

# Comparison of IUPAC $k_0$ values and neutron cross sections to determine a self-consistent set of data for neutron activation analysis

By R. B. Firestone<sup>1,\*</sup> and Zs. Revay<sup>2</sup>

<sup>1</sup> Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

<sup>2</sup> Institute of Isotope and Surface Chemistry, 1525 Budapest, Hungary

(Received December 1, 2009; accepted in revised form November 11, 2010)

*Cross section /  $k_0$  factor /  $P_\gamma$   $\gamma$ -ray emission probability /  
Statistical model / Neutron beam /  
Neutron activation analysis*

**Summary.** Independent databases of nuclear constants for Neutron Activation Analysis (NAA) have been independently maintained by the physics and chemistry communities for many years. They contain thermal neutron cross sections  $\sigma_0$ , standardization values  $k_0$ , and transition probabilities  $P_\gamma$ . Chemistry databases tend to rely upon direct measurements of the nuclear constants  $k_0$  and  $P_\gamma$  which are often published in chemistry journals while the physics databases typically include evaluated  $\sigma_0$  and  $P_\gamma$  data from a variety of experiments published mainly in physics journals. The IAEA/LBNL Evaluated Gamma-ray Activation File (EGAF) also contains prompt and delayed  $\gamma$ -ray cross sections  $\sigma_\gamma$  from Prompt Gamma-ray Activation Analysis (PGAA) measurements that can also be used to determine  $k_0$  and  $\sigma_0$  values. As a result several independent databases of fundamental constants for NAA have evolved containing slightly different and sometimes discrepant results. An IAEA CRP for a *Reference Database for Neutron Activation Analysis* was established to compare these databases and investigate the possibility of producing a self-consistent set of  $\sigma_0$ ,  $k_0$ ,  $\sigma_\gamma$ , and  $P_\gamma$  values for NAA and other applications. Preliminary results of this IAEA CRP comparison are given in this paper.

## 1. Introduction

Several sources of nuclear data are available for Neutron Activation Analysis (NAA). The chemistry community has largely adopted the  $k_0$  standardization method for NAA. A comprehensive database of  $k_0$  values has been adopted by the International Union of Pure and Applied Chemistry [1] that is based primarily on the measurements of De Corte and Simonits [2]. These  $k_0$  values can also be derived from total radiative thermal neutron cross sections  $\sigma_0$  that were evaluated by S. Mughabghab [3] and the  $P_\gamma$  transition probabilities that are available from two main sources, ENSDF [4] and the *Table of Radionuclides* [5]. In addition, prompt and delayed  $\gamma$ -ray cross sections  $\sigma_\gamma$  were measured with guided neutron beams at the Budapest Reactor [6], evaluated as part

of an IAEA Coordinated Research Project [7], and published in the Evaluated Gamma-ray Activation File (EGAF) [8].

The varying sources of  $k_0$ ,  $\sigma_0$ ,  $\sigma_\gamma$ , and  $P_\gamma$  data contain inconsistent and sometimes discrepant values. This problem was recognized by the IAEA which organized a Coordinated Research Project (CRP) on a Reference Database for Neutron Activation Analysis [9, 10]. A preliminary comparison of the NAA data for all activation products has been completed and some typical examples of discrepant data are discussed in this paper. The complete and self-consistent database of  $k_0$ ,  $\sigma_0$ ,  $\sigma_\gamma$ , and  $P_\gamma$  data is being developed by these authors for inclusion in the next version of the EGAF database and dissemination to the user community.

## 2. The $k_0$ standardization method

Neutron Activation Analysis (NAA) for the determination of elemental concentrations was traditionally standardized by either absolute or comparator modes [11, 12]. The absolute method suffers from the inaccuracy of nuclear data for activation and decay and the single-comparator method is dependent on local irradiation and counting conditions. The  $k_0$  standardization method was developed by Simonits and De Corte [13] to determine elemental concentration using  $k_0$  factors that are experimentally determined composite nuclear constants.

The concentration  $Q_x$  of an analyte  $x$  is measured by the  $k_0$  standardization method as shown in the following equation.

$$Q_x = \frac{(N_p/Wt_m\text{SDC})_x}{(N_p/wt_m\text{SDC})_{\text{Au}}} \times \frac{1}{k_{0,\text{Au}}(x)} \times \frac{f + Q_{0,\text{Au}}(\alpha) \varepsilon_{p,\text{Au}}}{f + Q_{0,x}(\alpha) \varepsilon_{p,x}} \quad (1)$$

Here Au is the co-irradiated gold monitor ( $E_\gamma = 411.8$  keV),  $N_p$  is the number of counts in the  $\gamma$ -ray peak,  $W$  is the weight of the sample,  $w$  is the weight of the gold monitor, and  $t_m$  is the counting time.  $S = 1 - \exp(-\lambda t_{\text{irr}})$  where  $\lambda$  is the decay constant and  $t_{\text{irr}}$  is the irradiation time.  $D = \exp(-\lambda t_d)$  where  $t_d$  is the decay time,  $C = [1 - \exp(-\lambda t_m)]/\lambda t_m$ ,  $f$  is the thermal to epithermal neutron flux ratio, and  $Q_0 = I_0/\sigma_0$  where  $I_0$  is the resonance integral and  $\sigma_0$  is the 2200  $\text{ms}^{-1}$  neutron cross section. The epithermal neutron flux distribution is approximated by  $1/E^{1+\alpha}$  assumption.

\* Author for correspondence (E-mail: rbfirestone@lbl.gov).

ing the cross section varies as  $1/v$ , and  $\varepsilon_p$  is the full-energy peak detection efficiency.

The  $k_{0,\text{Au}}(x)$  factor is defined in the following equation.

$$k_{0,\text{Au}}(x) = \frac{M_{\text{Au}}\theta_x\sigma_{0,x}P_{\gamma_x}}{M_x\theta_{\text{Au}}\sigma_{0,\text{Au}}P_{\gamma_{\text{Au}}}} \quad (2)$$

Here  $M$  is the atomic weight,  $\theta$  is the isotopic abundance, and  $P_\gamma$  is the emission probability. The gold monitor can be replaced by another monitor  $m$  in which case

$$k_{0,m}(x) = \frac{k_{0,\text{Au}}(x)}{k_{0,\text{Au}}(m)} \quad (3)$$

If the cross section in the thermal neutron energy region deviates from  $1/v$ , then  $f + Q_{0,\text{Au}}(\alpha)\varepsilon_{p,\text{Au}}/f + Q_{0,x}(\alpha)\varepsilon_{p,x}$  in Eq. (1) should be replaced by

$$\frac{g_{\text{Au}}(T_n) + r(\alpha)\sqrt{T_n/T_0} \times s_{0,\text{Au}}(\alpha)}{g_x(T_n) + r(\alpha)\sqrt{T_n/T_0} \times s_{0,x}(\alpha)} \quad (4)$$

where  $g(T_n)$  is the Westcott  $g$ -factor which depends on Maxwellian neutron temperature  $T_n$  and measures the deviation from  $1/v$  cross section dependence. The spectral index is  $r(\alpha)\sqrt{T_n/T_0}$  where  $T_0 = 293.6$  K and  $s_0(\alpha)$  modifies the  $1/E^{1+\alpha}$  epithermal neutron cross section distribution. If the cross section follows a  $1/v$  dependence then

$$s_0 = \frac{2}{\sqrt{\pi}}Q_0 - 0.484 \quad (5)$$

The conversion of  $Q_0$  to  $Q_0(\alpha)$  and  $s_0$  to  $s_0(\alpha)$  is given by

$$Q_0(\alpha) = \left[ \frac{Q_0 - 0.429}{(\bar{E}_r)^\alpha} + \frac{0.429}{(2\alpha + 1)(E_{\text{Cd}}^\alpha)} \right] (1 \text{ eV})^\alpha \quad (6)$$

and

$$s_0(\alpha) = s(\bar{E}_r)^{-\alpha} (1 \text{ eV})^\alpha \quad (7)$$

where  $E_{\text{Cd}} = 0.55$  eV is the cadmium cut-off energy and  $\bar{E}_r$  is the effective resonance energy defined by Ryves [14]. The  $(1 \text{ eV})^\alpha \equiv 1.0$  term is from the definition of the epithermal neutron flux distribution [15, 16].

### 3. Data sources

The relationship between the nuclear constants  $k_0$ ,  $\sigma_0$ , and  $P_\gamma$  is shown in Eq. (2). The quantity  $\sigma_\gamma$  is defined simply as  $\sigma_\gamma = P_\gamma\sigma_0$ . Values for these constants can be obtained from various, partially independent nuclear databases. The goal of this project is to evaluate a unified, self-consistent set of nuclear constants from all sources.

#### 3.1 Total radiative thermal neutron cross sections $\sigma_0$ and $k_0$ values

The IUPAC  $k_0$  database [1] is derived primarily from the direct experimental measurements of De Corte and Simonits [2] without consideration of other relevant nuclear decay data. These values were precisely measured although their uncertainties appear to reflect mainly statistical error. The De Corte and Simonits measurements are sometimes

used in Mughabghab's evaluation of total radiative neutron cross sections, published in the *Atlas of Neutron Resonances* [3] which is largely based on measurements compiled in the CSISRS library [17]. Many of those measurements are from unpublished private communications or difficult to obtain reports. The CSISRS coverage of cross sections published in physics and engineering journals is very good although cross sections published in chemistry journals or measured by the  $k_0$  method are often missed. Significant improvement in the  $\sigma_0$  data can be expected from an inter-comparison of data from the Atlas, the IUPAC  $k_0$  database, and other sources of data.

#### 3.2 Gamma-ray transition probabilities $P_\gamma$

$P_\gamma$  data are available for all radionuclides in ENSDF [4]. This file is generally organized to display data representative of each experiment for the purpose of adopting nuclear level properties. The decay data in ENSDF do not necessarily represent the best decay information that could be obtained from all available sources. ENSDF transition probabilities  $P_\gamma$  are not given explicitly but must instead be calculated through a series of intensity normalizations, each with its own explicit uncertainty. There are no guidelines for calculating the  $\Delta P_\gamma$  uncertainty for individual  $\gamma$ -rays in ENSDF. Cut-off dates for the ENSDF evaluations are commonly more than 10 years old so the data may be out of date. Conversion coefficients, necessary for determining decay scheme normalizations, are calculated with older, less reliable methods in most ENSDF decay datasets.

$P_\gamma$  data are also available for a limited number of radionuclides of applied interest from the *Table of Radionuclides* [5] which is evaluated by the Decay Data Evaluation Project. These data are available in ENSDF format but they are still not widely adopted by ENSDF evaluators. The *Table of Radionuclides* is evaluated with stricter standards than ENSDF and is aimed at providing the best  $E_\gamma$ ,  $P_\gamma$  and  $t_{1/2}$  data from all sources without requiring ENSDF type normalizations for  $P_\gamma$ . The coverage of the *Table of Radionuclides* is limited to selected radionuclides and does not include the full range of radionuclides of interest for NAA.

#### 3.3 Budapest Reactor guided neutron beam measurements

Neutron capture  $\gamma$ -ray cross sections for elemental targets with  $Z = 1-83, 90, 92$ , except for He and Pm, have been measured at the 10 MW Budapest Reactor with a guided thermal neutron beam [18]. These data have been published in the Handbook of Prompt Gamma Activation Analysis [6]. The target station is located  $\approx 30$  m from the Reactor where both primary and secondary  $\gamma$ -rays can be measured in low background conditions. Neutrons enter the evacuated target holder and continue to the beam stop at the rear wall of the guide hall. The thermal-equivalent neutron flux was  $2 \times 10^6$  n cm<sup>2</sup> s<sup>-1</sup>.

Prompt gamma-rays from the target were measured with an n-type high-purity, 25% efficient, germanium (HPGe) detector with closed-end coaxial geometry located 23.5 cm from the target. The detector is Compton-suppressed by a BGO-scintillator guard detector annulus surrounded by

10-cm thick lead shielding. Counting efficiency was calibrated from 50 keV to 10 MeV with radioactive sources and ( $n, \gamma$ ) reaction gamma rays to a precision of better than 1% from 500 keV to 6 MeV and better than 3% at all energies [19].

Thermal neutron  $\gamma$ -ray cross sections were determined using either stoichiometric compounds or accurately prepared mixtures containing the standard elements H, N, or Cl whose  $\gamma$ -ray cross sections are precisely known [20]. The  $\gamma$ -ray cross sections for nuclides of interest were then accurately determined from their intensity ratios to the standard  $\gamma$ -ray transition intensities of the comparators. These measurements are independent of target composition or neutron flux. The neutron beam used in these measurements is a pure thermal beam so the measured  $\gamma$ -ray cross sections do not need to be corrected for epithermal contributions.

### 3.4 Budapest Reactor $\sigma_0$ measurements

Numerous  $\sigma_0$  measurements discussed in this paper were measured at the Budapest Reactor. Gamma-ray cross sections  $\sigma_\gamma$  for the decay of short-lived activation products were observed together with the prompt  $\gamma$ -rays in the Budapest Reactor experiments. These  $\sigma_\gamma$  measurements, corrected for saturation when half-lives are long with respect to the measurement time, can be used with either  $P_\gamma$  data from ENSDF or the *Table of Radionuclides* to determine  $\sigma_0$  or with  $\sigma_0$  data from the Atlas to determine  $P_\gamma$ .

Prompt  $\sigma_\gamma$  data for low- $Z$  nuclides can also be used to determine  $\sigma_0$  when the decay scheme is complete. In these cases  $\sigma_0 = \Sigma\sigma_\gamma(\text{Ground State}) = \Sigma\sigma_\gamma(\text{Primary } \gamma\text{-rays})$ . The Budapest Reactor guided neutron beam measurements are the only comprehensive source of experimental  $\sigma_\gamma$  data. Many other precise measurements of the relative neutron capture  $I_\gamma$  intensities, sometimes normalized to per 100 neutron captures, have also been measured. In many cases the Budapest isotopic data, measured on natural elemental targets, is incomplete because of either low isotopic abundance or low cross section. The Budapest  $\sigma_\gamma$  data can be used to renormalize the  $I_\gamma$  data from the other experiments to get a more complete set of  $\sigma_\gamma$  data.

For heavy nuclides ( $Z \geq 20$ ) the prompt neutron capture  $\gamma$ -ray decay spectra generally are too complex to resolve a large continuum of weak transitions. In these cases only strong transitions deexciting lower lying levels and intense primary  $\gamma$ -rays are resolved. In order to measure  $\sigma_0$  it is necessary to determine the statistical contribution to the level scheme. This has been done with the statistical mode code DICEBOX [21] which calculates simulated level schemes for the higher levels above a cut-off energy  $E_{\text{crit}}$  and uses experimental level/gamma properties for levels below  $E_{\text{crit}}$  and measured primary  $\gamma$ -ray cross sections feeding levels below  $E_{\text{crit}}$ . A variety of level density functions and  $\gamma$ -ray strengths are supported by DICEBOX to produce the simulated level schemes which can be regenerated many times to determine the statistical fluctuations in the theory. The DICEBOX calculations are normalized to experiment by comparing the calculated feeding to levels below  $E_{\text{crit}}$  with the experimental cross section depopulating those levels. A discussion of the use of DICEBOX calculation to determine  $\sigma_0$  has been given by Krticka *et al.* [22].

## 4. Selected discrepant $\sigma_0/k_0/P_\gamma$ values

The majority of data from the different data sources have only minor variations, however in some cases the data are discrepant and must be reconciled by evaluation and/or further measurements. Several interesting examples follow.

### 4.1 $^{12}\text{C}(n, \gamma)^{13}\text{C}$ and $^2\text{H}(n, \gamma)^3\text{H}$

The simple  $^{12}\text{C}(n, \gamma)^{13}\text{C}$  decay scheme, measured at the Budapest Reactor, is shown in Fig. 1. The cross section  $\sigma_0(^{12}\text{C}) = 3.90 \pm 0.06$  mb determined from these complete decay scheme data is compared with previous measurements in Table 1. The new value is inconsistent with the Atlas [3] adopted value, which was based on the 1982 measurement by Journey *et al.* [23], but consistent with five other values. The average of the six consistent cross section measurements in Table 2 is  $\sigma_0(^{12}\text{C}) = 3.84 \pm 0.06$  mb.

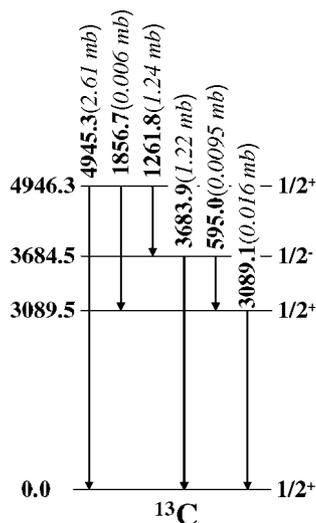
Journey *et al.* [23] also used their  $\sigma_0(^{12}\text{C})$  value in the same paper to determine the  $^2\text{H}(n, \gamma)$  cross section. The new  $^{12}\text{C}$  cross section suggests that Journey *et al.*'s value should be increased to  $552 \pm 16$  mb which is consistent with four other previous measurements. We propose an adopted cross section  $\sigma_0(^2\text{H}) = 549 \pm 10$  mb, based on the average of comparable values. This new value needs to be confirmed by future experiments.

### 4.2 $^{23}\text{Na}(n, \gamma)^{24}\text{Na}$

The  $^{23}\text{Na}(n, \gamma)^{24}\text{Na}$  decay scheme is shown in Fig. 2 where the activation  $\sigma_\gamma$  cross sections measured at the Budapest Reactor for the production of the 1368.6- and 2754.0-keV  $\gamma$ -rays ( $P_\gamma = 1.0$ ) are shown. The average activation cross

**Table 1.** Comparison of  $^{12}\text{C}(n, \gamma)$  cross section measurements. The new value measured at the Budapest Reactor is inconsistent with the Journey *et al.* [23] value. Journey *et al.* standardized their measurement of the  $^2\text{H}(n, \gamma)$  cross section with their  $^{12}\text{C}$  value indicating that this value, should be increased to correspond to the Budapest Reactor measurement.

$^{12}\text{C}$	Author (year)	$\sigma_0 \pm \Delta\sigma$ (mb)	$^2\text{H}$	Author (year)	$\sigma_0 \pm \Delta\sigma$ (mb)
	Prestwich (1981)	$3.50 \pm 0.16$		Trail (1964)	$0.36 \pm 0.03$
	Journey (1982)	$3.53 \pm 0.07$		Alfimenkov (1980)	$0.476 \pm 0.020$
	Nichols (1960)	$3.57 \pm 0.03$		Journey (1982)	$0.508 \pm 0.015$
	Sagot (1963)	$3.72 \pm 0.15$		Merritt (1968)	$0.521 \pm 0.009$
	Journey (1963)	$3.8 \pm 0.4$		Silk (1969)	$0.523 \pm 0.029$
	Starr (1962)	$3.83 \pm 0.06$		Ishikawa (1973)	$0.55 \pm 0.01$
	Hennig (1967)	$3.85 \pm 0.15$		Kaplan (1952)	$0.57 \pm 0.01$
	Matsue (2004)	$3.81 \pm 0.11$		Journey (1963)	$0.60 \pm 0.05$
	Budapest (2007)	$3.90 \pm 0.06$		Sargent (1947)	$0.92 \pm 0.22$
	Atlas	$3.53 \pm 0.07$		Atlas	$0.508 \pm 0.015$
	Adopted	$3.84 \pm 0.06$		Adopted	$0.549 \pm 0.010$



**Fig. 1.** Complete neutron Capture decay scheme for  $^{12}\text{C}(n, \gamma)^{13}\text{C}$  measured with the thermal neutron beam at the Budapest Reactor.

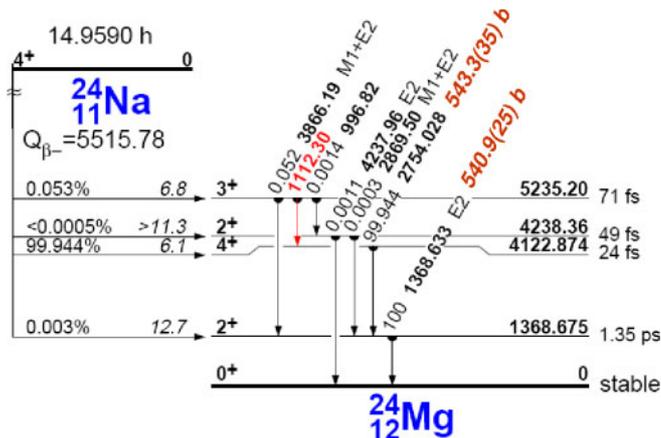
**Table 2.** Comparison of  $^{23}\text{Na}(n, \gamma)$  cross section measurements. The new EGAF [8] value is higher than the Atlas [3] value but consistent with other high values.

$^{23}\text{Na}$	Author (year)	$\sigma_0 \pm \Delta\sigma$ (mb)
	Coltman (1946)	$470 \pm 40$
	Pomerance (1951)	$470 \pm 24$
	Meadows (1961)	$470 \pm 60$
	Brooksbank (1955)	$500 \pm 50$
	Koehler (1963)	$500 \pm 20$
	Yamamuro (1970)	$500 \pm 30$
	Harris (1953)	$503 \pm 5$
	Grimeland (1955)	$510 \pm 30$
	De Corte (2003)	$513 \pm 6$
	Kennedy (2003)	$515 \pm 21$
	Heft (1978)	$523 \pm 5$
	Ryves (1970)	$527 \pm 5$
	Szentmiklosi (2006)	$527 \pm 8$
	Bartholomew (1953)	$530 \pm 32$
	Wolf (1960)	$531 \pm 8$
	Cocking (1958)	$536 \pm 6$
	Jowitt (1959)	$536 \pm 8$
	Rose (1959)	$539 \pm 8$
	Budapest-PGAA	$540 \pm 4$
	Budapest-NAA	$542 \pm 3$
	Gleason (1975)	$540 \pm 20$
	Kaminishi (1963)	$577 \pm 8$
	Seren (1947)	$630 \pm 130$
	Atlas	$517 \pm 4$
	Adopted	$541 \pm 4$

section from these measurements  $\sigma_0(^{23}\text{Na}) = 542 \pm 3$  mb is compared with previous measurements in Table 2. This new value is higher than the adopted value  $\sigma_0(^{23}\text{Na}) = 517 \pm 4$  mb from the Atlas [3] but it is comparable to several other measurements.

#### 4.3 $^{30}\text{Si}(n, \gamma)^{31}\text{Si}$

The cross section  $\sigma_0(^{30}\text{Si}) = 107 \pm 2$  mb adopted in the Atlas [3] is consistent with the Budapest Reactor value of  $112 \pm 6$  mb. For  $k_0(1266.2\gamma) = 1.45 \pm 0.01 \times 10^{-7}$  from De Corte and Simonits [2],  $\sigma_\gamma = 0.0630 \pm 0.0004$  mb. The tran-



**Fig. 2.** Activation decay scheme for  $^{23}\text{Na}(n, \gamma)^{24}\text{Na}$  measured with the thermal neutron beam at the Budapest Reactor. These data were taken in beam and have been corrected for bombardment time.

sition probability  $P_\gamma(1266.2) = \sigma_\gamma/\sigma_0 = 5.89 \pm 0.12 \times 10^{-4}$  which is more precise than  $P_\gamma = 5.0 \pm 0.4 \times 10^{-4}$  measured by McGuire and Hossain [24].

#### 4.4 $^{36}\text{S}(n, \gamma)^{37}\text{S}$

The Atlas [3] cross section  $\sigma_0(^{36}\text{S}) = 236 \pm 6$  mb is inconsistent with  $\sigma_0(^{36}\text{S}) = 160 \pm 3$  mb derived from  $k_0(3103.1\gamma) = 1.96(4) \times 10^{-6}$  measured by De Corte. These  $\sigma_0/k_0$  values are the only information available for neutron activation analysis of sulfur. The Atlas value is based on two consistent measurements,  $\sigma_0(^{36}\text{S}) = 233 \pm 2$  mb by Raman *et al.* [25] and  $\sigma_0(^{36}\text{S}) = 249 \pm 14$  mb by Beer *et al.* [26]. Both measurements were with isotopically enriched targets. The problem with  $k_0(^{37}\text{S})$  is that the abundance of  $^{36}\text{S}$  is  $0.02 \pm 0.01\%$  and varies widely in the environment. We recommend  $k_0 = 3.05(10) \times 10^{-6}$  which is based upon the adopted  $\sigma_0$  value assuming an isotopic abundance  $\equiv 0.02\%$ . This value cannot be used for analytical purposes unless the isotopic abundance has first been measured.

#### 4.5 $^{37}\text{Cl}(n, \gamma)^{38}\text{Cl}$

The Atlas [3] cross section  $\sigma_0(^{37}\text{Cl}) = 433 \pm 6$  mb is consistent with the  $\sigma_0(^{37}\text{Cl}) = 436 \pm 8$  mb derived from the De Corte and Simonits [2]  $k_0$  values. From ENSDF [4] for  $^{37}\text{Cl}$  ( $t_{1/2} = 37.230 \pm 0.014$  m) decay,  $P_\gamma(1643.4) = 0.333 \pm 0.005$  and  $P_\gamma(2167.5) = 0.444 \pm 0.009$  based on the well-known  $\gamma$ -ray branching ratios and assuming a ground state  $\beta^-$  feeding of  $55.6 \pm 0.9\%$ . From the De Corte and Simonits  $k_0$  values we determine that  $P_\gamma(1643.4) = 0.319 \pm 0.006$  and  $P_\gamma(2167.5) = 0.430 \pm 0.008$  which are consistent with the  $\gamma$ -ray branching ratios and a ground state  $\beta^-$  feeding of  $57.2 \pm 0.8\%$ . This new ground state feeding is consistent with  $57.6 \pm 1.3\%$  measured by van Klinken *et al.* [27] but discrepant with  $55.2 \pm 0.6\%$  from Miyahara *et al.* [28].

#### 4.6 $^{39,40,41}\text{K}(n, \gamma)^{40,41,42}\text{K}$

Gamma-ray cross sections  $\sigma_\gamma$  for the three potassium nuclides were measured at the Budapest Reactor. These data can be used to renormalize the nearly complete neutron capture  $\gamma$ -ray intensities of Krusche *et al.* [29–31] to

**Table 3.** Comparison of cross section measurements for the potassium nuclides.

	Author (year)	$\sigma_0 \pm \Delta\sigma$ (b)
<sup>39</sup> K	Pomerance (1952)	1.87 ± 0.15
	Gillette (1966)	1.4
	Hansen (1949)	2.9 ± 0.7
	von Egidy (1984)*	2.206 ± 0.025
	Atlas Adopted	2.1 ± 0.2 2.21 ± 0.03
<sup>40</sup> K	Asghar (1978)	30
	Beckstrand (1971)	30 ± 8
	Pomerance (1952)	66 ± 20
	Gillette (1966)	70
	Krusche (1984)*	90 ± 3
	Atlas Adopted	30 ± 8 90 ± 3
<sup>41</sup> K	Seren (1947)	1.0 ± 0.2
	Pomerance (1952)	1.19 ± 0.10
	Koehler (1967)	1.2 ± 0.1
	Gryntakis (1976)	1.28 ± 0.06
	De Corte (2003)	1.42 ± 0.02
	Gleason (1975)	1.43 ± 0.03
	Heft (1978)	1.43 ± 0.03
	Lyon (1960)	1.45
	Ryves (1970)	1.46 ± 0.03
	Kappe (1966)	1.49 ± 0.03
	Kaminishi (1982)	1.57 ± 0.17
	Krusche (1985)*	1.523 ± 0.022
		Atlas Adopted

\* Data were normalized to the Budapest cross section measurements.

obtain  $\sigma_0$  for <sup>39,40,41</sup>K( $n, \gamma$ ). These results are summarized in Table 3 where they are compared with previous measurements. For <sup>39</sup>K( $n, \gamma$ ) the Budapest renormalized von Egidy [29] cross section  $\sigma_0(^{39}\text{K}) = 2.206 \pm 0.025$  b is more precise and consistent with the Atlas [3] value.

A new  $\sigma_0(^{40}\text{K}) = 90 \pm 3$  b value, based on the Budapest Reactor  $\sigma_\gamma(1293.6) = 35.3 \pm 1.8$  b which was used to renormalize the data of Krusche *et al.* [30] is 3 × the Atlas [3] value and consistent with the measurement of Pomerance [32].

The new  $\sigma_0(^{41}\text{K}) = 1.523 \pm 0.022$  b is based on the renormalization of Kappe [33] data and is consistent with measurements by Ryves [34] and Kaminishi [35] but higher than the value derived from the De Corte and Simonits [2] <sup>42</sup>K  $k_0$  values. This value is based on the measurement of prompt  $\gamma$ -rays while most lower values are based activation experiments suggesting that the difference may be due to a problem with the decay scheme  $\gamma$ -ray normalization.  $P_\gamma(1524.6) = 0.1808 \pm 0.0009$  was adopted in ENSDF and is significantly higher than  $P_\gamma(1524.6) = 0.173 \pm 0.003$  derived from the IUPAC  $k_0 = 9.46 \pm 0.06 \times 10^{-4}$  and  $\sigma_0 = 1.46 \pm 0.03$  b from the Atlas [3]. New activation experiments are in progress to remeasure the <sup>41</sup>K( $n, \gamma$ ) activation cross section.

#### 4.7 <sup>45</sup>Sc( $n, \gamma$ )<sup>46m</sup>Sc

The ratio of the isomer <sup>46m</sup>Sc ( $t_{1/2} = 18.75 \pm 0.04$  s) to ground state cross sections  $\sigma_0(^{46m}\text{Sc})/\sigma_0(^{46g}\text{Sc}) = 0.56 \pm$

0.04 was measured by Simons [36] in the thermal column of their reactor. The Atlas [3] has adopted  $\sigma_0(^{45m}\text{Sc}) = 9.9 \pm 1.1$  b assuming  $\sigma_0(^{45g}\text{Sc}) = 17.4 \pm 1.1$  b. A new, more precise measurement of  $\sigma_0(^{45m}\text{Sc}) = 7.77 \pm 0.21$  b at the Budapest Reactor has been published by Szentmiklosi *et al.* [37]. No  $k_0$  value exists for the 142.5-keV  $\gamma$ -ray from <sup>46m</sup>Sc decay in the IUPAC database [1] although this short-lived activity can give more rapid analytical results for Sc than  $\gamma$ -rays from <sup>46g</sup>Sc decay ( $t_{1/2} = 83.788 \pm 0.022$  d). We recommend the value  $k_0(142.5\gamma) = 0.226 \pm 0.005$ .

#### 4.8 <sup>70</sup>Zn( $n, \gamma$ )<sup>71g</sup>Zn

The cross section  $\sigma_0(^{70g}\text{Zn}) = 83 \pm 5$  mb was adopted in the Atlas [3] based mainly on the measurement of Mannhart and Vonach [38]. This value is supported by four other less precised measurements [39–42]. De Corte and Simonits [2] report  $k_0(511.6\gamma) = 1.55 \pm 0.3 \times 10^{-6}$  which gives  $\sigma_0(^{70g}\text{Zn}) = 22$  mb assuming  $P_\gamma(511.6) = 0.32$  from Zoller *et al.* [43] as adopted in ENSDF. An alternate decay scheme normalization by Thwaites and Pratt [40] is  $P_\gamma(511.6) = 0.13$  gives  $\sigma_0(^{70}\text{Zn}) = 63$  mb which is in better agreement with the Atlas value. Assuming the Atlas cross section is correct and adopting the De Corte and Simonits  $k_0$  value we get  $P_\gamma(511.6) = 0.085 \pm 0.005$ .

#### 4.9 <sup>74</sup>Ge( $n, \gamma$ )<sup>75m</sup>Ge

The cross section  $\sigma_0(^{74m}\text{Ge}) = 163 \pm 5$  mb in the Atlas [3] was adopted from EGAF data [8] but is inconsistent with  $\sigma_0(^{74m}\text{Ge}) = 138 \pm 1$  mb that has been derived from  $k_0(139.7\gamma) = 5.73 \pm 0.06 \times 10^{-4}$  measured by De Corte and Simonits [2]. The EGAF values is consistent with  $k_0 = 6.76 \pm 0.03 \times 10^{-4}$ . A new neutron activation measurement is necessary to confirm this new value.

#### 4.10 <sup>99</sup>Tc( $n, \gamma$ )<sup>100</sup>Tc

The cross section  $\sigma_0(^{99}\text{Tc}) = 22.8 \pm 1.3$  b was adopted in the Atlas [3]. A new value  $\sigma_0(^{99}\text{Tc}) = 24.2 \pm 0.2$  b can be derived from  $\sigma_\gamma(539.5) = 1.604 \pm 0.014$  b and  $\sigma_\gamma(590.8) = 1.296 \pm 0.011$  b from Budapest Reactor data, published by Molnar *et al.* [44], and an improved <sup>100</sup>Tc (15.46 ± 0.19 s) decay scheme normalization by Furutaka *et al.* [45]. No  $k_0$  values are given for <sup>100</sup>Tc in the IUPAC compilation [1] and we adopt  $k_0(539.5\gamma) = 0.0334 \pm 0.0003$  and  $k_0(590.8\gamma) = 0.0272 \pm 0.0007$  here.

#### 4.11 <sup>103</sup>Rh( $n, \gamma$ )<sup>104m+g</sup>Rh

The decay scheme for <sup>104m+g</sup>Rh is shown in Fig. 3. From ENSDF [8]  $P_\gamma(555.8) = 0.020 \pm 0.005$  is poorly known because of a large uncertainty in the excited state feeding intensity. De Corte and Simonits [2] have measured  $k_0(555.8\gamma) = 0.0692 \pm 0.0010$  for the combined isomer and ground state feeding which corresponds to  $\sigma_\gamma(555.8) = 3.41 \pm 0.05$  b. Assuming the adopted cross section  $\sigma_0(^{103m+g}\text{Rh}) = 143.5 \pm 1.5$  b from the Atlas [3] we get a more precise value  $P_\gamma(555.8) = 0.0238 \pm 0.0004$ .

Also give 4.28 ± 0.04% IT and 95.72 ± 0.04% EC decay branching intensities for <sup>114</sup>In<sup>m1</sup> which disagree with the ENSDF [8] branchings reported as 3.25 ± 0.24% IT and 96.75% 0.24 EC.

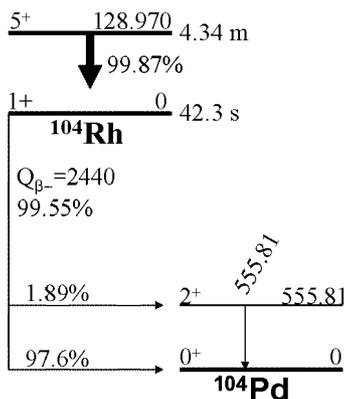


Fig. 3. Main features of the  $^{104m+g}\text{Rh}$  decay scheme.

### 4.12 $^{105}\text{Pd}(n, \gamma)^{106}\text{Pd}$

The prompt  $\gamma$ -ray decay scheme from  $^{105}\text{Pd}(n, \gamma)^{106}\text{Pd}$  is incomplete because of the contribution of unresolved continuum  $\gamma$ -rays. Statistical model calculations have been performed with the DICEBOX code to determine the missing statistical feeding to the ground state. The population/depopulation plot for  $^{105}\text{Pd}(n, \gamma)$  is shown in Fig. 4. The agreement between experiment and calculation is excellent. Krlicka *et al.* [22] determined the total radiative neutron capture cross sections  $\sigma_0$  in this way for all of the palladium isotopes using DICEBOX and the Budapest data and these results are summarized in Table 4.

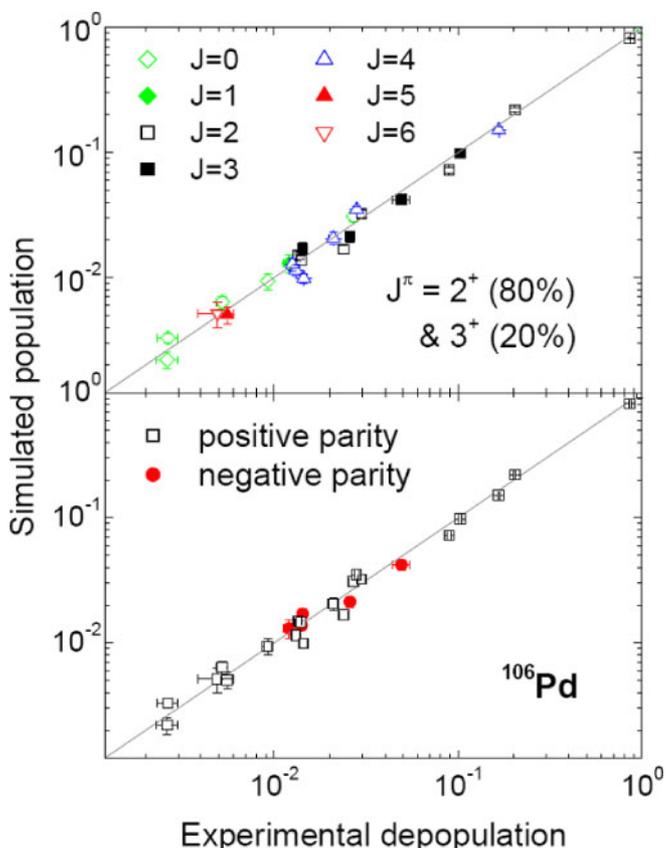


Fig. 4. Population/depopulation plot for  $^{105}\text{Pd}(n, \gamma)^{106}\text{Pd}$ . The spin distribution of the neutron capture state was determined by a least-squares minimization of the DICEBOX fit to the data.

Table 4. Palladium total radiative thermal neutron cross sections.

Isotope	$\sigma_0$ (literature) (barns)	$\sigma_0$ (this work) (barns)
$^{102}\text{Pd}$	$1.6 \pm 0.2$	$1.1 \pm 0.4$
$^{104}\text{Pd}$	$0.65 \pm 0.30$	$0.75 \pm 0.26$
$^{105}\text{Pd}$	$21.0 \pm 1.5$	$21.7 \pm 0.5$
$^{106}\text{Pd}$	$0.30 \pm 0.03$	$0.36 \pm 0.10$
$^{108}\text{Pd}$	$7.6 \pm 0.5$	$8.6 \pm 0.6^*$
$^{110}\text{Pd}$	$0.70 \pm 0.17$	$0.34 \pm 0.10$

\* Value from Ref. [22] has been revised here.

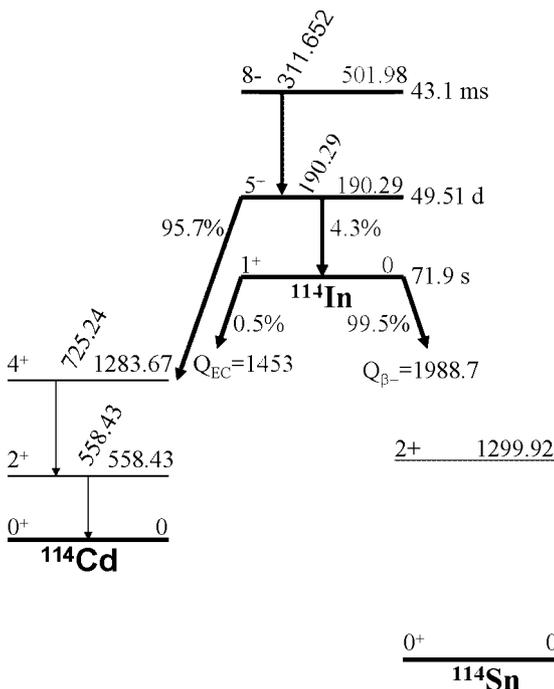


Fig. 5. Main features of the  $^{114m1}\text{In}$  decay scheme. The decay branches are from ENSDF [8].

### 4.13 $^{113}\text{In}(n, \gamma)^{114m1}\text{In}$

The decay scheme for  $^{114m1+m2}\text{In}$  is shown in Fig. 5. The  $^{114m1}\text{In}$  decay scheme consists of three  $\gamma$ -rays whose  $k_0$  values have been measured by De Corte and Simonits [2]. From these data, after correction for internal conversion, we get  $\sigma_{\gamma+e}(190.3) = 8.28 \pm 0.09$  b,  $\sigma_{\gamma+e}(558.4) = 0.368 \pm 0.003$  b, and  $\sigma_{\gamma+e}(725.2) = 0.372 \pm 0.002$  b. These data give  $\sigma_0(^{114m1+m2}\text{In}) = 8.65 \pm 0.09$  b which is more precise and in good agreement with  $\sigma_0(^{114m1+m2}\text{In}) = 8.1 \pm 0.8$  b from the Atlas [3].

The Budapest Reactor data give  $\sigma_0(^{114m2}\text{In}) = \sigma_{\gamma+e}(311.7) = 3.4 \pm 0.8$  b which is comparable to  $\sigma_0(^{114m2}\text{In}) = 3.1 \pm 0.7$  b that was adopted in the Atlas [2]. From this value and the data above we derive  $\sigma_0(^{114m1}\text{In}) = 5.5 \pm 0.7$  b.

### 4.14 $^{127}\text{I}(n, \gamma)^{128}\text{I}$

The cross section  $\sigma_0(^{127}\text{I}) = 6.15 \pm 6$  b adopted in the Atlas [3] is consistent with many precise measurements that don not involve neutron activation.  $P_\gamma(442.9) = 0.1261 \pm 0.0008$  was measured by Miyahara *et al.* [46], and  $\sigma_0(^{127}\text{I}) = 5.39 \pm 0.06$  b assuming the  $k_0$  data of De Corte and Simonits [2] or  $\sigma_0(^{127}\text{I}) = 5.63 \pm 0.08$  b assuming the  $\sigma_\gamma$

data of Szentmiklosi *et al.* [37]. For an average value  $\sigma_0(^{127}\text{I}) = 5.48 \pm 0.12$  b from the two activation measurements,  $P_\gamma(442.9) = 0.112 \pm 0.003$  which is in substantial disagreement with the Miyahara *et al.* measurement.

#### 4.15 $^{151}\text{Eu}(n, \gamma)^{152g}\text{Eu}$

The cross section  $\sigma_0(^{151}\text{Eu}) = 5900 \pm 200$  b was adopted in the Atlas [3] based largely on the data of Gryntakis [47]. De Corte and Simonits data [2]  $k_0$  data give  $\sigma_0(^{151}\text{Eu}) = 6885 \pm 15$  b which is consistent with Budapest Reactor data that give  $\sigma_0(^{151}\text{Eu}) = 6750 \pm 170$  b. We recommend a new adopted value of  $\sigma_0(^{151}\text{Eu}) = 6880 \pm 100$  b.

#### 4.16 $^{181}\text{Ta}(n, \gamma)^{182}\text{Ta}$

The cross section  $\sigma_0(^{181}\text{Ta}) = 20.5 \pm 0.5$  b was adopted in the Atlas [3] based on numerous consistent measurements. This cross section is also consistent with the  $k_0$  measurements from De Corte and Simonits [2] for  $E_\gamma \geq 152.4$  keV but inconsistent with two lower energy  $\gamma$ -rays from  $^{182}\text{Ta}$  ( $t_{1/2} = 114.43 \pm 0.03$  d). The transition probabilities for these two  $\gamma$ -ray are well established in the *Table of Radionuclides* and we adopt  $k_0(67.8\gamma) = 0.0975 \pm 0.0028$  and  $k_0(100.1\gamma) = 0.0334 \pm 0.0008$  based on the adopted  $P_\gamma$  and  $\sigma_0$  values.

#### 4.17 $^{186}\text{W}(n, \gamma)^{186}\text{W}$

The cross section  $\sigma_0(^{186}\text{W}) = 38.1 \pm 0.5$  b was adopted in the Atlas [3] based on the measurements reported in Table 5. Significant variation exists in these measurements. The precise  $\sigma_0$  values in Table 4 measured by Beitins *et al.* [48],

**Table 5.** Comparison of  $^{186}\text{W}(n, \gamma)$  cross section measurements.

$^{186}\text{W}$	Author (year)	$\sigma_0 \pm \Delta\sigma$ (b)
	Gillette (1966)	33
	Pomerance (1952)	$34.1 \pm 2.7$
	Seren (1947)	$34.2 \pm 7$
	Beitins (1992)	$42.3 \pm 0.4$
	De Corte (2003)	$42.22 \pm 0.22$
	Szentmiklosi (2006)	$42.8 \pm 0.4$
	Damle (1967)	$35.4 \pm 0.8$
	Bondarenko (2008)	$35.9 \pm 1.1$
	Heft (1978)	$36.6 \pm 0.8$
	Gleason (1977)	$37.0 \pm 1.5$
	Anufriev (1981)	$37 \pm 3$
	Nguyen (2008)	$37.2 \pm 2.1$
	Friesenhahn (1966)	$37.8 \pm 1.2$
	Knopf (1987)	$38.5 \pm 0.8$
	Uddin (2008)	$38.7 \pm 2.3$
	Karadag (2004)	$39.5 \pm 2.3$
	Hogg (1970)	$40.0 \pm 1.5$
	Lyon (1960)	41.3
	Lyon (1960)	51.0
	Atlas	$38.1 \pm 0.5$
	Beitins (1992)*	$34.8 \pm 0.3$
	De Corte (2003)*	$34.72 \pm 0.18$
	Szentmiklosi (2006)*	$35.2 \pm 0.3$
	Adopted	$34.8 \pm 0.2$

\* Value based on new decay scheme normalization [51].

De Corte and Simonits [2], and Szentmiklosi *et al.* [37] are all much higher than those measured by other methods. Previous activation data were all based on an older decay scheme normalization [49]. A new decay scheme normalization measured by Marnada *et al.* [50] leads to a new, more precise adopted value  $\sigma_0(^{186}\text{W}) = 34.8 \pm 0.2$  b that is in better agreement with other measurements.

## 5. Conclusions

Significant progress has been made on the intercomparison of  $k_0$ ,  $\sigma_0$  and  $P_\gamma$  data from various sources. Several discrepancies discussed here have been tentatively resolved. Still a large body of slightly different nuclear constants needs to be resolved into a single, self-consistent data base. Recently a  $k_0$  nuclear data committee, headed by Zsolt Revay, has been formed by the  $k_0$  users group to look into this problem and develop the next generation  $k_0$  database for nuclear applications. A parallel effort is underway to incorporate a new set of  $k_0$  and  $\sigma_0$  values into the next version of the EGAF database for the eventual adoption by ENSDF, ENDF, and DDEP evaluators.

*Acknowledgment.* We thank Andrej Trkov, Institute Jožef Stefan, and Mark Kellett, IAEA, for organizing and running the IAEA CRP on a Reference Database for Neutron Activation Analysis that got this project started. Valuable discussions at the CRP meetings with Maria Arribere, Centro Atomico Bariloche, Argentina; Frans De Corte, Ghent University, Belgium; Sunday Jonah, Ahmadu Bello University, Zaria; Radojko Jaćimović, Institute Jožef Stefan, Slovenia; Peter Schillebeeckx, IRMM, Belgium; Menno Blaauw, Reactor Institute Delft, Netherlands; and Maria Angela Menezes, CDTN/CNEN, Brazil are especially appreciated. This work was performed under the auspices of the US Department of Energy by the University of California, supported by the Director, Office of Science, Office of Basic Energy Sciences, of the US Department of Energy at Lawrence Berkeley National Laboratory under Contract No. DE-AC02-05CH11231.

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