of g and s coefficients for natural In. Deviation of g from unity is caused by the strong resonance in In^{115} at 1.46 eV

Table 6.1

$_{50}Sn$

Reference	Mass no.	Half -life	$\hat{\sigma}$ barns	σ_o barns	Σ'_r barns	Reaction	Method and comments
ROSE et al. (1958)	114	Stable	$\lesssim 89$	*		Absorption	Reactivity oscillator in thermal well, $r \approx 0$. Known activation cross-sections subtracted from σ_A [natural Sn]
WALKER (1960)				$\gtrsim 0.15$	~ 4.6	Absorption	Calculated from resonance parameters
ROSE et al. (1958)	115	Stable	$\lesssim 170$	*		Absorption	As for Sn^{114} above
WALKER (1960)				$\gtrsim 0.04$	~ 1.9	Absorption	Calculated from resonance parameters
NELSON et al. (1950)	116	Stable	6 ± 2 mb			$\rightarrow$ 14 day	Activation in reactor of Sn^{117} isomer
ROSE et al. (1958)			$\lesssim 4.1$	*		Absorption	As for Sn^{114} above
WALKER (1960)				$\gtrsim 0.2$	~ 13	Absorption	Calculated from resonance parameters
ROSE et al. (1958)	117	Stable	$\lesssim 7.6$	*		Absorption	As for Sn^{114} above
WALKER (1960)				$\gtrsim 0.17$	≈ 15	Absorption	Calculated from resonance parameters
HILL (1951)	118	Stable	~ 3 mb	*		$\rightarrow$ 245 day	Activation of Sn^{119} isomer, with a reactor spectrum probably
BOWE & AXEL (1951)			11 mb	*		$\rightarrow$ 245 day	- ditto -
ROSE et al. (1958)			$\lesssim 2.4$	*		Absorption	As for Sn^{114} above
WALKER (1960)				$\gtrsim 0.09$	~ 4.0	Absorption	Calculated from resonance parameters

Table 6.1 $_{50}Sn$ continued

Reference	Mass no.	Half -life	$\hat{\sigma}$ barns	σ_o barns	Σ'_r barns	Reaction	Method and comments
ROSE et al. (1958)	119	Stable	$\lesssim 6.7$	*		Absorption	As for Sn^{114} above
WALKER (1960)				$\gtrsim 0.046$	≈ 5.6	Absorption	Calculated from resonance parameters
SEREN et al. (1947)	120	Stable	55 ± 11 mb 0.22 ± 0.04	* *		→ (>400) day → 27.5 hr	Activation in reactor
NELSON et al. (1950)			~1 mb ~30 mb	* *		→ (>400) day → 27.5 hr	- ditto -
HUGHES et al. (1953)			0.13	*		→ 27.5 hr	- ditto -
WALKER (1960)				$\gtrsim 5.3$ mb	~0.75	Absorption	Calculated from resonance parameters
SEREN et al. (1947)	122	Stable	0.30 ± 0.06			→ 40 min	Activation in reactor
NELSON et al. (1950)			1 mb 0.1			→ 130 day → 40 min	Activation
HUGHES et al. (1953)			0.16 ± 0.04			→ 40 min	Activation in reactor
SUNYAR & GOLDHABER (1949)					$\lesssim 10$	?	Probably from activation Cd-ratios
					Small	Absorption	No resonance known below 100 eV
SEREN et al. (1947)	124	Stable	0.15 ± 0.03 0.65 ± 0.13			→ 9.7 day → 9.6 min	Activation in reactor
NELSON et al. (1950)			2 mb 0.5			→ 9.7 day → 9.6 min	Activation
HUGHES et al. (1953)			5 mb 0.15			→ 9.7 day → 9.6 min	Activation in reactor
WALKER (1960)				$\gtrsim 0.18$	~12	Absorption	Calculated from resonance parameters

Upper limits are given above for the thermal cross-sections of Sn^{114} to Sn^{116}. These data are correlated, so that if the maximum value holds for one isotope the other two must have very small cross-sections.

Table 6.1

$_{51}Sb$

Reference	Mass no.	Half-life	σ barns	σ_0 barns	$\Sigma' r$ barns	Reaction	Method and comments
SEREN et al. (1947)	121	Stable	6.8 ± 1.4	*		→ 2.8 day	Activation in reactor. Revised to allow for 3.1% decay of Sb^{122} by orbital electron capture
POMERANCE (1952)				5.9 ± 0.5		Absorption	Local oscillator; r ≈ 0
SEHGAL et al. (1959)			0.19 ± 0.03	*		→ 3.5 min	Activation in thermal column
WALKER (1960)				≳ 5.3	≈ 200	Absorption	Calculated from resonance parameters
The 3.5 min isomeric state of Sb^{122} decays by isomeric transition to the ground state. The value given above for σ_{act} [→ 2.8 day] is for production of the 2.8 day ground state both directly and by decay of the short-lived isomer.							
SEREN et al. (1947)	123	Stable	2.6 ± 0.5	*		→ 61 day	Activation in reactor. Includes decay of isomeric states
der MATEOSIAN et al. (1947)			~30 mb	*		→ 1.3 min	Activation with thermal neutrons
OVERMAN et al. (1948)			4.4	*		→ 61 day	Activation in reactor
POMERANCE (1952)				4.1 ± 0.3		Absorption	Local oscillator; r ≈ 0
ANL unpublished work quoted in BNL 325 (1955)			30 ± 15 mb	*		→ 21 min	Activation
WALKER (1960)				≳ 2.0	≈ 160	Absorption	Calculated from resonance parameters
MURIN et al. (1957)	124	61 day	~1500			→ 2.0 yr	Activation in reactor. Detection of 58 day Te^{125m} daughter activity. Revised for product half-life.

Table 6.1

$_{52}Te$

Reference	Mass no.	Half-life	σ barns	σ_0 barns	Σ'_r barns	Reaction	Method and comments
HILL (1949)	122	Stable	1.2 ± 0.5	*		→ 112 day	Activation in reactor of Te^{123} isomer. Revised for half-life of product
POMERANCE (1952)				2.8 ± 1.0		Absorption	Local oscillator; r ≈ 0
WALKER (1960)					~ 55	Absorption	Calculated from resonance parameters
POMERANCE (1952)	123	Stable		404 ± 32		Absorption	Local oscillator; r ≈ 0
WALKER (1960)				* ≳ 470	≈ 6560	Absorption	Calculated from resonance parameters. Strong resonance at 2.33 eV
HILL (1949)	124	Stable	5 ± 3	*		→ 58 day	Activation in reactor of Te^{125} isomer
POMERANCE (1952)				6.7 ± 1.3		Absorption	Local oscillator; r ≈ 0
WALKER (1960)					~ 2.1	Absorption	Calculated from resonance parameters
POMERANCE (1952)	125	Stable		1.54 ± 0.15		Absorption	Local oscillator; r ≈ 0
WALKER (1960)				*	~ 23	Absorption	Calculated from resonance parameters
SEREN et al. (1947)	126	Stable	75 ± 15 mb 0.80 ± 0.16	* *		→ 105 day → 9.4 hr	Activation in reactor
POMERANCE (1952)				0.80 ± 0.20		Absorption	Local oscillator; r ≈ 0
WALKER (1960)					~ 9	Absorption	Calculated from resonance parameters
SEREN et al. (1947)	128	Stable	16 ± 3 mb 0.14 ± 0.03	* *		→ 34 day → 72 min	Activation in reactor
POMERANCE (1952)				0.3 ± 0.3		Absorption	Local oscillator; r ≈ 0
WALKER (1960)				≳ 0.9	~ 10	Absorption	Calculated from resonance parameters
SEREN et al. (1947)	130	Stable	< 9 mb 0.21 ± 0.04	* *		→ 30 hr → 25 min	Activation in reactor
POMERANCE (1952)				0.5 ± 0.3		Absorption	Local oscillator; r ≈ 0

Table 6.1

53^{I}

Reference	Mass no.	Half-life	σ barns	σ_0 barns	Γ'_r barns	Reaction	Method and comments
SEREN et al. (1947)	127	Stable	6.65 ± 1.3	*		→ 25 min	Activation in thermal column. Corrected for 6.4% decay of I^{128} by orbital electron capture
WU et al. (1947)				7.04 ± 0.31		Absorption	Transmission, using pulsed cycletron
JONES (1947)				6.64 ± 0.25		Absorption	- ditto -
POMERANCE (1951)				6.3 ± 0.32		Absorption	Local oscillator; r ≈ 0
GRIMELAND (1952)			5.72 ± 0.3	* 5.72 ± 0.3		→ 25 min	Activation in thermal column, relative to σ_{act} [Na] = 0.534 barns. g = 1.000 assumed
TATTERSALL et al.(1960)			6.6 ± 0.3	* 6.6 ± 0.3		Absorption	Reactivity oscillator in thermal well; r ≈ 0. g = 1.00 assumed
HARRIS et al. (1950 a)					130	→ 25 min	Activation Cd - ratio. Recalculated
TATTERSALL et al. (1960)					180 ± 30	Absorption	Reactivity oscillator in thermal well and lattice spectra
WALKER (1960)					160 ± 30	Absorption	Calculated from resonance parameters
	Recommended values			6.45 ± 0.3	160 ± 30		
PURKAYASTHA & MARTIN (1956)	129	1.7×10^7 yr	36	*		→ 12.5 hr	Activation in reactor. Revised using σ_{act} [Cu^{63} → 12.8 hr β] = 2.53 ± 0.06 barns
ROY & WUSCHKE (1958)			27.8 ± 2.1	27.8 ± 2.1		→ 12.5 hr	Activation with sub-Cd neutrons. Revised g = 1.000 assumed
BLOCK et al. (1960)				31 ± 5		Absorption	Transmission using a fast chopper
PATTENDEN (1960)				28.0 ± 2		Absorption	- ditto -
ROY & WUSCHKE (1958)					25 ± 5.8	→ 12.5 hr	Activation Cd-ratio, with revised σ_0
WALKER (1960)					28 ± 7.6	Absorption	Calculated from resonance parameters
ROY & WUSCHKE (1958)	130	12.5 hr	18.9 ± 3.1			→ 8.1 day	Activation in reactor; r_0 = 0.032. Revised
KENNETT & THODE (1958)	131	8.1 day	54 ± 42			(n, γ)	Mass spectrometry. Revised

Table 6.1

$_{54}Xe$

Reference	Mass no.	Half-life	σ barns	σ_0 barns	Σ'_r barns	Reaction	Method and comments
MACNAMARA & THODE (1950)	128	Stable	< 5		Small?	(n, γ) Absorption	Mass spectrometry. Reactor spectrum. No resonance known
MACNAMARA & THODE (1950) WALKER (1960)	129	Stable	45 ± 15	≳ 7.5	~ 240	(n, γ) Absorption	Mass spectrometry. Reactor spectrum. Calculated from resonance parameters
MACNAMARA & THODE (1950)	130	Stable	< 5		Small?	(n, γ) Absorption	Mass spectrometry. Reactor spectrum. No resonance known
MACNAMARA & THODE (1950) WALKER (1960)) NEPHEW (1960))	131	Stable	120 ± 15	≳ 70	760 ± 175	(n, γ) Absorption	Mass spectrometry. Reactor spectrum. Calculated from resonance parameters
KERN & SNELL (1943)	132	Stable	0.2 ± 0.1			5.27 day	Activation. Probably includes production through decay of the 2.3 day Xe^{133} isomer
MACNAMARA & THODE (1950)			< 5		Small?	(n, γ) Absorption	Mass spectrometry. Reactor spectrum. No resonance known
KENNETT & THODE (1958)	133	5.27 day	198 ± 94			(n, γ)	Mass spectrometry. Reactor spectrum. Revised
TURKEVICH et al. (1944)	134	Stable	0.2 ± 0.1			→ 9.18 hr	Activation. Probably includes production through decay of the 15 min Xe^{135} isomer
MACNAMARA & THODE (1950)			< 5		Small?	(n, γ)	Mass spectrometry. Reactor spectrum. No resonance known
	135	9.18 hr		See section 6.5			
TURKEVICH et al. (1945)	136	Stable	0.14 ± 0.08		Small?	→ 3.9 min Absorption	Activation in reactor spectrum. 30 yr Cs^{137} daughter activity measured. Result corrected for Cs^{137} half-life and for conversion electrons from Ba^{137m}. No resonance known

Table 6.1

$_{55}Cs$

Reference	Mass no.	Half-life	σ barns	σ_0 barns	$\Sigma' r$ barns	Reaction	Method and comments
SERREN et al. (1947)	133	Stable	16 ± 3 mb 32 ± 6	* *		-> 3.2 hr -> 2.17 hr	Activation in reactor - Ditto- . Revised half life
HARRIS et al. (1950 b)			38.2	*		Absorption	Reactivity oscillator in reactor spectrum; r_o = 0.046
POMERANCE (1951)				30.0 ± 1.5		Absorption	Local oscillator; r ≈ 0
ROSE et al. (1958)			28 ± 1			Absorption	Reactivity oscillator in thermal well; r ≈ 0, g = 1.002 at 20°C
BIDINOSTI et al. (1958)			41.7	*		(n, γ)	Mass spectrometry. Reactor spectrum with r_o ≈ 0.03. Revised
BAYLY et al. (1958)			31.8 ± 1.2	*		-> 2.17 yr	Activation in reactor; r_o ≈ 0.02. Revised
Chalk River unpublished work quoted in BNL 325 (1960)			3.0 ± 0.3	*		-> 3.2 hr	Activation of Cs^{134m} isomer
KLIMENTOV & GRYAZEV (1957)					195 ± 35	Absorption	Reactivity measurements sub-Cd. Revised
TATTERSALL et al. (1960)					490 ± 80	Absorption	Reactivity oscillator in thermal well and lattice spectra
NEWPHEW (1960)					375 ± 73	Absorption	Calculated from resonance parameters
	Recommended value			29 ± 1			
The 3.2 hr Cs^{134} isomer decays predominantly by isomeric transitions to the ground state. The values given above for σ_{act} [-> 2.17 yr] are for production of the 2.17 yr ground state both directly and by decay of the short-lived isomer.							
BAYLY et al. (1958)	134	2.17 yr	193 ± 17			(n, γ)	Mass spectrometry; r_o ≈ 0.03. Revised using σ [Cs^{133}] = 41.7 barns
SUGARMAN (1949)	135	2.6×10^6 y	14.5 ± 4.4			-> 13 day	Activation
BAERG et al. (1958)			9.1 ± 0.5			-> 13 day	Mass spectrometry and activations in sub-Cd spectrum. Revised
- ditto -					56.3 ± 2.4	-> 13 day	- Ditto - , with Cd-ratios
COCKING (1958)					Small	Absorption	Transmission using fast chopper No resonance found below 52 eV
STUPEGIA (1960)	137	30 yr	0.11 ± 0.05			-> 32 min	Activation in reactor tamper; r_o = 0.0025

Table 6.1

$_{56}Ba$

Reference	Mass no.	Half-life	σ barns	σ_0 barns	Σ'_r barns	Reaction	Method and comments
POMERANCE (1952)	134	Stable		2 ± 2 *		Absorption	Local oscillator; r ≈ 0
POMERANCE (1952)	135	Stable		5.8 ± 0.9 *		Absorption	As for Ba^{134}
POMERANCE (1952) WALKER (1960)	136	Stable		0.4 ± 0.4 *	≈ 13	Absorption Absorption	As for Ba^{134} Calculated from resonance parameters
POMERANCE (1952)	137	Stable		5.1 ± 0.4 *	Small	Absorption	As for Ba^{134} No resonance known below 100 eV
SEREN et al. (1947) POMERANCE (1952) SUNYAR & GOLDHABER (1949)	138	Stable	0.51 ± 0.10	* 0.70 ± 0.11 *	≲ 10 Small	-> 84 min Absorption ?	Activation in thermal column As for Ba^{134} Probably from activation cadmium ratio No resonance known below 400 eV
KATCOFF (1945) YAFFE et al. (1949)	139	84 min	3.8 ± 1 4.7 ± 1.2			-> 12.8 day -> 12.8 day	Activation Activation in reactor
EASTWOOD et al. (1958)	140	12.8 day	<20			-> 18 min	Activation in reactor; $r_0 \approx 0.02$. 32 day C_e^{141} activity was measured

Table 6.1

$_{57}La$

Reference	Mass no.	Half-life	σ barns	σ_0 barns	Σ barns	Reaction	Method and comments
BOTHE (1946)	139	Stable	> 8.5	*		-> 40 hr	Activation
SEREN et al. (1947)			8.4 ± 1.7	*		-> 40 hr	Activation in reactor
WATTENBERG & THOMAS (1948)			7.6	*		Absorption	Reactivity measurements in reactor spectrum. Revised using σ_A [B] = 758 barns
HARRIS et al. (1950 b)			9.62	*		Absorption	Reactivity oscillator; r_o = 0.047
POMERANCE (1951)				9.1 ± 0.46		Absorption	Local oscillator; r ≈ 0
BENOIST et al. (1951)			8.93 ± 0.11	*		Absorption	Reactivity oscillator in reactor spectrum. r_o = 0.031
ROSE et al. (1958)			8.9 ± 0.3	8.9 ± 0.3		Absorption	Reactivity oscillator in thermal well; r ≈ 0. g = 1.00 assumed
NEPHEW (1960)					25 ± 8		Calculated from resonance parameters
		Recommended value		9.0 ± 0.3			
KATCOFF et al. (1949)	140	40 hr	3.1 + 1.0			3.8 hr.	Activation in reactor tamper

Reference	Mass no.	Half-life	σ barns	σ_0 barns	Σ'_r barns	Reaction	Method and comments
BOTHE (1946)	140	Stable	> 0.55	*		-> 33 day	Activation
KATCOFF et al. (1949)			0.31 ± 0.07	*		-> 33 day	Activation in reactor tamper
HUGHES & SHERMAN (1950)			0.24	*		-> 33 day	Activation in reactor spectrum
POMERANCE (1952)				0.65 ± 0.07		Absorption	Local oscillator; r ≈ 0. Samples were contaminated with Cd; see ROY & YAFFE (1956 b)
KLIMENTOV & GRYAZEV (1957)					≲ 5	Absorption	Reactivity measurements with natural Ce under Cd. Revised
BIDINOSTI et al. (1958)	141	33 day	A few hundred			(n, γ)	Mass spectrometry. Reactor spectrum
BOTHE (1947)	142	5×10^{15} yr	1.3	*		-> 33 hr	Activation
KATCOFF et al. (1949)			0.95 ± 0.18	*		-> 33 hr	Activation in reactor tamper
HUGHES & SHERMAN (1950)			0.72	*		-> 33 hr	Activation in reactor
POMERANCE (1952)				1.82 ± 0.27		Absorption	As for Ce^{140}, above
ROY & YAFFE (1956 b)			0.99 + 0.05	*		-> 33 hr	Activation in reactor where spectrum was predominantly thermal
ORNL unpublished work quoted in BNL 325 (1960)			0.94 ± 0.05	*		-> 33 hr	Activation
KLIMENTOV & GRYAZEV (1957)					≲ 40	Absorption	As for Ce^{140} above
ROY & YAFFE (1956 a)	143	33 hr	6.3 ± 0.7			-> 280 day	Activation in reactor. Revised

A somewhat lower value was obtained from activation in a low neutron flux. The difference may have been due to experimental uncertainties. On the other hand the higher values may have resulted from resonance absorption in Ce^{143}. This alternative interpretation leads to the values: σ = 4.4 barns for thermal neutrons, $\Sigma'_r \lesssim 16$ barns

Table 6.1

$_{59}Pr$

Reference	Mass no.	Half-life	σ barns	σ_0 barns	Σ_r' barns	Reaction	Method and comments
BOTHE (1946)	141	Stable	16	*		-> 19.2 hr	Activation
SEREN et al. (1947)			10.1 ± 2	*		-> 19.2 hr	Activation in thermal column
POMERANCE (1951)				11.6 + 0.6		Absorption	Local oscillator; r ≈ 0
ROSE et al. (1958)			11.5 ± 0.3	*		Absorption	Reactivity oscillator in thermal well; r ≈ 0
ORNL unpublished work quoted in BNL 325 (1960)			10.8 ± 1.0	*		-> 19.2 hr	Activation
HARRIS et al (1950 a)					6.6	-> 19.2 hr	Activation Cd ratio. Recalculated
WALKER (1960)					≈ 19	Absorption	Calculated from resonance parameters
SMITH & REEDER (1955)	142	19.2 hr	20 ± 3			-> 13.7 day	Activation. s = 0 assumed. Revised
BIDINOSTI et al. (1958)	143	13.7 day	400 ± 200			(n, γ)	Mass spectrometry. Reactor spectrum
ROY & ROY (1959)			91 ± 10			-> 17.3 min	Activation with sub-Cd spectrum
- ditto -					178 ± 25	-> 17.3 min	Activation Cd-ratios

Table 6.1

$_{60}Nd$

Reference	Mass no.	Half-life	σ barns	σ_0 barns	$\Sigma' r$ barns	Reaction	Method and comments
HESS & INGHRAM (1949)	142	Stable	< 17	*		(n, γ)	Mass spectrometry. Reactor spectrum. Data renormalised so that $\sigma[Nd^{143}] \approx 340$ b
POMERANCE (1952)				19.2 ± 2.3		Absorption	Local oscillator; r ≈ 0
WALKER & THODE (1953)			13 ± 5	*		(n, γ)	Mass spectrometry. Reactor spectrum
					Small		No resonance known below 80 eV
		Recommended value 18 ± 3					
POMERANCE (1952)	143	Stable		302 ± 24		Absorption	Local oscillator; r ≈ 0
WALKER & THODE (1953)			334 ± 12			(n, γ)	Mass spectrometry. Reactor spectrum
HAY & PATTENDEN (1959)				343 ± 20		Absorption	Transmission using crystal spectrometer. Two independent samples used
- ditto -							Tables of g and s coefficients
TATTERSALL et al. (1960)			336 ± 10		※	Absorption	Reactivity oscillator in thermal well; r ≈ 0. g = 0.996 ± 0.001 at 20°C assumed
HAY & PATTENDEN (1959)					57	Absorption	Calculated from resonance parameters
TATTERSALL et al. (1960)					< 50	Absorption	Reactivity oscillator in thermal well and lattice spectra
NEPHEW (1960)					37 ± 12	Absorption	Calculated from resonance parameters
		Recommended values 341 ± 10			48 ± 16		
POMERANCE (1952)	144	Stable		5.0 ± 0.6		Absorption	Local oscillator; r ≈ 0
				*	Small	Absorption	No resonance known below 80 eV
HESS & INGHRAM (1949)	145	Stable	< 42	*		(n, γ)	As for Nd^{142}, above
POMERANCE (1952)				54 ± 4		Absorption	Local oscillator; r ≈ 0
WALKER & THODE (1953)			37 ± 6			Absorption	Mass spectrometry. Reactor spectrum
PATTENDEN (1958)				51.0 ± 4		Absorption	Transmission with crystal spectrometer
- ditto -					※	Absorption	Tables of g and s coefficients
TATTERSALL et al. (1960)			49.3 ± 1.5	47.0 ± 1.6		Absorption	Reactivity oscillator in thermal well; r ≈ 0. g = 1.050 at 20°C assumed
- ditto -					130 ± 15	Absorption	Reactivity oscillator in thermal well and lattice spectra
NEPHEW (1960)					310 ± 70	Absorption	Calculated from resonance parameters
		Recommended values 49 ± 2			220 ± 90		

Table 6.1 60^{Nd} continued

Reference	Mass no.	Half-life	σ barns	σ_o barns	Σ'_r barns	Reaction	Method and comments
MARINSKY & GLENDENIN (1945)	146	stable	1.0 ± 0.3	*		→ 11.1 day	Activation in reactor
BOTHE (1946)			1.7 ± 0.4	*		→ 11.1 day	Activation
POMERANCE (1952)				10.2 ± 0.8		Absorption	Local oscillator; r ≈ 0
WALKER & THODE (1953)			3.5 ± 5	*		(n, γ)	Mass spectrometry. Reactor spectrum
					Small	Absorption	No resonance known below 80 eV
MARINSKY & GLENDENIN (1945)	148	stable	3.2 ± 1.0	*		→ 1.8 hr	Activation in reactor
BOTHE (1946)			3.9 ± 1.0	*		→ 1.8 hr	Activation. Both product and daughter activities observed
POMERANCE (1952)							
POMERANCE (1952)				3.4 ± 1.0		Absorption	Local oscillator; r ≈ 0
WALKER & THODE (1953)			3.5 ± 9	*		(n, γ)	Mass spectrometry. Reactor spectrum
					Small	Absorption	No resonance known below 80 eV
MARKINSKY & GLENDENIN (1945)	150	stable	1.3 ± 0.4	*		→ 14 min	Activation in reactor
POMERANCE (1952)				3.0 ± 1.5		Absorption	Local oscillator; r ≈ 0
WALKER & THODE (1953)			≤ 11	*		(n, γ)	Mass spectrometry. Reactor spectrum
SEHGAL et al. (1959)			1.5 ± 0.2	*		→ 14 min	Activation in thermal column
					Small	Absorption	No resonance known below 80 eV

Table 6.1 $_{61}Pm$ continued

Reference	Mass no.	Half-life	σ barns	σ_o barns	Σ_r' barns	Reaction	Method and comments
PARKER et al. (1947)	147	2.65 yr	60 ± 20			→ 5.3 day	Activation in reactor
ANIKINA et al. (1958)			90 ± 20			(n, γ)	Mass spectrometry. Reactor spectrum
BIDINOSTI et al. (1958)			209 ± 50			(n, γ)	- ditto - Revised
HARVEY et al.				180		Absorption	Transmission using neutron chopper. Tentative result
WALKER (1960) NEPHEW (1960)				≳ 78	2050±400	Absorption	)Calculated from resonance)parameters
			Recommended value	140 ± 40			

The activation result is low if Pm^{148} decays appreciably to Nd^{148} by orbital electron capture.

Table 6.1

$_{62}Sm$

Reference	Mass no.	Half-life	δ barns	σ_o barns	Σ_r' barns	Reaction	Method and comment
GORSHKOV et al. (1957)	147	1.3×10^{11} yr	1000 ± 50			(n, γ)	Mass spectrometry of fission-products produced in a reactor. This result was omitted from a subsequent report by ANIKINA et al. (1958)
JOWITT et al. (1958)			87 ± 60	*		Absorption	Reactivity oscillator in thermal well; r ≈ 0
PATTENDEN (1960)				150 ± 210		Absorption	Transmission using neutron chopper. Sm^{150} contribution subtracted
TATTERSALL et al. (1960)					<1350	Absorption	Reactivity oscillator in thermal well and lattice spectra
WALKER (1960)					680	Absorption	Calculated from resonance parameters
McREYNOLDS & ANDERSEN (1954)	149	Stable		39200		Absorption	Transmission with natural Sm, using a crystal spectrometer; from graphical data in BNL 325 (1958). Small contribution from other isotopes substracted
PATTENDEN (1958)				39900 ± 600		Absorption	Transmission, using a crystal spectrometer
ROSE et al. (1958)			68200 ± 700	41200 ± 1000		Absorption	Reactivity oscillator in thermal well; r ≈ 0. T = 20°C, g = 1.656 ± 0.036 assumed
			Recommended value	39800 ± 900			
PATTENDEN (1958)) WESTCOTT (1960))						Absorption	Tables of g and s coefficients

There is a strong resonance at 0.097 eV. Because of this δ in a reactor depends strongly on the effective temperature of the thermal neutron component. This sensitivity has been exploited by TATTERSALL et al. (1960). Measurements of δ in reactor spectra have been reported also by BIDINOSTI et al. (1958) and by others, but are better regarded as spectral indicators, so the results are not listed here.

Table 6.1 — $_{62}Sm$ — continued

Reference	Mass no.	Half-life	σ barns	σ_0 barns	Σ_r' barns	Reaction	Method and comments
CORNISH & AITKEN (1958)	150	Stable	102 ± 10	*		(n, γ)	Mass spectrometry Reactor spectrum
PATTENDEN (1960)				200 ± 220			Transmission using neutron chopper. Sm^{147} contribution subtracted
					Small	(n, γ)	No resonance known below 21 eV
INGHRAM et al. (1950)	151	~ 90 yr	12400			(n, γ)	Mass spectrometry. Reactor spectrum. Renormalised with σ[natural Eu] = 4470 b
MELAIKA et al. (1955)			12000			(n, γ)	Mass spectrometry. Reactor spectrum
ANIKINA et al. (1958)			8000 ± 1500			(n, γ)	Mass spectrometry of fission-products produced in a reactor
BIDINOSTI et al. (1958)			12600			(n, γ)	Mass spectrometry. Reactor spectrum
COCKING (1958)				11500 ± 1500		Absorption	Transmission with neutron chopper
PATTENDEN (1960)				15400 ± 1500		Absorption	Transmission with neutron chopper Two samples
			Recommended value	14800 ± 1300		Absorption	Not 1/v in thermal region
BOTHE (1946)	152	Stable	~ 340			-> 47 hr	Activation
SEREN et al. (1947)			134 ± 27			-> 47 hr	Activation in thermal column
PATTENDEN (1958)				200 ± 6		Absorption	Transmission with crystal spectrometer
ROSE et al. (1958)			224 ± 7	231 ± 7		Absorption	Reactivity oscillator in thermal well; r ≈ 0. g = 0.970 at 20°C
TATTERSALL et al. (1960)					2850±300	Absorption	Reactivity oscillator in thermal well and lattice spectra. Mainly due to 8.1 eV resonance
HARRIS et al. (1950a)					2410	-> 47 hr	Activation Cd-ratio. Revised
WALKER (1960)					2100	Absorption	Calculated from resonance parameters
			Recommended value	213 ± 14			
SEREN et al. (1947)	154	Stable	4.9 ± 1.0	*		-> 24 min.	Activation in thermal column
					Small	Absorption	No resonance known below ~100 eV

Table 6.1

$_{63}Eu$

Reference	Mass no.	Half-life	σ barns	σ_0 barns	Σ'_r barns	Reaction	Method and comments
BOTHE (1946)	151	Stable	2500 ± 600			→ 9.2 hr	Activation. Corrected to allow for 23% decay of 9.2 hr Eu^{152} by orbital electron capture, and for revised standard
SEREN et al. (1947)			1850 ± 370			→ 9.2 hr	Activation in thermal column. Corrected for electron capture decay of product
SEREN et al. (1947)			4400 ± 1100			→ 12.6 yr	Activation in thermal column Corrected for Eu^{154} activity and for 73% decay of 13 yr Eu^{152} by electron capture
OVERMAN et al. (1948)			6830			→ 12.6 yr	Activation in reactor. Corrected as above
HAYDEN et al. (1949)			1700 ± 260 7200 ± 1100			→ 9.2 hr → 12.6 yr	Mass spectrometer and activation studies. Renormalised to give σ[natural] Eu = 4470 b in reactor spectrum
STURM (1947)				9000		Absorption	Transmission with natural Eu using crystal spectrometer; from graphical data in BNL 325 (1958). Eu^{153} contribution subtracted
PATTENDEN (1958)				7700 ± 80		Absorption	Transmission using crystal spectrometer
TATTERSALL et al. (1960)			8790 ± 90	8810 ± 90		Absorption	Reactivity oscillator in thermal well; r 0. g = 0.9981 assumed
TATTERSALL et al. (1960)					3000	Absorption	Reactivity oscillator in thermal well and lattice spectra
TATTERSALL et al. (1960)			Recommended values	8160 ± 330	3470 ± 300	Absorption	Calculated from resonance parameters

Table 6.1 — $_{63}Eu$ — continued

Reference	Mass no.	Half-life	σ barns	σ_0 barns	Σ_r' barns	Reaction	Method and comments
HAYDEN et al. (1949)	152	12.6 yr	5500 ± 1500			(n, γ)	Mass spectrometry. Reactor spectrum. Renormalised as for Eu^{151} above
HAYDEN et al. (1949)	153	Stable	410 ± 100			(n, γ)	As for Eu^{151} above
GLENDENIN & MARINSKY (1949)			630			- 16 yr	Activation in reactor. Revised for half-lives involved
PATTENDEN (1958)				448 ± 16		Absorption	Transmission with crystal spectrometer
PATTENDEN (1958)							Tables of g and s coefficients
TATTERSALL et al. (1960)			317 ± 5	309 ± 5		Absorption	Reactivity oscillator in thermal well; r ≈ 0. g = 1.026 at 20°C assumed
PATTENDEN (1958)					1780	Absorption	)Calculated from resonance
WALKER (1960)					1400±300	Absorption	)parameters
TATTERSALL et al. (1960)					1280±100	Absorption	Reactivity oscillator in thermal well and lattice spectra
			Recommended values	400 ± 50	1400±300	Absorption	
HAYDEN et al. (1949)	154	16 yr	1510 ± 300			(n, γ)	As for Eu^{151} above
INGHRAM et al. (1947)	155	1.7 yr	~14000			(n, γ)	Mass spectrometry. Reactor spectrum
MARINSKY (1949)			~30000			-> 15 day	From expected and observed fission-product activities
HAYDEN et al. (1949)			13600 ± 3000			(n, γ)	As for Eu^{151} above

Table 6.1

$_{64}Gd$

Reference	Mass no.	Half-life	σ barns	σ_0 barns	Σ'_r barns	Reactions	Method and comments
ROSE et al. (1958)	155	Stable	49800 ± 600	58300 ± 700		Absorption	Reactivity oscillator in thermal well; r ≈ 0. g = 0.854 at 20°C assumed
PATTENDEN (1958)				66000 ± 2000		Absorption	Transmission using crystal spectrometer
PATTENDEN (1958)						Absorption	Tables of g and s coefficients
			Recommended value	62000 ± 3500		Absorption	
WALKER (1956)	156	Stable	<14	*	Small	Absorption Absorption	Reactor neutrons No resonance known below 3.7 eV
BRILL & LICHTENBERGER (1947)	157			233000±7000		Absorption	Transmission with natural Gd using neutron chopper; from graphical data in BNL 325 (1958) isotopes subtracted
ROSE et al. (1958)		Stable	213000 ± 2000	249000±2000		Absorption	Reactivity oscillator in thermal well; r ≈ 0. g = 0.854 at 20°C assumed
PATTENDEN (1958)				264000±4500		Absorption	Transmission using crystal spectrometer
PATTENDEN (1958)						Absorption	Tables of g and s coefficients
			Recommended value	255000±8500		Absorption	
SEREN et al. (1947)	158	Stable	3.6	*		→ 18.0 hr	Activation in reactor
BUTEMENT (1949)			4.5			→ 18.0 hr	Activation in reactor
ORNL unpublished work quoted in BNL 325 (1960)			3.9 ± 0.4			→ 18.0 hr	Activation
					Small	Absorption	No resonances known below 3.7 eV
SEREN et al. (1947)	160	Stable	~ 2.7			→ 3.6 min	Activation of Tb^{161} daughter in reactor
BUTEMENT (1949)			0.8			→ 3.6 min	Activation in reactor. Both product and daughter activities observed

LAPP et al. (1947) first showed, by mass spectrometric analyses, that the neutron absorption in natural Gd is due mainly to the isotopes Gd^{155} and Gd^{157}. INGHRAM et al. (1950) attempted to derive the cross-sections of these two isotopes from a mass spectrometric study of fission products. However the derivations are extremely complex and rely on assumed fission yield values. We have ignored these results which add nothing to the data listed.

Table 6.1

$_{65}Tb$

Reference	Mass no.	Half-life	$\hat{\sigma}$ barns	σ_o barns	$\Sigma\acute{r}$ barns	Reaction	Method and comments
BOTHE (1945) POMERANCE (1951) WALKER (1960)	159	Stable	> 27	* 46 ± 5	370	-> 73 day Absorption	Activation Local oscillator; r ≈ 0 Calculated from resonance parameters
SMITH et al. (1956)	160	73 day	575 ± 100			-> 6.9 day	Activation in reactor spectrum

Table 6.1

$_{66}Dy$

Reference	Mass no.	Half-life	σ barns	σ_0 barns	Σ'_r barns	Reaction	Method and comments
WALKER (1956)	160	Stable	100 ± 70	*	Small		Reactor spectrum No resonance known below 40 eV
WALKER (1956) WALKER (1960)	161	Stable	620 ± 35	≳ 40	950		Reactor spectrum Calculated from resonance parameters
WALKER (1956) WALKER (1960)	162	Stable	330 ± 90	* ≳ 210	2570		Reactor spectrum Calculated from resonance parameters
WALKER (1956) WALKER (1960)	163	Stable	420 ± 150	≳ 90	1230		Reactor spectrum Calculated from resonance parameters
ATTERLING et al. (1945)	164	Stable	2460	*		-> 139 min	Activation
BOTHE (1946)			2680 ± 300	*		-> 139 min	Activation
FLAMMERSFELD (1946)			2150	*		->1.25 min	Activation
SEREN et al. (1947)			2580 ± 260	*.		-> 139 min	
BRILL & LICHTENBERGER (1947)				2690 ± 200		Absorption	Transmission with natural Dy, using a neutron chopper. Graphical data from BNL 325 (1958). Contributions of other isotopes subtracted
POMERANCE (1951)				≈ 2290		Absorption	Local oscillator with natural dy; Dy; r ≈ 0 Contributions of other isotopes subtracted
WEBER (1954)			1860 ± 100	*		->1.25 min	Activation
SEHGAL et al. (1959)			2520 ± 300 < 3360	*		->1.25 min ->139 min	)Activation with sub-Cd neutrons.)Revised using σ[Au]= 98.9 barns
The 1.25 min isomeric state of Dy^{165} decays mainly by isomeric transition to the 139 min ground state. The values given above for σ [→ 139 min] are for production of the ground state both directly and by decay of the short-lived isomer.							
KETELLE (1949)	165	139 min	5000			-> 81 hr	Activation in reactor
BUTEMENT (1950)			1210			-> 81 hr	Activation in reactor. Revised

The slow neutron absorption cross-section $\sigma_A(E)$ may be calculated from the resonance parameters. The cross-section below ~1 eV is a perfect example of an isolated resonance, to which the Breit-Wigner single-level formulae may be applied with confidence, and with the simplification that the potential scattering is quite negligible. Unfortunately the spin of the resonant state is not known. The spin of the Xe^{135} ground-state is probably 3/2, THULIN (1955), so the statistical weight factor g^* is either 3/8 or 5/8. With either value of g^*, resonance parameters may be evaluated which give almost equally good fits to the total cross-section data. Thus to each of the two studies of $\sigma_T(E)$ correspond two sets of resonance parameters; hence there are four possible curves for $\sigma_A(E)$. The four values for σ_o are given in Table 6.2.

No direct measurement of the scattering or absorption cross-section of Xe^{135} has been reported. However a considerable number of measurements of σ_A have been made in broad neutron spectra in reactors:

(i) By observing reactivity transients either at start-up or in decay. This sort of measurement determines y σ_A where y is the yield of Xe^{135} per fission.

(ii) By "de-activation" methods; measurements of the loss of Xe^{135} activity caused by neutron capture in a high flux irradiation.

(iii) By mass-spectrometer measurements. Usually the long-lived daughter Cs^{135} has been observed.

The most recent measurements are listed in Table 6.3. The best data appear to be those of FICKEL & TOMLINSON (1959). In a reactor σ_A [Xe^{135}] must be fairly sensitive to both the shape of the thermal component of the neutron spectrum and to that of the slowing-down component below about 0.3 eV. Therefore the data collected in table 6.3 must be used with caution. The better measurements appear to support the data of SMITH et al. (1959) with $g^* = 5/8$, but not quite decisively. If $g^* = 3/8$ the data of BERNSTEIN et al. (1956) seem to be ruled out.

Besides the data listed in table 6.3 several earlier measurements have been cited, by FREEDMAN et al. (1945), and by BERNSTEIN & SMITH (1955). Probably many of the results quoted were given in the "true flux" convention rather than in that of WESTCOTT (1958). However details of the flux calibrations are not available and the accuracy claimed was not very high so we have ignored these early data.

Table 6.2, $_{54}Xe^{135}$

Absorption cross-section at 2200 m/sec from transmission measurements

Reference	σA at 2200 m/sec 10^6 barns		Method and comments
	$g^* = 3/8$	$g^* = 5/8$	
BERNSTEIN et al. (1956)	2.19 ± 0.10	2.40 ± 0.10	Transmission, using bent crystal focussing spectrometer. Samples of fission-product iodine were separated in the form PdI_2, with Xe^{135} as a decay product. Assay by absolute β counting and comparative γ counting of I activities, and also by absolute $\gamma\beta$ coincidence counting of Xe^{135}; there was good agreement. Resonance analysis not corrected for Doppler effect
SMITH et al. (1959)	2.50 ± 0.06	2.76 ± 0.06	Transmission, using fast chopper. Samples were of fission-product Xe. Assay was by mass-spectrometry of the Cs^{135} daughter, with isotopic dilution, after decay of all the Xe^{135}. Resonance analysis was corrected for Doppler effect

(i) The recommended expedient is to use the data of SMITH et al. (1959) with either $g^* = 3/8$ or $5/8$. The data of table 6.2 tend to support the higher value of g^*, but not decisively.

(ii) The symbol g^* used above is the spin statistical factor in the Breit-Wigner formulae. Tables of the g-coefficient for a Maxwellian spectrum are given by WESTCOTT (1958 and 1960).

(iii) The resonance absorption integral must depend sensitively on the shape of the slowing-down spectrum below 0.3 eV. As a rough guide $\Sigma'_r/\sigma_o \sim 0.3$; Σ'_r includes the $1/v$ component.

Table 6.3. $_{54}Xe^{135}$

Absorption cross-section in various thermal reactor spectra

Reference	$10^6 \sigma_A$ barns	Spectrum T^oC and r	Weight	Method and comments
FREEDMAN et al. (1945)	3.02 ± 0.24	130°C sub-Cd r ~ 0.03	0.1	De-activation by irradiation in CP3 reactor. Result virtually for sub-Cd spectrum as the sub-Cd flux was compared with that in calibrated standard pile by Au activations. Flux also estimated from Ba^{140} activity induced in natural U monitor, but cross-section assumed is not reported. Result amended to WESTCOTT convention
PETRUSKA et al. (1955)	3.21 ± 0.15	(138 ± 10)°C r~0.01	0.2	Mass-spectrometer comparison of Cs^{135}/Cs^{137} abundance ratio in fission products formed at high and low fluxes. Original results revised by DEUTSCH (1956) to give $\sigma_A [Xe^{135}]/\sigma_A [B^{10}] = 834 \pm 40$. The spectrum given here follows the comments of FICKEL & TOMLINSON (1959); see below
IVANOV et al. (1957)	3.2 ± 1.0		0	Mass-spectrometric measurements of Cs^{135} yield in highly irradiated sample of U^{233}. Details of flux calibration and neutron spectrum are not available
HOPKINS & JAMIESON (1957 and 1958)	2.34 ± 0.12	~ 20°C	0	Reactivity measurements in low power reactor gave $y [I^{135}]. \sigma_A [Xe^{135}] = 1.48 \times 10^5$ barns. Very complex flux determination appears to ignore cumulative effect of stable fission-product poisons in highly irradiated U monitor. We assume $y[I^{135}] = 6.32\%$

Table 6.3, $_{54}XE^{135}$, Continued

Reference	$10^6 \sigma_A$ barns	Spectrum T^oC and r	Weight	Method and comments
MAKAROV & SAMOILOVA (1958)	1.75 ± 1.15	530 ± 50°C	0	De-activation measurment. Details not reported. Cross-section given might be in the "true flux" convention
FICKEL & TOMLINSON (1959)	3.26 ± 0.06	(120 ± 10°C (r = 0.018	1	Mass-spectrometric measurements of Cs^{135}/Cs^{137} abundance ratio in fission-products formed at high flux. Compared with the zero flux value for this ratio, PETRUSKA et al. (1955). Neutron spectra characterised by BIGHAM (1958), but thermal components are probably not truly Maxwellian. Results recalculated with revised data for Co flux monitor
	3.39 ± 0.11	(138 ± 10°C (r = 0.010	0.3	
For comparison:				
BERNSTEIN et al. (1956)	(2.70 ± 0.10 (3.03 ± 0.10	$g^* = 3/8$ $g^* = 5/8$	T 130°C r 0	Evaluated from the resonance parameters for purely Maxwellian spectra; WESTCOTT (1958). Slightly lower values of σ_A would result if the neutron spectrum has a small slowing-down component
SMITH et al. (1959)	(2.99 ± 0.07 (3.38 ± 0.07	$g^* = 3/8$ $g^* = 5/8$		

6.6 Recommendations for further work

Assessments of the relative importance on the various fission-product poisons in thermal reactors have been given by PATTENDEN & ROSE (1958), PATTENDEN (1959), SHAFTMAN (1959), and WALKER (1960). Four groups of poisons may be distinguished.

(1) Stable and long-lived fission products with high absorption cross-sections, $\sigma_A \gtrsim 10^4$ barns, namely:

Sm^{149}, Sm^{151}, Eu^{155}, Cd^{113}, Gd^{157}

in order of importance.

In a power reactor these fission-products tend fairly quickly to their equilibrium concentrations. Thereafter as may be seen from equation (6.2), their poisoning effect depends only on their fission yields and not on their absorption cross-sections.

(2) Xe^{135}. This is the most important of the poisons in spite of its short half-life of 9.18 hours. The uncertainties of the cross-section data have been discussed in section 6.5.

(3) Stable and long-lived fission products with small cross-sections, $\sigma_A \lesssim$ 1000 barns. These nuclides approach their saturation concentrations rather slowly so that their poisoning effect depends on their absorption cross-sections as well as their fission-yields. From the papers cited above it appears that the major uncertainties to the poisoning of U233, U235 or Pu239 fuel arise from the following nuclides which are listed roughly in order of importance:

Nuclide	Parameters contributing the largest uncertainties to the poisoning
Pm^{147}	σ_o and Σ'_r
Xe^{131}	σ_o and Σ'_r
Nd^{143}	σ_o and fission-yield, (Σ'_r is small)
Sm^{152}	Σ'_r
Rh^{103}	Σ'_r and fission-yield
Cs^{133}	Σ'_r
Te^{99}	Σ'_r
Nd^{145}	Σ'_r
Ag^{109}	Σ'_r
Ru^{101}	σ_o
Zr^{93}	σ_o
Kr^{83}	σ_o
Pd^{104}	σ_o
Pd^{105}	σ_o
Sm^{147}	σ_o
Sm^{148}	σ_o
Sm^{150}	σ_o
Xe^{134}	σ_o
Kr^{85}	σ_o

(4) Long-lived and stable fission-products whose absorption cross-sections are unknown. Following is a list of all such fission-products and capture products whose half-lives exceed 1 day. It does not seem likely that there is another significant poison, other than Xe^{135}, with a half-life shorter than 1 day. However the possibility cannot altogether be excluded.

Nuclide	Half-life	Nuclide	Half-life
As^{76}	1.10 day	Sn^{125}	9.5 day
As^{77}	1.62 day	Sn^{126}	2×10^5 yr
Se^{79}	6×10^4 yr	Sb^{122}	2.8
Br^{82}	1.5 day	Sb^{124}	61 day
Rb^{86}	18.7 day	Sb^{125}	2.0 yr
Sr^{89m}	~10 day	Sb^{126}	28 day
Nb^{93m}	12 yr	Sb^{127}	3.7 day
Nb^{95m}	3.75 day	Sb^{128m}	58 day
Nb^{95}	35 day	Te^{125m}	58 day
Zr^{95}	63 day	Te^{127m}	110 day
Mo^{99}	2.8 day	Te^{129m}	33 day
Ru^{103}	40 day	Te^{131m}	1.25 day
Ru^{106}	1.0 yr	Te^{132}	3.23 day
Rh^{105}	1.52 day	Xe^{129m}	8.0 day
Pd^{107}	7.5×10^6 yr	Xe^{131m}	12.0 day
Ag^{110m}	270 day	Xe^{133m}	2.2 day
Ag^{111}	7.5 day	Cs^{136}	13 day
Cd^{110}	stable	Ba^{135m}	1.21 day
Cd^{111}	stable	Ce^{141}	32 day
Cd^{112}	stable	Ce^{144}	285 day
Cd^{113m}	5.1 yr	Nd^{147}	11.1 day
Cd^{115m}	43 day	Pm^{148}	5.3 day
Cd^{116}	stable	Pm^{148}	44 day
In^{114}	49 day	Pm^{149}	2.2 day
Sn^{117m}	14 day	Pm^{151}	1.15 day
Sn^{119m}	245 day	Sm^{153}	1.96 day
Sn^{121m}	>400 day	Eu^{156}	15 day
Sn^{121}	1.15 day	Tb^{161}	6.9 day
Sn^{123m}	130 day		

In addition to the deficiencies which have been outlined above, perusal of the table of cross-sections will reveal many descrepancies and uncertainties. Most of the early activation data are highly unreliable because the decay schemes of the product nuclei were not well characterised at the time. Many of the resonance integrals have been estimated from very sparse information. The following may be noted particularly:

(i) Br^{79}. Directly measured resonance integral is much smaller than that calculated from the resonance parameters. The activation measurement is complicated by the excitation of isomeric states.

(ii) Rb. The calculated resonance integrals for Rb^{85} and Rb^{87} are much too small to account for the value ~11 barns obtained by KLIMENTOV & GRYAZEV (1957) for natural Rb.

(iii) Mo^{100}. The values of σ_0 and Σ_r' estimated by WALKER (1960) from the resonance parameters are twice as large as the values measured directly by CABELL (1960).

(iv) To^{99}. The data by TATTERSALL et al. (1960) for σ_0 and Σ_r' appear to be too small.

(v) In^{113}. The activation resonance integral is much greater than the calculated from the resonance parameters.

(vi) Sb. Activation data for Sb in reactor spectra appear too low in comparison with the calculated resonance integrals and thermal cross-sections.

(vii) Te. The estimates from resonance parameters appear to be inconsistent with the activation and oscillator data.

(viii) Cs^{133}, La^{139}. The activation data in reactor spectra appear too low in comparison with other data, when the strong resonance absorption is taken into account.

(ix) Ce^{140}, Ce^{142}. For each, σ_A and σ_{act} differ by a factor of two.

(x) Pr^{141}. The directly measured resonance integral, HARRIS et al. (1950a), is only about 1/3rd of the value calculated from the resonance parameters.

(xi) Pm^{147}. The available data are discordant and unreliable.

(xii) Nd^{146}. The pile oscillator value for σ_0 is much higher than the activation data.

(xiii) Sm^{152}. The activation data for σ are erratic.

(xiv) Eu^{151}. The activation data are very poor.

(xv) Eu^{152}, Eu^{154}, Eu^{155}. The data are not very reliable.

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