Comparison of IUPAC k0 Values and Neutron Cross Sections to Determine a Self-consistent Set of Data for Neutron Activation Analysis

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Abstract. Independent databases of nuclear constants for Neutron Activation Analysis (NAA) have been independently maintained by the physics and chemistry communities for many year. They contain thermal neturon cross sections σ_0, standardization values k_0, and transition probabilities P_γ. Chemistry databases tend to rely upon direct measurements of the nuclear constants k_0 and P_γ which are often published in chemistry journals while the physics databases typically include evaluated σ_0 and P_γ 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 γ-ray cross sections σ_γ from Prompt Gamma-ray Activation Analysis (PGAA) measurements that can also be used to determine k_0 and σ_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 possibilitiy of producing a self-consistent set of σ_0, k_0, σ_γ, and P_γ values for NAA and other applications. Preliminary results of this IAEA CRP comparison are given in this paper.

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 F. De Corte and A. Simonits [2]. These k_0 values can also be derived from total radiative thermal neutron cross sections σ_0 that were evaluated by S. Mughabghab [3] and the P_γ transition probabilities that are available from two main sources, ENSDF [4] and the Table of Radionuclides [5]. In addition, prompt and delayed γ-ray cross sections σ_γ 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, σ_0, σ_γ, and P_γ 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, σ_0, σ_γ, and P_γ data is being developed by these authors for inclusion in the next version of the EGAF database and dissemination to the user community.

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 k0 standardization method as shown in the following equation.

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

Here *Au* is the co-irradiated gold monitor (E_γ=411.8 keV), N_p is the number of counts in the γ-ray peak, *W* is the weight of the sample, *w* is the weight of the gold monitor, and t_m is the counting time. $S=1-exp(-\lambda t_{irr})$ where λ is the decay constant and t_{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 σ_0 is the 2200 ms^{-1} neutron cross section. The epithermal neutron flux distribution is approximated by $1/E^{1+\alpha}$ assuming the cross section varies as $1/v$, and ε_p is the full-energy peak detection efficiency.

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

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

Here M is the atomic weight, θ is the isotopic abundance, and P_γ is the emission probability. The gold monitor can be replaced by another monitor *m* in which case

$$k_{0,m}(x)={k_{0,Au}(x)}\Big/{k_{0,Au}(m)} \tag{3}$$

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

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

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

$$s_0=\frac{2}{\sqrt{\pi}}Q_0-0.484 \tag{5}$$

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

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

and

$$s_0(\alpha)=s(\bar{E}_r)^{-\alpha}(1\,\mathrm{eV})^\alpha \tag{7}$$

where E_{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 eV)$^\alpha$≡1.0 term is from the definition of the epithermal neutron flux distribution [15,16].

Data Sources

The relationship between the nuclear constants k_0, σ_0, and P_γ is shown in Eq. (2). The quantity σ_γ 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.

Total radiative thermal neutron cross sections σ_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 communions or difficult to obtain reports. The CSISRS coverage of cross sections published in physics and engineering journals in is very good although cross sections published in chemistry journals or measured by the k_0 method are often missed. Significant improvement in the σ_0 data can be expected from an intercomparison of data from the Atlas, the IUPAC k_0 database, and other sources of data.

Gamma-ray transition probabilities P_γ

P_γ data are available for all isotopes 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 does not necessarily represent the best decay information that could be obtained from all available sources. ENSDF transition probabilities P_γ are not given explicitly but must instead be calculated through a series of intensity normalizations, each with their own explicit uncertainty. There are no guidelines for calculating the ΔP_γ uncertainty for individual γ-rays in ENSDF. Cutoff 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_γ data are also available for a limited number of isotopes 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_γ, P_γ and $t_{1/2}$ data from all sources without requiring ENSDF type normalizations for P_γ. The coverage of the *Table of Radionuclides* is limited to selected isotopes and does not include the full range of isotopes of interest for NAA.

Budapest Reactor guided neutron beam measurements

Neutron capture -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 ≈30 m from the Reactor where both primary and secondary γ-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 2×10^6 n cm^2 s^{-1}.

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,γ) reaction gamma rays to a precision of better that 1% from 500 keV to 6 MeV and better than 3% at all energies [19].

Thermal neutron γ-ray cross sections were determined using either stoichiometric compounds or accurately prepared mixtures containing the standard elements H, N, or Cl whose γ-ray cross sections are precisely known [20]. The γ-ray cross sections for isotopes of interest were then accurately determined from their intensity ratios to the standard γ-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 -ray cross sections do not need to be corrected for epithermal contributions.

Budapest Reactor σ_0 measurements

Numerous σ_0 measurements discussed in this paper were measured at the Budapest Reactor. Gamma-ray cross sections σ_γ for the decay of short-lived activation products were observed together with the prompt γ-rays in the Budapest Reactor experiments. These σ_γ measurements, corrected for saturation when half-lives are long with respect to the measurement time, can be used with either P_γ data from ENSDF or the Table of Radionuclides to determine σ_0 or with σ_0 data from the Atlas to determine P_γ.

Prompt σ_γ data for low-Z isotopes can also be used to determine σ_0 when the decay scheme is complete. In these cases $\sigma_0=\Sigma\sigma_\gamma$(Ground State)$=\Sigma\sigma_\gamma$(Primary γ-rays). The Budapest Reactor guided neutron beam measurements are the only comprehensive source of experimental σ_γ data. Many other precise measurements of the relative neutron capture I_γ 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 σ_γ data can be used to renormalize the I_γ data from the other experiments to get a more complete set of σ_γ data.

For heavy isotopes ($Z\geq20$) the prompt neutron capture γ-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 γ-rays are resolved. In order to measure σ_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_{crit} and uses experimental level/gamma properties for levels below E_{crit} and measured primary γ-ray cross sections feeding levels below E_{crit}. A variety of level density functions and γ-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_{crit} with the experimental cross section depopulating those levels. A discussion of the use of DICEBOX calculation to determine σ_0 has been given by Krticka et al [22].

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.

^{12}C(n,γ)^{13}C and ^{2}H(n,γ)^{3}H

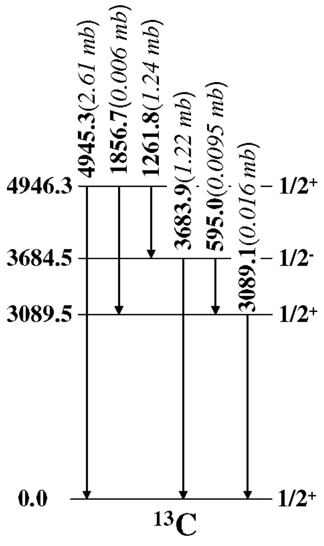

Fig. 1. Complete neutron Capture decay scheme for ^{12}C(n,γ)^{13}C measured with the thermal neutron beam at the Budapest Reactor.

Table 1. Comparison of ^{12}C(n,γ) cross section measurements. The new EGAF [8] value, based on Budapest Reactor measurements is inconsistent with the Jurney et al [23] measurement which is also the basis for the ^{2}H(n,γ) cross section suggesting the value in the Atlas, also based on the Jurney et al ^{12}C value, should be larger.

^{12}C	**Author (Year)**	**σ0±Δσ (mb)**	^{2}H	**Author (Year)**	**σ0±Δσ (mb)**
	Prestwich (1981)	3.50±0.16		Trail (1964)	0.36±0.03
	Jurney (1982)	3.53±0.07		Alfimenkov (1980)	0.476±0.020
	Nichols (1960)	3.57±0.03		Jurney (1982)	0.508±0.015
	Sagot (1963)	3.72±0.15		Merritt (1968)	0.521±0.009
	Jurney (1963)	3.8±0.4		Silk (1969)	0.523±0.029
	Starr (1962)	3.83±0.06		Ishikawa (1973)	0.55±0.01
	Hennig (1967)	3.85±0.15		Kaplan (1952)	0.57±0.01
	Matsue (2004)	3.81±0.11		Jurney (1963)	0.60±0.05
	Budapest (2007)	3.90±0.06		Sargent (1947)	0.92±0.22
	Atlas	**3.53±0.07**		**Atlas**	**0.508±0.015**
	Adopted	**3.84±0.06**		**Adopted**	**0.549±0.010**

The simple ^{12}C(n,γ)^{13}C decay scheme, measured at the Budapest Reactor, is shown in Fig. 1. The cross section σ_0(^{12}C)=3.90±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 measurement by Jurney et al [23], but consistent with five other values. The average of comparable the cross section measurements in Table 2 is σ_0(^{12}C)=3.84±0.06 mb.

Jurney et al [23] also used their σ_0(^{12}C) value in the same paper to determine the ^{2}H(n,γ) cross section. The new ^{12}C cross section suggests that Jurney et al's value should be increased to 552±16 mb which is consistent with four other previous measurements. We propose an adopted cross section σ_0(^{2}H)=549±10 mb, based on the average of comparable values. This new value needs to be confirmed by future experiments.

^{23}Na(n,γ)^{24}Na

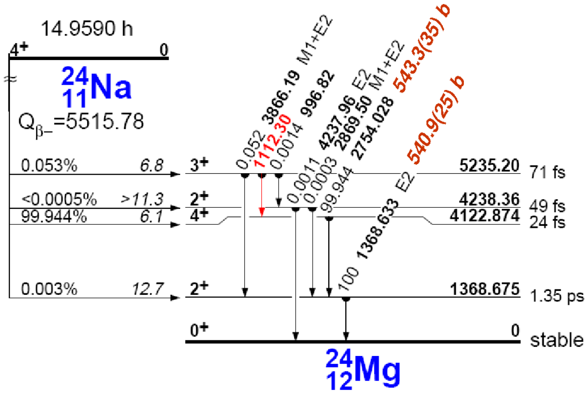

Fig. 2. Activation decay scheme for ^{23}Na(n,γ)^{24}Na measured with the thermal neutron beam at the Budapest Reactor. These data were taken in beam and have been corrected for bombarment time.

The ^{23}Na(n,γ)^{24}Na decay scheme is shown in Fig. 2 where the activation σ_γ cross sections measured at the Budapest Reactor for the production of the 1368.6- and 2754.0-keV γ-rays (P_γ=1.0) are shown. The average activation cross section from these measurements σ_0(^{23}Na)=542±3 mb is compared with previous measurements in Table 2. This new value is higher than the adopted value σ_0(^{23}Na)=517±4 mb from the Atlas [3] but it is comparable to several other measurements.

^{30}Si(n,γ)^{31}Si

The cross section σ_0(^{31}Si)=107±2 mb adopted in the Atlas [3] is consistent with the Budapest Reactor value of 112±6 mb. For k_0(1266.2γ)=1.45±0.01×10^{-7} from De Corte and Simonits [2], σ_γ=0.0630±0.0004 mb. The transition probability P_γ(1266.2)=σ_γ/σ_0=5.89±0.12×10^{-4} which is more precise that P_γ= 5.0±0.4×10^{-4} measured by McGuire and Hossain [24].

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

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

^{36}S(n,γ)^{37}S

The Atlas [3] cross section $\sigma_0(^{36}\mathrm{S})$=236±6 mb is inconsistent with $\sigma_0(^{36}\mathrm{S})$=160±3 mb derived from $k_0(3103.1\gamma)=1.96(4)\times10^{-6}$ measured by De Corte. These σ_0/k_0 values are the only information available for neutron activation analysis of sulfur. The Atlas value is based on two consistent measurements, $\sigma_0(^{36}\mathrm{S})$=233±2 mb by Raman et al [25] and $\sigma_0(^{36}\mathrm{S})$=249±14 mb by Beer et al [26]. Both measurements were with isotopically enriched targets. The problem with $k_0(^{37}\mathrm{S})$ is that the abundance of ^{36}S is 0.02±0.01% and varies widely in the environment. We recommend $k_0=3.05(10)\times10^{-6}$ which is based upon the adopted σ_0 value assuming an isotopic abundance ≡0.02%. This value cannot be used for analytical purposes unless the isotopic abundance has first been measured.

^{37}Cl(n,γ)^{38}Cl

The Atlas [3] cross section $\sigma_0(^{37}\mathrm{Cl})$=433±6 mb is consistent with the $\sigma_0(^{37}\mathrm{Cl})$=436±8 mb derived from the De Corte and Simonits [2] k_0 values. From ENSDF [4] for ^{37}Cl ($t_{1/2}$=37.230±0.014 m) decay, $P_\gamma(1643.4)=0.333\pm0.005$ and $P_\gamma(2167.5)=0.444\pm0.009$ based on the well-known γ-ray branching ratios and assuming a ground state β^- feeding of 55.6±0.9%. From the De Corte and Simonits k_0 values we determine that $P_\gamma(1643.4)=0.319\pm0.006$ and $P_\gamma(2167.5)=0.430\pm0.008$ which are consistent with the γ-ray branching ratios and a ground state β^- feeding of 57.2±0.8%. This new ground state feeding is consistent with 57.6±1.3% measured by van Klinken et al [27] but discrepant with 55.2±0.6% from Miyahara et al [28].

^{39,40,41}K(n,γ)^{40,41,42}K

Table 3. Comparison of cross section measurements for the potassium isotopes.

	Author (Year)	$\sigma_0 \pm \Delta\sigma$ (b)
^{39}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	**2.1±0.2**
	Adopted	**2.21±0.03**
^{40}K	Asghar (1978)	30
	Beckstrand (1971)	30±8
	Pomerance (1952)	66±20
	Gillette (1966)	70
	Krusche (1984)*	90±3
	Atlas	**30±8**
	Adopted	**90±3**
^{41}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	**1.46±0.03**
	Adopted	**1.522±0.022**

* Data were normalized to the Budapest cross section measurements.

Gamma-ray cross sections σ_γ for the three potassium isotopes were the measured at the Budapest Reactor. These data can be used to renormalize the nearly complete neutron capture γ-ray intensities of Krusche et al [29,30,31] to obtain σ_0 for ^{39,40,41}K(n,γ). These results are summarized in Table 3 where they are compared with previous measurements. For ^{39}K(n,γ) the Budapest renormalized von Egidy [29] cross section $\sigma_0(^{39}\mathrm{K})$=2.206±0.025 b is more precise and consistent with the Atlas [3] value.

A new $\sigma_0(^{40}K)=90\pm3$ b value, based on the Budapest Reactor $\sigma_\gamma(1293.6)=35.3\pm1.8$ 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 $\sigma_0(^{41}K)=1.523\pm0.022$ 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] ^{42}K k_0 values. This value is based on the measurement of prompt γ-rays while most lower values are based activation experiments suggesting that the difference may be due to a problem with the decay scheme γ-ray normalization.
$P_\gamma(1524.6)=0.1808\pm0.0009$ was adopted in ENSDF and is significantly higher than $P_\gamma(1524.6)=0.173\pm0.003$ derived from the IUPAC $k_0=9.46\pm0.06\times10^{-4}$ and $\sigma_0=1.46\pm0.03$ from the Atlas [3]. New activation experiments are in progress to remeasure the $^{41}K(n,\gamma)$ activation cross section.

$^{45}Sc(n,\gamma)^{46}Sc^m$

The ratio of the isomer $^{46}Sc^m$ ($t_{1/2}=18.75\pm0.04$ s) to ground state cross sections $\sigma_0(^{46}Sc^m)/\sigma_0(^{46}Sc^g)=0.56\pm0.04$ was measured by Simons [36] in the thermal column of their reactor. The Atlas [3] has adopted $\sigma_0(^{45}Sc^m)=9.9\pm1.1$ b assuming $\sigma_0(^{45}Sc^g)=17.4\pm1.1$ b. A new, more precise measurement of $\sigma_0(^{45}Sc^m)=7.77\pm0.21$ b at the Budapest Reactor has been published by Szentmiklosi et al [37]. No k_0 value exists for the 142.5-keV γ-ray from $^{46}Sc^m$ decay in the IUPAC database [1] although this short-lived activity can give more rapid analytical results for Sc than γ-rays from $^{46}Sc^g$ decay ($t_{1/2}=83.788\pm0.022$ d). We recommend the value $k_0(142.5\gamma)=0.226\pm0.005$.

$^{70}Zn(n,\gamma)^{71}Zn^g$

The cross section $\sigma_0(^{70}Zn^g)=83\pm5$ 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 [39,40,41,42]. De Corte and Simonits [2] report $k_0(511.6\gamma)=1.55\pm0.3\times10^{-6}$ which gives $\sigma_0(^{70}Zn^g)=22$ 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 [44] is $P_\gamma(511.6)=0.13$ gives $\sigma_0(^{70}Zn^g)=63$ 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 $P_\gamma(511.6)=0.085\pm0.005$.

$^{74}Ge(n,\gamma)^{75}Ge^m$

The cross section $\sigma_0(^{74}Ge^m)=163\pm5$ mb in the Atlas [3] was adopted from EGAF data [8] but is inconsistent with $\sigma_0(^{74}Ge^m)=138\pm1$ mb that has been derived from $k_0(139.7\gamma)=5.73\pm0.06\times10^{-4}$ measured by De Corte and Simonits [2]. The EGAF values is consistent with $k_0=6.76\pm0.03\times10^{-4}$. A new neutron activation measurement is necessary to confirm this new value.

$^{99}Tc(n,\gamma)^{100}Tc$

The cross section $\sigma_0(^{99}Tc)=22.8\pm1.3$ b was adopted in the Atlas [3]. A new value $\sigma_0(^{99}Tc)=24.2\pm0.2$ b can be derived from $\sigma_\gamma(539.5)=1.604\pm0.014$ b and $\sigma_\gamma(590.8)=1.296\pm0.011$ b from Budapest Reactor data, published by Molnar et al [45], and an improved ^{100}Tc (15.46 ± 0.19 s) decay scheme normalization by Furutaka et al [46]. No k_0 values are given for ^{100}Tc in the IUPAC compilation [1] and we adopt $k_0(539.5\gamma)=0.0334\pm0.0003$ and $k0(590.8\gamma)=0.0272\pm0.0007$ here.

$^{103}Rh(n,\gamma)^{104}Rh^{m+g}$

The decay scheme for $^{104}Rh^{m+g}$ is shown in Fig. 3. From ENSDF [8] $P_\gamma(555.8)=0.020\pm0.005$ is poorly known because of a large uncertainty in the excited state feeding intensity. De Corte and Simonits [2] have measured $k_0(555.8\gamma)=0.0692\pm0.0010$ for the combined isomer and ground state feeding which corresponds to $\sigma_\gamma(555.8)=3.41\pm0.05$ b. Assuming the adopted cross section $\sigma_0(^{103}Rh^{m+g})=143.5\pm1.5$ b from the Atlas [3] we get a more precise value $Pg(555.8)=0.0238\pm0.0004$.

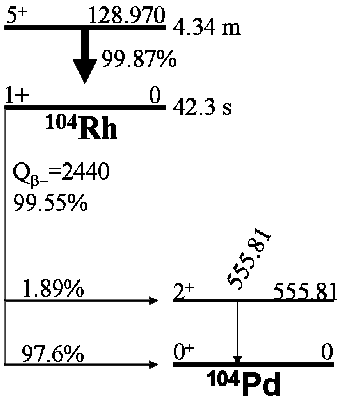

Fig. 3. Main features of the $^{104}Rh^{m+g}$ decay scheme.

also give 4.28±0.04% IT and 95.72±0.04% EC decay branching intensities for $^{114}In^{m1}$ which disagree with the ENSDF [8] branchings reported as 3.25±0.24% IT and 96.75±0.24% EC.

^{105}Pd(n,γ)^{106}Pd

The prompt γ-ray decay scheme form ^{105}Pd(n,γ)^{106}Pd is incomplete because of the contribution of unresolved continuum γ-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}Pd(n,γ) is shown in Fig. 4. The agreement between experiment and calculation is excellent. Krtiĉka et al [22] determined the total radiative neutron capture cross sections *σ_0* in this way for all of the palladium isotopes using DICEBOX and the Budapest data and these results are summarized in Table 4.

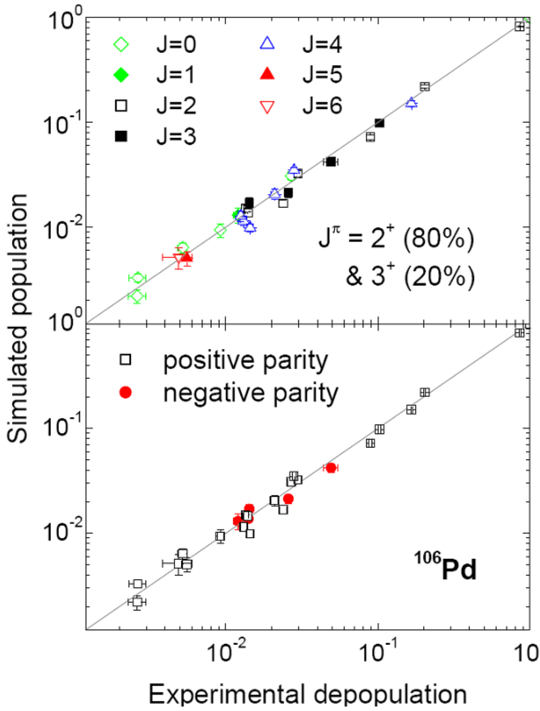

Fig. 4. Population/Depopulation plot for ^{105}Pd(n,γ)^{106}Pd. The spin distribution of the neutron capture state was determined by a least-squares minimization of the DICEBOX fit to the data.

Table 4. Palladium total radiative thermal neutron cross sections.

Isotope	σ_0(literature) (barns)	σ_0(this work) (barns)
^{102}Pd	1.6±0.2	1.1±0.4
^{104}Pd	0.65±0.30	0.75±0.26
^{105}Pd	21.0±1.5	21.7±0.5
^{106}Pd	0.30±0.03	0.36±0.10
^{108}Pd	7.6±0.5	8.6±0.6*
^{110}Pd	0.70±0.17	0.34±0.10

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

^{113}In(n,γ)^{114}In^{m1}

The decay scheme for ^{114}In^{m1+m2} is shown in Fig 5. The ^{114}In^{m1} decay scheme consists of three γ-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±0.09 b, $\sigma_{\gamma+e}$(558.4)=0.368±0.003 b, and $\sigma_{\gamma+e}$(725.2)= 0.372±0.002 b. These data give σ_0(^{114}In^{m1+m2})=8.65±0.09 b which is more precise and in good agreement with σ_0(^{114}In^{m1+m2})=8.1±0.8 b from the Atlas [3].

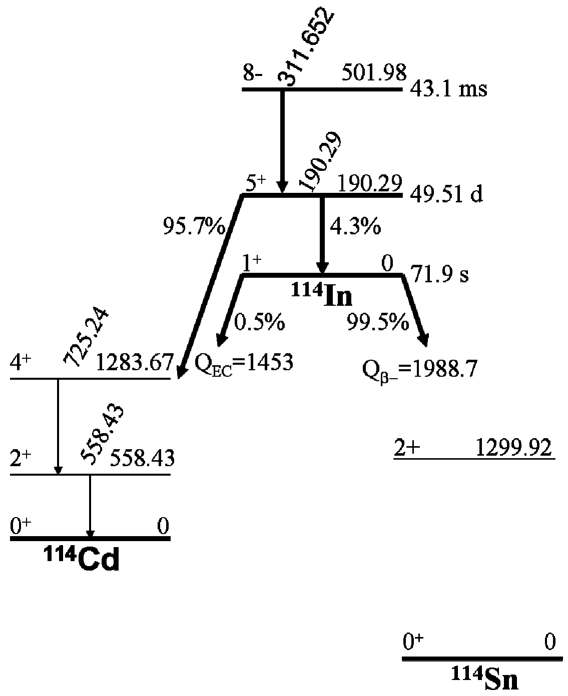

Fig. 5. Main features of the ^{114}In^{m1} decay scheme. The decay branchings are from ENSDF [8].

The Budapest Reactor data give σ_0(^{114}In^{m2})=$\sigma_{\gamma+e}$(311.7) =3.4±0.8 b which is comparable to σ_0(^{114}In^{m2})=3.1±0.7 b that was adopted in the Atlas [2]. From this value and the data above we derive σ_0(^{114}In^{m1})=5.5±0.7 b.

^{127}I(n,γ)^{128}I

The cross section σ_0(^{127}I)=6.15±6 b adopted in the Atlas [3] is consistent with many precise measurements that don't involve neutron activation. P_γ(442.9)=0.1261±0.0008 was measured by Miyahara et al [47], and σ_0(^{127}I)=5.39±0.06 b assuming the k_0 data of De Corte and Simonits [2] or σ_0(^{127}I)=5.63±0.08 b assuming the σ_γ data of Szentmiklosi et al [37]. For an average value σ_0(^{127}I)=5.48±0.12 b from the two activation measurements, P_γ(442.9)=0.112±0.003 which is in substantial disagreement with the Miyahara et al measurement.

^{151}Eu(n,γ)^{152}Eu^{g}

The cross section $\sigma_0(^{151}\mathrm{Eu})=5900\pm200$ b was adopted in the Atlas [3] based largely on the data of Gryntakis [48]. De Corte and Simonits data [2] k_0 data give $\sigma_0(^{151}\mathrm{Eu})=6885\pm15$ b which is consistent with Budapest Reactor data that give $\sigma_0(^{151}\mathrm{Eu})=6750\pm170$ b. We recommend a new adopted value of $\sigma_0(^{151}\mathrm{Eu})=6880\pm100$ b.

^{181}Ta(n,γ)^{182}Ta

The cross section $\sigma_0(^{181}\mathrm{Ta})=20.5\pm0.5$ b was adopted in the Atlas [3] based on many consistent measurements. This cross section is also consistent with the k_0 measurements from De Corte and Simonits [2] for $E_\gamma\geq152.4$ keV but inconsistent with two lower energy γ-rays from ^{182}Ta ($t_{1/2}=114.43\pm0.03$ d). The transition probablilities for these two γ-ray are well established in the Table of Radionuclides and we adopt $k_0(67.8\gamma)=0.0975\pm0.0028$ and $k_0(100.1\gamma)=0.0334\pm0.0008$ based on the adopted P_γ and σ_0 values.

Table 5. Comparison of ^{186}W(n,γ) cross section measurements.

^{186}W	Author (Year)	$\sigma_0\pm\Delta\sigma$ (b)
	Gillette (1966)	33
	Pomerance (1952)	34.1.0±2.7
	Seren (1947)	34.2±7
	Beitins (1992)	42.3±0.4
	De Corte (2003)	42.22±0.22
	Szentmiklosi (2006)	42.8±0.4
	Damle (1967)	35.4±0.8
	Bondarenko (2008)	35.9±1.1
	Heft (1978)	36.6±0.8
	Gleason (1977)	37.0±1.5
	Anufriev (1981)	37±3
	Nguyen (2008)	37.2±2.1
	Friesenhahn (1966)	37.8±1.2
	Knopf (1987)	38.5±0.8
	Uddin (2008)	38.7±2.3
	Karadag (2004)	39.5±2.3
	Hogg (1970)	40.0±1.5
	Lyon (1960)	41.3
	Lyon (1960)	51.0
	Atlas	38.1±0.5
	Beitins (1992)*	34.8±0.3
	De Corte (2003)*	34.72±0.18
	Szentmiklosi (2006)*	35.2±0.3
	Adopted	34.8±0.2

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

^{185}W(n,γ)^{186}W

The cross section $\sigma_0(^{186}\mathrm{W})=38.1\pm0.5$ b was adopted in the Atlas [3] based on the measurements reported in Table 5. Significant variation exists in these measurements. The precise σ_0 values in Table 4 measured by Beitins et al [49], 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 [50]. A new decay scheme normalization measured by Marnada et al [51] leads to a new, more precise adopted value $\sigma_0(^{186}\mathrm{W})=34.8\pm0.2$ b that is in better agreement with other measurements.

Conclusions

Significant progress has been made on the intercomparison of k_0, σ_0 and P_γ 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 singlem 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 σ_0 values into the next version of the EGAF database for the eventual adoption by ENSDF, ENDF, and DDEP evaluators.

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