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RESEARCH GROUP

THERMAL NEUTRON ABSORPTION AND CROSS-SECTION STANDARDS

(CHAPTER 3 OF 'NUCLEAR DATA FOR REACTOR DESIGN' VOL. 1.)

N. G. SJÖSTRAND J. S. STORY

Industrial Power Reactors Division

Atomic Energy Establishment,

Winfrith, Dorchester,

Dorset.

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By

N. G. Sjöstrand* J. S. Story

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* A.B. Atomenergi, Stockholm, Sweden.

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THERMAL NEUTRON ABSORPTION AND ACTIVATION CROSS-SECTION STANDARDS

1. INTRODUCTION

Absorption and activation cross-sections are used in every branch of reactor physics. They are usually measured by comparison with specially chosen standard absorbers. With the pile oscillator method, for example, the effect of an absorber on the reactivity of a reactor is compared with the effect of a standard. Similarly, in activation cross-section measurements, a standard cross-section is used for determining the neutron flux. The result of a comparative measurement is therefore the ratio of the measured cross-section to that of the standard used. Both these methods permit accurate comparisons even when the absorption is weak, and a variety of other techniques is available. However, comparative measurements are usually made in broad neutron spectra, so their interpretation is most reliable if the cross-sections which are compared have approximately the same variation with energy.

Almost all thermal absorption and activation cross-sections are related directly or indirectly to those of boron, gold, or hydrogen, which have been determined by careful absolute measurements, and which are themselves linked by comparative measurements of similar or greater precision.

In this chapter we shall start with an analysis of the measurements made on hydrogen, boron, and gold and evaluate a consistent set of data from them. Using these results, we shall then turn to useful sub-standards such as Li, Na, V, Mn, Co, Ag, and In, and find the best cross-sections to use for them.

All the data are referred to a neutron velocity of 2,200 m/sec unless otherwise stated.

2. METHODS OF ABSOLUTE MEASUREMENT

Absolute measurements of absorption cross-sections have been made by two methods only, and reliable results are obtained only with a few specially chosen materials. The methods employed are:

(a) Transmission measurements with a neutron spectrometer. These give the total cross-section of the sample as a function of neutron energy. The absorption is evaluated by subtracting the scattering cross-section; this is not usually known with high precision, and often varies rather erratically in the thermal region as a result of diffraction effects in the coherent elastic component.

HARVEY (1955) gives a useful account of some of the techniques which are used with this method.

(b) The pulsed-source method. The decay with time of the neutron density in a homogeneous medium is observed, after a burst of neutrons has been injected. This is the only method for direct absolute measurement of an absorption cross-section, but broad neutron spectra are used and the measurements can only reliably be interpreted if the variation of the cross-section with energy is known. The general principles may be found in the review by von DARDEL and SJÖSTRAND (1958).

There are several ways of using this method, which are briefly:

(1) Asymtotic decay rate in small geometries. This technique was used for example by von DARDEL and SJÖSTRAND (1954a) to measure neutron absorption in hydrogen.

(2) Mean-lifetime of neutrons in large geometry. This technique was used by MEADS et al. (1956) to measure neutron absorption in hydrogen. The modification of this method used by COLLIE et al. (1956) with boron solutions is more questionable.

(3) Decay of the ratio of neutron densities with and without added absorber. This technique was used by von DARDEL and SJÖSTRAND (1954b) to measure neutron absorption in boron.

(4) Lifetimes of individual neutrons. This technique has been used by STOOKSBERRY and CROUCH (1959) to measure neutron absorption in hydrogen. The timing device was triggered by gamma rays emitted in association with the neutron.

The pulsed-source method has not been very widely used so far. For high accuracy it is essential to consider very carefully the effects of neutron transport across the boundaries of the homogeneous absorber: in particular the effects of the detection device must be considered. For 1/v absorbers the method appears to be at least as accurate, potentially, as the transmission method. Direct comparisons of results by both methods are therefore especially interesting.

3. SUITABLE CROSS-SECTION STANDARDS

Some of the properties which may be needed in a standard absorber are:

(i) Reasonable availability, and convenience in handling.

(ii) Ease of production in pure form with a known composition, or at least with an invariable composition.

(iii) 1/v dependence up to 1 eV at least.

(iv) Scattering cross-section small compared with absorption.

(v) For neutron flux or density calibration the absorption of a neutron must lead to the emission of a charged particle. This demands either an instantaneous reaction such as (n, p), (n, α), (n, fission), or the formation of a radioactive isotope which should have a simple decay-scheme and convenient half-life.

(vi) For pulsed-source measurements solubility in water of a suitable compound may be desired.

For most nuclei the absorption of slow neutrons results from radiative capture. Because the interaction between nuclear particles and electromagnetic radiation is relatively weak, strong absorption occurs only near resonance energies. Nevertheless, Rh, Ag, In, Au have (n, γ) cross-sections which are large and do not deviate strongly from the 1/v law in the thermal region. Of these four, gold best fulfils the conditions (i) to (v) above. Hydrogen too is sometimes used as a standard, for comparisons of absorption rates in a hydrogenous moderator, although the capture cross-section is small.

Interactions between nuclear particles are much stronger than the electromagnetic interaction. The emission of charged particles is usually strongly inhibited by the coulomb barrier except at high bombarding energies. However a few nuclei of low atomic numbers have strong exothermic (n, p) or (n, α) reactions under thermal neutron bombardment; also, with a few nuclei of high atomic numbers, thermal neutrons may induce fission by virtue of the large excess energy available.

Considering the light stable isotopes, the reactions

$$He^{3}\ (n, p),\quad Li^{6}\ (n,\alpha),\quad B^{10}\ (n, \alpha)$$

have large thermal cross-sections. Among these He^3 is very rare and is inconvenient to handle, and from a nuclear point of view boron appears significantly superior to lithium. The use of samples enriched in B^{10} is possible nowadays and may have advantages.

Accurate absolute measurements have been made, by the transmission method, of absorption in some fissile isotopes. These might be used as standards; U^{233} in particular since it satisfies condition (iii) very well. However, these measurements are listed in chapter 4 and we do not discuss them here.

4. HYDROGEN

Capture of slow neutron by protons is associated with a magnetic dipole transition of the neutron-proton system, from an S-state of zero spin to the ground state of the deuteron, which has spin 1.

On theoretical grounds the capture cross-section is expected to be proportional to

$$E^{-\frac{1}{2}}.\ (W + E)^{-1}$$

for neutron energies below about 100 keV, where E is the kinetic energy of the neutron and W ≈ 146 keV. Thus the cross-section follows the 1/v law very accurately up to the keV region. At higher energies this formula is too low, but the cross-section is negligibly small for reactor purposes.

Absolute measurements of the capture cross-section of hydrogen for slow neutrons have been made only by pulsed neutron-source methods. The best measurements are given in Table 1 below. Other measurements have been reported by von DARDEL and WALTNER (1953) and by SCOTT et al. (1954). These measurements have been discussed by von DARDEL and SJOSTRAND (1954a), but as they are less reliable the results have not been listed in table 1.

Notes on table 1

With small geometry the neutrons are quickly thermalised and decay in the fundamental mode. However the decay rate is governed by leakage as well as absorption, so it is necessary to determine the asymptotic decay rate with various sizes of geometric buckling, and to extrapolate to zero buckling. The cross-section depends slightly on the value used for the "extrapolation length" when calculating the bucklings. We have taken the view that the various measurements should be self-contained; i.e. the extrapolation length should be derived from the diffusion constant which is obtained from the same set of observations. However the concepts of buckling and of extrapolation length are based on approximate theories, and so limit the accuracy of the extrapolation to zero buckling.

TABLE 1

Absorption cross-section of light hydrogen of 2,200 m/sec. velocity.

Item	Reference	σ [H] millibarns	Technique, using the decay-rate method
1	von DARDEL and SJÖSTRAND (1954a)	335 ± 4	Small geometries. Decay of fundamental mode in H_2O
2	ANTONOV et al. (1956)	329 ± 10	- ditto -
3	BRACCI and COCEVA (1956)	337 ± 10	- ditto -
4	MEADS et al. (1956)	335 ± 4	Large geometry. Mean neutron lifetime in H_2O
5	DIO (1958)	328 ± 5	Small geometries. Decay of fundamental mode in H_2O
6	SJÖSTRAND et al. (1959)	337 ± 5	Small geometries. Decay of fundamental mode in polyethylene
7	STOOKSBERRY and CROUCH (1959)	330 ± 8	Neutron lifetimes in large H_2O system
	WEIGHTED MEAN	333.7 ± 2.6	Recommended value from table 7 is 331.3 ± 2.6 millibarns

Item 1 of table 1 was corrected originally for terms of third order in the buckling. As there is some doubt about the magnitude of this correction we have deleted it and have increased the uncertainty somewhat.

5. BORON

Natural boron consists of the isotopes B^{10} and B^{11} in the ratio 1:4 approximately. Absorption of thermal neutrons is due to the reaction $B^{10}(n,\alpha)\,Li^7$ almost entirely; other reactions contribute less than 0.2 barns. According to BLATT and WEISSKOPF (1952) the large cross-section for slow neutrons results mainly from a broad resonance at about 100 keV. The cross-section obeys the $1/v$ law rigorously at low energies - an inevitable consequence of the large level widths.

Comparison of boron standard samples

The neutron absorption varies slightly in different samples of boron, as a result of small variations in the isotopic composition. These are due partly to discriminatory effects during chemical processing, and partly to different geographical origins; SHIUTTSE (1955), PARWEL et al. (1956).

For this reason some laboratories have found it convenient to establish standard boron samples, and careful comparative measurements of some of these standards have been made with pile oscillators. The results, which were reported by GREEN et al. (1954) are:

$$\left.\begin{array}{lcl} \dfrac{\sigma\,[\text{Stockholm boron}]}{\sigma\,[\text{Harwell boron}]} & = & 0.983 \pm 0.003 \\[2ex] \dfrac{\sigma\,[\text{ANL boron}]}{\sigma\,[\text{Harwell boron}]} & = & 0.985 \pm 0.003 \end{array}\right\}\ \text{measured at Harwell}$$

$$\left.\begin{array}{lcl} \dfrac{\sigma\,[\text{Harwell boron}]}{\sigma\,[\text{ANL boron}]} & = & 1.009 \pm 0.005 \\[2ex] \dfrac{\sigma\,[\text{Stockholm boron}]}{\sigma\,[\text{ANL boron}]} & = & 0.991 \pm 0.005 \end{array}\right\}\ \text{measured at ANL*}$$

Of all the measurements discussed in this chapter these careful comparisons of almost identical samples, similarly prepared, are the least likely to contain hidden errors. Least-squares adjustment of these data gives the values listed in Table 2, which we shall regard as fixed. In what follows they are used to relate measurements with Harwell or Stockholm boron to the ANL standard.

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* Argonne National Laboratory, at Lemont, Illinois.

TABLE 2

Adjusted cross-section ratios for different boron standards

Boron sample	Relative B absorption cross-section
ANL standard	1
Harwell standard	1.0126 ± 0.0023
Stockholm standard	0.9942 ± 0.0030

The isotopic composition of the ANL standard boron has been discussed rather carefully by STEHN et al. (1958). They conclude that the atomic abundance of B^{10} is 19.80 ± 0.25 per cent. The relative data of table 2 above then show that the B^{10} content of the Harwell standard must be 20.04 ± 0.26 per cent, which seems unusually high: however, no direct measurement of the isotopic composistion of the Harwell standard boron has been reported.

Absolute measurements

The most accurate absolute measurements of the absorption cross-section of boron are given in table 3 below. Estimates of the cross-section of the ANL standard are derived by using the comparative measurements, and are given in the fourth column.

It is doubtful whether the quoted errors really show the relative merits of the different measurements, so we have followed our own judgement in weighting the data.

TABLE 3

Absorption cross-section of natural boron for neutrons of 2,200 m/sec velocity

Item	References	Measured cross-section, barns	Equivalent for ANL standard boron, barns	Weight	Method and remarks
1	CARTER et al. (1953)	749.3 ± 4	749.3 ± 4	1	Transmission, with slow-neutron chopper in range 0.0007 to 0.03 eV, using B_2O_3 dissolved in D_2O at 40°C.
2	KIMBALL et al. (1953)	755 ± 3	755 ± 3	1	Transmission, with slow-neutron chopper at 0.005 and 0.0013 eV, using B_2O_3 dissolved in D_2O at about 40°C.
3	von DARDEL and SJOSTRAND (1954b and 1958)	760 ± 4	760 ± 3	0.8	Pulsed neutron source in small geometry. From asymptotic decay rate of ratio of neutron densities with and without boron. Used ANL standard H_3BO_3 in water.
4	-ditto-	758 ± 4	762 ± 4.6	0.7	As for item 3, but using Stockholm standard borax in water.
5	COLLIE et al. (1956)	761 ± 2.5	750 ± 3	0.6	Pulsed neutron source in large water tank. Six different concentration of borax were used.
6	EGELSTAFF (1957)	774 ± 6	764 ± 6	0.5	Transmission, with slow-neutron chopper in range 0.01 to 0.1 eV, using B_2O_3 dissolved in weak solution of NaOD in D_2O at room temperature.
7	-ditto-	765 ± 8	757 ± 8	0.4	As for item 6, but using powdered anhydrous borax, $Na_2B_4O_7$.
8	HAVENS et al. (1957)	753.3 ± 6.1	753.3 ± 6.1	0.6	Transmission, with crystal spectrometer in the range 0.0006 to 0.005 eV, using specially prepared samples of pyrex glass.
9	-ditto-	760.0 ± 6.4	760.0 ± 6.4	0.3	Transmission, by time-of-flight with a pulsed cyclotron, in the range 0.01 to 0.1 eV. Samples from the same stock as for item 8.
10	IGNATEV et al. (1958)	757.5 ± 3.5		0	Transmission, by time-of-flight with a pulsed cyclotron. Unfortunately no other details have been published yet.
	WEIGHTED MEAN		756.0 ± 2.5		Recommended value from table 7 is 757.7 ± 3.0 barns.

The data in table 3 should be contrasted with the values given on page 23 from comparisons of boron with hydrogen and gold, 770 ± 9 and 766 ± 8 barns respectively, and with the final recommended value of 758 ± 3 barns from table 7 on page 24.

Notes on table 3

Uncertainties in the chemical assay of the amount of boron in a sample contribute to the uncertainty in the cross-section obtained. Chemical analyses of boron from the same sample were made at Argonne National Laboratory, at Harwell, and in Stockholm, and are said to have been in good agreement though numerical comparisons have not been published. It seems unlikely that the residual discrepancies between the cross-section data of table 3 are attributable to faulty chemistry.

Transmission measurements

Items 1, 2, and 8 were measured with neutron spectrometers at long wavelengths with 1/v extrapolation of the absorption cross-section to a neutron velocity of 2,200 m/sec. At long wavelengths the absorption cross-section is very large, so that the uncertainty in the scattering cross-section is relatively unimportant. These three measurements average 752 ± 4 barns.

Items 6, 7, and 9 were measured with neutron spectrometers in the energy range 0.01 to 0.1 eV, in which the uncertainty in the scattering cross-section is relatively more important, so that we give these data lower weights. These three measurements average 761 ± 5 barns. The averaging should reduce the uncertainties due to the scattering because the boron had a different chemical environment for each of these three measurements.

As shown in the table, the boron for items 1, 2, and 6 was diluted with D_2O. For items 1 and 2 the samples were maintained at about 40°C to improve the solubility, and for item 6 a small quantity of NaOD was added for the same purpose. In each of these experiments the transmission of the solvent was measured separately: however to determine the absorption cross-section of boron one still needs to know the scattering to be associated with the B_2O_3 which was dissolved. According to HARVEY (1955) the scattering cross-section assumed for item 1 was 30 barns per B_2O_3 molecule at thermal energy and 40 barns below 0.003 eV: for item 2 a constant value of 18 barns was assumed. For item 6, which was measured in the thermal region EGELSTAFF assumed 21 barns per B_2O_3 molecule from "the bound-atom scattering cross-sections" of the constituent, but the datum for the boron atom is questionable. The origin of the rather high value of σ_s used for item 1 is obscure, but even if it were reduced to 20 barns the corresponding datum for $\sigma_a[B]$ at 2,200 m/sec would be increased by 3 barns only. A further small contribution to the uncertainty in the scattering cross-section has been discussed by EGELSTAFF (1957).

The boron used in item 7 was compared with the Harwell standard by pile-oscillator measurements, with the result

$$\frac{\sigma_a\,[\text{B in borax}]}{\sigma_a\,[\text{Harwell boron}]} = 0.998 \pm 0.003.$$

and the relationship to ANL standard boron was completed by using table 2.

In assigning relative weights to items 8 and 9 it must be noted that a large part of the uncertainties quoted is common to both measurements, namely the uncertainty of ± 0.75% in the boron content of the glass. We have given item 8 lower weight than items 1 and 2 because, firstly the boron assay is less precise, and secondly the boron was not compared with the ANL standard, though their common geographical origin is reassuring.

We have not been able to make use of item 10 because the experiment has not been reported in detail, and the sample has not been compared with other boron standards.

Pulsed-source measurements in table 3

Items 3 and 4, which were measured in small geometry, are of very great importance, for they permit the only convincing comparisons of a pulsed-source technique with measurements by the transmission method. Since the measurements were not completely independent we assign them a total weight somewhat less than 2.

Item 5 was measured in Oxford with weak aqueous solutions of borax, which was compared with Harwell standard boron by measurements with a pile-oscillator, from which

$$\frac{\sigma a\ [\text{Oxford boron}]}{\sigma a\ [\text{Harwell boron}]} = 1.0016 \pm 0.002$$

The relationship to ANL standard boron was completed by using table 2. The analysis of the absolute measurements for item 5 is not wholly convincing, for it seems likely that both the diffusion correction and the effects of the perspex light guide would vary systematically with the boron concentration in the solutions, and thereby affect the results.

6. GOLD

Gold consists of only the single stable isotope Au^{197}. No long-lived isomers have been found in the compound nucleus formed by neutron capture, so the absorption cross-section should be equal to that for activation of the 2.695 day half-period of Au^{198}.

The neutron absorption cross-section deviates slightly from the 1/v law in the thermal region, because the absorption is caused mainly by the strong resonance at 4.91 eV. However, the deviation can be calculated sufficiently accurately from our knowledge of the resonance parameters. According to WESTCOTT (1958) the g-factor for Maxwellian neutron spectrum at 20°C is equal to 1.005.

Absolute measurements of the absorption cross-section have been made only by the transmission method, with metallic samples, and the most reliable values are listed in Table 4. In the thermal region the scattering is predominantly coherent: it fluctuates considerably with neutron energy and practically disappears beyond the Bragg limit at 0.0037 eV. At low energies too the absorption is large, which makes the residual scattering relatively insignificant. For these reasons the most reliable values of the thermal absorption are those obtained by extrapolation from measurements at low energies: this technique was devised by EGELSTAFF in 1951.

Notes on table 4

The good agreement of the results in table 4 may be due in part to the restricted class of measuring techniques, but apart from this the measurements were quite independent. For item 3 the scattering correction is rather crude, and for item 5 there is a dearth of information.

From the data given in sections 8 and 9 it may be thought that the values given in table 4 may be slightly too high. They could be reduced slightly if one postulates the existence of a level with resonance energy very close to zero and with a very small neutron width. These hypotheses are rather improbable.

TABLE 4

Absorption cross-section of gold for neutrons of 2,200 m/sec velocity

Item	Reference	Absorption cross-section, barns	Weight	Method
1	EGELSTAFF (1953), (1954) and (1957)	97.7 ± 0.9	1.2	Transmission, with a slow chopper in the energy range 0.001 to 0.0037 eV.
2	CARTER et al. (1953)	98.7 ± 0.6	2.8	Transmission, with a slow chopper in the energy range 0.0011 to 0.0037 eV.
3	ALLEN et al. (1954)	96.5 ± 0.7	0	Transmission, with a crystal spectrometer in the energy range 0.0039 to 0.16 eV. A constant scattering cross-section has been assumed.
4	HAVENS et al. (1956)	98.7 ± 0.4	6.3	Transmission, with a crystal spectrometer in the energy range 0.0006 to 0.0034 eV.
5	IGNATEV et al. (1958)	99.2 ± 1.0.	0	Transmission, by time-of-flight with a pulsed-cyclotron. No further details have been published.
	Weighted mean	98.58 ± 0.44		Recommended value from table 7 is 98.40 ± 0.52 barns.

7. BORON-HYDROGEN COMPARISONS

Precise comparisons of the thermal neutron absorption in boron and hydrogen are quite difficult to make, mainly because the absorption cross-section of hydrogen is small, and the scattering cross-section is large.

The most reliable results are given in Table 5. We ignore some of these data in taking the mean because we do not know the origin of the boron which was used: nevertheless, some corrections to these results are suggested in the notes following the table.

As may be seen from the table, two methods of measurement have been used:

A. In the "water bath" method all the neutrons from a steady source are captured by surrounding it with a large volume of water, or of water containing boron in solution, so that the neutron capture rate must be the same in either medium. The neutron spectrum is essentially thermal in each medium, and with 1/v absorption the cross-section is inversely proportional to the neutron population in each. The populations are compared by using a 1/v detector.

B. The pile oscillator method can give an accurate comparison only if care is taken to minimise self-shielding by the boron, and scattering effects by the hydrogen. Scattering may change the neutron transport in a reactor, unless the perturbing sample is in a position where the density has zero gradient: it may modify neutron "streaming" in the oscillator channel: by moderation it may change the reactivity value of a fast neutron.

It is perhaps worthwhile to remark that the mean is, perforce, rather heavily weighted by the British measurements, items 7, 8 and 9.

The value expected from the absolute measurements given in tables 1 and 3 is $\sigma[B]/\sigma[H] = 2266 \pm 19$.

TABLE 5

Cross-section ratio for absorption by ANL standard boron to that of hydrogen, for thermal neutrons

Item	Reference	$\sigma[B]/\sigma[H]$	Weight	Method
1	KUBITSCHEK (1944)	2380 ± 70	0	) Water bath. Some corrections are proposed in the notes below.
2	WALKER (1946)	2270 ± 30	0	)
3	WHITEHOUSE and GRAHAM (1947)	2270 ± 30	0	)
4	HAMERMESH et al. (1953)	2292 ± 27	1	Water bath.
5	HARRIS et al. (1953a)	2274 ± 50	0.3	Pile-oscillator.
6	LARSSON (1954 and 1955)	2269 ± 45	0.3	Water bath.
7	CUMMINS (1957)	2315 ± 14	1.1	Pile-oscillator in a thermal well.
8	BAKER (1958)	2337 ± 31	0.7	Water bath.
9	TATTERSALL et al. (1959)	2323 ± 29	0.4	Pile-oscillator in a thermal well.
	Weighted Mean	2307 ± 20		Recommended value from table 7 is 2287 ± 18.

Notes on table 5

Item 2 was measured in the course of making an absolute calibration of a Ra-Be(α,n) source. A small correction is needed because the absorption of thermal neutrons by the source itself would decrease with increasing boron concentration. A rough estimate of this effect suggests that the result listed should be increased to 2282 ± 33.

A similar correction is needed for item 3. This measurement also needs correction for the perturbations caused by the neutron detectors. Making use of some subsidiary data reported in the reference it appears that the result should be increased to 2335 ± 52.

Item 4 is from a careful measurement using a neutron beam from a reactor thermal-column, instead of the more usual (α,n) fast neutron source.

Item 6 has been converted to the ANL standard, by assuming that the boron used had the same isotopic composition as the Stockholm standard and using table 2. Because this is an assumption we have given this item reduced weight.

Items 7 and 9 were measured with Harwell standard boron, and have been converted to the ANL standard by using table 2. These very similar careful measurements appear to avoid the difficulties mentioned at B above. However we are reluctant to give them too much weight.

For item 8, small pieces of photographic emulsion impregnated with boron were used as neutron detectors, to minimise the disturbance of the neutron field. The result given was 2352 ± 28 relative to Harwell standard boron. However a correction similar to that propos   above for item 2, appears to be needed and we estimated it as + (0.6 ± 0.6) per cent. Conversion to the ANL standard is made by using table 2. A further very small positive correction may be needed for fast neutron reactions, such as O^{16} (n,α), in the photographic emulsion.

8. BORON-GOLD COMPARISONS

A number of measurements have been made which compare the thermal absorption cross-sections of boron and gold. High precision, however, has been attempted only at Harwell, whence come the results given in Table 6.

In making measurements with gold in a thermal neutron spectrum it is important to correct the results for non-1/v absorption in the thermal region, and to eliminate resonance absorption of epithermal neutrons.

As may be seen from table 6 two different classes of pile oscillator were used in the measurements:

(a) The local oscillator in BEPO is sited in a region where the epithermal neutron flux is low. Moreover, to a fair approximation, the device measures the absorption rate in the sample weighted by the 1/v response of the detector. This weighting discriminates strongly against any residual epithermal absorption, and it also makes trivial the correction for non-1/v absorption in gold at thermal energies.

On the other hand, the instrument is likely to be rather sensitive to small spectral changes induced locally by inelastic scattering of slow neutrons in the sample. It must be doubted if one can rely on this class of pile oscillator for comparitive measurements of very high precision. For this reason we have given reduced weight in table 6 to the measurements with the local oscillator.

(b) For the reactivity oscillator in DIMPLE the epithermal neutron flux is nearly eliminated by moving fuel elements away from the vicinity of the oscillator. The detecting system is remote from the sample and it seems highly improbable that there is any significant sensitivity to small shifts in the slow neutron spectrum near the sample.

TABLE 6

Cross-section ratio for absorption by Harwell standard boron to that of gold, for neutrons of 2,200 m/sec

Item	Reference	$\frac{\sigma[B]}{\sigma[Au]}$	Weight	Method
1	GREEN et al. (1954)	7.97 ± 0.08	0.8	Local oscillator, using silver as an intermediary: see table 13.
2	SMALL (1955)	7.90 ± 0.09	0.7	- ditto -
3	COCKING and RAFFLE (1956) LITTLER and LOCKETT (1952) JOWITT et al. (1958)	7.85 ± 0.15	0.7	Au and Na compared by activation; B and Na compared by reactivity oscillators; see table 9.
4	CUMMINS and SPURWAY (1957) CUMMINS (1957) TATTERSALL et al. (1959)	7.93 ± 0.18	0.3	Reactivity oscillator in a thermal well, using silver as an intermediary: see table 13.
5	JOWITT et al. (1958)	7.72 ± 0.15	0.7	Reactivity oscillator in a thermal well. A direct comparison corrected for non-1/v and epithermal absorption in the gold.
	Weighted Mean	7.870 ± 0.078		The recommended value from table 7 is, with Harwell standard boron, 7.797 ± 0.052

The values expected from the absolute measurements given in tables 3 and 4 are 7.765 ± 0.044 with Harwell standard boron, and 7.668 ± 0.040 with ANL standard boron.

Notes on table 6

Items 1 and 2 are from experiments designed explicitly to measure the boron to gold absorption ratio. To minimise self-shielding corrections dilute solutions of boric acid and of silver nitrate in D_2O were compared; silver and gold foils of the same surface area and absorptivity were compared also.

Measurements were made with 10 different dilutions and 10 different foil thicknesses. The silver used in all measurements was from the same metallic source.

Item 4 was a similar comparison made with a reactivity oscillator in a thermal well along the axis of the D_2O moderated reactor DIMPLE, in a Maxwellian spectrum at about 20°C. However the silver used in these measurements was not all from the same source. We have corrected the result for non-1/v absorption by the gold, using WESTCOTT's (1958) factor, $g = 1.005$. No such correction is needed for items 1 and 2.

The observations which were used in item 3 are listed in more detail in table 9 on page 29. The activation measurement with Au was corrected by the experimenters for non-1/v absorption, and we have increased their result by (0.8 ± 0.8) per cent to allow for branching decay of the isomeric state in Na^{24}: see section 9.

Item 5 was not measured so fastidiously as items 1 and 2. However, the comparison is more direct, and this oscillator is insensitive to local spectral distortions.

9. ADJUSTMENT OF THE DATA FOR H. B. AND Au. RECOMMENDED VALUES

From the data collected in tables 1, 3, 4, 5 and 6, on the thermal absorption cross-sections of hydrogen, boron, and gold, and their ratios, we have now to form a consistent set.

One method is to undertake a least-squares analysis of all the data listed, assuming that the uncertainties stated by the experimenters are valid. The following results are obtained:

$$\sigma[H] = 0.3301 \pm 0.0017 \text{ barns}$$

$$\sigma[B] = 758.5 \pm 1.7 \text{ barns for ANL standard boron}$$

$$\sigma[Au] = 97.93 \pm 0.34 \text{ barns}$$

$$\sigma[B]/\sigma[H] = 2298 \pm 11$$

$$\sigma[B]/\sigma[Au] = 7.746 \pm 0.030$$

for absorption of neutrons of 2,200 m/sec. A χ^2 test shows, however, that there is less than 0.1 per cent probability that the data are distributed statistically. This indicates the presence of systematic errors, or that the uncertainties have been underestimated.

Going to the opposite extreme we made a least-squares analysis of the five weighted averages given in tables 1, 3, 4, 5 and 6. Even these averages are barely consistent, as can be seen by looking at the boron cross-section. For ANL standard boron the following values result:

B BARNS	WEIGHTED AVERAGES USED
756.0 ± 2.5	Direct measurements, table 3.
769.8 ± 9.0	Absolute measurements for H, table 1, and ratios of B/H, table 5.
766.3 ± 8.4	Absolute measurements for Au, table 4, and ratios of B/Au, table 6.

The five input data, and the recommended values obtained by least-squares adjustment are given in Table 7.

TABLE 7

Recommended values for absorption cross-sections of H, B and Au, for neutrons of 2,200 m/sec

Item	Source of input datum	Absorption cross-section, for 2,200 m/s neutrons	Input datum	Recommended value, from least-squares adjustment
1	Table 1	σ [H]	333.7 ± 2.6 millibarns	331.3 ± 2.6 millibarns
2	Table 3	σ [B] ANL standard	756.0 ± 2.5 barns	757.7 ± 3.0 barns
3	Table 4	σ [Au]	98.6 ± 0.4 barns	98.40 ± 0.52 barns
4	Table 5	σ [B] / σ [H] ANL boron	2307 ± 20	2287 ± 18
5	Table 6	σ [B] / σ [Au]	7.772 ± 0.079	7.700 ± 0.048
6	Table 2	$\frac{\sigma[\text{Harwell boron}]}{\sigma[\text{ANL boron}]}$		1.0126 ± 0.0023

A χ^2 test shows that the deviations of the input data from the recommended values have 19 per cent probability, showing that the somewhat more liberal uncertainties assigned to the averages are realistic. The differences between the input data and the recommended values all lie within the uncertainties assigned. In relation to the uncertainties the largest shifts are for $\sigma[B]/\sigma[H]$, $\sigma[B]/\sigma[Au]$, and $\sigma[H]$ respectively. The measured values for these constants appear to be about 0.8% too high. An alternative view is that the data for boron are still over-weighted; the three low evergy transmission measurements appear to be systematically low.

10. LITHIUM

Natural lithium is a mixture of the two isotopes Li^6 and Li^7 in atomic ratio 1:12.5 approximately. One might reasonably anticipate small variations in the isotopic composition of lithium from different geographic regions. This appears to be borne out by the available evidence, though there is some conflict of opinion; CAMERON (1955), ORDZHONIKIDZE and SHIUTTSE (1955).

Absorption of thermal neutrons is due almost entirely to the reaction $Li^6(n, \alpha) H^3$; radiative capture in lithium contributes only about 40 millibarns. For slow neutrons the reaction is attributed mainly to a broad state in the compound nucleus Li^7, for which the neutron resonance energy is negative, about - 0.8 MeV. The cross-section obeys the 1/v law rigorously at low energies because of the large level widths. However, deviations occur above about 1 keV because of the energy dependence of the alpha particle width, and because of a strong p-wave resonance at 260 keV.

The most reliable measurements of the thermal absorption cross-section are given in Table 8. The measurements agree surprisingly well, but are mostly not very precise. The best precision has been claimed for item 7, but no details of the measurement have been published.

Because of the likelihood of variations in the isotopic composition of natural lithium we assign a rather broad uncertainty to our recommended value for the lithium cross-section, which is

$$\sigma = 71.0 \pm 1.5 \text{ barns}$$

for absorption of neutrons of 2,200 m/sec.

For precision use it seems necessary for laboratories to stockpile standard samples, and the use of Li^6 rather than natural lithium may offer some advantages.

TABLE. 8

Absorption cross-section of Li for neutrons of 2,200 m/sec

	Reference	$\frac{\sigma[\mathrm{Li}]}{\sigma[\mathrm{B}]}$ Harwell boron	$\frac{\sigma[\mathrm{Li}]}{\sigma[\mathrm{B}]}$ ANL boron	$\frac{\sigma[\mathrm{Li}]}{\sigma[\mathrm{Au}]}$	$\sigma[\mathrm{Li}]$ *	Method
1	HAVENS and RAINWATER (1946)				72.3 ± 1.3	Transmission measurement using time-of-flight with a pulsed cyclotron. Scattering cross-section 1.7 ± 0.2 is subtracted.
2	FENNING et al. (1947)		0.0948 ± 0.0013		71.8 ± 1.5	Water bath using solutions of equal absorption. Isotopic composition of boron unknown but assumed to be American standard.
3	COLMER and LITTLER (1950)	0.0922 ± 0.0028			70.7 ± 2.2	Reactivity oscillator.
4	GRIMELAND et al. (1951)	0.0897 ± 0.0014				Pile oscillator. Boron composition unknown.
5	POMERANCE (1951)			0.705 ± 0.035	69.4 ± 3.5	Local oscillator.
6	AILLOUD et al. (1952)	0.094 ± 0.005				Local oscillator. Boron composition unknown.
7	KAPLAN et al. (1952)		0.0941 ± 0.0006		71.3 ± 0.5	Danger coefficient method.

*We have assumed 767.2 ± 3.5 barns for Harwell boron, 757.7 ± 3.0 barns for ANL boron and 98.4 ± 0.5 barns for gold.

11. SODIUM

Natural sodium consists of the single stable isotope Na^{23}. The neutron absorption cross-section follows the 1/v law below about 10 eV, but deviates above that energy because of the strong resonance at 2.85 keV.

By neutron capture the compound nucleus Na^{24} is formed. This isotope has a ground state of 15 hours half-life, and an isomeric state at 470 keV excitation with a half-life of 20 milliseconds. The isomeric state decays mainly to the ground state through gamma radiation, but it is estimated that about 1.3 per cent goes directly to Mg^{24} through beta emission; DROPESKY and SCHARDT (1956).

Studies of the spectrum of gamma radiation following thermal neutron capture in Na^{23} show that (66 ± 10) per cent of the compound nuclei lead to the isomeric state; see GROSHEV et al. (1958).

From these details it follows that the total thermal neutron cross-section for activation of the 15 hour period is about 0.8 per cent less than the absorption cross-section in Na^{23}.

The most recent measurements of the absorption and activation cross-sections are listed in Table 9. The data from Harwell, items 1, 4, 6, 9, are very consistent, but they disagree seriously with item 5 which is the only other precision measurement. The other data in the table are of low precision and show a correspondingly wide scatter.

Because no details of the measurement listed as item 5 have been published, and because the Harwell measurements are self-consistent we prefer the latter for the time being, and recommend for the absorption cross-section of sodium for neutrons of 2,200 m/sec:

$$\sigma_{abs} = 0.538 \pm 0.007 \text{ barns}$$

The activation cross-section for the Na^{24} ground state of 15 hours half-life directly and by isomeric transition is about 0.004 ± 0.004 barns lower, say:

$$\sigma_{act}[\rightarrow 15 \text{ hr}] = 0.534 \pm 0.007 \text{ barns,}$$

and for activation of the 20 millisecond isomer:

$$\sigma_{act}[\rightarrow 20 \text{ millisec}] = 0.36 \pm 0.05 \text{ barns.}$$

Notes on table 9

For item 7 the uncertainty quoted is the statistical variation of several measurements about their mean. The standard deviation of the mean is only 2%. However, we have not reduced the error quoted by the authors because no other uncertainties were taken into account.

For item 8 several comparison measurements were reported. These were not of very high precision, so we omit the details for the sake of simplicity, but have used revised values for the standard cross-sections and give a weighed mean of the various results.

TABLE 9

Absorption and activation cross-sections of Na for neutrons of 2,200 m/sec

	Reference	$10^4 \times \frac{\sigma[\text{Na}]}{\sigma[\text{B}]}$ Harwell boron	$10^4 \times \frac{\sigma[\text{Na}]}{\sigma[\text{B}]}$ ANL boron	$10^3 \times \frac{\sigma[\text{Na}]}{\sigma[\text{Au}]}$	σ [Na] *	Method
	Absorption:-					
1	COLMER and LITTLER (1950)	7.04 ± 0.21			0.54 ± 0.02	Reactivity oscillator. No correction for resonance effects in Na.
2	HARRIS et al. (1950a)		7.32		0.55	- ditto -
3	POMERANCE (1951)			4.95 ± 0.25	0.49 ± 0.03	Local oscillator.
4	LITTLER and LOCKETT (1952)	6.96 ± 0.20			0.534 ± 0.014	Reactivity oscillator, with Cd difference correcting by activation.
5	HARRIS et al. (1953b)		6.66 ± 0.07		0.505 ± 0.005	Reactivity oscillator. No details.
6	JOWITT et al. (1958)	6.99 ± 0.10			0.536 ± 0.008	Reactivity oscillator in thermal well.
	Activation of 15 hr. half period, directly and by decay of the isomeric state:-					
7	BARTHOLOMEW et al. (1953)			5.74 ± 0.3	0.565 ± 0.03	Activation with Cd difference, and non-1/v correction for Au.
8	GRIMELAND (1955)				0.515 ± 0.022	Activation in thermal spectrum, relative to Li, B, Au, U fiss.
9	COCKING and RAFFLE (1956)			5.44 ± 0.06	0.535 ± 0.007	Activation in thermal spectrum, with non-1/v correction for Au.

*We have assumed 767.2 ± 3.5 barns for Harwell boron, 757.7 ± 3.0 barns for ANL boron, and 98.4 ± 0.5 barns for gold.

12. VANADIUM

Natural vanadium consists of the isotopes V^{50} and V^{51} with atomic abundances of 0.24 and 99.76 per cent respectively. V^{51} is stable, and V^{50}, with a half-life of the order of 10^{14} years, is virtually so.

Neutron absorption in vanadium follows the 1/v law in the thermal region. The first resonance is at 170 eV and is rather weak. Neutron capture by V^{50} leads to the stable V^{51}. The cross-section for this reaction is not well known: an estimate of "between 40 and 400 barns" has been given by BARTHOLOMEW and KINSEY (1953), from a study of the gamma rays following neutron capture. Hence neutron absorption in natural vanadium is mainly due to the abundant isotope V^{51}. This is supported by the activation measurement of SEREN et al. (1947) who reported 4.5 ± 0.9 barns for production of the 3.76 minute activity of V^{52}.

Neutron scattering in vanadium metal is almost entirely incoherent, for the coherent cross-section is only about 0.03 barns. In consequence one expects that the scattering will vary only slowly with energy, and the small variation can be estimated. This considerably enhances the possibility of measuring the absorption cross-section accurately by the transmission method.

The most recent measurements of the absorption cross-section are given in Table 10. They are in reasonable agreement, but most are not very precise. In spite of the feasibility and interest of transmission measurements the work reported so far is disappointing. EGELSTAFF (1953) used a very impure sample. RUSTAD et al. (1956) made measurements with very good statistical accuracy, but only above 0.1 eV where the absorption cross-section is low: it is doubtful if the extrapolation to 2,200 m/sec can be good to ± 1%. Probably the result quoted is a slight overestimate because the scattering cross-section should increase towards the "bound atom" value with falling neutron energy. With this remark, and taking item 10 into account, our recommended value for the absorption cross-section of vanadium for 2,200 m/sec neutrons is

$$\sigma = 5.00 \pm 0.07 \text{ barns.}$$

TABLE 10

Absorption cross-section of V for neutrons of 2,200 m/sec

	Reference	$10^3 \times \frac{\sigma[V]}{\sigma[B]}$ Harwell boron	$10^3 \times \frac{\sigma[V]}{\sigma[B]}$ ANL boron	$10^2 \times \frac{\sigma[V]}{\sigma[Au]}$	$\sigma[V]$ *	Method
1	COLMER and LITTLER (1950)	6.20 ± 0.42			4.8 ± 0.3	Reactivity oscillator, assuming no resonance contribution.
2	HARRIS et al. (1950a)		6.94		5.26	- ditto -
3	LEVIN et al. (1950)				5.50	Transmission, using time-of-flight with a pulsed cyclotron.
4	GRIMELAND et al. (1951)	6.74 ± 0.11				Pile oscillator. Isotopic composition of boron unknown.
5	POMERANCE (1951)			4.95 ± 0.25	4.9 ± 0.3	Local oscillator.
6	LOCKETT (1952)	6.48 ± 0.20			4.97 ± 0.16	Reactivity oscillator, assuming no resonance contribution.
7	BROCKHOUSE (1953)				5.26 ± 0.20	Transmission, using a crystal spectrometer in the range 0.02 to 5 eV. Scattering cross-section taken as 5.07 ± 0.15 b.
8	EGELSTAFF (1953 and 1954)				5.50 ± 0.2	Transmission, using a slow chopper in the range 0.0004 to 0.04 eV. Bound atom scattering cross-section taken as 4.8 ± .2 barns. Corrected for revised velocity calibration, (1954)
9	RUSTAD et al. (1956)				5.00 ± 0.05	Transmission, using a crystal spectrometer in the range 0.1 to 4 eV. Free atom scattering cross-section taken as 4.93 ± 0.02 barns
10	JOWITT et al. (1958)	6.54 ± 0.09			5.02 ± 0.07	Reactivity oscillator in thermal well.

*We have assumed: 767.2 ± 3.5 barns for Harwell boron, 757.7 ± 3.0 barns for ANL boron, and 98.4 ± 0.5 barns for gold.

13. MANGANESE

Natural manganese consists of the single stable isotope Mn^{55}. The neutron absorption cross-section follows the 1/v law below about 1 eV but deviates above that energy because of the strong resonance at 337 eV. Resonance absorption contributes significantly to the effective absorption cross-section in a thermal reactor.

Neutron absorption creates the compound nucleus Mn^{56}. No long-lived metastable states are known, so the absorption cross-section should be equal to that for activation of the Mn^{56} ground state, which has a half-life of 2.58 hours.

The best measurements of the absorption cross-section, which are listed in Table 11, agree very well. Measurements by BALLINI et al. (1947), COLMER and LITTLER (1950), GRIMELAND et al. (1951), POMERANCE (1951), and DAVIDENKO and KUCHER (1951), have been omitted because they are of somewhat lower accuracy. However, within their limitations, they too agree reasonably well with the data tabulated.

The uncertainty quoted by HARRIS et al. (1950b), for item 1, seems unrealistic. It is doubtful if this measurement can be any more precise than item 3. Item 2 is calculated both from data above 0.1 eV and from data at low energies, where diffraction effects in the scattering cross-section are likely to be small. Allowing for some residual scattering at long wavelengths the value given in the table appears too high and should be reduced to 13.30 ± 0.20 barns.

Taking these comments into account a weighted mean of the data gives

$$\sigma = 13.17 \pm 0.10 \text{ barns}$$

for absorption by manganese of 2,200 m/sec neutrons.

TABLE 11

Absorption and activation cross-section of Mn for neutrons of 2,200 m/sec

Item	Reference	$100\,\frac{\sigma[\mathrm{Mn}]}{\sigma[\mathrm{B}]}$ Harwell B	$100\,\frac{\sigma[\mathrm{Mn}]}{\sigma[\mathrm{B}]}$ ANL boron	$\frac{\sigma[\mathrm{Mn}]}{\sigma[\mathrm{Au}]}$	$\frac{\sigma[\mathrm{Mn}]}{\sigma[\mathrm{H}]}$	$\sigma[\mathrm{Mn}]$ *	Method
1	HARRIS et al. (1950a, b, c)		1.697 ± 0.007			12.86 ± 0.07	Reactivity oscillator, with Cd difference correction by activation.
2	BENDT and RUDERMAN (1950)					13.45 ± 0.13	Transmission, using time-of-flight with a pulsed cyclotron. Free-atom scattering cross-section taken as 1.80 ± 0.05 b.
3	LITTLER and LOCKETT (1952)	1.71 ± 0.03				13.1 ± 0.2	Reactivity oscillator, with Cd difference correction by activation.
4	BARTHOLOMEW et al. (1953)			0.137 ± 0.007		13.5 ± 0.3	Activation, with Cd difference. We have corrected for non-1/v thermal absorption in Au.
5	DE JUREN and CHIN (1955)		1.75 ± 0.04			13.3 ± 0.3	Activation, with Cd difference, in a calibrated neutron density.
6	CUMMINS and SPURWAY (1957)	1.68 ± 0.03				12.9 ± 0.2	Reactivity oscillator in a thermal well. Sample assayed as Mn SO_4
7	MEISTER (1958)			0.1350 ± 0.0039		13.3 ± 0.4	Activation, with Cd difference: corrected for non-1/v thermal absorption in Au.
8	WUNDERER (1958)				40.2 ± 0.6	13.3 ± 0.2	Water bath with standard neutron sources: corrected for resonance absorption.
9	TATTERSALL et al. (1959)	1.728 ± 0..2.				13.26 ± 0.17	Reactivity oscillator in a thermal well. Sample weighed in metallic form.

*We have assumed 767.2 ± 3.5 barns for Harwell boron, 757.7 ± 3.0 barns for ANL boron, 98.4 ± 0.5 barns for gold, 0.3313 ± 0.0026 barns for hydrogen.

14. COBALT

Natural cobalt consits of the single stable isotope Co^{59}. The neutron absorption cross-section follows the 1/v law below about 1 eV, but deviates above that energy because of the strong resonance at 132 eV. Resonance absorption contributes appreciably to the effective absorption cross-section in a thermal reactor.

By neutron capture the compound nucleus Co^{60} is formed. This nucleus has a ground state of 5.2 years half-life, and an isomeric state at 59 keV excitation with a half-life of 10.5 minutes. The isomeric state decays mainly to the ground state by conversion electron and gamma ray emission, but in (0.28 ± 0.06) per cent of transitions it goes directly by beta emission to the first excited state of Ni^{60}, at 1.33 MeV; DEUTSCH and SCHARFF-GOLDHABER (1951). Activation studies by the same experimenters, and by MOSS and YAFFE (1953), have shown that after thermal neutron capture (50 ± 5) per cent of the compound nuclei go to the isomeric state.

From these details it follows that the total thermal neutron cross-section for activation of the 5.2 year half-period is only (0.14 ± 0.04) per cent less than the absorption cross-section of Co^{59}.

The most recent measurements on the absorption and activation cross-sections are listed in Table 12 below. The only precision measurement is that of JOWITT et al(1958) item 8. The two transmission measurements, items 1 and 7, agree reasonably well with the other data, but are not wholly convincing because no attempt was made to minimise the effects of variations in the scattering cross-section: we have allowed for this approximately in table 12 by doubling the errors which were assigned by the experimenters to the 1/v component of the total cross-section.

A weighted mean of items 1, 3, 5, 7, 8, 9 gives the recommended value

$$\sigma = 37.8 \pm 0.7 \text{ barns}$$

for absorption by cobalt of 2,200 m/sec neutrons.

The cross-section for activation of the isomeric state of Co^{60}, of 10.5 minutes half-life is then

$$\sigma = 19 \pm 2 \text{ barns.}$$

TABLE 12

Absorption and activation cross-sections of Co for neutrons of 2,200 m/sec

Item	Reference	$100 \times \frac{\sigma[\mathrm{Co}]}{\sigma[\mathrm{B}]}$ Harwell boron	$100 \times \frac{\sigma[\mathrm{Co}]}{\sigma[\mathrm{B}]}$ ANL boron	$\frac{\sigma[\mathrm{Co}]}{\sigma[\mathrm{Au}]}$	$\sigma[\mathrm{Co}]$*	*Method*
	Absorption:-					
1	HAVENS et al. (1947)				40.2 ± 1.8	Transmission using time-of-flight with a pulsed cyclotron.
2	COLMER and LITTLER (1950)	5.38 ± 0.42			41 ± 3	Reactivity oscillator. No correction for resonance absorption.
3	HARRIS et al. (1950a, c)		4.82		36.5	Reactivity oscillator. Roughly corrected for resonance absorption by activation.
4	GRIMELAND et al. (1951)	4.78 ± 0.06				Reactivity oscillator. Isotopic composition of boron unknown. Estimated correction for resonance absorption.
5	POMERANCE (1951)			0.365 ± 0.020	36.0 ± 2.0	Local oscillator.
6	AILLOUD et al. (1952)	4.99 ± 0.14				Local oscillator. Isotopic composition of boron unknown.
7	BERNSTEIN et al. (1952)				38.4 ± 1.2	Transmission, with crystal spectrometer, in the range 0.03 to 1.2 eV.
8	JOWITT et al. (1958)	4.98 ± 0.09			38.2 ± 0.7	Reactivity oscillator in a thermal well.
	Activation of 5.2 year half-period, directly and by decay of the isomeric state:					
9	YAFFE et al. (1951)			0.370 ± 0.015	36.4 ± 1.5	Activation, with Cd difference. We have corrected for non-1/v absorption of thermal neutrons by Au.

TABLE 12 (continued)

Absorption and activation cross-sections of Co for neutrons of 2,200 m/sec

Item	References	$100 \times \frac{\sigma[\mathrm{Co}]}{\sigma[\mathrm{B}]}$ Harwell boron	$100 \times \frac{\sigma[\mathrm{Co}]}{\sigma[\mathrm{B}]}$ ANL boron	$\frac{\sigma[\mathrm{Co}]}{\sigma[\mathrm{Au}]}$	σ [Co]*	Method
10	Activation of 10.5 minute isomer: DEUTSCH and SCHARFF-GOLDHABER (1951)				16 ± 4	$\frac{\sigma[\to 5.2\ \mathrm{yr}]}{\sigma[\to 10.5\ \mathrm{min}]} = 2.4 \pm 0.6$ by comparing x-ray and γ -ray intensities.
11	MOSS and YAFFE (1953			0.198 ± 0.018	19.5 ± 1.8	Activation, with Cd difference. We have corrected for non-1/v absorption by the Au.

*We have assumed 767.2 ± 3.5 barns for Harwell boron, 757.7 ± 3.0 for ANL boron, 98.4 ± 0.5 barns for gold.

15. SILVER

Natural silver consists of the two stable isotopes Ag^{107} and Ag^{109} with atomic abundances of 51.35 and 48.65 per cent respectively, and they are comparable as neutron absorbers.

The strong absorption of slow neutrons by Ag^{107} is mainly due to a negative energy resonance, (bound level). Available evidence indicates that the cross-section follows the 1/v law in the thermal region.

The absorption of slow neutrons by Ag^{109} results mainly from the strong resonance at 5.2 eV. This causes a small deviation from the 1/v law in the thermal region. According to WESTCOTT (1958) the g-factor for natural silver in a Maxwellian neutron spectrum at 20°C is equal to 1.0045. There is a large resonance absorption integral.

The compound nuclei Ag^{108} and Ag^{110} are formed by neutron capture in natural silver. Ag^{108} has a ground state of 2.3 minutes half-life, and no long-lived metastable state is known. It transforms mainly to Cd^{108} by beta emission, but 2.0 per cent goes to Pd^{108} by orbital-electron capture and positron emission. The ground state of Ag^{110} has a half-life of 24 seconds, and there is an isomeric state of 253 days half-life at 116 keV excitation. This isomeric state decays to the ground state in only about 5 per cent of transitions, by emission of conversion electrons: mainly it goes directly to Cd^{110} by beta emission.

Recent measurements of the absorption cross-section of natural silver are listed in Table 13. Values for the absorption and activation cross-sections of the separated isotopes are given in Table 14.

A measurement by the pulsed-source method has been reported by SCOTT et al. (1954) but has not been included as the method used seems rather unreliable: see von DARDEL and SJOSTRAND (1954a).

The measurements of GREEN et al. (1954) were designed to permit very accurate comparison of the cross-sections of boron and gold. The silver served only as an intermediary: silver from the same source was used in every measurement, but no especial care was taken to establish its purity, and in the results no allowance was made for this uncertainty. We have assigned increased errors to these results in the penultimate column of table 13.

Item 1 in table 13 is very unreliable because of the large correction for resonance absorption. A weighted mean of the other data gives

$$\sigma = 62.9 \pm 0.8 \text{ barns}$$

for absorption by natural silver of 2,200 m/sec neutrons.

For isotopic absorption cross-sections we recommend:

$$\sigma\ [Ag^{107}] = 34.9 \pm 2.5 \text{ barns}$$

$$\sigma\ [Ag^{109}] = 92.4 \pm 2.7 \text{ barns}$$

Of the latter, 0.9 ± 0.6 barns leads to production of the isomeric state of Ag^{110} of 253 days half-life.

TABLE 13

Absorption cross-section of natural Ag for neutrons of 2,200 m/sec

Item	Reference	$100\frac{\sigma[Ag]}{\sigma[B]}$ Harwell boron	$100\frac{\sigma[Ag]}{\sigma[B]}$ ANL boron	$\frac{\sigma[Ag]}{\sigma[Au]}$	$\sigma[Ag]$ *	Method
1	HARRIS et al. (1950a, c)		7.98		61	Reactivity oscillator, with a large correction for resonance absorption by activation methods. Corrected for non-1/v absorption.
2	POMERANCE (1951)			0.631 ± 0.032	62.1 ± 3.1	Local oscillator, using natural silver.
3	POMERANCE (1952)			0.590 ± 0.047	58.1 ± 4.7	Local oscillator, using enriched isotopes.
4	ALLEN et al. (1954)				63.6 ± 1.0	Transmission, with a crystal spectrometer in the range 0.004 to 0.17 eV. Error increased to allow for trends in the scattering cross-section.
5	GREEN et al. (1954)	8.11 ± 0.05			62.2 ± 0.7	Local oscillator. Solution samples used of 10 different concentrations.
6	- ditto -			0.646 ± 0.001	63.6 ± 0.6	Local oscillator. Metallic foils used of 10 different thicknesses.
7	CUMMINS and SPURWAY (1957)	7.99 ± 0.13			61.3 ± 1.0	Reactivity oscillator in a thermal well. Corrected for non-1/v and epithermal absorption by silver.
8	CUMMINS (1957)			0.6420 ± 0.0095	63.2 ± 0.9	Reactivity oscillator in a thermal well. Corrected for non-1/v and epithermal absorption by Ag and Au.
9	TATTERSALL et al. (1959)	8.27 ± 0.16			63.4 ± 1.2	Reactivity oscillator in a thermal well. Corrected for non-1/v absorption by silver.

*We have assumed 767.2 ± 3.5 barns for Harwell boron, 757.7 ± 3.0 barns for ANL boron, and 98.4 ± 0.5 barns for gold.

TABLE 14

Absorption and activation cross-sections of Ag^{107} and Ag^{109} for neutrons of 2,200 m/sec

Item	Reference	Target isotope:	Ag^{107}	Ag^{109}		Method
		Half-period activated:	2.3 mins.	253 days	24 secs.	
1	SEREN et al. (1947)		45 ± 9	1.3 ± 0.5	95 ± 19	Activation with thermal neutrons. A reactor spectrum was used for activation of the 253 day isomer: we have crudely corrected for strong resonance absorption, following HARRIS et al. (1950a, c).
2	OVERMAN et al. (1948)			0.59 ± 0.3		Activation with reactor neutrons in comparison with cobalt. We have attempted a crude correction for strong resonance absorption by following HARRIS et al. (1950a, c).
3	POMERANCE (1952)		30.9 ± 2.5	87 ± 7		Local oscillator, relative to absorption in gold, for which we have assumed 98.4 ± 0.5 barns.
4	SEHGAL (1957)		46 ± 5		114 ± 13	Activation in a standard pile, relative to manganese as standard, but the cross-section value is not reported.
5	TATTERSALL et al. (1959)		36.3 ± 3.0	92 ± 2		Reactivity oscillator in a thermal well, relative to Harwell boron as standard; for which $\sigma = 767.2 \pm 3.5$ barns has been assumed. For Ag^{107} we used the results for natural silver and Ag^{109}, from the same reference.

16. INDIUM

Natural indium consists of In^{113} and In^{115} with atomic abundances 4.24 and 95.76 per cent respectively. Both isotopes have half-lives greater than 10^{14} years and so are virtually stable.

The strong absorption of slow neutrons by In^{113} must be due mainly to a negative energy resonance (bound level). Probably the cross-section does not deviate markedly from the 1/v law in the thermal region, but the evidence is weak. Absorption of slow neutrons by In^{115} stems mainly from the strong resonance at 1.46 eV. This causes some deviation from the 1/v law in the thermal region. According to WESTCOTT (1958) the g-factor for natural indium in a Maxwellian neutron spectrum at 20°C is equal to 1.019. The resonance integral is very large.

By neutron capture the compound nuclei In^{114} and In^{116} are formed. The ground state of In^{114} has a half-life of 72 seconds. It decays mainly to Sn^{114} by beta emission, but in 1.9 per cent of transitions goes by orbital-electron capture to Cd^{114}. There is also an isomeric state of In^{114} of 49 days half-life at 191 keV excitation. This decays mainly to the ground state by emission of gamma radiation and conversion electrons, but 3.5 per cent goes directly to Cd^{114} by orbital-electron capture. In^{116} has a ground state of 13 seconds half-life. There is also an isomeric state of 54 minutes half-life at a low excitation energy, which transforms by beta emission to Sn^{116}: isomeric transitions to the ground state of In^{116} are very weak, and have not yet been observed.

Activation measurements of slow neutron absorption by indium are listed, for illustration, in Table 15. The measurements were not very precise, but the results are consistent with the total absorption cross-section for natural indium.

Recent measurements of the absorption cross-section of natural indium are given in Table 16 and are reasonably consistent. The weighted average is

$$\sigma = 190 \pm 2 \text{ barns}$$

for neutrons of 2,200 m/sec.

TABLE 15

Activation cross-sections of In^{113} and In^{115} for neutrons of 2,200 m/sec

Item	Reference	Target isotope:	In^{113}		In^{115}		Method
		Half-period activated:	49 days	72 secs	54 mins.	13 secs.	
1	SEREN et al. (1947)		61 ± 6		141 ± 14	51 ± 5	Activation with thermal neutrons. We have corrected for non 1/v absorption by In^{115}.
2	GOLDHABER and MUEHLHAUSE (1948)			2 ± 0.3			No details known
3	OVERMAN et al. (1948)		23				Activation with reactor neutrons in comparison with cobalt. We have attempted a crude correction for resonance absorption by following HARRIS et al. (1950a,c)
4	MYASISHCHEVA et al. (1957)				159 ± 10		Activation with gold as a standard, using the Cd-difference technique in a reactor spectrum. We have corrected for non-1/v absorption by Au and In^{115}.
5	SEHGAL (1957)				134 ± 10		Activation, in standard pile relative to manganese as standard, but the cross-section value used is not reported.
6	MEISTER (1958)				157 ± 4		Activation, with gold as a standard. Corrected for non-1/v absorption by Au and In^{115}.

TABLE 16

Absorption cross-section of natural indium for neutrons of 2,200 m/sec

Item	Reference	$\frac{\sigma\ [In]}{\sigma\ [B]}$ Harwell boron	$\frac{\sigma\ [In]}{\sigma\ [Au]}$	σ [In] *	
1	POMERANCE (1951)		2.01 ± 0.10	198 ± 10	Local oscillator.
2	ALLEN et al. (1954)			190 ± 3	Transmission method, using a crystal spectrometer in the range 0.004 to 0.17 eV. Error increased to allow for possible energy dependence of the scattering cross-section.
3	CUMMINS and SPURWAY (1957)	0.249 ± 0.004		191 ± 3	Reactivity oscillator in a thermal well. Original datum corrected for non-1/v and epithermal absorption by In.
4	JOWITT et al (1958)	0.248 ± 0.003		190 ± 2	Reactivity oscillator in a thermal well. Corrected for non-1/v and epithermal absorption by In

*We have assumed 767.2 ± 3.5 barns for Harwell boron, and 98.4 ± 0.5 barns for gold.

TABLE 17

Summary of recommended values for standard absorption cross-sections for 2200 m/sec. neutrons

Element	Parameter	σ , barns	Reference
H	σ_{γ}	0.3313 ± 0.0026	Table 7
Li	σ_A	71.0 ± 1.5	Section 10
B	σ_A AND standard	757.7 ± 3.0	Table 7
	σ_A Harwell standard	767.2 ± 3.5	Table 2
	σ_A Stockholm standard	753.3 ± 3.7	Table 2
Na	σ_A	0.538 ± 0.007	Section 11
	σ act [->20 millisec]	0.36 ± 0.05	
	σ act [->15 hr]	0.534 ± 0.007	(includes isomeric decay)
V	σ_A	5.00 ± 0.07	Section 12
Mn	σ_A	13.17 ± 0.10	Section 13
Co	σ_A	37.8 ± 0.7	Section 14
	σ act [->10.5 min]	19. ± 2	
	σ act [-> 5.2 yr]	37.7 ± 0.7	
Ag	σ_A	62.9 ± 0.8	Section 15
Ag^{107}	σ_A	34.9 ± 2.5	
Ag^{109}	σ_A	92.4 ± 2.7	
	σ act [Ag^{109}->253 day]	0.9 ± 0.6	
In	σ_A	190 ± 2	Section 16
Au	σ_A	98.4 ± 0.5	Table 7

17. SUMMARY AND RECOMMENDATIONS F[illegible]ER WORK

Table 17 summarises the "best [illegible], recommended in the preceding pages, of reaction cross-sections for neutron[illegible]200 m/sec.

Small systematic discrepancies noted in this chapter suggest that there remain undiscovered sources of errors. We make the following comments and recommendations for further work:

(1) Confidence in the interpretation of pulsed-source measurements is of general practical significance in reactor physics. With such measurements all possible sources of error should be investigated carefully and explicitly reported. Whenever possible the analysis should make use of more than one observable so that small systematic effects can be exposed; see pages 2 and 3.

(2) Absorption in hydrogen can be directly measured <u>only</u> by pulsed-source techniques. Direct comparisons between the pulsed-source and the transmission method have only been made with boron. Such comparisons should be made with other absorbers also, such as lithium, gold, or silver. Absorption in manganese and possibly vanadium and cobalt could also be measured by the pulsed-source method.

(3) For precise comparative measurements there is at present too little competition with the reactivity oscillator in DIMPLE at Harwell; CUMMINS et al. (1957), JOWITT et al. (1958), TATTERSALL et al. (1959). This is regrettable, but is clearly revealed from a study of tables 5, 9 to 15, and section 8.

(4) In section 8 we have questioned the reliability of local oscillators for very precise work.

(5) Further precision measurements of the boron-gold absorption ratio are needed.

(6) We have discounted the likelihood of errors in the comparisons of different standard boron samples. However, greater confidence would result in the long run if several national and international laboratories should concoct and share common standard stocks of boron and lithium, or even of B^{10} and Li^6.

(7) Lithium would be a useful addition to the primary standard absorbers. Its low energy cross-section obeys the 1/v law. The cross-section is lower than that of boron, but the disintegration products are more energetic.

(8) In using the transmission method, with samples containing boron for example, the scattering effect is uncertain. The uncertainty can be reduced in several ways.

By using different diluents.

By using a B^{10} standard.

By measuring at long wavelengths.

By measuring with high statistical accuracy in the region 0.5 to 20 eV, where the scattering is effectively that of incoherent free atoms and is constant.

(9) For measurements of high precision there is a self-evident need for reliable chemistry. It is worthwhile to emphasise that, with light elements in particular such as lithium and boron, it is important that all chemical reactions should be carried to completion: otherwise there is a risk of isotopic discrimination.

(10) Sodium is an important reactor coolant. There is a serious discrepanc between American and British measurements of the thermal absorption cross-section. Further measurements, including a comparison of samples, are needed.

(11) The decay modes of the isomeric state of Na^{24} of 20 milliseconds half-life should be re-examined.

(12) The absorption cross-section of V^{50} is known only to an order of magnitude.

(13) The activation cross-sections of V^{51}, Ag^{107}, Ag^{109}, In^{113}, In^{115}, have not been measured very accurately.

REFERENCES:

AILLOUD J., BRETON D., ERTAUD A. & RAIEVSKI V. (1952) J.Phys. Rad. 13, 171.

ALLEN R.G., STEPHENSON T.E., STANFORD C.P. & BERNSTEIN S. (1954) Phys.Rev. 96, 1297.

ANTONOV A.V., ISAKOFF A.I., MURIN I.D., NEUPOCOYEV B.A., FRANK I.M. & SHAPIRO F.L. (1955) Proc. Geneva 1, 5, 3.

BAKER A.R. (1958) Proc.Roy.Soc. A 248, 539.

BALLINI R., BERTHELOT A., & SMEETS C. (1947) Comptes rendus 225, 328.

BARTHOLOMEW G.A. & KINSEY B.B. (1953) Phys.Rev. 89, 386.

BARTHOLOMEW R.M., HAWKINS R.C., MERRITT W.F. & YAFFE L.(1953) Can.J.Chem. 31, 204.

BENDT P.J. & RUDERMAN I.W. (1950) Phys.Rev. 77, 575.

BERNSTEIN S., BORST L.B., STANFORD C.P., STEPHENSON T.E., & DIAL J.B. (1952) Phys. Rev. 87, 487.

BLATT J.M. & WEISSKOPF V.F. (1952) "Theoretical Nuclear Physics", JOHN WILEY & SONS, New York.

BROCKHOUSE B.N. (1953) Can.J.Phys. 31, 432.

BRACCI A. & COCEVA C. (1956) Nuovo Cim. 4, 59 (1956).

CAMERON A.E. (1955) J.Amer.Chem.Soc. 77, 2731.

CARTER R.S., PALEVSKY H., MYERS V.W. & HUGHES D.J. (1953) Phys.Rev. 92, 716. See also HARVEY (1955).

COCKING S.J. & RAFFLE J.F. (1956) J.Nucl.En. 3, 70.

COLMER F.C.W. & LITTLER D.J. (1957) Proc. Phys. Soc. A63 1175

COLLIE C.H., MEADS R.E. & LOCKETT E.E. (1956) Proc.Phys.Soc. A 69, 463.

CUMMINS J.D. (1957) AERE R/R 2333.

CUMMINS J.D. & SPURWAY A.H. (1957) AERE R/M 100.

von DARDEL G. & WALTNER A.W. (1953) Phys.Rev. 91, 1284.

von DARDEL G. & SJÖSTRAND N.G. (1954 a) Phys.Rev. 96, 1245.

" " " " " " (1954 b) Phys.Rev. 96, 1566.

" " " " " " (1958) Progr.Nucl.En.Ser. 1, Vol. 2.

DAVIDENKO V.A. & KUCHER A.M. (1951) Atomnaya Energiya 2, 334 (1957).

DEJUREN J. & CHIN J. (1955) Phys.Rev. 99, 191.

DEUTSCH M. & SCHARFF-GOLDHABER G. (1951) Phys.Rev. 83, 1059.

DIO W.H. (1958) Nukleonik 1, 13.

DROPESKY B.J. & SCHARDT A.W. (1956) Phys.Rev. 102, 426.

EGELSTAFF P.A. (1953) AERE N/R 1147.

" " (1954) J.Nucl.En. 1, 57.

" " (1957) J.Nucl.En. 5, 41.

FENNING F.W., GRAHAM G.A.R. & SELIGMAN H. (1947) Can.J.Res. A 25, 73.

GOLDHABER M. & MUEHLHAUSE C.O. (1948) Phys.Rev. 74, 1248.

GREEN A., LITTLER D.J. LOCKETT E.E., SMALL V.G., SPURWAY A.H. & BOWELL E. (1954) J.Nucl.En. 1, 144.

GRIMELAND B., HELLSTRAND E. & NETTER F. (1951) Comptes rendus 232, 2089.

GRIMELAND B. (1955) J.Nucl.En. 1, 231.

GROSHEV L.V., DEMIDOV A.M., LUTSENKO V.H. & PELEKHOV V.I. (1958) "Atlas of γ-ray spectra from radiative capture of thermal neutrons"; translated to English by J.B. SYKES, PERGAMON PRESS (1959).

HAMMERMESH B., RINGO G.R. & WEXLER S. (1953) Phys.Rev. 90, 603.

HARRIS S.P., MUEHLHAUSE C.O., RASMUSSEN S., SCHROEDER H.P. & THOMAS G.E. (1950 a) Phys.Rev. 80, 342.

HARRIS S.P., HIBSON C.T. & MUEHLHAUSE C.O. (1950 b) Phys.Rev. 80, 1014.

HARRIS S.P., MUEHLHAUSE C.O. & THOMAS G.E. (1950 c) Phys.Rev. 79, 11 (1950)

HARRIS S.P., MUEHLHAUSE C.O., ROSE D., SCHROEDER H.P.,THOMAS G.E. & WEXLER S. (1953 a) Phys.Rev. 91, 125.

HARRIS S.P., ROSE D. & SCHROEDER H.P. (1953 b), ANL-5031.

HARVEY J.A. (1955) Proc. Geneva I, 4, 147.

HAVENS Jr. W.W. & RAINWATER J. (1946) Phys.Rev. 70, 154.

HAVENS Jr. W.W., GOULD F., TAYLOR T.I., RUSTAD B.M., & MELKONIAN E. (1956) CR-1765.

HAVENS Jr. W.W., MELKONIAN E. & RUSTAD B.M. (1957) CU-160.

IGNATEV, KIRPICHIKOV & SUKHORUCHKIN unpublished. Verbal communication by MOSTOVOI V.1. (1958) Proc. Geneva II, 16, 209.

JOWITT D., PATTENDEN S.K., ROSE H., SMALL V.G. & TATTERSALL R.B. (1958) AERE R/R 2516.

KAPLAN L., RINGO G.R. & WILZBACH K.E. (1952) Phys.Rev. 87, 785.

KIMBALL C.W., RINGO G.R., ROBILLARD T.R. & WEXLER S. (1953). Quoted by HAMERMESH et al. (1953); see also HARVEY (1955).

KUBITSCHEK H. (1944) CP 1824. Quoted by WHITEHOUSE & GRAHAM (1947).

LARSSON K. -E. (1954) Arkiv Fys. 7, 323.

" " (1955) Private communication.

LEVIN M., RAINWATER J., HAVENS Jr. W.W., & BENDT P. (1950) CUD-61.

LITTLER D.J. & LOCKETT E.E. (1952) AERE R/R 961.

LOCKETT E.E. (1952). Cited by EGELSTAFF (1953).

MEADS R.E., ENGLAND C.J., COLLIE C.H. & WEEKS G.C. (1956) Proc.Phys.Soc. A 69, 31.

MEISTER H. (1958) Zeitschr. Naturf. 13 a, 820.

MOSS N. & YAFFE L. (1953) Can.J.Chem. 31, 391.

MYASISHCHEVA G.G., ANIKINA M.P., GOLDIN L.L. & ERSHLER B.V. (1957) Atomnaya Evergiya 2, 22; J.Nucl.En. 5, 230.

ORDZHONIKIDZE K. & SHIUTTSE V. (1955) Soviet Phys. JETP 2, 396.

OVERMAN R.T., FRY L.M., JONES J.W., BALDWIN W.D., LAMB E. & SAVOLAINEN J.E. (1948) ORNL 4.

PARWEL A., von UBISCH H. & WICKMAN F.E. (1956) Geochim. et Cosmochim.Acta 10, 185.

POMERANCE H. (1951) Phys.Rev. 83, 641.

POMERANCE H. (1952) Phys.Rev. 88, 412. See also ORNL-1304.

RUSTAD B.M., MELKONIAN E. & HAVENS W.W. Jr. (1956) CU-154, p. 20. See also CU-160, table I, by HAVENS et al. (1957).

SCOTT F.R., THOMSON D.B. & WRIGHT W. (1954) Phys.Rev. 95, 582.

SEHGAL M.L. (1957) Ind.J.Phys. 31, 630.

SEREN L., FRIEDLÄNDER H.N. & TURKEL S.H. (1947) Phys.Rev. 72, 888.

SHIUTTSE V. (1955) Soviet Phys. JETP 2, 402.

SMALL V.G. (1955) Quoted by EGELSTAFF (1957).

SJÖSTRAND N.G., MEDNIS J. & NILSSON T. (1959) Arkiv Fys. 15, 471.

STEHN J.R., COLLINS T.L. & JOHNSON W.H. (1958) KAPL-2000-4. See also Trans.Amer.Nucl. Soc. 1, No. 2, p.26.

STOOKSBERRY R.W. & CROUCH M.F. (1959) Phys.Rev. 114, 1561.

TATTERSALL R.B., ROSE H., PATTENDEN S.K., & JOWITT D. (1959) AERE R/R, 2887.

WALKER R.L. (1946) MDDC 414.

WESTCOTT C.H. (1958) AECL 670.

WHITEHOUSE W.J. & GRAHAM G.A.R. (1947) Can.J.Res. A 25, 261.

WUNDERER P. (1958) Zeitschr.Angew.Phys. 10, 537.

YAFFE L., HAWKINGS R.C., MERRITT W.F. & CRAVEN J.H. (1951) Phys.Rev. 82, 553.

NGS/IG/3ex
12.4.60