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## RENORMALIZATION OF PILE OSCILLATOR THERMAL NEUTRON CAPTURE CROSS SECTION DATA

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A PREPRINT

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## ABSTRACT

467 pile oscillator measurements have been weighted least squares averaged to provide a database of 81 elemental, 18 actinides,  $^{59}\text{Ni}$  and  $^{230}\text{Th}$  thermal neutron capture cross sections. The pile oscillator cross sections were renormalized to values calculated from the modern recommended isotopic cross sections of Pritychenko and Mughabghab (2012) and the atomic abundances of Berglund and Wieser (2011). The pile oscillator elemental cross section database is as precise as the elemental database derived from the recommended values. Discrepancies between the elemental cross sections from the two data sources for Fe, Br, Rb, Ru, Gd, Tb, Tm, Lu, Os, and Es have been resolved through additional review of the literature values.

## 1 Introduction

More than 50 years ago a primary way to measure elemental thermal neutron capture cross sections was the pile oscillator method Weinberg and Schweinler (1948). This method is based on the determination that the oscillation of a neutron absorber in the reactor pile causes the reactor neutron flux to oscillate proportionally to the absorbers thermal neutron cross section. The pile oscillator method assumes that although the reactor pile may not have a purely thermal temperature, the relative cross sections will follow the same  $1/v$  dependence so that a series of measurements can be renormalized to the cross section of an element with a well known thermal neutron capture cross section. Only minor corrections for non  $1/v$  elements, neutron scattering, and other effects were applied. The pile oscillator method could precisely measure the relative elemental cross sections but its accuracy was limited, at the time, by the lack of a well known reference standard cross section to normalize the values. Most measurements were standardized with respect the gold or boron cross sections that were only known to a few percent accuracy.

Pile oscillator cross section measurements are inherently as precise as any other method, including activation analysis, with the added advantage that they directly determine the elemental cross section. They are rarely measured today because of their high demand on reactor resources. The pile oscillator measurements are normally considered in the evaluation of isotopic cross sections and evaluators typically renormalize them to modern cross section standards. Recommended elemental cross sections are then calculated from the isotopic cross sections and abundances. Evaluations of elemental cross sections often neglect pile oscillator data, especially for elements that have multiple stable isotopes.

In this paper I have compiled a nearly complete set of elemental thermal neutron capture cross sections based on pile oscillator measurements. The data were obtained from an extensive search of the literature and the EXFOR Zerkin and Pritychenko (2018) database. The pile oscillator data were renormalized with respect to modern recommended elemental cross section values, based on the isotopic cross sections of Pritychenko and Mughabghab (2012) and the natural isotopic abundances of Berglund and Wieser (2011). The pile oscillator elemental cross section data have been compared with the recommended cross sections to identify discrepancies and a new set of recommended values has been adopted based on all data.

## 2 Elemental thermal neutron capture cross sections

The elemental thermal (2200 m/s) neutron capture cross sections,  $\sigma_0(El)$ , are normally calculated from the sum of the product of the isotopic thermal cross section,  $\sigma_0(^AZ)$ , and fractional abundances,  $f(^AZ)$  for each stable isotope of the element plus contributions from charged particle emission and fission. The elemental abundances are well known Berglund and Wieser (2011) and usually terrestrially invariable. Isotopic thermal neutron cross section data have been compiled by Mughabghab (2006) and the most recent recommended values are available from Pritychenko and Mughabghab (2012). The cross sections for all elements derived from these sources and updated, where indicated, from the current literature are given in Table 2 and are referred to as the recommended cross sections in this paper.

### 2.1 Pile oscillator elemental thermal neutron capture cross sections

A total of 467 pile oscillator cross section measurements from 56 references for 81 stable elements and 20 unstable elements are summarized in Table 2. These values were uncovered by an extensive Google and EXFOR Zerkin and Pritychenko (2018) search. In many cases the original data were buried in old, unavailable laboratory reports so the data were retrieved directly from the EXFOR database. Many of these measurements were performed at the Argonne, Harwell, and Oak Ridge pile reactors.

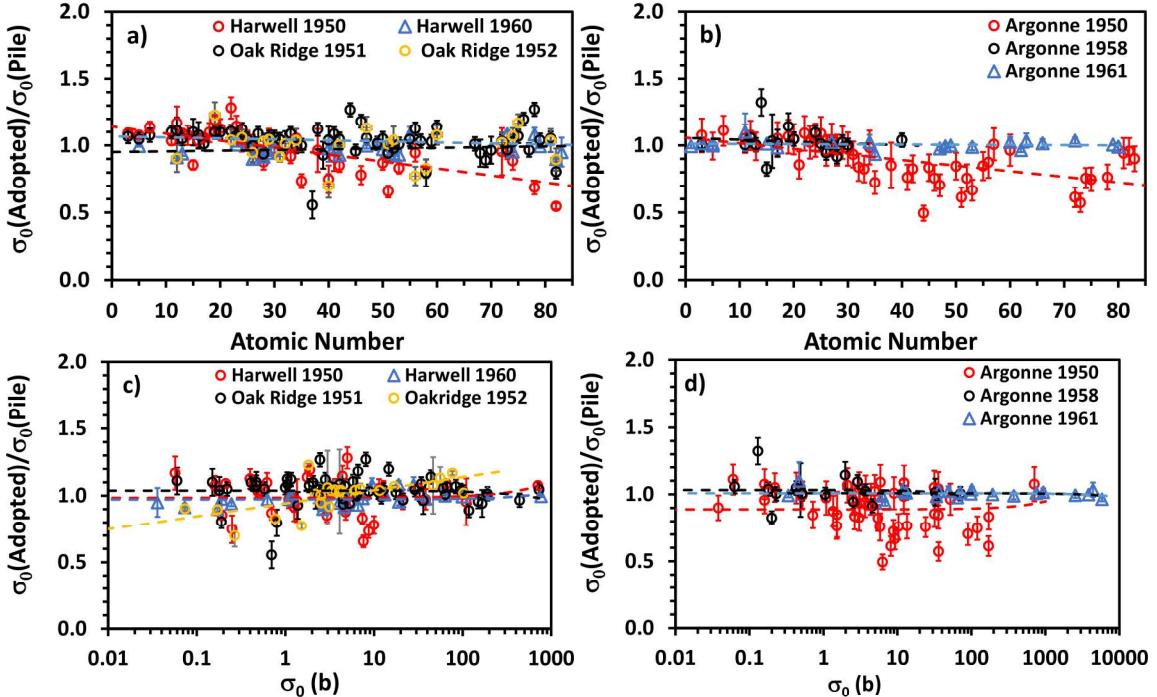


Figure 1: Dependence of the ratio of recommended to pile oscillator thermal neutron capture cross sections on atomic number and cross section magnitude. The dotted lines show the least-squares fits to the data.

### 2.2 Elemental data

The elemental pile oscillator cross sections published in each reference can all be renormalized to recommended cross sections by a factor  $N$  with an uncertainty  $\Delta N$  that is calculated by a standard weighted least-squared average of the ratios of the recommended cross sections to pile oscillator cross sections,  $R_i$ , for all measured elements where

$$R_i = \frac{\sigma_0(El_i)_{\text{Rec}}}{\sigma_0(El_i)_{\text{pile}}}, \quad \Delta R_i = R_i \left\{ \left[ \frac{\Delta \sigma_0(El_i)_{\text{Rec}}}{\sigma_0(El_i)_{\text{Rec}}} \right]^2 + \left[ \frac{\Delta \sigma_0(El_i)_{\text{pile}}}{\sigma_0(El_i)_{\text{pile}}} \right]^2 \right\}^{1/2}$$

$$N = \sum_i \frac{R_i}{\Delta R_i^2} / \sum_i \frac{1}{\Delta R_i^2}, \quad \Delta N = \left[ \sum_i (1/\Delta R_i^2) \right]^{-1/2} \quad (1)$$

The measured elemental cross sections are renormalized to the scale of the recommended cross sections by  $\sigma_0(El_i)_{\text{Adopt}} = N \sigma_0(El_i)_{\text{pile}}$ . If no uncertainty was reported for a pile oscillator cross section it is either ignored in

the calculation of  $N$  or an uncertainty is assigned so that for  $f$  elemental cross section measurements

$$\chi^2/f = \sum_i \left[ \frac{\sigma_0(El_i)_{Adopt} - \sigma_0(El_i)_{Rec}}{\Delta\sigma_0(El_i)_{Adopt} + \Delta\sigma_0(El_i)_{rec}} \right]^2 / f = 1.0. \quad (2)$$

The normalization factors for each reference are given in Table 1 and the renormalized pile oscillator cross section values are given in Table 2.

Some experiments reported numerous elemental thermal neutron capture cross sections allowing a more detailed investigation of the normalization as a function of atomic number and cross section magnitude. Cross sections for 61 elements were measured at the Argonne pile Harris et al. (1950); Meadows and Whalen (1961), 48 elements at the Harwell pile Colmer and Littler (1950); Tattersall et al. (1960), and 70 elements at the Oak Ridge pile Pomerance (1951). The ratios of recommended thermal neutron capture cross sections Pritychenko and Mughabghab (2012) to measured cross sections for these pile oscillator experiments are plotted as a function of both atomic number and cross section magnitude in Fig 1. Although significant scatter in the data exists, both the 1950 Argonne Harris et al. (1950) and the 1950 Harwell Colmer and Littler (1950) data exhibited a significant dependence on atomic number but no dependence on cross section magnitude. Their normalization factors were consistent with a linear dependence on atomic number ( $Z$ ) and are also included in Table 1.

Table 1: Pile Oscillator normalization factors.

Reference	Normalization	Reference	Normalization
Ailloud et al. (1952)	1.065(15)	Kirouac and Eiland (1975)	0.988(16)
Aitken et al. (1952)	1.073(3)	Kocic and Markovic (1968)	0.9998(19)
Aitken et al. (1957)	0.996(8)	Laponche et al. (1972)	1.018(6)
Anderson et al. (1947)	1.086(3)	Leconte et al. (2013)	1.002(9)
Anno et al. (1958)	1.007(8)	Littler and Lockett (1953)	1.0751(25)
Bartholomew et al. (1953)	1.045(19)	Lockett and Bowell (1953)	1.0751(25)
Benoist et al. (1951)	1.0753(25)	Markovic and Kocic (1971)	0.9982(8)
Bollinger et al. (1953)	1.011(4)	Meadows and Whalen (1961)	1.0034(21)
Bouzyk et al. (1961)	1.008(7)	Muehlhause (1959)	1.010(3)
Bouzyk et al. (1963)	1.014(15)	Nichols (1960)	1.002(5)
Cabell (1959)	1.08(4)	Pomerance (1951)	1.019(5)
Carre et al. (1961)	1.003(6)	Pomerance (1952)	0.97(7)
Carre and Vidal (1965)	0.998(3)	Pomerance (1953)	0.94(3)+0.042(11)ln( $\sigma_0$ )
Colmer and Littler (1950)	1.14(3)-0.0055(9) $Z$	Pomerance (1955a)	1.038(5)
Cummins (1957)	0.984(3)	Pomerance (1955b)	0.97(4)
Egelstaff (1953)	0.975(11)	Pomerance (1955b)	1.011(20)
Fuketa and Otomo (1960)	1.0078(24)	Rose et al. (1958)	0.9949(23)
Green et al. (1954)	0.989(5)	Ross and Story (1949)	0.98(5)
Green et al. (1957)	0.991(11)	Russell et al. (1962)	1.002(3)
Grimeland et al. (1951)	1.0751(25)	Scott et al. (1954)	1.039(23)
Halperin et al. (1959)	0.997(5)	Small (1955)	0.992(5)
Hamermesh et al. (1953)	1.011(4)	Sokolowski et al. (1964)	1.00(3)
Harris et al. (1950)	1.05(4)-0.0041(9) $Z$	Sokolowski and Bladh (1969)	1.008(7)
Harris et al. (1953a)	1.011(4)	Stefanescu and Sabau (1961)	0.995(7)
Harris et al. (1953b)	1.0106(4)	Tattersall et al. (1960)	0.986(3)
Harvey et al. (1954)	0.673(21)	Vidal (1963)	0.86(5)
Hoover et al. (1948)	1.052(8)	R.Vidal and J.C.Carre (1965)	0.88(4)+0.016(11)ln( $\sigma_0$ )
Huettel and Liewers (1963)	1.009(3)	Yaffe et al. (1951)	1.07(3)

## 2.3 Isotopic pile oscillator data

In addition to the elemental data pile oscillator thermal neutron cross sections were measured for 111 enriched isotopes at the Oak Ridge pile Pomerance (1952) and for 15 isotopes at the Harwell pile Tattersall et al. (1960). These measurements are for the isotopes that contribute most significantly to their elemental cross sections. The Oak Ridge values showed a significant dependence on cross section magnitude when compared to the recommended values, as shown in Fig. 1. The normalization factor for these data is consistent with a logarithmic dependence on cross section as shown in Table 1. The isotopic cross sections were combined with the recommended cross sections for the isotopes that

were not included in the pile oscillator measurements to generate elemental cross sections as shown in Table 3 and included in Table 2.

Table 2. Comparison of the renormalized pile oscillator elemental thermal neutron capture cross sections with the recommended values. The pile oscillator elemental uncertainties are derived from a weighted average of all measured values and were increased by the factor  $\Sigma\chi^2/f$  if  $\Sigma\chi^2/f > 1$ . The proposed values are a weighted average of the pile oscillator and recommended values except as noted.

Z	Element/ Isotope	Measured <sup>ref</sup>	Cross Section ( barns)			
			Renormalized	Average	Recommended <sup>1</sup>	Proposed
1	H	0.334(2) <sup>o</sup>	0.3286(22)	0.3321(14)	0.3326(7)	0.3325(6)
		0.334(2) <sup>o</sup>	0.3286(22)			
		0.332(2) <sup>l</sup>	0.333(3)			
		0.332(7) <sup>x</sup>	0.336(3)			
		0.335(5) <sup>aj</sup>	0.336(7)			
		0.323(8) <sup>av</sup>	0.336(10)			
3	Li	70.4(4) <sup>aj</sup>	70.6(4)	70.8(4)	71.4(3)	71.16(24)
		65.5(20) <sup>n</sup>	74(2)			
		71.3(21) <sup>j</sup>	72.3(24)			
		67(3) <sup>am</sup>	70(4)			
		66.8(34) <sup>a</sup>	71(4)			
4	Be	0.0085(3) <sup>d</sup>	0.0092(3)	0.0091(3)	0.00849(34)	0.00883(22)
		0.0093(16) <sup>bb</sup>	0.0080(14)			
		0.008 <sup>as</sup>	0.0080(10)			
5	B	766.6 <sup>as</sup>	762.7(18)	762.2(6)	763.3(18)	762.3(5)
		766.6 <sup>as</sup>	762.7(18)			
		703 <sup>d</sup>	763.3(18)			
		755 <sup>q</sup>	760.9(20)			
		710 <sup>ag</sup>	763(2)			
		759(2) <sup>ai</sup>	757.6(24)			
		759(2) <sup>ad</sup>	758.8(25)			
		760(2) <sup>m</sup>	759(3)			
		760.8(19) <sup>ax</sup>	761(3)			
		755(2) <sup>ak</sup>	762(3)			
		710 <sup>b</sup>	762(3)			
		710 <sup>ah</sup>	763(3)			
		710 <sup>t</sup>	763(3)			
		755 <sup>y</sup>	763.0(11)			
		755(4) <sup>au</sup>	757(4)			
		758(4) <sup>aj</sup>	761(4)			
		755 <sup>ab</sup>	762(4)			
		710 <sup>g</sup>	764(4)			
		783 <sup>o</sup>	770(4)			
		767(4) <sup>ba</sup>	756(5)			
		755(3) <sup>v</sup>	763(5)			
		783(5) <sup>r</sup>	774(6)			
		755(5) <sup>az</sup>	751(7)			
		755(5) <sup>i</sup>	761(7)			
		783(6) <sup>aw</sup>	778(7)			
		755(3) <sup>x</sup>	777(10)			

Table 2. Comparison of the renormalized pile oscillator elemental thermal neutron capture cross sections with the recommended values. The pile oscillator elemental uncertainties are derived from a weighted average of all measured values and were increased by the factor  $\Sigma\chi^2/f$  if  $\Sigma\chi^2/f > 1$ . The proposed values are a weighted average of the pile oscillator and recommended values except as noted.

Z	Element/ Isotope	Measured <sup>ref</sup>	Cross Section (barns)			
			Renormalized	Average	Recommended <sup>1</sup>	Proposed
6	C	757(9) <sup>ay</sup>	763(11)			
		782(9) <sup>p</sup>	763(12)			
		784(13) <sup>s</sup>	777(15)			
		710(21) <sup>n</sup>	790(24)			
		744(20) <sup>av</sup>	773(25)			
		730(36) <sup>am</sup>	764(39)			
		760.3(30) <sup>bc</sup>	754(43)			
		710(76) <sup>w</sup>	739(49)			
		710 <sup>w</sup>	739(91)			
		0.00380(4) <sup>al</sup>	0.00381(4)	0.00381(4)	0.00384(3)	0.003830(24)
7	N	0.0049 <sup>as</sup>	0.0049(10)			
		1.79(1) <sup>ab</sup>	1.806(11) <sup>2</sup>	1.92(4)	2.00(5)	1.94(3)
		1.76(5) <sup>n</sup>	1.94(6)			
		1.88(5) <sup>l</sup>	1.89(5)			
8	O	1.86(9) <sup>am</sup>	1.95(10)			
				0.000170(3) <sup>3</sup>	0.000261(9) <sup>9</sup>	
9	F			0.00951(9)	0.00951(9)	
10	Ne	2.38(4) <sup>l</sup>	2.39(4)	2.39(4)	2.39(3)	0.2390(24)
11	Na	0.500(15) <sup>n</sup>	0.541(17)	0.527(6)	0.517(4)	0.520(3)
		0.539(8) <sup>as</sup>	0.526(7)			
		0.470(23) <sup>am</sup>	0.492(25)			
		0.53(3) <sup>f</sup>	0.55(3)			
		0.49 <sup>ag</sup>	0.527(5)			
		0.47(6) <sup>aj</sup>	0.47(6)			
		0.52(5) <sup>w</sup>	0.54(6)			
		0.503(5) <sup>x</sup>	0.523(5)			
12	Mg	0.0610(9) <sup>ab</sup>	0.0615(9)	0.0635(18)	0.0666(11)	0.0658(11)
		0.0642(15) <sup>m</sup>	0.0641(18)			
		0.073(2) <sup>ba</sup>	0.0720(19)			
		0.065(5) <sup>az</sup>	0.065(5)			
		0.057(6) <sup>n</sup>	0.061(6)			
		0.060(6) <sup>am</sup>	0.063(6)			
		0.060(6) <sup>w</sup>	0.061(7)			
		0.074(8) <sup>ao</sup>	0.061(7)			
		0.246(3) <sup>ba</sup>	0.243(3)	0.2360(20)	0.231(3)	0.2345(17)
		0.229(3) <sup>m</sup>	0.229(4)			
13	Al	0.234(5) <sup>q</sup>	0.236(5)			
		0.212(5) <sup>n</sup>	0.227(6)			
		0.219(6) <sup>g</sup>	0.235(6)			
		0.229(11) <sup>am</sup>	0.230(12)			
		0.239(14) <sup>az</sup>	0.238(14)			
		0.220(22) <sup>w</sup>	0.222(24)			
14	Si	0.160(16) <sup>w</sup>	0.161(17)	0.168(9)	0.172(4)	0.171(4)

Table 2. Comparison of the renormalized pile oscillator elemental thermal neutron capture cross sections with the recommended values. The pile oscillator elemental uncertainties are derived from a weighted average of all measured values and were increased by the factor  $\Sigma\chi^2/f$  if  $\Sigma\chi^2/f > 1$ . The proposed values are a weighted average of the pile oscillator and recommended values except as noted.

Z	Element/ Isotope	Measured <sup>ref</sup>	Cross Section (barns)			
			Renormalized	Average	Recommended <sup>1</sup>	Proposed
15	P	0.16(1) <sup>n</sup>	0.171(11)			
		0.160(16) <sup>w</sup>	0.161(17)			
		0.10(3) <sup>ao</sup>	0.11(3) <sup>2</sup>			
		0.193(7) <sup>n</sup>	0.205(8) <sup>2</sup>	0.0157(16)	0.165(3)	0.165(3)
16	S	0.150(15) <sup>am</sup>	0.157(16)			
		0.49(2) <sup>n</sup>	0.518(22)	0.507(16)	0.506(10)	0.506(8)
		0.49(4) <sup>i</sup>	0.49(4)			
		0.47(5) <sup>am</sup>	0.49(5)			
17	Cl	0.51(5) <sup>w</sup>	0.51(5)			
		0.49(5) <sup>at</sup>	0.48(6)			
		33.6(3) <sup>aj</sup>	33.7(3)	33.6(3)	33.1(3)	33.36(20)
		31.3(8) <sup>n</sup>	32.9(10)			
18	Ar	32.3(10) <sup>j</sup>	32.8(11)			
		32.7(16) <sup>am</sup>	34.2(17)			
		32(4) <sup>w</sup>	31(4)			
		0.62(4) <sup>n</sup>	0.65(4)	0.65(5)	0.68(1)	0.680(10)
19	K	1.89(6) <sup>n</sup>	1.97(7) <sup>2</sup>	2.14(9)	2.25(4) <sup>4</sup>	2.23(4)
		2.15 <sup>i</sup>	2.17(16)			
		2.11(25) <sup>w</sup>	2.06(25)			
		1.83(14) <sup>ao</sup>	1.77(14) <sup>2</sup>			
20	Ca	2.05(10) <sup>am</sup>	2.14(11)			
		0.41(2) <sup>am</sup>	0.429(22)	0.421(14)	0.450(19)	0.432(12)
		0.40(2) <sup>n</sup>	0.414(22)			
		0.43(4) <sup>w</sup>	0.42(4)			
21	Sc	24(2) <sup>ah</sup>	25.8(22)	25.9(16)	27.2(2)	27.18(20)
		23.0(23) <sup>8am</sup>	24.1(24)			
		32(4) <sup>w</sup>	31(4)			
		5.0(3) <sup>n</sup>	5.1(3) <sup>2</sup>	6.10(24)	6.41(12)	6.35(11)
22	Ti	5.8(3) <sup>am</sup>	6.1(3)			
		6.2(45) <sup>ao</sup>	6.3(5)			
		5.9(7) <sup>w</sup>	5.7(7)			
		4.5(5) <sup>at</sup>	4.4(5) <sup>2</sup>			
23	V	4.01(7) <sup>ba</sup>	4.94(7)	5.05(22)	5.04(4)	5.04(4)
		5.13(9) <sup>af</sup>	5.14(9)			
		4.79(8) <sup>t</sup>	5.15(10)			
		4.7(2) <sup>am</sup>	4.92(25)			
24	Cr	4.4(3) <sup>n</sup>	4.5(3)			
		4.65 <sup>i</sup>	4.7(3)			
		6.29(34) <sup>az</sup>	6.3(3)			
		4.9(6) <sup>w</sup>	4.7(6)			
	Cr	2.83(14) <sup>am</sup>	2.96(15)	2.99(10)	3.17(6)	3.12(6)
		2.99(15) <sup>ao</sup>	2.95(17)			
		3.1(2) <sup>n</sup>	3.15(21)			

Table 2. Comparison of the renormalized pile oscillator elemental thermal neutron capture cross sections with the recommended values. The pile oscillator elemental uncertainties are derived from a weighted average of all measured values and were increased by the factor  $\Sigma\chi^2/f$  if  $\Sigma\chi^2/f > 1$ . The proposed values are a weighted average of the pile oscillator and recommended values except as noted.

Z	Element/ Isotope	Measured <sup>ref</sup>	Cross Section (barns)			
			Renormalized	Average	Recommended <sup>1</sup>	Proposed
25	Mn	3.0(4) <sup>w</sup>	2.9(4)			
		13.30(8) <sup>ab</sup>	13.42(9)	13.27(4)	13.36(5)	13.31(3)
		13.2(1) <sup>aj</sup>	13.24(10)			
		13.2(1) <sup>m</sup>	13.18(12)			
		13.39(10) <sup>aw</sup>	13.31(13)			
		13.25(15) <sup>ba</sup>	13.06(15)			
		13.20(15) <sup>ay</sup>	13.30(18)			
		13.2(2) <sup>o</sup>	12.99(20)			
		12.4(2) <sup>t</sup>	13.33(22)			
		13.27(23) <sup>af</sup>	13.30(23)			
		12.7(3) <sup>f</sup>	13.3(4)			
		14.34(6) <sup>bc</sup>	13.3(5)			
		13.4(4) <sup>j</sup>	13.6(5)			
		12.8(6) <sup>am</sup>	13.4(7)			
26	Fe	12.8(8) <sup>n</sup>	12.9(9)			
		12.3(14) <sup>w</sup>	11.7(14)			
		2.53(3) <sup>m</sup>	2.53(4)	2.57(4)	2.413(19) <sup>5</sup>	2.53(3) <sup>10</sup>
		2.65(10) <sup>ba</sup>	2.61(9)			
		2.69(2) <sup>bc</sup>	2.42(10)			
		2.39(12) <sup>am</sup>	2.50(13)			
		2.73(4) <sup>e</sup>	2.69(5)			
		2.52(18) <sup>ao</sup>	2.47(19)			
		2.76(20) <sup>i</sup>	2.78(20)			
		2.65(10) <sup>ba</sup>	2.61(9)			
27	Co	2.5(3) <sup>w</sup>	2.3(3)			
		36.3(6) <sup>aj</sup>	36.4(6)	37.2(3)	37.18(6)	37.18(6)
		38.0(3) <sup>m</sup>	37.9(3)			
		36.6(6) <sup>af</sup>	36.7(6)			
		38.1(7) <sup>ba</sup>	37.6(7)			
		37.2(6) <sup>ac</sup>	36.8(8)			
		38.4(10) <sup>az</sup>	38.2(10)			
		38.4(10) <sup>i</sup>	38.4(10)			
		35.4(10) <sup>a</sup>	37.7(12)			
		43.1(3) <sup>bc</sup>	40.7(17)			
		34.2(17) <sup>am</sup>	35.8(18)			
		34.2(14) <sup>bd</sup>	36.8(19)			
		38(3) <sup>n</sup>	38(3)			
		36(4) <sup>w</sup>	34(4)			
		36.5(3) <sup>k</sup>	39(4)			
28	Ni	4.6(1) <sup>ba</sup>	4.54(10)	4.38(11)	4.23(7)	4.27(6)
		4.6(1) <sup>m</sup>	4.59(13)			
		4.5(2) <sup>am</sup>	4.71(24)			
		4.09(23) <sup>ao</sup>	4.09(25)			

Table 2. Comparison of the renormalized pile oscillator elemental thermal neutron capture cross sections with the recommended values. The pile oscillator elemental uncertainties are derived from a weighted average of all measured values and were increased by the factor  $\Sigma\chi^2/f$  if  $\Sigma\chi^2/f > 1$ . The proposed values are a weighted average of the pile oscillator and recommended values except as noted.

Z	Element/ Isotope	Measured <sup>ref</sup>	Cross Section (barns)			
			Renormalized	Average	Recommended <sup>1</sup>	Proposed
28	<sup>59</sup> Ni	4.09(8) <sup>e</sup>	4.21(7)			
		4.8(3) <sup>n</sup>	4.8(3)			
		4.4(5) <sup>w</sup>	4.1(5)			
	<sup>63</sup> Cu	92(4) <sup>ac</sup>	91(4)	91(4)	78(4)	85(8)
		3.77(3) <sup>al</sup>	3.78(3)	3.79(5)	3.781(16)	3.782(15)
		3.74(4) <sup>m</sup>	3.73(4)			
		3.85(5) <sup>ai</sup>	3.84(5)			
		4.0(1) <sup>ba</sup>	3.94(10)			
		4.14(10) <sup>az</sup>	4.13(10)			
		3.62(12) <sup>j</sup>	3.67(13)			
30	<sup>65</sup> Zn	4.00(2) <sup>bc</sup>	362(15)			
		3.57(18) <sup>am</sup>	3.73(19)			
		3.62(14) <sup>ao</sup>	3.60(17)			
		3.60(25) <sup>n</sup>	3.6(3)			
		3.7(4) <sup>w</sup>	3.5(4)			
	<sup>67</sup> Ga	1.09(2) <sup>ba</sup>	1.075(19)	1.067(16)	1.06(5)	1.067(16)
		1.00(5) <sup>am</sup>	1.05(5)			
		1.09(5) <sup>n</sup>	1.07(6)			
		1.00(7) <sup>i</sup>	1.01(7)			
		1.09(13) <sup>w</sup>	1.02(13)			
31	<sup>69</sup> Ge	2.77(14) <sup>am</sup>	2.90(15)	3.01(9)	2.89(7)	2.93(6)
		3.15(10) <sup>ao</sup>	3.11(13)			
		3.1(3) <sup>w</sup>	2.9(3)			
	<sup>71</sup> Ge	2.18(10) <sup>ao</sup>	2.13(12)	2.23(9)	2.21(5)	2.21(4)
33	<sup>75</sup> As	2.23(20) <sup>a</sup>	2.38(22)			
		2.2(2) <sup>am</sup>	2.30(23)			
		2.6(3) <sup>w</sup>	2.4(3)			
		4.19(7) <sup>ay</sup>	4.22(8)	4.27(9)	4.5(1)	4.35(10)
	<sup>77</sup> Se	4.14(22) <sup>am</sup>	4.33(22)			
34	<sup>79</sup> Br	4.90(25) <sup>n</sup>	4.7(3)			
		5.5(6) <sup>w</sup>	5.0(6)			
		11.7(1) <sup>aj</sup>	11.74(10)	11.82(14)	12.0(6)	11.83(14)
		12.5(2) <sup>p</sup>	12.19(24)			
		11.4(5) <sup>n</sup>	11.0(6)			
		12.1(6) <sup>am</sup>	12.3(6)			
		11.6(7) <sup>ao</sup>	12.1(6)			
35	<sup>81</sup> Kr	13.6(10) <sup>i</sup>	13.7(10)			
		12.2(14) <sup>w</sup>	11.2(14)			
		6.82(6) <sup>aj</sup>	6.84(6)	6.84(6)	6.84(6) <sup>10</sup>	
		6.4(3) <sup>am</sup>	6.7(3)			
36	<sup>83</sup> Kr	8.8(10) <sup>n</sup>	8.0(10) <sup>2</sup>			
		8.7(6) <sup>w</sup>	8.3(6) <sup>2</sup>			
				25.4(12)	25.4(12)	

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Z	Element/ Isotope	Measured <sup>ref</sup>	Cross Section (barns)			
			Renormalized	Average	Recommended <sup>1</sup>	Proposed
37	Rb	0.70(7) <sup>am</sup>	0.73(7)	0.71(7)	0.389(5)	0.395(4) <sup>10</sup>
38	Sr	1.35(5) <sup>n</sup>	1.27(6)	1.25(4)	1.30(21)	1.25(4)
		1.16(6) <sup>am</sup>	1.21(6)			
		1.53(18) <sup>w</sup>	1.37(17)			
39	Y	1.38(14) <sup>am</sup>	1.44(14)	1.41(12)	1.28(2)	1.284(20)
		1.25(2) <sup>g</sup>	1.34(22)			
40	Zr	0.191(4) <sup>ba</sup>	0.188(4)	0.188(3)	0.187(18)	0.188(3)
		0.188(8) <sup>ad</sup>	0.188(8)			
		0.188(8) <sup>ai</sup>	0.188(8)			
		0.182(2) <sup>m</sup>	0.192(18)			
		0.18(2) <sup>am</sup>	0.188(19)			
		0.250(25) <sup>n</sup>	0.233(25) <sup>2</sup>			
		0.298(15) <sup>bc</sup>	0.257(17) <sup>2</sup>			
		0.268(22) <sup>ao</sup>	0.237(20) <sup>2</sup>			
		≈0.4 <sup>w</sup>	≈0.4			
		<0.7 <sup>at</sup>	<0.7			
41	Nb	1.17(2) <sup>ba</sup>	1.154(19)	1.16(3)	1.15(5)	1.16(3)
		1.06(5) <sup>am</sup>	1.11(6)			
		1.26(13) <sup>n</sup>	1.17(13)			
		1.4 <sup>d</sup>	1.56(13)			
		1.27(16) <sup>at</sup>	1.25(17)			
		1.51(18) <sup>w</sup>	1.34(17)			
		0.725(50) <sup>e</sup>	0.71(5) <sup>2</sup>			
42	Mo	2.70(4) <sup>ba</sup>	2.66(4)	2.64(3)	2.51(6)	2.61(5)
		2.60(5) <sup>m</sup>	2.60(8)			
		2.40(12) <sup>am</sup>	2.51(13)			
		2.95(15) <sup>n</sup>	2.72(17)			
		2.50(19) <sup>ao</sup>	2.45(19)			
		3.0(4) <sup>w</sup>	2.7(3)			
		2.91(3) <sup>at</sup>	2.9(3)			
		5.20(10) <sup>bc</sup>	4.73(21) <sup>2</sup>			
		19(2) <sup>ar</sup>	19.2(21)	18.9(20)	22.8(13)	21.6(16)
		16(7) <sup>ba</sup>	15(7)			
44	Ru	2.46(12) <sup>am</sup>	2.57(13)	2.57(13)	3.12(16)	2.64(12) <sup>10</sup>
		6.3(6) <sup>w</sup>	5.5(6)			
45	Rh	143(3) <sup>af</sup>	144(3)	146.5(25)	143.5(15)	144.3(13)
		149(4) <sup>o</sup>	147(4)			
		150(8) <sup>am</sup>	157(8)			
		164(11) <sup>q</sup>	165(11)			
		172(20) <sup>w</sup>	150(18)			
46	Pd	10.3(12) <sup>w</sup>	8.9(11)	8.7(7)	7.8(4)	8.0(3)
		6.6(3) <sup>am</sup>	6.9(3)			
		10.0(7) <sup>n</sup>	9.0(7)			

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Z	Element/ Isotope	Measured <sup>ref</sup>	Cross Section (barns)			
			Renormalized	Average	Recommended <sup>1</sup>	Proposed
47	Ag	62.9(4) <sup>ab</sup>	63.5(4)	63.7(6)	63.9(8)	63.8(5) <sup>10</sup>
		64.8(4) <sup>aj</sup>	65.0(4)			
		65.5(4) <sup>r</sup>	62.1(5)			
		63.7(4) <sup>r</sup>	64.7(5)			
		63.1(9) <sup>o</sup>	62.1(9)			
		64.8(2) <sup>m</sup>	64.7(9)			
		63(1) <sup>au</sup>	63.1(10)			
		59.8(9) <sup>aa</sup>	63.0(11)			
		63.4(12) <sup>ba</sup>	62.5(12)			
		58(2) <sup>av</sup>	60.3(23)			
		60(3) <sup>am</sup>	63(3)			
		64(3) <sup>q</sup>	65(3)			
		56(4) <sup>ao</sup>	62(4)			
		63(5) <sup>i</sup>	63(5)			
		90(11) <sup>w</sup>	78(10)			
		2537(9) <sup>aj</sup>	2546(11)	2522(85)	2520(50)	2520(40)
		2360(30) <sup>ax</sup>	2360(31)			
		2450(50) <sup>au</sup>	2455(50)			
48	Cd	3599(55) <sup>ba</sup>	3548(56) <sup>2</sup>			
		3500 <sup>am</sup>	3660(180) <sup>2</sup>			
		194.0(11) <sup>ab</sup>	195.7(13)	195(3)	193.8(19)	194.2(16)
		191(2) <sup>ba</sup>	188.3(20)			
		194(2) <sup>aj</sup>	194.7(21)			
		191.1(13) <sup>aa</sup>	201.3(21)			
		193.3(12) <sup>m</sup>	193.0(23)			
		199(3) <sup>ay</sup>	201(3)			
		191(3) <sup>au</sup>	191(3)			
		196(7) <sup>q</sup>	197(7)			
		191(10) <sup>am</sup>	200(10)			
		193(14) <sup>i</sup>	194(14)			
50	Sn	0.626(1) <sup>ba</sup>	0.617(9)	0.616(8)	0.609(3)	0.610(3)
		0.58(3) <sup>am</sup>	0.61(3)			
		0.605(35) <sup>az</sup>	0.60(4)			
		0.70(4) <sup>n</sup>	0.62(4)			
		0.72(8) <sup>w</sup>	0.61(8)			
51	Sb	5.3(3) <sup>am</sup>	5.5(3)	5.5(4)	4.99(8)	5.02(12)
		4.95(21) <sup>ao</sup>	5.0(3)			
		7.6(5) <sup>n</sup>	6.7(5)			
		8.2(10) <sup>w</sup>	6.9(9)			
52	Te	4.7(1) <sup>ba</sup>	4.63(10)	4.61(9)	4.4(3)	4.59(8)
		4.5(2) <sup>am</sup>	4.71(24)			
		4.2(3) <sup>ao</sup>	4.2(3)			
		5.8(7) <sup>w</sup>	4.9(6)			

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Z	Element/ Isotope	Measured <sup>ref</sup>	Cross Section (barns)			
			Renormalized	Average	Recommended <sup>1</sup>	Proposed
53	I	6.22(15) <sup>aj</sup>	6.24(15)	6.34(12)	6.15(6)	6.19(6)
		6.6(3) <sup>am</sup>	6.5(3)			
		6.1(3) <sup>ba</sup>	6.4(3)			
		7.4(4) <sup>n</sup>	6.4(4)			
		9.2(11) <sup>w</sup>	7.7(10)			
54	Xe				24.6(23)	24.6(23)
55	Cs	28(1) <sup>ba</sup>	27.6(9)	28.2(5)	30.3(11)	28.6(7)
		28.7(7) <sup>o</sup>	28.2(7)			
		28(1) <sup>m</sup>	28.0(14)			
		29.0(14) <sup>am</sup>	30.3(15)			
		36(4) <sup>w</sup>	30(4)			
56	Ba	1.25(4) <sup>n</sup>	1.06(6)	1.14(8)	1.18(7)	1.16(5)
		1.05(5) <sup>am</sup>	1.10(6)			
		1.35(16) <sup>w</sup>	1.11(14)			
		1.53(10) <sup>ao</sup>	1.46(10)			
57	La	9.1(2) <sup>o</sup>	8.95(20)	8.96(9)	9.08(4)	9.06(4)
		8.8(4) <sup>am</sup>	9.2(5)			
		9.0(11) <sup>w</sup>	7.4(9)			
		8.35(10) <sup>g</sup>	8.98(11)			
58	Ce	0.80(8) <sup>am</sup>	0.84(8) <sup>2</sup>	0.71(6)	0.637(18)	0.640(17)
		0.77(6) <sup>ao</sup>	0.71(6)			
		$\approx 0.65^w$	$\approx 0.5$			
		$< 0.92^n$	$< 0.8$			
59	Pr	11.6(2) <sup>o</sup>	11.41(20)	11.7(6)	11.5(3)	11.5(3)
		11.2(6) <sup>am</sup>	11.7(6)			
60	Nd	49.9 $^{+3}_{-22}$ <sup>aj</sup>	49.5(4)	49.2(8)	50.1(12)	49.5(6)
		51.4(12) <sup>ba</sup>	50.7(12)			
		43.2(10) <sup>a</sup>	46.0(13)			
		49.0(1.2) <sup>aj</sup>	49.1(13)			
		44(2) <sup>am</sup>	46.0(23)			
		47(3) <sup>ao</sup>	51(3)			
		52(6) <sup>w</sup>	42(5)			
62	Sm	5828(3) <sup>aj</sup>	5848(33)	5840(30)	6000(400)	5840(30)
		5820(60) <sup>ax</sup>	5821(63)			
		5600(200) <sup>au</sup>	5610(200)			
		8200(960) <sup>w</sup>	6560(810)			
		10380(160) <sup>c</sup>	10343(180) <sup>2</sup>			
		10200(160) <sup>ba</sup>	8380(180) <sup>2</sup>			
		10600 <sup>am</sup>	11090(550) <sup>2</sup>			
63	Eu	4406(30) <sup>aj</sup>	4421(32)	4378(25)	4560(230)	4380(25)
		4368(43) <sup>ba</sup>	4306(45)			
		4300(100) <sup>au</sup>	4310(100)			
		4200 <sup>am</sup>	4390(220)			

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Z	Element/ Isotope	Measured <sup>ref</sup>	Cross Section (barns)			
			Renormalized	Average	Recommended <sup>1</sup>	Proposed
64	Gd	35000 <sup>am</sup>	36210(1830)	33200(1300)	71500(1600) <sup>6</sup>	71500(1600)
		37600(1500) <sup>n</sup>	30400(2100)			
		36500(4300) <sup>w</sup>	29800(3600)			
		46617(100) <sup>aj</sup>	46300(300)	46600(300)		
		46730(400) <sup>ax</sup>	46700(400)			
		46000(1000) <sup>au</sup>	46000(1000)			
		48739(975) <sup>af</sup>	48800(1000)			
		58800(800) <sup>ba</sup>	57900(800) <sup>2</sup>			
65	Tb	44(4) <sup>am</sup>	46(4)	45(4)	23.4(4)	23.51(12) <sup>10</sup>
66	Dy	936(20) <sup>aj</sup>	939(20)	939(17)	950(20)	944(13)
		890 <sup>am</sup>	931(47)			
		950(50) <sup>au</sup>	950(50)			
67	Ho	64(3) <sup>am</sup>	67(3)	66.0(21)	64.7(12)	65.0(10)
		65(3) <sup>au</sup>	65(3)			
68	Er	166(17) <sup>am</sup>	174(17)	156(12)	156.4(19)	156.4(19)
		137(17) <sup>au</sup>	137(17)			
		$\approx 0.65^w$	$\approx 62$			
69	Tm	118(6) <sup>am</sup>	123(6)	120(6)	105(2)	107(3) <sup>10</sup>
70	Yb	36(4) <sup>am</sup>	38(4)	38(3)	34.7(8)	34.9(8)
		37(4) <sup>au</sup>	37(4)			
71	Lu	89.8(11) <sup>ax</sup>	89.8(11)	89.8(11)	75.2(21)	80.7(10) <sup>10</sup>
		112(5) <sup>au</sup>	112(5)			
		108(5) <sup>am</sup>	113(6)			
72	Hf	101.4(5) <sup>aj</sup>	101.7(5)	101.8(5)	104.9(22)	102.0(7)
		101.4(5) <sup>m</sup>	101.3(22)			
		102(5) <sup>am</sup>	107(5)			
		105(5) <sup>au</sup>	105(5)			
		103(7) <sup>ao</sup>	117(9)			
		107(11) <sup>h</sup>	108(11)			
		109(16) <sup>at</sup>	107(17)			
		110(20) <sup>n</sup>	84(16)			
		134(40) <sup>ba</sup>	132(38) <sup>2</sup>			
		171(20) <sup>w</sup>	130(16) <sup>2</sup>			
73	Ta	19.0(2) <sup>ba</sup>	18.73(20)	22(4)	20.6(5)	20.6(5)
		24.7(2) <sup>ai</sup>	24.65(20)			
		21.3(11) <sup>am</sup>	22.3(11)			
		21.2(15) <sup>n</sup>	16.2(15) <sup>2</sup>			
		36(4) <sup>w</sup>	27(3) <sup>2</sup>			
74	W	19.0(5) <sup>ba</sup>	18.7(5)	18.5(4)	18.14(17) <sup>7</sup>	18.26(17)
		17.7(9) <sup>am</sup>	18.5(9)			
		17.0(9) <sup>ao</sup>	18.0(11)			
		20.5(15) <sup>n</sup>	15.5(15)			
		24.0(24) <sup>w</sup>	18.0(19)			

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Z	Element/ Isotope	Measured <sup>ref</sup>	Cross Section (barns)			
			Renormalized	Average	Recommended <sup>1</sup>	Proposed
75	Re	77(5) <sup>ao</sup>	86(5)	85(3)	89.7(12)	89.0(16)
		77(4) <sup>am</sup>	83(4)			
		120(14) <sup>w</sup>	90(11)			
76	Os	14.7(7) <sup>am</sup>	15.4(8)	15.4(8)	17.6(7)	14.2(4) <sup>10</sup>
77	Ir	440(22) <sup>am</sup>	460(23)	460(23)	425(5)	427(8)
		$\approx 470^w$	$\approx 348$			
78	Pt	13.5(16) <sup>w</sup>	9.9(12)	9.7(3)	10.3(4)	9.90(24)
		9.5(2) <sup>ba</sup>	9.37(19)			
		8.1(4) <sup>am</sup>	8.5(4)			
		10.0(7) <sup>aq</sup>	9.7(7)			
		15(1) <sup>n</sup>	11.0(11)			
79	Au	98.9(2) <sup>ai</sup>	98.7(3)	98.82(14)	98.65(9)	98.70(8)
		98.9(2) <sup>ad</sup>	98.9(3)			
		98.8(3) <sup>au</sup>	99.0(3)			
		98.2(5) <sup>aj</sup>	98.5(5)			
		98 <sup>a</sup>	99.6(6)			
		98.6(6) <sup>r</sup>	97.5(7)			
		99 <sup>u</sup>	98.7(7)			
		98.5(6) <sup>ab</sup>	99.4(7)			
		98.7(6) <sup>al</sup>	98.9(8)			
		98.0(10) <sup>e</sup>	98.7(13)			
		99.3(15) <sup>ba</sup>	97.9(15)			
		98.6 <sup>s</sup>	97.7(19)			
		98 <sup>ar</sup>	99(2)			
		95 <sup>aa</sup>	100(3)			
		98.9(2) <sup>bc</sup>	95(4)			
		93 <sup>f</sup>	97(4)			
		95(5) <sup>am</sup>	99(5)			
80	Hg	95(5) <sup>ao</sup>	108(6)			
		93 <sup>bd</sup>	100(6)			
		90(7) <sup>i</sup>	91(7)			
		95 <sup>an</sup>	92(8)			
		95 <sup>ap</sup>	98.6(5)			
		$\approx 157^w$	$\approx 115$			
		374(5) <sup>aj</sup>	375(5)	375(4)	370(8)	374(3)
		354 <sup>a</sup>	377(6)			
		341 <sup>am</sup>	357(18)			
		$\approx 380^w$	$\approx 276$			
81	Tl	3.27(16) <sup>am</sup>	3.42(17)	3.4(4)	3.44(6)	3.44(6)
		3.6(4) <sup>w</sup>	2.6(3)			
		3.8(3) <sup>ao</sup>	4.1(3)			
82	Pb	0.171(2) <sup>ba</sup>	0.1686(20)	0.169(17)	0.153(3)	0.153(3)
		0.162(5) <sup>b</sup>	0.174(5)			

Table 2. Comparison of the renormalized pile oscillator elemental thermal neutron capture cross sections with the recommended values. The pile oscillator elemental uncertainties are derived from a weighted average of all measured values and were increased by the factor  $\Sigma\chi^2/f$  if  $\Sigma\chi^2/f > 1$ . The proposed values are a weighted average of the pile oscillator and recommended values except as noted.

Z	Element/ Isotope	Measured <sup>ref</sup>	Cross Section (barns)			
			Renormalized	Average	Recommended <sup>1</sup>	Proposed
83	Bi	0.190(10) <sup>am</sup>	0.199(10)			
		0.189(10) <sup>bb</sup>	0.155(11)			
		0.160(16) <sup>w</sup>	0.115(12)			
		0.28(1) <sup>n</sup>	0.200(16)			
		0.172(19) <sup>az</sup>	0.171(19)			
		0.171(15) <sup>ao</sup>	0.0148(14)			
	Bi	0.0215(15) <sup>n</sup>	0.0146(15) <sup>2</sup>	0.0315(17)	0.0342(7)	0.0338(8)
		0.0308(22) <sup>ag</sup>	0.0331(24)			
		0.038(4) <sup>w</sup>	0.027(3)			
		0.036(4) <sup>ba</sup>	0.035(4)			
89	<sup>227</sup> Ac	814(13) <sup>k</sup>	878(35)	878(35)	890(30)	885(23)
90	<sup>230</sup> Th	26(2) <sup>ap</sup>	27.0(21)	27.0(21)	22.9(3)	23.0(3)
90	<sup>232</sup> Th	7.5(3) <sup>ba</sup>	7.4(3)	7.45(14)	7.35(3)	7.35(3)
		7.57(17) <sup>aw</sup>	7.52(18)			
		7.0(4) <sup>ao</sup>	7.2(4)			
92	U	7.07(12) <sup>aw</sup>	7.03(13) <sup>2</sup>	7.8(4)	7.672(21)	7.673(21)
		7.83(42) <sup>az</sup>	7.8(4)			
92	<sup>233</sup> U	581(7) <sup>ak</sup>	587(7)	585(7)	587.5(10)	587.4(10)
		578(17) <sup>s</sup>	573(18)			
92	<sup>234</sup> U	88(6) <sup>an</sup>	86(9)	86(9)	99.8(13)	99.5(23)
92	<sup>235</sup> U	683(4) <sup>ae</sup>	695(6)	697(5)	694.8(12)	694.9(12)
		694(8) <sup>ak</sup>	701(8)			
92	<sup>236</sup> U	5.8(17) <sup>an</sup>	5.6(17)	5.6(17)	5.09(10)	5.09(10)
92	<sup>238</sup> U	2.76(6) <sup>aw</sup>	2.74(6)	2.74(4)	2.680(19)	2.692(17)
		2.71(5) <sup>y</sup>	2.74(5)			
		2.81(8) <sup>an</sup>	2.73(22)			
93	<sup>237</sup> Np	169(3) <sup>ba</sup>	161(4)	161(9)	175.9(29)	174(3)
94	<sup>239</sup> Pu	1026(13) <sup>ak</sup>	1036(13)	1040(12)	1025.3(29)	1026(3)
		1030(20) <sup>ae</sup>	1048(21)			
94	<sup>240</sup> Pu	280(10) <sup>ae</sup>	285(10)	293(14)	289.5(14)	289.5(14)
		280(10) <sup>ae</sup>	285(10)			
		370(40) <sup>ba</sup>	353(38)			
95	<sup>241</sup> Am	625(35) <sup>aq</sup>	605(42)	605(42)	587(12)	588(12)
95	<sup>243</sup> Am	140(50) <sup>z</sup>	94(34)	94(34)	75.1(18)	75.2(18)
97	<sup>249</sup> Bk	1100(300) <sup>z</sup>	740(200)	740(200)	711	730(140)
98	<sup>249</sup> Cf	$\approx 900^z$	$\approx 547$	$\approx 547$	497(21)	497(21)
98	<sup>252</sup> Cf	30 <sup>z</sup>	20(3)	20(3)	20.4(15)	20.3(13)
98	<sup>254</sup> Cf	<2 <sup>z</sup>	<1.3	<1.3	4.5(15)	4.5(15)
99	<sup>253</sup> Es	160 <sup>z</sup>	108(4)	108(4)	183.9	170(12) <sup>10</sup>
99	<sup>254</sup> Es	<15 <sup>z</sup>	<10	<10	28.3(25)	28.3(25)

Table 2. Comparison of the renormalized pile oscillator elemental thermal neutron capture cross sections with the recommended values. The pile oscillator elemental uncertainties are derived from a weighted average of all measured values and were increased by the factor  $\Sigma\chi^2/f$  if  $\Sigma\chi^2/f > 1$ . The proposed values are a weighted average of the pile oscillator and recommended values except as noted.

Z	Element/ Isotope	Measured <sup>ref</sup>	Renormalized	Average	Recommended <sup>1</sup>	Proposed
<sup>1</sup> Pritychenko and Mughabghab (2012) except as noted.	<sup>2</sup> Value excluded from weighted average.					
<sup>3</sup> Firestone and Revay (2016)	<sup>4</sup> Firestone et al. (2013)	<sup>5</sup> From Firestone et al. (2017) + $\sigma(n, \alpha)=0.0054$ mb from Jasielska et al. (1965).	<sup>6</sup> Choi et al. (2014)	<sup>7</sup> <sup>180</sup> W cross section updated to Hurst et al. (2015)	<sup>8</sup> Revised value reported as private communication in Lockett and Bowell (1953)	<sup>9</sup> Corrected for contribution from $\sigma(^{17}O(n, \alpha)=0.237(23)$ , weighted average of values from Hanna et al. (1961); Seppi (1956); Wagemans et al. (2000); Gledenov et al. (1997).
<sup>10</sup> Discrepant value, see text.						
<sup>a</sup> Ailloud et al. (1952)	<sup>b</sup> Aitken et al. (1952)	<sup>c</sup> Aitken et al. (1957)	<sup>d</sup> Anderson et al. (1947)	<sup>e</sup> Anno et al. (1958)	<sup>f</sup> Bartholomew et al. (1953)	<sup>g</sup> Benoist et al. (1951)
<sup>h</sup> Bollinger et al. (1953)	<sup>i</sup> Bouzyk et al. (1961)	<sup>j</sup> Bouzyk et al. (1963)	<sup>k</sup> Cabell (1959)	<sup>l</sup> Carre et al. (1961)	<sup>m</sup> Carre and Vidal (1965)	<sup>n</sup> Colmer and Littler (1950)
<sup>o</sup> Cummins (1957)	<sup>p</sup> Egelstaff (1953)	<sup>q</sup> Fuketa and Otomo (1960)	<sup>r</sup> Green et al. (1954)	<sup>s</sup> Green et al. (1957)	<sup>t</sup> Grimeland et al. (1951)	<sup>u</sup> Halperin et al. (1959)
<sup>v</sup> Hamermesh et al. (1953)	<sup>w</sup> Harris et al. (1950)	<sup>x</sup> Harris et al. (1953a)	<sup>y</sup> Harvey et al. (1954)	<sup>z</sup> Hoover et al. (1948)	<sup>aa</sup> Huettel and Liewers (1963)	<sup>ab</sup> Kirouac and Eiland (1975)
<sup>ac</sup> Kocic and Markovic (1968)	<sup>ad</sup> Laponche et al. (1972)	<sup>ae</sup> Leconte et al. (2013)	<sup>af</sup> Littler and Lockett (1953)	<sup>ag</sup> Lockett and Bowell (1953)	<sup>ah</sup> Markovic and Kocic (1971)	<sup>ai</sup> Meadows and Whalen (1961)
<sup>aj</sup> Muehlhausen (1959)	<sup>ak</sup> Nichols (1960)	<sup>al</sup> Pomerance (1951)	<sup>am</sup> Pomerance (1952)	<sup>an</sup> Pomerance (1955a)	<sup>ao</sup> Pomerance (1955b)	<sup>ap</sup> Rose et al. (1958)
<sup>aq</sup> Ross and Story (1949)	<sup>ar</sup> Scott et al. (1954)	<sup>as</sup> Small (1955)	<sup>at</sup> Sokolowski et al. (1964)	<sup>au</sup> Sokolowski and Bladh (1969)	<sup>av</sup> Stefanescu and Sabau (1961)	<sup>aw</sup> Tattersall et al. (1960)
<sup>ax</sup> Vidal (1963)	<sup>ay</sup> R.Vidal and J.C.Carre (1965)	<sup>az</sup> Yaffe et al. (1951)				

Table 2. Elemental thermal neutron capture cross sections derived from the isotopic pile oscillator cross sections from Pomerance (1952) except as noted. The atomic abundances are from Berglund and Wieser (2011).

$zEl^A$	Abund	$\sigma_0$ (b) <sup>a</sup> Isotopic	Elemental $\sigma_0$ (b) Data	Renorm <sup>b</sup>	$zEl^A$	Abund	$\sigma_0$ (b) <sup>a</sup> Isotopic	Elemental $\sigma_0$ (b) Data	Renorm <sup>b</sup>
<sup>12</sup> Mg <sup>25</sup>	0.78990	[0.0538(13)]	0.074(8)	0.061(7)	<sup>28</sup> Ni <sup>61</sup>	0.01140	1.9(10)		
<sup>12</sup> Mg <sup>25</sup>	0.10000	0.27(8)			<sup>28</sup> Ni <sup>62</sup>	0.03635	14.6(22)		
<sup>12</sup> Mg <sup>25</sup>	0.11010	[0.0384(6)]			<sup>28</sup> Ni <sup>64</sup>	0.00926	[1.64(4)]		
<sup>19</sup> K <sup>39</sup>	0.93258	1.87(15)	1.83(14)	1.77(14)	<sup>29</sup> Cu <sup>63</sup>	0.69150	4.3(3)	3.62(14)	3.60(17)
<sup>19</sup> K <sup>40</sup>	0.00012	66(20)			<sup>29</sup> Cu <sup>65</sup>	0.30850	2.11(17)		
<sup>19</sup> K <sup>41</sup>	0.06739	1.19(10)			<sup>31</sup> Ga <sup>69</sup>	0.60108	1.99(16)	3.15(10)	3.11(13)
<sup>22</sup> Ti <sup>46</sup>	0.08250	0.57(17)	6.2(4)	6.3(5)	<sup>31</sup> Ga <sup>71</sup>	0.39892	4.9(4)		
<sup>22</sup> Ti <sup>47</sup>	0.07440	1.6(3)			<sup>32</sup> Ge <sup>70</sup>	0.20570	3.3(3)	2.18(10)	2.13(12)
<sup>22</sup> Ti <sup>48</sup>	0.73720	8.0(6)			<sup>32</sup> Ge <sup>72</sup>	0.27450	0.94(9)		
<sup>22</sup> Ti <sup>49</sup>	0.05410	1.8(4)			<sup>32</sup> Ge <sup>73</sup>	0.07750	13.7(11)		
<sup>22</sup> Ti <sup>50</sup>	0.05185	[0.179(3)]			<sup>32</sup> Ge <sup>74</sup>	0.35500	[0.52(4)]		
<sup>24</sup> Cr <sup>50</sup>	0.04345	16.3(13)	2.99(15)	2.95(17)	<sup>32</sup> Ge <sup>76</sup>	0.07730	[0.155(10)]		
<sup>24</sup> Cr <sup>52</sup>	0.83789	0.73(6)			<sup>34</sup> Se <sup>74</sup>	0.00890	48(7)	11.6(7)	12.1(8)
<sup>24</sup> Cr <sup>53</sup>	0.09501	17.5(14)			<sup>34</sup> Se <sup>76</sup>	0.09370	82(7)		
<sup>24</sup> Cr <sup>54</sup>	0.02365	[0.41(4)]			<sup>34</sup> Se <sup>77</sup>	0.07630	40(4)		
<sup>26</sup> Fe <sup>54</sup>	0.05845	2.17(17)	2.52(18)	2.47(19)	<sup>34</sup> Se <sup>78</sup>	0.23770	[0.43(2)]		
<sup>26</sup> Fe <sup>56</sup>	0.91754	2.55(20)			<sup>34</sup> Se <sup>80</sup>	0.49610	0.59(6)		
<sup>26</sup> Fe <sup>57</sup>	0.02119	2.4(3)			<sup>34</sup> Se <sup>82</sup>	0.08730	[0.044(3)]		
<sup>26</sup> Fe <sup>58</sup>	0.00282	[1.32(3)]			<sup>40</sup> Zr <sup>90</sup>	0.51450	[0.077(6)]	0.268(22)	0.237(20)
<sup>28</sup> Ni <sup>58</sup>	0.68077	4.2(3)	4.09(23)	4.09(25)	<sup>40</sup> Zr <sup>91</sup>	0.11220	1.52(12)		
<sup>28</sup> Ni <sup>60</sup>	0.26223	2.54(20)			<sup>40</sup> Zr <sup>92</sup>	0.17150	0.25(8)		

Table 2. Elemental thermal neutron capture cross sections derived from the isotopic pile oscillator cross sections from Pomerance (1952) except as noted. The atomic abundances are from Berglund and Wieser (2011).

$zEl^A$	Abund	$\sigma_0$ (b) <sup>a</sup> Isotopic	Elemental $\sigma_0$ (b) Data	Renorm <sup>b</sup>	$zEl^A$	Abund	$\sigma_0$ (b) <sup>a</sup> Isotopic	Elemental $\sigma_0$ (b) Data	Renorm <sup>b</sup>
$_{40}\text{Zr}^{94}$	0.17380	0.08(4)			$_{60}\text{Nd}^{143}$	0.12174	292(23)		
$_{40}\text{Zr}^{92}$	0.17150	0.25(8)			$_{60}\text{Nd}^{144}$	0.23798	4.8(10)		
$_{40}\text{Zr}^{94}$	0.17380	0.08(4)			$_{60}\text{Nd}^{145}$	0.08293	52(4)		
$_{40}\text{Zr}^{96}$	0.02800	[0.0229(10)]			$_{60}\text{Nd}^{146}$	0.17189	[1.49(6)]		
$_{42}\text{Mo}^{92}$	0.14836	0.08(2)	2.50(19)	2.45(19)	$_{60}\text{Nd}^{148}$	0.05756	3.3(10)		
$_{42}\text{Mo}^{94}$	0.09247	[0.34(6)]			$_{60}\text{Nd}^{150}$	0.05638	[1.04(4)]		
$_{42}\text{Mo}^{95}$	0.15840	13.4(11)			$_{60}\text{Nd}^{142}$	0.27152	[18.7(7)]	51.4(12) <sup>c</sup>	50.7(12)
$_{42}\text{Mo}^{96}$	0.16670	[0.05(2)]			$_{60}\text{Nd}^{143}$	0.12174	336(10)		
$_{42}\text{Mo}^{97}$	0.09600	2.1(6)			$_{60}\text{Nd}^{144}$	0.23798	[3.6(3)]		
$_{42}\text{Mo}^{98}$	0.24390	[0.130(6)]			$_{60}\text{Nd}^{145}$	0.08293	49.3(15)		
$_{42}\text{Mo}^{100}$	0.09820	[0.199(3)]			$_{60}\text{Nd}^{146}$	0.17189	[1.49(6)]		
$_{47}\text{Ag}^{107}$	0.51839	29.9(24)	56(4)	62(4)	$_{60}\text{Nd}^{148}$	0.05756	[2.58(7)]		
$_{47}\text{Ag}^{109}$	0.48161	84(7)			$_{60}\text{Nd}^{150}$	0.05638	[1.04(4)]		
$_{48}\text{Cd}^{106}$	0.01250	[1.0(5)]	3599(55) <sup>c</sup>	3548(56)	$_{63}\text{Eu}^{151}$	0.47810	8790(90)	4368(43) <sup>c</sup>	4306(45)
$_{48}\text{Cd}^{108}$	0.00890	[0.72(13)]			$_{63}\text{Eu}^{153}$	0.52190	317(5)		
$_{48}\text{Cd}^{110}$	0.12490	[11(1)]			$_{64}\text{Gd}^{152}$	0.00200	[735(20)]	58800(800) <sup>c</sup>	57900(800)
$_{48}\text{Cd}^{111}$	0.12800	[6.9(8)]			$_{64}\text{Gd}^{154}$	0.02180	[22310(300)]		
$_{48}\text{Cd}^{112}$	0.24130	[2.2(5)]			$_{64}\text{Gd}^{155}$	0.14800	46800(900)		
$_{48}\text{Cd}^{113}$	0.12220	29400(450)			$_{64}\text{Gd}^{156}$	0.20470	46800(900)		
$_{48}\text{Cd}^{114}$	0.28730	[0.330(18)]			$_{64}\text{Gd}^{157}$	0.15650	[1.8(7)]		
$_{48}\text{Cd}^{116}$	0.07490	[0.075(10)]			$_{64}\text{Gd}^{158}$	0.24840	196000(3000)		
$_{51}\text{Sb}^{121}$	0.57210	5.7(5)	4.95(21)	5.0(3)	$_{64}\text{Gd}^{160}$	0.21860	[2.2(2)]		
$_{51}\text{Sb}^{123}$	0.42790	3.9(3)			$_{72}\text{Hf}^{174}$	0.00160	[549(7)]	103(7)	117(9)
$_{52}\text{Te}^{120}$	0.00090	[2.0(3)]	4.2(3)	4.2(3)	$_{72}\text{Hf}^{176}$	0.05260	[23.5(31)]		
$_{52}\text{Te}^{122}$	0.02550	2.7(9)			$_{72}\text{Hf}^{177}$	0.18600	375(30)		
$_{52}\text{Te}^{123}$	0.00890	390(31)			$_{72}\text{Hf}^{178}$	0.27280	72(11)		
$_{52}\text{Te}^{124}$	0.04740	6.5(13)			$_{72}\text{Hf}^{179}$	0.13620	50(25)		
$_{52}\text{Te}^{125}$	0.07070	1.49(15)			$_{72}\text{Hf}^{180}$	0.35080	13(5)		
$_{52}\text{Te}^{126}$	0.18840	0.77(19)			$_{74}\text{W}^{180}$	0.00120	[21.7(8)]	17.0(9)	18.0(11)
$_{52}\text{Te}^{128}$	0.31740	[0.200(8)]			$_{74}\text{W}^{182}$	0.26500	19.2(20)		
$_{52}\text{Te}^{130}$	0.34080	[0.195(10)]			$_{74}\text{W}^{183}$	0.14310	10.9(10)		
$_{56}\text{Ba}^{130}$	0.00106	[8.7(9)]	1.53(10)	1.46(10)	$_{74}\text{W}^{184}$	0.30640	2.0(3)		
$_{56}\text{Ba}^{132}$	0.00101	[6.5(8)]			$_{74}\text{W}^{186}$	0.28430	34(3)		
$_{56}\text{Ba}^{134}$	0.02417	[1.5(3)]			$_{75}\text{Re}^{185}$	0.37400	100(8)	77(5)	86(5)
$_{56}\text{Ba}^{135}$	0.06592	5.6(8)			$_{75}\text{Re}^{187}$	0.62600	63(5)		
$_{56}\text{Ba}^{136}$	0.07854	[0.68(17)]			$_{79}\text{Au}^{197}$	1.00000	95(5)	95(5)	108(6)
$_{56}\text{Ba}^{137}$	0.11232	4.9(4)			$_{81}\text{Tl}^{203}$	0.29520	11.0(9)	3.3(3)	3.3(3)
$_{56}\text{Ba}^{138}$	0.71698	0.68(10)			$_{81}\text{Ti}^{205}$	0.70480	[0.104(17)]		
$_{58}\text{Ce}^{136}$	0.00185	[7.4(10)]	0.77(6)	0.71(6)	$_{82}\text{Pb}^{204}$	0.01400	[0.703(35)]	0.171(15)	0.148(14)
$_{58}\text{Ce}^{138}$	0.00251	[1.02(24)]			$_{82}\text{Pb}^{206}$	0.24100	[0.0266(12)]		
$_{58}\text{Ce}^{140}$	0.88450	0.63(6)			$_{82}\text{Pb}^{207}$	0.22100	0.70(7)		
$_{58}\text{Ce}^{142}$	0.11114	1.8(3)			$_{82}\text{Pb}^{208}$	0.52400	[0.00023(2)]		
$_{60}\text{Nd}^{142}$	0.27152	18.5(22)	47(3)	51(3)	$_{90}\text{Th}^{232}$	1.00000	7.0(4)	7.0(4)	7.2(4)

<sup>a</sup> Values in square brackets are from Pritychenko and Mughabghab (2012). <sup>b</sup> Renormalized by the factor 0.940(26)+0.42(11) $\sigma_0$ . <sup>c</sup> From Tattersall et al. (1960), renormalized by factor 0.986(3).

## 2.4 Adopted cross sections

The renormalized pile oscillator cross section measurements for each element, after rejecting clear outliers, were weighted least-squares averaged, as described in Eq. 1, to compare with the recommended values. This comparison is justified by the assumption that the recommended values are primarily based on different methods although the source of those values is not documented. The precision of the averaged pile oscillator elemental cross sections is comparable to the recommended values with an average uncertainty of 2.18% compared to 2.23% for the recommended values. In 30 cases the adopted pile oscillator cross sections were more precise than the recommended values. The renormalized pile oscillator data confirm the B and Au cross section primary calibration standards that were used in many experiments. The pile oscillator value  $\sigma_0(B)=762.2(6)$  b agrees with the recommended value  $\sigma_0(B)=763.3(18)$  b, and  $\sigma_0(Au)=98.82(14)$  b agrees with the recommended value  $\sigma_0(B)=98.65(9)$  b.

## 3 Discussion

Experimental and renormalized pile oscillator thermal neutron capture cross sections were measured for 81 elements, 17 actinides,  $^{59}\text{Ni}$ ,  $^{230}\text{Th}$  and are given in Table 2 where they are compared to the recommended cross sections. In eleven comparisons the weighted average cross section gave a  $\chi^2/f > 2$ . These cases are discussed in greater detail below.

### 3.1 Iron

Nine pile oscillator measurements give an average thermal neutron capture cross section  $\sigma_0(\text{Fe})=2.57(4)$  b which varies markedly from the recommended value Firestone et al. (2017)  $\sigma_0(\text{Fe})=2.413(19)$  b, corrected for particle emission Haenni and Rossel (1952). The large number of self-consistent pile oscillator measurements likely makes them highly reliable. The recommended value is based on a prompt  $\gamma$ -ray measurement using the internal cross section standards  $^1\text{H}$  and  $^{32}\text{S}$  and is dominated by the  $^{56}\text{Fe}$  isotopic cross section,  $\sigma_0(^{56}\text{Fe})=2.394(19)$  b. Notably the pile oscillator measurements were performed at thermal neutron temperatures (2200 m/s) while the prompt  $\gamma$ -ray measurement was done with a cold, 0.012 meV (1500 m/s), neutron beam Belgia (2012). The prompt  $\gamma$ -ray measurement assumed that the  $^{56}\text{Fe}$ ,  $^1\text{H}$ , and  $^{32}\text{S}$  cross sections all follow a  $1/v$  energy dependence when extrapolating to thermal energies. This assumption is consistent with the recommended Westcott g-factors  $g_W = 1.000$  Pritychenko and Mughabghab (2012) for all three cases. The  $^{56}\text{Fe}((n, \gamma)$  cross section has been measured by the TOF method Shcherbakov et al. (1977) from 0.012–0.25 eV and is plotted in Fig. 2. A weighted least-squares fit to these data gives  $g_W(^{56}\text{Fe}) = 1.049(6)$  and  $\sigma_0(^{56}\text{Fe})=2.556(14)$  b in agreement with the pile oscillator data. Assuming  $g_W=1.000$ , a fit to the same data gives  $\sigma_0(^{56}\text{Fe})=2.43(1)$  b, which is consistent with the prompt  $\gamma$ -ray data. This non- $1/v$  dependence likely is due to the presence of a  $J^\pi = 1/2^-$  resonance at 1 keV that likely strongly effects the cross section. The pile oscillator Fe cross section is validated by this analysis and is recommended here.

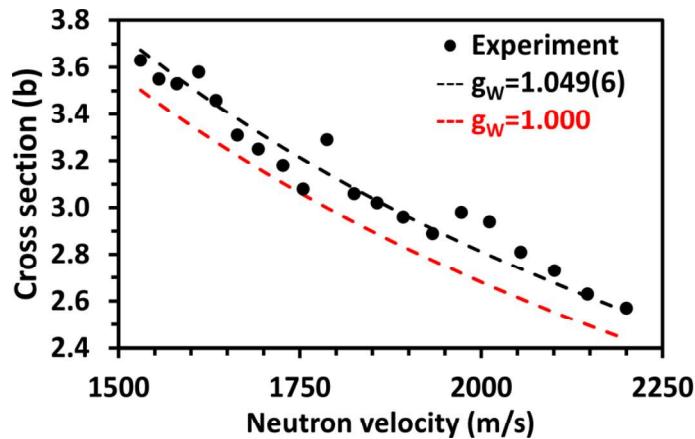


Figure 2: Westcott g-factor dependence of the  $^{56}\text{Fe}$  neutron cross section Shcherbakov et al. (1977).

### 3.2 Bromine

The four pile oscillator measurements of the Br elemental thermal neutron capture cross section are significantly larger than the recommended value,  $\sigma_0(Br)=6.39(13)$  b. The two largest pile oscillator measurements Colmer and Littler (1950); Harris et al. (1950) give  $\sigma_0(Br)=8.2(5)$  b and are rejected as outliers. The two smaller pile oscillator measurements Meadows and Whalen (1961); Pomerance (1951) give  $\sigma_0(Br)=6.84(6)$  which is still substantially larger than the recommended value. The primary contribution to the Br elemental cross section is the  $^{79}\text{Br}$  isotopic cross section which is based on the neutron activation and prompt  $\gamma$ -ray measurements summarized in Table 4. These measurements are based on the transition probability of the 616.7 keV  $\gamma$ -ray from  $^{80}\text{Br}$  decay. Although the weighted least-squares average isotopic cross section,  $\sigma_0(^{79}\text{Br})=7.968(15)$  b, is very precise, the emission probability of the 616.3 keV  $\gamma$ -ray is  $P_\gamma(616.7)=0.067(7)$  Singh (2005) with an uncertainty of 10%. This uncertainty was clearly neglected in the measurements. If the pile oscillator cross section is correct, then the  $^{80}\text{Br}$  decay scheme can be renormalized to give a consistent value,  $P_\gamma(616.7)=0.0734(16)$ , and the  $^{79}\text{Br}$  isotopic cross section becomes  $\sigma_0(^{79}\text{Br})=7.38(16)$  b. The pile oscillator cross section  $\sigma_0(Br)=6.39(13)$  b is recommended here.

Table 4:  $^{79}\text{Br}$  thermal neutron capture cross section measurements.

Reference	Value (b)	Reference	Value (b)
Seren et al. (1947)	8.1(1.6)	Firestone et al. (2007)	8.7(0.7)
Heft (1978)	7.88(0.12)	Keisch (1963)	7.9(0.5)
De Corte and Simonits (1988)	7.97(0.02)	Bacso et al. (1965)	8.1(0.3)
Szentmiklosi et al. (2006)	7.9(0.6)	Weighted Average	7.968(15)
Kennedy and St-Pierre (2003)	7.8(0.8)	Recommended <sup>1</sup>	7.88(24)

<sup>1</sup> Pritychenko and Mughabghab (2012)

### 3.3 Rubidium

A single pile oscillator measurement is available for Rb,  $\sigma_0(Rb)=0.71(7)$  b Pomerance (1951) that is discrepant from the recommended value of  $\sigma_0(Rb)=0.389(5)$  b. The experimental cross sections for  $^{85,87}\text{Rb}$  are given in Table 5. The more recent measurements for  $^{85}\text{Rb}$  and all measurements for  $^{87}\text{Rb}$  thermal neutron capture radiative cross sections are all consistent with the recommended values Mughabghab (2006). The elemental cross section for Rb,  $\sigma_0(Rb)=0.395(4)$  b, derived from the data in Table 5 is comparable to the recommended value and has been adopted here.

Table 5:  $^{85,87}\text{Rb}$  thermal neutron capture cross section measurements.

Reference	Value (b)	Reference	Value (b)
$^{85}\text{Rb}$ Seren et al. (1947)	0.72(14)	$^{87}\text{Rb}$ Seren et al. (1947)	0.122(24)
Keisch (1963)	0.45(2)	Heft (1978)	0.096(12)
Sims and Juhnke (1967)	0.396(5)	Farina Arbocco et al. (2013)	0.094(3)
Foglio Para and Mandelli Bettoni (1967)	0.405(4)	De Corte and Simonits (1988)	0.102(1)
Heft (1978)	0.519(11)	Szentmiklosi et al. (2006)	0.117(6)
Takiue and Ishikawa (1978)	0.488(10)	Kennedy and St-Pierre (2003)	0.108(7)
De Corte and Simonits (1988)	0.494(5)	Firestone et al. (2007)	0.1128(10)
Kafala et al. (1997)	0.480(17)	Weighted Ave	0.107(3)
Kennedy and St-Pierre (2003)	0.502(3)	Recommended <sup>2</sup>	0.116(6)
Firestone et al. (2007)	0.483(8)		
Farina Arbocco et al. (2013)	0.521(5)		
Weighted Ave <sup>1</sup>	0.502(5)		
Recommended <sup>2</sup>	0.494(7)		

<sup>1</sup>Average of measurements done since 1978.

<sup>2</sup>Pritychenko and Mughabghab (2012)

### 3.4 Ruthenium

The recommended elemental cross section  $\sigma_0(Ru)=3.12(16)$  is discrepant from the pile oscillator value  $\sigma_0(Ru)=2.57(13)$  b of Pomerance (1951). A second pile oscillator measurement  $\sigma_0(Ru)=5.5(6)$  b Harris et al. (1950) is rejected as an outlier. The recommended value is based, in part, on the isotopic recommended cross section  $\sigma_0(^{99}Ru)=7.1(10)$  b. No such value was found in the literature so the origin of this value is unknown. The only literature value is  $\sigma_0(^{99}Ru)=4.4(10)$  b Halperin et al. (1965). Substituting this value into the calculation of the recommended cross section gives  $\sigma_0(Ru)=2.76(17)$  b which is in agreement with the pile oscillator value. A weighted average of the revised recommended value and the pile oscillator value,  $\sigma_0(Ru)=2.64(12)$  b, had been adopted.

### 3.5 Silver

The recommended isomeric cross section,  $\sigma_0(^{109}Ag^m)=0.33(8)$  b, was based on an early half-life measurement,  $t_{1/2}(^{110}Ag^m)=127(21)$  y Habbotte (1970). Recent half-life measurements give  $t_{1/2}(^{110}Ag^m)=418(15)$  y Schötzig et al. (1992),  $t_{1/2}(^{110}Ag^m)=438(9)$  y Schrader (2004), and  $t_{1/2}(^{110}Ag^m)=448(27)$  y Shugart et al. (2018) for a weighted average of  $t_{1/2}(^{110}Ag^m)=434(7)$  y. The recommended cross section is from Rao et al. (1978) and has been superseded by  $\sigma_0(^{109}Ag^m)=0.366(63)$  b Ryves (1979) and  $\sigma_0(^{109}Ag^m)=0.477(33)$  b Gavrilas and Guinn (1987) which give the weighted average  $\sigma_0(^{109}Ag^m)=0.44(3)$  b. The cross measurements are proportional to the measured half-life so the increased half-life gives a revised cross section of  $\sigma_0(^{109}Ag^m)=1.50(3)$  b increasing the recommended Ag elemental cross section to  $\sigma_0(Ag)=63.9(8)$  b, in excellent agreement with the pile oscillator value,  $\sigma_0(Ag)=63.7(6)$  b.

### 3.6 Gadolinium

The  $^{155,157}\text{Gd}$  isotopic thermal neutron capture cross sections are large and strongly influenced by very low lying resonances. Two sets of pile oscillator thermal neutron capture cross section measurements giving  $\sigma_0(Gd)=33200(1300)$  b and  $\sigma_0(Gd)=46600(300)$  b respectively, both lower than the recommended value  $\sigma_0(Gd)=71500(1600)$  b. The pile oscillator values cannot be reconciled with the recommended value which is adopted here.

### 3.7 Terbium

The pile oscillator Tb elemental thermal neutron capture cross section,  $\sigma_0(Tb)=46(5)$  b Pomerance (1951), is twice the recommended value,  $\sigma_0(Tb)=23.4(4)$  b Pritychenko and Mughabghab (2012). Experimental activation analysis values from the literature are listed in Table 6. All measurements are consistent with the recommended value. The weighted average cross section  $\sigma_0(Tb)=23.51(13)$  b is adopted here.

Table 6:  $^{159}\text{Tb}$  thermal neutron capture cross section measurements.

Reference	Value (b)	Reference	Value (b)
Alstad et al. (1967)	22(2)	Kennedy and St-Pierre (2003)	24.0(11)
Ryves and Zieba (1974)	23.2(5)	Rajput et al. (2003)	23.6(4)
Heft (1978)	22.4(4)	Farina Arbocco et al. (2013)	23.9(2)
Takue and Ishikawa (1978)	22.8(4)	Weighted Average	23.51(13)
Kafala et al. (1997)	23.5(5)	Recommended <sup>1</sup>	23.4(4)
De Corte and Simonits (2003)	23.7(3)		

<sup>1</sup>Pritychenko and Mughabghab (2012)

### 3.8 Thulium

The pile oscillator measurement,  $\sigma_0(Tl)=123(6)$  b Pomerance (1951), is 17% larger than the recommended value,  $\sigma_0(Tl)=105(2)$  b Pomerance (1951). Ten activation measurements from the literature are summarized in Table 7 and agree well giving a weighted average value  $\sigma_0(Tl)=107.3(7)$  b. Sims and Juhnke (1970) have shown that the neutron spectrum must be corrected for a Westcott g-factor where the uncorrected data gave  $\sigma_0(Tl)=127(3)$  b, consistent with the pile oscillator value, while the corrected spectrum gave  $\sigma_0(Tl)=106(3)$  b. The  $^{170}\text{Tm}$  decay scheme normalization is accurate to 2.7% so adding this uncertainty to the statistical uncertainty in the weighted average the adopted cross section is  $\sigma_0(Tl)=107(3)$  b.

Table 7:  $^{169}\text{Tm}$  thermal neutron capture cross section measurements.

Reference	Value (b)	Reference	Value (b)
Seren et al. (1947)	106(21)	Takiue and Ishikawa (1978)	105(2)
Zimmerman et al. (1967)	106(3)	Dexing et al. (1984)	104.6(31)
Sims and Juhnke (1970)	106(3)	Koester and Knopf (1986)	100(2)
Alstad et al. (1972)	105(3)	Danon et al. (1998)	109.0(7)
Heft (1978)	106(5)	De Corte and Simonits (2003)	106.3(18)
Takiue and Ishikawa (1978)	105(2)	Farina Arbocco et al. (2014)	107(8)
Dexing et al. (1984)	104.6(31)	Weighed Average	107.3(7)
		Recommended <sup>1</sup>	105(2)

<sup>1</sup>Pritychenko and Mughabghab (2012)

Table 8:  $^{175,176}\text{Lu}$  thermal neutron capture cross section measurements.

	Abundance	Reference	Value (b)	Method
$^{175}\text{Lu}$	0.02599	Widder (1975)	25.8(9)	NTOF
		Baston et al. (1960)	23(3)	NTOF
	Weighted Average		25.6(9)	
		Recommended <sup>1</sup>	23.3(11)	
$^{176}\text{Lu}$	0.97401	Baston et al. (1960)	2100(150)	NTOF
		Albert and Schumann (1967)	2010(70)	Activation
		Young (1970)	2129(60)	NTOF
		Widder (1975)	2312(94)	NTOF
		De Corte and Simonits (2003)	2190(30)	Activation
		Firestone et al. (2007)	2119(42)	Prompt Gamma
		Roig et al. (2016)	1912(132)	NTOF
		Weighted Average	2148(21)	
		Recommended <sup>1</sup>	2020(70)	
Lu		Elemental Cross Section	80.7(10)	

<sup>1</sup>Pritychenko and Mughabghab (2012)

### 3.9 Lutetium

All three pile oscillator measurements of the Lu elemental thermal neutron capture cross section  $\sigma_0(\text{Lu})=89.8(11)$  b Sokolowski et al. (1964),  $\sigma_0(\text{Lu})=112(5)$  b Russell et al. (1962), and  $\sigma_0(\text{Lu})=113(6)$  Pomerance (1951) are significantly larger than the recommended value,  $\sigma_0(\text{Lu})=75.2(21)$  b. The experimental data for the  $^{175,176}\text{Lu}$  isotopic thermal neutron capture cross sections are shown in Fig. 8. Both isotopic cross sections were measured by a variety of methods leading to very consistent values. The large Westcott g-factor,  $g_W=1.76$  Pritychenko and Mughabghab (2012), likely explains why the pile oscillator values are discrepant. The weighted aveage elemental cross section,  $\sigma_0(\text{Lu})=80.7(10)$  b, is 7% larger than the recommended value and has been adopted here.

### 3.10 Osmium

The pile oscillator measurement of the thermal neutron capture cross section,  $\sigma_0(\text{Os})=15.4(8)$  b Pomerance (1951), is discrepant from the recommended value  $\sigma_0(\text{Os})=17.6(7)$  b. The experimental Os isotopic cross sections and abundances are shown in Table 9. The abundance of  $^{184}\text{Os}$  is often cited as 0.02(1)% however the more precise value, 0.0197% Völkening et al. (1991), is adopted here. The recommended  $^{186-189}\text{Os}$  cross sections all come from a single NTOF reference Vertebnyi et al. (1975). Inspection of this reference indicates that these values included elastic scattering and were extrapolated from higher energies by a  $1/v$  approximation. More recent and much lower values are available from the Evaluated Gamma-ray Activation File Firestone et al. (2007). Substituting these values for the determination of the elemental cross sections gives  $\sigma_0(\text{Os})=13.9(4)$  b which is in better agreement with the pile

Table 9: Os isotopic thermal neutron capture cross section measurements.

	Abundance	Reference	Value (b)
<sup>184</sup> Os	0.000197 <sup>1</sup>	Nabro et al. (1958)	4400(630) <sup>2</sup>
		Krane (2012)	3480(150)
		Firestone et al. (2007)	4410(60)
		Kim and Adams (1968)	3470(140)
		De Corte and Simonits (2003)	3752(56)
		Weighted average	3979(38)
		Recommended <sup>3</sup>	3000(150)
<sup>186</sup> Os	0.0159	Vertebnyi et al. (1975)	80(13)
		Firestone et al. (2007)	16.4(16)
		Recommended <sup>3</sup>	80(13)
<sup>187</sup> Os	0.0196	Vertebnyi et al. (1975)	320(10)
		Firestone et al. (2007)	169(3)
		Recommended <sup>3</sup>	320(10)
<sup>188</sup> Os	0.1324	Vertebnyi et al. (1975)	5
		Firestone et al. (2007)	5.5(11)
		Recommended <sup>3</sup>	5.5(11)
<sup>189</sup> Os	0.1615	Vertebnyi et al. (1975)	61(16)
		Firestone et al. (2007)	26.1(5)
		Recommended <sup>3</sup>	25(4)
<sup>190</sup> Os <sup>g</sup>	0.2626	Krane (2012)	1.93(10) <sup>4</sup>
		Nabro et al. (1958)	5.3(20)
		De Corte and Simonits (2003)	3.48(6)
		Mangal and Gill (1963)	3.9(8)
		Firestone et al. (2007)	>3
		Weighted average	3.48(6)
		Recommended <sup>3</sup>	3.9(1)
<sup>190</sup> Os <sup>m</sup>		Krane (2012)	9.0(5)
		Mangal and Gill (1963)	8.6(15)
		Seren et al. (1947)	8.3(17)
		Butler et al. (1983)	8(2)
		Weighted average	8.9(4)
		Recommended <sup>3</sup>	9.2(7)
<sup>190</sup> Os <sup>g+m</sup>	0.2626	Vertebnyi et al. (1975)	16(5)
		Gijbels et al. (1970)	13.4(6)
		Kim and Adams (1968)	13.2(3)
		Recommended sum	12.4(4)
		Weighted average	13.0(2)
		Recommended <sup>3</sup>	13.1(3)
<sup>192</sup> Os	0.4078	Krane (2012)	3.19(0.16)
		De Corte and Simonits (2003)	3.17(4)
		Firestone et al. (2007)	3.10(5)
		Seren et al. (1947)	1.6(3)
		Nabro et al. (1958)	1.6(4)
		Kim and Adams (1968)	2.0(1)
		Vertebnyi et al. (1975)	11(5)
		Weighted average	3.14(3)
		Recommended <sup>3</sup>	3.12(16)
Os		Elemental	13.9(4)
		Pile	15.4(8)
		Weighted average	14.2(4)

<sup>1</sup> Völkening et al. (1991), <sup>2</sup> Renormalized,  $\sigma_0(^{184}\text{Os})/\sigma_0(^{192}\text{Os})=1400(200)$ <sup>3</sup> Pritychenko and Mughabghab (2012), <sup>4</sup> Value not included in weighted average.

oscillator value. The weighted average of the pile oscillator and revised recommended value,  $\sigma_0(Os)=14.2(4)$  b, is adopted here.

### 3.11 Einsteinium

The pile oscillator thermal neutron capture cross sections measured for  $^{243}\text{Am}$ ,  $^{249}\text{Bk}$ , and  $^{249,252,254}\text{Cf}$  Harvey et al. (1954) all are consistent with the recommended values Pritychenko and Mughabghab (2012) although they were renormalized by the large factor of 0.67. The renormalized pile oscillator  $^{253}\text{Es}$  value,  $\sigma_0(^{253}\text{Es})=108(4)$  b, is inconsistent with the ENDF/B recommended value,  $\sigma_0(^{253}\text{Es})=183.9$  b. Two consistent measurements,  $\sigma_0(^{253}\text{Es})=155(20)$  b Harbour and MacMurdo (1973) and  $\sigma_0(^{253}\text{Es})=178(15)$  b Halperin et al. (1984), are consistent with the recommended value and agree with the original, unrenormalized pile oscillator measurement,  $\sigma_0(^{253}\text{Es})=160$  b. The weighted average of the two measurements,  $\sigma_0(^{253}\text{Es})=170(12)$  b, is adopted here.

The pile oscillator thermal neutron capture cross section for  $^{254}\text{Es}$ ,  $\sigma_0(^{254}\text{Es})<10$  b, is inconsistent with the recommended value,  $\sigma_0(^{253}\text{Es})=28.3(25)$  b, based on the measurement by Halperin et al. (1985). As no other measurements are available the recommended value is retained here.

## 4 Conclusions

There is remarkable agreement between the renormalized pile oscillator elemental thermal neutron capture data and the recommended cross section data Pritychenko and Mughabghab (2012). The precision of these data makes them useful both as a stand alone database or, as averaged with the recommended values, as a comprehensive database of elemental cross sections. Unfortunately the recommended values are not well undocumented. A more completely documented evaluation of isotopic thermal neutron capture cross sections with a clearer methodology would greatly improve the reliability of both the elemental and isotopic cross section databases.

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