Workshop on

Nuclear Data for Activation Analysis

7 – 18 March 2005

Miramare – Trieste, Italy

NUCLEAR DATA FOR NEUTRON ACTIVATION ANALYSIS: NEEDS, DETERMINATION, STATUS

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When considering the simple equation (in "relative standardization") for obtaining concentrations via reactor neutron activation analysis:

$$(\mathrm{conc})_a = \frac{(N_p / t_m \, SDCW)_a}{(N_p / t_m \, SDCw)_s}$$

with:

a - analyte

s - co-irradiated standard

N_p - net peak area

t_m – measuring time

$S = 1-\exp(-\lambda t_{irr})$; t_{irr} – irradiation time

$D = \exp(\lambda t_d)$; t_d – decay time

$C = [1-\exp(-\lambda t_m)]/ \lambda t_m$

W – sample mass

w – mass of standard

WHY ARE NUCLEAR DATA (OTHER THAN THE HALF-LIFE) NEEDED ?

NEED FOR NUCLEAR DATA IN NAA

pre-irradiation:

feasibility of determination

⇒ Advance prediction

post-irradiation:

interpretation of measured gamma-spectra

and identification of isotopes/elements

parametric standardization protocols:

absolute, k_0, ---

corrections:

spectral and reaction interferences

neutron self-shielding, gamma-attenuation

burn-up

WHICH NUCLEAR DATA ?
⇒ see fundamental equation of NAA

Høgdahl formalism

$$G_{th}\phi_{th}\sigma_0 + G_e\phi_e I_0(\alpha) = \frac{M}{N_A\theta\,\gamma\varepsilon_p}\frac{N_p / t_m}{wSDC}$$

- σ_0 - 2200 ms^{-1} (n,γ) cross section;
- $I_0(\alpha)$ - resonance integral for non-ideal $(1/E^{1+\alpha})$ epithermal flux energy dependence; ⇒ measurement of α requires nuclear data;
- ϕ_{th}, ϕ_e - thermal resp. epithermal neutron flux; ⇒ determination requires nuclear data;
- G_{th}, G_e - thermal resp. epithermal neutron self-shielding factor; ⇒ determination requires nuclear data.

WHICH NUCLEAR DATA ?

⇒ see fundamental equation of NAA

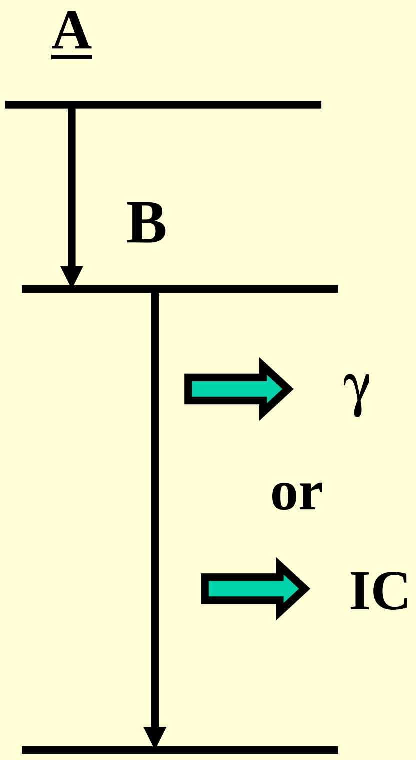
Høgdahl formalism

$$G_{th}\phi_{th}\sigma_0 + G_e\phi_e I_0(\alpha) = \frac{M}{N_A \theta\, \gamma \varepsilon_p} \frac{N_p / t_m}{wSDC}$$

- **M – atomic weight; N_A – Avogadro's number;**
- **θ - isotopic abundance;**
- **γ - absolute gamma-intensity;**
- **ε_p - peak detection effficiency, with correction for gamma-attenuation;**
  ⇒ requires nuclear data.
- **N_p/t_m - (net) peak count rate; ⇒ correction for true-coincidence, reaction & spectral interferences and burn-up requires nuclear data.**

$N_p = (N_p)_{meas}/COI$ ⟹ true-coincidence correction factor requires gamma-intensities and internal conversion coefficients

$$N_p = (N_p)_{meas}/COI$$



COI(A) = 1 – L(A) [L(A) = probability for loss of A]

L (A) = probability that A is followed by transition B
= a_B (branching ratio of B)

x probability that gamma B is emitted
= $1 / (1 + \alpha_{t,B})$ [α_t = total IC coefficient]

x probability that gamma B gives a total or partial energy deposition in the detector
= $\varepsilon_{t,B}$ [total detection efficiency]

$$= a_B \cdot \varepsilon_{t,B} / (1 + \alpha_{t,B})$$

NEED FOR NUCLEAR DATA IN NAA

pre-irradiation:

feasibility of determination

Based on estimation of detectability of analyte peak in gamma-ray spectrum of irradiated matrix, via calculation, for analyte and matrix elements, of

$$N_p = \frac{N_A \theta \gamma}{M} wt_m SDC \left[\phi_{th}\sigma_0 + \phi_e I_0\right]\varepsilon_p$$

E.g. :

Can phosphorus be determined in semiconductor silicon ?

Can iodine be determined in milk powder ?

Can selenium be determined in human blood serum ?

Can uranium be determined in loess ?

Can lanthanum be determined in estuarine sediment ?

Title Advance prediction of neutron activation analysis spectra and detection limits

Creator/Author Guinn, V.P. ; Leslie, J.C. ; Murray, L.E.

Publication Date 1977 Jan 01

APCP

Luymes, R.J., (R.E. Jervis), "An Adaption of the Advance Prediction Computer Program".

IAEA1411 NAAPRO. (Abstract last modified 06-AUG-2004)

NAAPRO, Neutron Activation Analysis Prognosis and Optimization code

- V.K.Basenko, A.N.Berlizov, I.A.Malyuk, V.V.Tryshyn:
NAAPRO: A Code for Predicting Results and Performance of Neutron Activation Analysis, The Sixth International Conference on Methods and Applications of Radioanalytical Chemistry - MARC VI, Kailua-Kona, Hawaii, USA, April 7-11, 2003, Book of Abstracts, p.71; to be published in Jour. Rad. Nucl. Chem.

IAEA1411/03:

- V.K.Basenko, A.N.Berlizov, R.H.Filby, I.A.Malyuk, V.V.Tryshyn:
NAAPRO (Neutron Activation Analysis PRognosis and Optimization) Version 01.beta User's Guide

NAAPRO http://www.nea.fr/abs/html/iaea1411.html

NEED FOR NUCLEAR DATA IN NAA

post-irradiation:

interpretation of measured gamma-spectra

and identification of isotopes/elements

Example:

Peak at 676.0 ± 0.5 keV is found in gamma-spectrum

Search gives 2 possibilities: 675.9 keV of ^{198}Au, or 675.5 keV of ^{143}Ce

if ^{198}Au: peak at 411.8 keV should be seen

if ^{143}Ce: peak at 293.3 keV should be seen

check peak ratios: $(\gamma\varepsilon_p)_{peak1} / (\gamma\varepsilon_p)_{peak2}$

NEED FOR NUCLEAR DATA IN NAA

parametric standardization protocols:

ABSOLUTE STANDARDIZATION

$$(\mathrm{conc})_a = \frac{M_a}{N_A \theta_a \gamma_a} \frac{(N_p / Wt_m SDC)_a}{\left[G_{th,a}\phi_{th}\sigma_{0,a} + G_{e,a}\phi_e I_{0,a}(\alpha)\right]\varepsilon_{p,a}}$$

combined with co-irradiation of neutron flux monitor (m):

$$(\mathrm{conc})_a = \frac{(N_p / Wt_m SDC)_a}{(N_p / wt_m SDC)_m} \frac{M_a \theta_m \gamma_m \sigma_{0,m}}{M_m \theta_a \gamma_a \sigma_{0,a}} \frac{\left[G_{th,m} f + G_{e,m} Q_{0,m}(\alpha)\right]}{\left[G_{th,a} f + G_{e,a} Q_{0,a}(\alpha)\right]} \frac{\varepsilon_{p,m}}{\varepsilon_{p,a}}$$

with $f = \phi_{th} / \phi_e$

$Q_0(\alpha) = I_o(\alpha) / \sigma_0$

NEED FOR NUCLEAR DATA IN NAA

parametric standardization protocols:

k_0-STANDARDIZATION

$$(\mathrm{conc})_a = \frac{\left(N_p / Wt_m SDC\right)_a}{\left(N_p / wt_m SDC\right)_m} \frac{M_a \theta_m \gamma_m \sigma_{0,m}}{M_m \theta_a \gamma_a \sigma_{0,a}} \frac{\left[G_{th,m} f + G_{e,m} Q_{0,m}(\alpha)\right]}{\left[G_{th,a} f + G_{e,a} Q_{0,a}(\alpha)\right]} \frac{\varepsilon_{p,m}}{\varepsilon_{p,a}}$$

$$(\mathrm{conc})_a = \frac{\left(N_p / Wt_m SDC\right)_a}{\left(N_p / wt_m SDC\right)_m} \frac{1}{k_{0,m}(a)} \frac{\left[G_{th,m} f + G_{e,m} Q_{0,m}(\alpha)\right]}{\left[G_{th,a} f + G_{e,a} Q_{0,a}(\alpha)\right]} \frac{\varepsilon_{p,m}}{\varepsilon_{p,a}}$$

With $k_{0,m}(a)$ defined as:

$$k_{0,m}(a) = \frac{M_m \theta_a \gamma_a \sigma_{0,a}}{M_a \theta_m \gamma_m \sigma_{0,m}}$$

$$I_0(\alpha) = \left[\frac{I_0 - 0.429\sigma_0}{\left(\overline{E}_r\right)^{\alpha}} + \frac{0.429\sigma_0}{\left(E_{Cd} = 0.55\,eV\right)^{\alpha}(2\alpha + 1)} \right] .1eV^{\alpha}$$

$$Q_0(\alpha) = \left[\frac{Q_0 - 0.429}{\left(\overline{E}_r\right)^{\alpha}} + \frac{0.429}{\left(E_{Cd} = 0.55\,eV\right)^{\alpha}(2\alpha + 1)} \right] .1eV^{\alpha}$$

$\overline{E}_r$ = effective resonance energy

α from Cd-ratio for multi-monitor method (implicit)

minus α is slope of straight line when plotting:

$$\log \frac{\bar{E}_{r,i}^{-\alpha}}{\left(F_{Cd,i} R_{Cd,i} - 1\right) . Q_{0,i}(\alpha) . G_{e,i} / G_{th,i}}$$

versus $\log \bar{E}_{r,i}$

F_{Cd} – **Cd transmission factor for epithermal neutrons**

Required:

Q_0, $\bar{E}_r$ **and** F_{Cd}

Journal of Radioanalytical Chemistry, Vol. 67, No 2 (1981) 421–435

EPICADMIUM NEUTRON ACTIVATION ANALYSIS (ENAA) BASED ON THE k_0-COMPARATOR METHOD

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Table 3
Literature survey of Cd epithermal neutron transmission factors (preferred values underlined)

Reaction	F_{Cd} (references)
$^{185}Re(n,\gamma)^{186}Re$	possibly $F_{Cd} < 1$**
$^{193}Ir(n,\gamma)^{194}Ir$	possibly $F_{Cd} < 1$**
$^{196}Pt(n,\gamma)^{197}Pt$	1.00[21]
$^{198}Pt(n,\gamma)^{199}Pt$	1.00[19,21]
$^{197}Au(n,\gamma)^{198}Au$	0.98[24]
	0.990[13,17,30]
	0.991[11,12,15,23]
	0.998*[20,22]
	1.0[19]

to be updated

α from bare triple monitor method (implicit equation)

$$(a-b).Q_{0,1}(\alpha)\frac{G_{e,1}}{G_{th,1}} - a.Q_{0,2}(\alpha)\frac{G_{e,2}}{G_{th,2}} + b.Q_{0,3}(\alpha)\frac{G_{e,3}}{G_{th,3}} = 0$$

$$a = \left\{1 - \frac{A_{sp,2}}{A_{sp,1}}\frac{k_{0,Au}(1)}{k_{0.Au}(2)}\frac{\varepsilon_{p,1}}{\varepsilon_{p,2}}\right\}^{-1}$$

$$b = \left\{1 - \frac{A_{sp,3}}{A_{sp,1}}\frac{k_{0,Au}(1)}{k_{0.Au}(3)}\frac{\varepsilon_{p,1}}{\varepsilon_{p,3}}\right\}^{-1}$$

$$A_{sp} = \frac{N_p / t_m}{SDCw}$$

Required:

k_0, Q_0 and $\bar{E}_r$

f from Cd-ratio method:

$$f = Q_0(\alpha).\left[F_{Cd}R_{Cd} - 1\right].G_e / G_{th}$$

$$R_{Cd} = A_{sp} / \left(A_{sp}\right)_{Cd}$$

Required:

Q_0, $\bar{E}_r$ and F_{Cd}

f from bare dual monitor method:

$$f = \frac{G_{e,1}\dfrac{k_{0,Au}(1)}{k_{0,Au}(2)}\dfrac{\varepsilon_{p,1}}{\varepsilon_{p,2}}Q_{0,1}(\alpha) - G_{e,2}\dfrac{A_{sp,1}}{A_{sp,2}}Q_{0,2}(\alpha)}{G_{th,2}\dfrac{A_{sp,1}}{A_{sp,2}} - G_{th,1}\dfrac{k_{0,Au}(1)}{k_{0,Au}(2)}\dfrac{\varepsilon_{p,1}}{\varepsilon_{p,2}}}$$

Required:

k_0, Q_0 and $\overline{E}_r$

NEED FOR NUCLEAR DATA IN NAA

parametric standardization protocols:

k_0-STANDARDIZATION

Experimental measurements of k_0-factors:

$$k_{0,m}(a) = \frac{\left(N_p / wt_m SDC\right)_a}{\left(N_p / wt_m SDC\right)_m} \frac{\left[G_{th,m} f + G_{e,m} Q_{0,m}(\alpha)\right]}{\left[G_{th,a} f + G_{e,a} Q_{0,a}(\alpha)\right]} \frac{\varepsilon_{p,m}}{\varepsilon_{p,a}}$$

Experimental measurement of k_0-factors:

***A priori* outlined methodology:**

Parallel but independent experimental measurement of k_0, $Q_{0,}$ etc.

at INW, Gent and KFKI, Budapest

↓

Detection and elimination of systematic errors

Experimental measurements of k_0-factors:

INW, Gent and KFKI, Budapest:

parallel but independent measurements

different target preparation

different reactors/irradiation sites (≠ neutron thermalization)

different Ge-detectors (≠ DT correction)

different computer codes for gamma-spectrum analysis

Experimental measurements of k_0-factors:

Sample preparation	Isotope E_{γ}, keV	Measured $k_{0,Au}$ (uncertainty in %)				**<u>$k_{0,Au}$ recommended</u>** (uncert.,%)
		KFKI “WWR-M” Channel:		INW “THETIS” Channel:		
		MILA f = 35	CSÖPI f = 18	3 f = 25	15 f = 72	
<u>KFKI:</u> 1mg NaCl on Al-foil; pellet 6.4mm diam. x 0.2 mm <u>INW:</u> Na_2CO_3 powder in PE vial; 20mg (Ch.3); 50mg (Ch.15)	^{24}Na	DT correction: pulser Spectr. anal. : Hypermet		DT correction: DTS Spectr. anal. : Seqal		
	1368.6	4.71E-2(2.2)	4.74E-2(2.4)	4.61E-2(2.5)	4.65E-2(1.8)	<u>4.68E-2</u>(0.6)
	2754.0	4.60E-2(1.6)	4.74E-2(1.6)	4.56E-2(1.8)	4.59E-2(0.5)	<u>4.62E-2</u>(0.9)

Experimental measurements of k_0-factors:

Measurement of k_0, Q_0, etc.: later contributions/co-operations:

LNETI - Sacavém

Atominstitut - Wien

National Laboratory - Risø

SCK - Mol + IRMM - Geel

IJS - Ljubljana (+Podgorica)

KFA – Jülich

TUM - Garching

DSM - Geleen

Choice of comparator/monitor in k_0-NAA:

$^{197}Au(n,\gamma)^{198}Au$, $E_\gamma = 411.8$ keV → tabulation of $k_{0,Au}(a)$

Simple conversion: $k_{o,m}(a) = k_{0,Au}(a) / k_{0,Au}(m)$

IRMM/Geel - INW/Gent co-operation:

NIM A, 1991: "Aluminium-gold reference material for the k_0-standardisation of neutron activation analysis"

IRMM-530 CRM Al-(0.100±0.002)%Au foil or wire

(accuracy-checked at KFKI; increases traceability)

Sample preparation	Isotope E_γ, keV	Measured $k_{0,Au}$ (uncertainty in %)				<u>$k_{0,Au}$ recommended</u> (uncert.,%)
		KFKI "WWR-M" Channel:		INW "THETIS" Channel:		
		15/2 f = 30	17/2 f = 20	3 f = 25	15 f = 72	
<u>KFKI:</u> 20µg $CsNO_3$ (in H_2O) on Al-foil; pellet 6.4mm diam. x 0.2 mm	^{134}Cs	DT correction: pulser Spectr. anal. : Hypermet		DT correction: DTS Spectr. anal. : Seqal Intern. Compar.: ^{69m}Zn		
<u>INW:</u> CsCl (in H_2O) [+Zn (in HNO_3] on W41; 0.7mg (Ch.3); 1.7mg (Ch.15); pellet 10 mm diam. x 4 mm	604.7 795.8	4.81E-1(1.0) 4.21E-1(0.7)	4.75E-1(2.1) 4.18E-1(1.8)	4.93E-1(0.3) 4.26E-1(0.4)	4.53E-1(0.2) 3.93E-1(0.5)	<u>4.76E-1</u>(2.0) <u>4.15E-1</u>(2.0)

Journal of Radioanalytical and Nuclear Chemistry, Articles, Vol. 179, No. 1 (1994) 93–103

THE USE OF A MODIFIED WESTCOTT-FORMALISM IN THE k_o-STANDARDIZATION OF NAA: THE STATE OF AFFAIRS

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$$(\mathrm{conc})_a = \frac{\left(N_p / Wt_m SDC\right)_a}{\left(N_p / wt_m SDC\right)_m} \frac{1}{k_{0,m}(a)} \, x$$

$$x \, \frac{\left[G_{th,m} g_m (T_n) + G_{r,m} . r(\alpha)\sqrt{T_n / T_0} . s_{0,m}(\alpha)\right]}{\left[G_{th,a} g_a (T_n) + G_{r,a} . r(\alpha)\sqrt{T_n / T_0} . s_{0,a}(\alpha)\right]} \frac{\varepsilon_{p,m}}{\varepsilon_{p,a}}$$

$$(\mathrm{conc})_a = \frac{\left(N_p / Wt_m SDC\right)_a}{\left(N_p / wt_m SDC\right)_m} \frac{1}{k_{0,m}(a)} \mathrm{x}$$

$$\mathrm{x} \frac{\left[G_{th,m} g_m\left(T_n\right) + G_{r,m} . r(\alpha)\sqrt{T_n / T_0} . s_{0,m}(\alpha)\right]}{\left[G_{th,a} g_a\left(T_n\right) + G_{r,a} . r(\alpha)\sqrt{T_n / T_0} . s_{0,a}(\alpha)\right]} \frac{\varepsilon_{p,m}}{\varepsilon_{p,a}}$$

$g(T_n)$	Westcott g-factor; T_n – neutron temperature
$r(\alpha)\sqrt{T_n / T_0}$	modified spectral index
$s_0(\alpha) = s_0\left(\bar{E}_r\right)^{-\alpha} .1eV^{\alpha}$	measure for epith./thermal cross section
$s_0 = 2Q_0 / \sqrt{\pi} - 0.484$	for 1/v cross sections (Westcott g = 1)

RIJKSUNIVERSITEIT GENT

Faculteit van de Wetenschappen

Instituut voor Nucleaire Wetenschappen
Laboratorium voor Analytische Scheikunde

Bestuurders : Prof. emer. J. HOSTE (tot 1986)

THE k_0-STANDARDIZATION METHOD

A MOVE TO THE OPTIMIZATION OF NEUTRON ACTIVATION ANALYSIS

FRANS DE CORTE

Detailed info on k_0-NAA

In English

Nederlandse samenvatting - Résumé en français

Proefschrift voorgelegd tot het verkrijgen van de graad van
Geaggregeerde voor het Hoger Onderwijs - 1987

General info on k_0-NAA

Journal of Radioanalytical and Nuclear Chemistry, Vol. 248, No. 1 (2001) 13–20

ACTIVATION ANALYSIS TECHNIQUES

The standardization of standardless NAA

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(Received December 13, 2000)

This review describes how the original 'standardless' (absolute and single-comparator) NAA-calibration methods, introduced in the mid-1960s, were stepwise upgraded with respect to their accuracy and manageability, leading to the launching of the k_0-method in the mid 1970s. Next, an account is given of the achievements in the continuous development of the k_0-standardization of NAA up to the present. Topics highlighted are: the k_0-data library, the development of dedicated calibration procedures, extensions and limitations, computerization and quality control/assurance. Finally, a short outline is given of the international dissemination of the k_0-methodology.

NEED FOR NUCLEAR DATA IN NAA

corrections:
spectral interferences

Se in presence of Hg:	$^{74}Se(n,\gamma)\,^{75}Se$; E_γ = 279.5 keV
spectral interference:	$^{202}Hg(n,\gamma)^{203}Hg$; E_γ = 279.2 keV

correction essentially requires gamma-intensity data

U in loess:	$^{238}U(n,\gamma)^{239}U(\beta^-)^{239}Np$; E_γ = 228.2, 277.6 keV
spectral interference:	$^{235}U(n,f)^{132}Te$; E_γ = 228.2 keV

correction requires both cross section/resonance integral and gamma-intensity data

NEED FOR NUCLEAR DATA IN NAA

corrections:
reaction interferences

P in Si:	$^{31}P(n,\gamma)^{32}P$
2nd order interference:	$^{30}Si(n,\gamma)^{31}Si(\beta^-)^{31}P(n,\gamma)^{32}P$

Na in presence of Al:	$^{23}Na(n,\gamma)^{24}Na$
Threshold interference	$^{27}Al(n,\alpha)^{24}Na$

La in estuarine sediment:	$^{139}La(n,\gamma)^{140}La$
fission reaction interference:	$^{235}U(n,f)^{140}Ba(\beta^-)^{140}La$

correction essentially requires cross section/resonance integral data

NEED FOR NUCLEAR DATA IN NAA

corrections:

neutron self-shielding

Bromine (~75%) in flame retardant: possibility of thermal and epithermal neutron self-shielding

thermal shielding correction: contains <<exp(-σ_{abs}N)>> terms

$\sigma_{abs} = \Sigma(\theta_i \sigma_{0,i})/100$ – elemental absorption cross section; N - nuclei.cm^{-3}

epithermal shielding correction: more complex calculation, based on resonance parameters

correction essentially requires cross section/resonance data

NEED FOR NUCLEAR DATA IN NAA

corrections:

gamma-attenuation

U in loess: $^{238}U(n,\gamma)^{239}U$; $E_\gamma = 74.7$ keV
if voluminous matrix: → **possibility of gamma-attenuation**
[also: spectral interference possible from 75.0 keV Pb KX ray (Pb-castle)]

Gamma-attenuation correction: contains <<exp(-μd)>> terms
μ– linear absorption coefficient (total *minus* coherent scattering);
d – thickness of absorbing layer

correction essentially requires gamma-absorption coefficients

Nuclear Science Software

PHOTKOEF

A PC program (running under 32-bit WINDOWS Operating Systems), for the calculation of X-ray and gamma ray coefficients, shielding, dose deposition, and detector response. This is the only fast PC program (based on semi-empirical and patents-applied-for algorithms) which calculates dose buildup in absorbers and behind shields, dose deposition in internal substances (organs, mechanical components) including the effects of secondary (degraded) radiation, and dose enhancement due to electron transport at interfaces of dissimilar substances in multilayered objects. Licenses are available for personal use and for use in classrooms. Volume discounts and discounts to dealers and distributors are available.

PKjunior

A junior version of PHOTKOEF. Calculates, plots and prints photon interaction coefficients only. Licenses are available for personal use. Discounts are given to universities, to organizations using this program for promotional purposes, and to dealers and distributors, if at least fifty programs are ordered.

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www.aicsoftware.net
Edited on 15 October 2003 - E-mail to the Webmaster

NEED FOR NUCLEAR DATA IN NAA

corrections:

Burn-up

E.g.: Au at high fluxes / long irradiation times

$^{197}Au(n,\gamma)^{198}Au(n,\gamma)^{199}Au$

high σ_0 and I_0 values

Correction requires cross sections / resonance integrals

<u>Sources of Nuclear Data</u>

Atomic Weights and Isotopic Abundances

Pure Appl. Chem., Vol. 75, No. 8, pp. 1107–1122, 2003.

INTERNATIONAL UNION OF PURE AND APPLIED CHEMISTRY

INORGANIC CHEMISTRY DIVISION
COMMISSION ON ATOMIC WEIGHTS AND ISOTOPIC ABUNDANCES*

ATOMIC WEIGHTS OF THE ELEMENTS 2001

(IUPAC Technical Report)

Prepared for publication by
R. D. LOSS

Department of Applied Physics, Curtin University of Technology, Perth, Western Australia

http://www.chem.qmul.ac.uk/iupac/AtWt/

INTERNATIONAL UNION OF PURE AND APPLIED CHEMISTRY

INORGANIC CHEMISTRY DIVISION
COMMISSION ON ATOMIC WEIGHTS AND ISOTOPIC ABUNDANCES*

SUBCOMMITTEE FOR ISOTOPIC ABUNDANCE MEASUREMENTS**

ISOTOPIC COMPOSITIONS OF THE ELEMENTS 1997

Prepared for publication by
K.J.R. ROSMAN[1] AND P.D.P. TAYLOR[2]

http://www.iupac.org/reports/1998/7001rosman/iso.pdf

ALSO: M AND θ

FROM OTHER DATA COMPILATIONS

Sources of Nuclear Data: General

Activation and Decay

http://www-nds.iaea.or.at/

Welcome to the IAEA Nuclear Data Centre

Nuclear Data Services

http://www-nds.iaea.or.at/

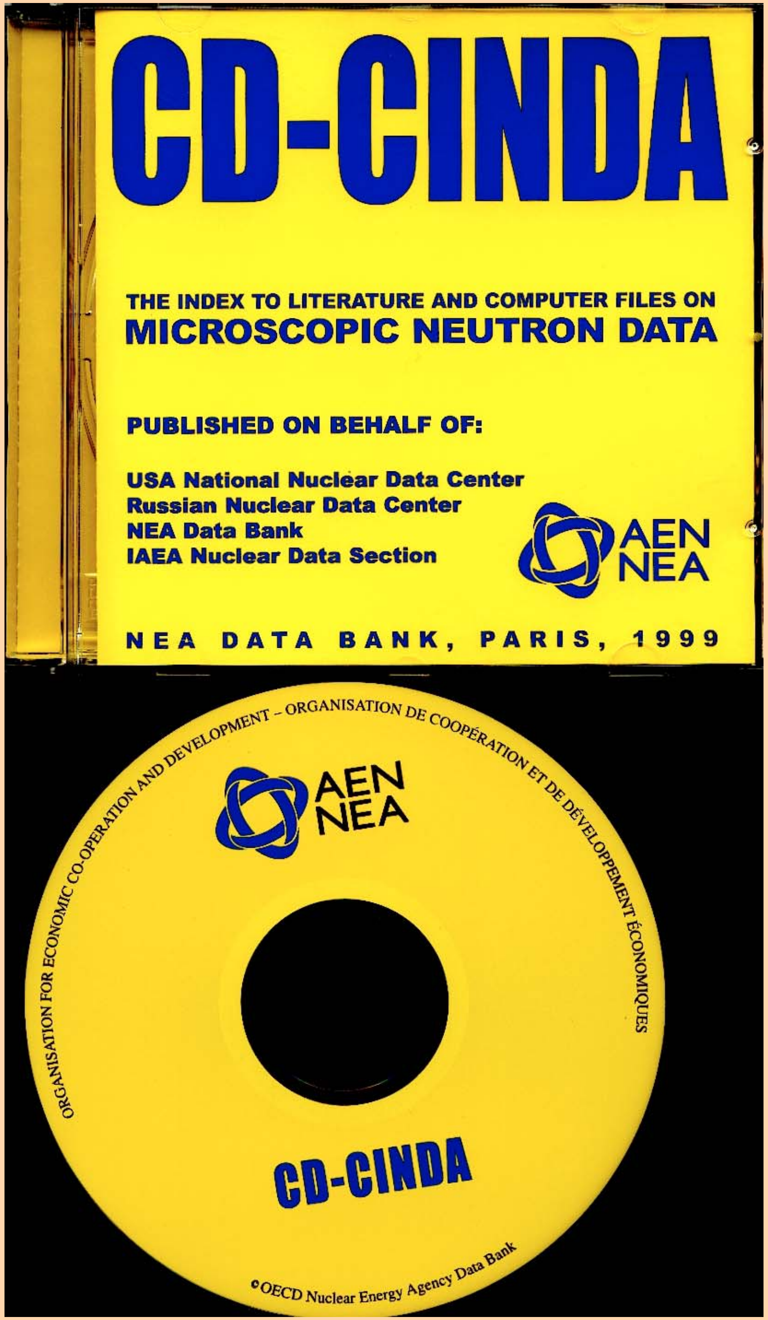
Major Databases

CINDA - neutron reaction data bibliography
ENDF - evaluated nuclear reaction cross section libraries
ENSDF - evaluated nuclear structure and decay data
EXFOR - experimental nuclear reaction data *(with graphics)*
NSR - Nuclear Science References
NuDat 2.0 - selected evaluated nuclear data

Nuclear Databases and Files

General

Masses 2003 - atomic mass evaluation data file
Q-values, Thresholds - atomic masses, Q-values and threshold energies
Thermal neutron capture gamma rays - by target and by energy
Wallet cards - ground and metastable state properties


CD-CINDA
THE INDEX TO LITERATURE AND COMPUTER FILES ON
MICROSCOPIC NEUTRON DATA
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USA National Nuclear Data Center
Russian Nuclear Data Center
NEA Data Bank
IAEA Nuclear Data Section
AEN NEA
NEA DATA BANK, PARIS, 1999
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CD-CINDA
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NAPC Nuclear Data Section

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Scientific Publications

(1991 - 2003)

IAEA publications resulting from the data development activities of the Nuclear Data Section.

- IAEA-TECDOC Reports

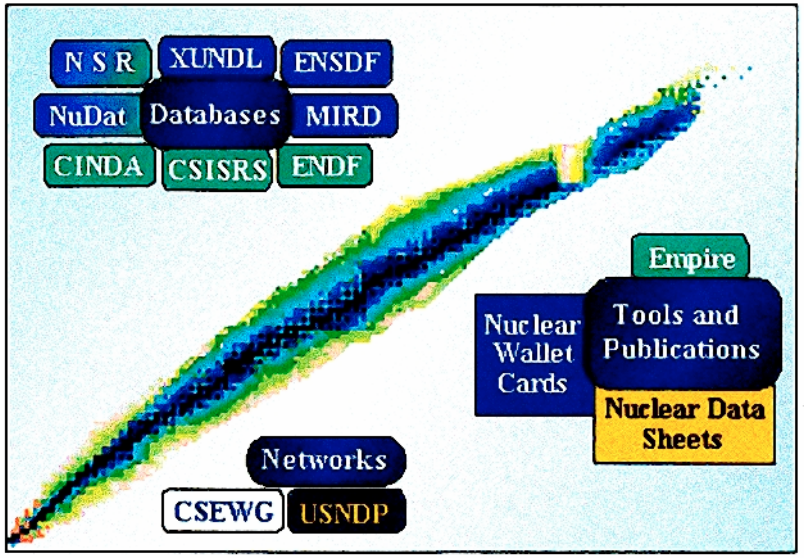
Scientific publications in archival journals and contributions to conferences in:

- Nuclear Data for Applications
- Atomic, Molecular and Plasma-Material Interaction Data

Technical and scientific reports produced by the Nuclear Data Section under the auspices of the International Nuclear Data Committee (INDC).

- INDC(NDS) Reports
- INDC(SEC) Reports

http://www.iaea.or.at/programmes/ripc/nd/publications.html



National Nuclear Data Center

NNDC

BROOKHAVEN NATIONAL LABORATORY

- Nuclear Structure and Decay Databases
- Nuclear Structure and Decay Tools
- Nuclear Reaction Databases
- Nuclear Reaction Tools
- Bibliography Databases
- Networks and Links
- About the Center
- Publications
- Meetings

New: Article about NNDC Web services

Site Index - Search the NNDC: go

CapGam Thermal Neutron Capture Gamma-rays

CINDA Computer Index of Neutron Data

CSEWG Cross Section Evaluation Working Group

CSISRS alias EXFOR Nuclear reaction experimental data

Empire Nuclear reaction model code

ENDF Evaluated Nuclear (reaction) Data File

ENSDF Evaluated Nuclear Structure Data File

For NMMSS and DoE NMIRDC Standards for decay data

IRDF International Reactor Dosimetry File

MIRD Medical Internal Radiation Dose

NSR Nuclear Science References

Nuclear Data Sheets Nuclear structure and decay data journal

Nuclear Wallet Cards Ground and isomeric states properties

Nuclear Wallet Cards for Homeland Security

NuDat Nuclear structure and decay data

RIPL Reference Input Parameter Library

USNDP U.S. Nuclear Data Program

XUNDL Experimental Unevaluated Nuclear Data List

Coming soon: **Atlas of Neutron Resonances**

Coming soon: **Empire 2.19**

http://www.nndc.bnl.gov/index.jsp

LBNL Isotopes Project - LUNDS Universitet
Nuclear Data Dissemination Home Page

LUNDS UNIVERSITET

ERNEST ORLANDO LAWRENCE
BERKELEY NATIONAL LABORATORY

Isotopes Project
Lund Nuclear Data WWW Service

Table of Isotopes	Isotope Explorer	Database Downloads	Table of Radioactive Isotopes	References	Education
Astrophysics	High Spin	Neutron Capture Gamma	Fission	Atomic Masses	Systematics
Atomic Data	Elemental Data	Interaction with Matter	Nuclear Moments	Sites of Interest	

http://ie.lbl.gov/toi.html

Sources of Nuclear Data: General

Activation

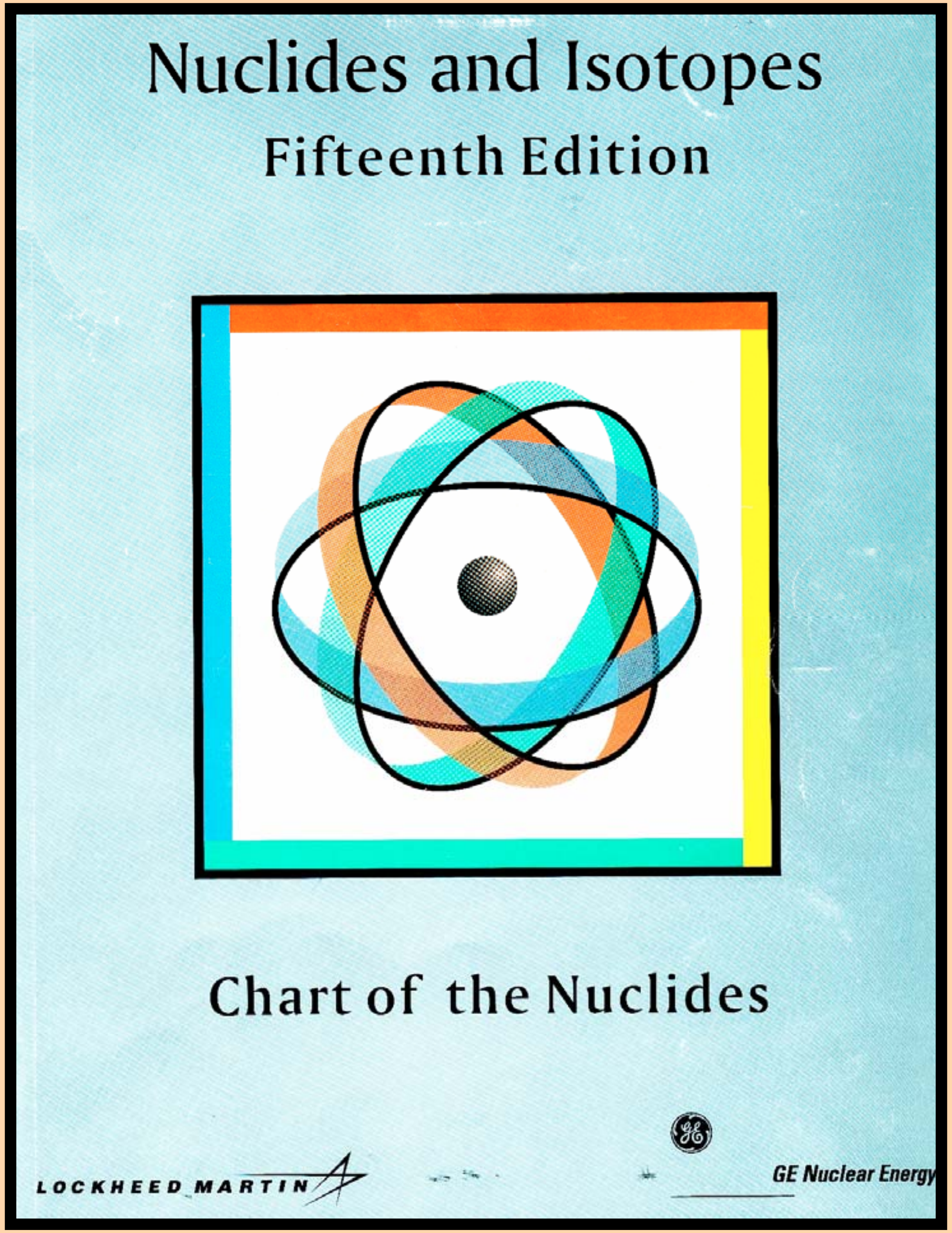

Nuclides and Isotopes
Fifteenth Edition
Chart of the Nuclides
LOCKHEED MARTIN
GE Nuclear Energy

Chart of the Nuclides

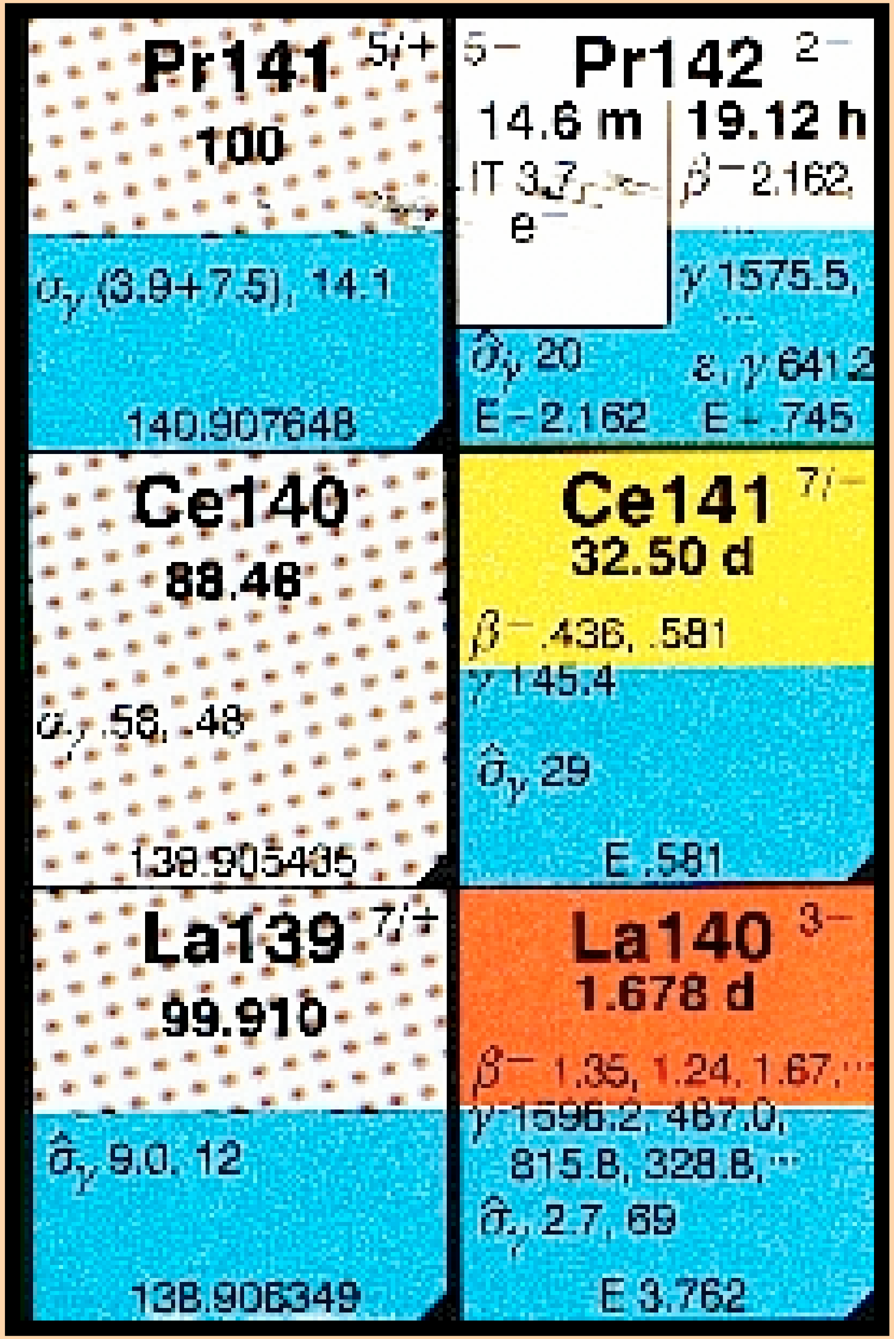
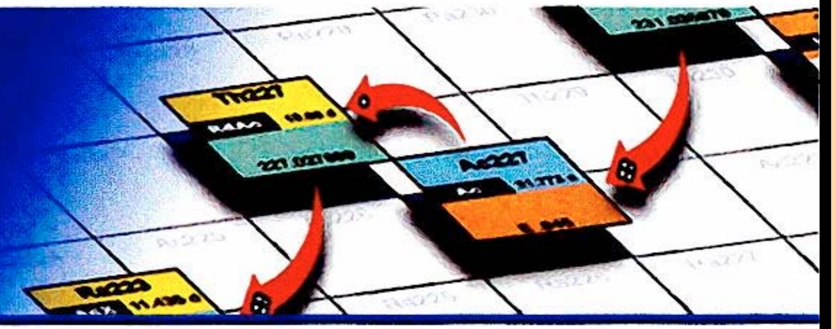


Chart of the Nuclides & Isotopes



http://www.chartofthenuclides.com/

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- TO ORDER
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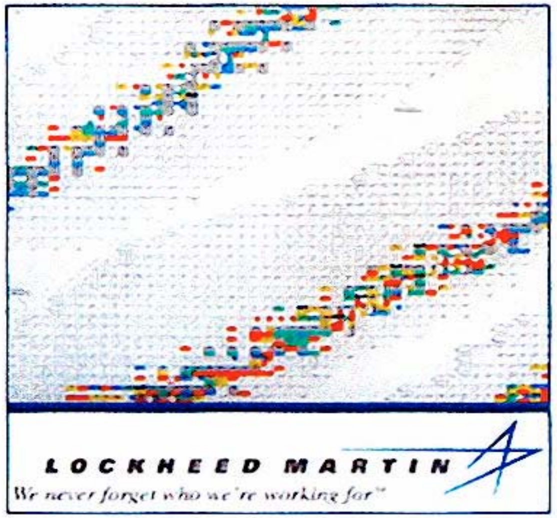
- RELATED LINKS
- CONTACT US

The Sixteenth Edition Is Now Available!

Continuing a half-century tradition, Knolls Atomic Power Laboratory (operated by Lockheed Martin) has published the 16th edition of its classic, "Chart of the Nuclides." Available in both Wallchart and Textbook versions, this document presents the key nuclear properties of every known stable and radioactive form of each element.

Evaluated nuclear data is given for about 3100 known nuclides and 580 known isomers in a format similar to a periodic table. The nuclides are arranged with atomic number Z (number of protons) along the vertical axis and neutron number N along the horizontal axis. For each nuclide the half-life, atomic mass, decay modes, relative abundances, nuclear cross-section, and other nuclear properties are detailed. Color coding is used to emphasize half-lives and neutron absorption properties.



The updated (2003) chart includes approximately 300 new nuclides and 100 new isomers not found in the 15th (1996) edition. There has been at least one change in more than 95% of the squares on the chart.

The Chart of the Nuclides and Isotopes is available as a 36" x 60" single sheet (known as a *Wallchart*) or a bound 88-page soft-cover book (known as a *Textbook*). The Wallchart comes with a 48-page booklet of explanatory information. The explanatory information includes:

- A short history of the development of the periodic table.
- Detailed descriptions of the types of information given on the Chart
- A discussion of trends in stability and instability of nuclides on the Chart

Neutron Cross Sections

Volume 1

NEUTRON RESONANCE PARAMETERS
AND THERMAL CROSS SECTIONS

Part A

Z = 1 - 60

S. F. MUGHABGHAB

M. DIVADEENAM

N. E. HOLDEN

National Nuclear Data Center
Brookhaven National Laboratory
Upton, New York

ACADEMIC PRESS 1981
A Subsidiary of Harcourt Brace Jovanovich, Publishers

New York London
Paris San Diego San Francisco São Paulo Sidney Tokyo Toronto

Neutron Cross Sections

Volume 1

NEUTRON RESONANCE PARAMETERS
AND THERMAL CROSS SECTIONS

Part B

Z = 61 – 100

S. F. MUGHABGHAB

National Nuclear Data Center
Brookhaven National Laboratory
Upton, New York

1984

ACADEMIC PRESS, INC.
(Harcourt Brace Jovanovich, Publishers)

Orlando San Diego New York London
Toronto Montreal Sydney Tokyo

THERMAL CROSS SECTIONS

$\sigma_\gamma = 0.072 \pm 0.004$ b [13.8 hr $^{69}Zn^{m}$] [9/2+]
$\sigma_\gamma = 1.0 \pm 0.1$ b [56 min $^{69}Zn^{g}$] [1/2−]
$\sigma_s = 5.4 \pm 0.3$ b
$\sigma_\alpha < 0.020$ mb
$b_{coh} = 6.7 \pm 0.2$ fm

Zn-68(n,gamma)

RESONANCE PROPERTIES

$\langle \Gamma_{\gamma 0} \rangle = 0.32 \pm 0.04$ eV
$\langle \Gamma_{\gamma 1} \rangle = 0.17 \pm 0.02$ eV
$D_0 = 5.77 \pm 0.73$ keV
$D_1 = 1.29 \pm 0.09$ keV
$S_0 = 2.2 \pm 0.3$
$S_1 = 0.39 \pm 0.03$
$I_\gamma = 3.1 \pm 0.2$ b

Mughabghab et al., 1981 (BNL)

CRC Handbook of Chemistry and Physics

NEUTRON SCATTERING AND ABSORPTION PROPERTIES*
(Revised 1996)

Norman E. Holden
Reactor Division
Brookhaven National Laboratory
Upton, New York 11973

NEUTRON SCATTERING AND ABSORPTION PROPERTIES (continued) (* - Extrapolated Value)

Elem. or Isot.	Natural Abundance (%)	Half-life	Thermal Neut. Cross Section (barns)	Resonance Integral (barns)	Coh. Scat. Length (fm)	σ(30KEV) Maxw. Avg. (barns)
^{114}Cd	28.73(42)		(0.04+0.29)	16.(7)	7.5(1)	0.16(3)
^{116}Cd	7.49(18)		(26.+52.)mb	1.2	6.3(1)	0.09(1)
$_{49}$In			197.(4)	3.3(2)x10^3	4.07(2)	
^{113}In	4.29(5)		(3.1+5.0+3.9)	(220.+90)	5.39(6)	0.79(7)
^{115}In	95.71(5)	4.4x10^{14} y	(88.+73.+44.)	(1.5+1.2+0.7)x10^3	4.01(2)	0.74(7)
$_{50}$Sn			0.61(3)	8.(2)	6.225(2)	

International Atomic Energy Agency

INDC(NDS)-440
Distr. PG+R

INDC

INTERNATIONAL NUCLEAR DATA COMMITTEE

THERMAL NEUTRON CAPTURE CROSS SECTIONS RESONANCE INTEGRALS AND G-FACTORS

S.F. Mughabghab
Brookhaven National Laboratory
Upton, NY 11973-5000
U.S.A.

Research carried out under the auspices of the U.S. Department of Energy under Prime Contract No. DE-AC02-98CH10886, and under IAEA contract No 11376/USA

⇒ ⇒ ⇒

http://www-nds.iaea.org/reports/indc-nds-440.pdf

February 2003

IAEA NUCLEAR DATA SECTION, WAGRAMERSTRASSE 5, A-1400 VIENNA

Mughabghab, 2003

Table I. (continued)

Isotope	Abundance (%)[a]	Capture Cross Section (b)[b]	Capture Cross Section (b)[c]	Westcott g-factor	Resonance Integral (b)
Cu-00		3.78 ± 0.02	3.78 ± 0.02		4.1 ± 0.1
Cu-63	69.174	4.52 ± 0.02	4.50 ± 0.02	1.0002	4.97 ± 0.08
Cu-65	30.826	2.17 ± 0.03	2.17 ± 0.03	1.0002	2.19 ± 0.07
Zn-00		1.11 ± 0.02	1.11 ± 0.02		
Zn-64	48.63	1.1 ± 0.1	0.76 ± 0.02		1.45 ± 0.06
Zn-66	27.90	0.62 ± 0.06	0.85 ± 0.20		1.8 ± 0.3
Zn-67	4.10	9.5 ± 1.4	6.8 ± 0.8		25 ± 3
Zn-68	18.75	0.072 ± 0.004	0.072 ± 0.004		3.4 ± 0.03
Zn-70	0.62	0.091 ± 0.005	0.091 ± 0.005		0.86 ± 0.06

JEF Report 14

TABLE OF SIMPLE INTEGRAL NEUTRON CROSS SECTION DATA FROM JEF-2.2, ENDF/B-VI, JENDL-3.2, BROND-2 AND CENDL-2

AEN
NEA

NUCLEAR ENERGY AGENCY
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT
AGENCE POUR L'ÉNERGIE NUCLÉAIRE
ORGANISATION DE COOPÉRATION ET DE DÉVELOPPEMENT ÉCONOMIQUES

Jef Report 14, 1994

NUCLIDE	REACTION	FILE	MAT	THERMAL CROSS SECT. (B)		
				2200 M/S	MAXW.AVG.	RES.INTEG.
44-Ru- 96	Inel.	JEF-2.2	4425			
		ENDF/B-VI	4425			
		JENDL-3.2	4425			
	n,2n	JENDL-3.2	4425			
	n,g	JEF-2.2	4425	0.2489	0.2207	12.22
		ENDF/B-VI	4425	0.7633	1.482	12.29
		JENDL-3.2	4425	0.2902	0.2572	6.867
	n,p	JEF-2.2	4425			0.1039-04
		JENDL-3.2	4425			

Nuclear Wallet Cards

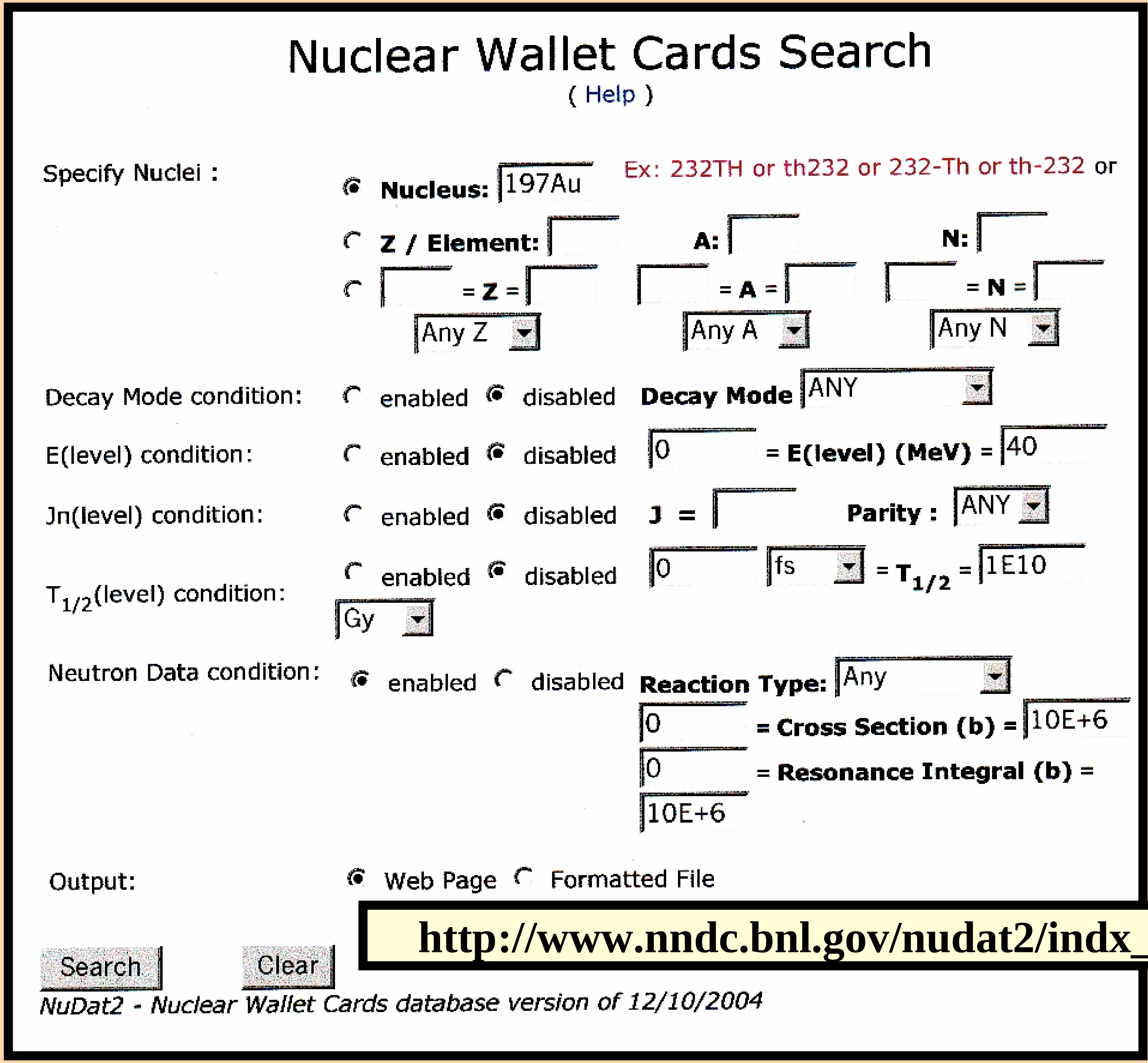
Nuclear Wallet Cards present properties for ground and isomeric states of all known nuclides. Properties given are:

- Spin and parity assignments
- Nuclear mass excesses
- Half-life, isotopic abundances
- Decay modes

Sixth Edition
2000

Appendices contain properties of elements, fundamental constants and other userful information. Nuclear Wallet Cards booklet is published by the National Nuclear Data Center and its electronic (current) version is periodically updated by Dr. Jagdish K. Tuli. Nuclear Wallet Cards are distributed as a booklet as well as in PDA-adaptable Palm Pilot format, ASCII version is available upon request. A web-based version of Nuclear Wallet Cards provides **search** capabilities on ground and isomeric states level properties. For additional nuclear properties see **NuDat 2.0**.

http://www.nndc.bnl.gov/wallet/index.html



Nuclear Wallet Cards Search

(Help)

Specify Nuclei :
- **Nucleus:** 197Au — Ex: 232TH or th232 or 232-Th or th-232 or
- **Z / Element:** **A:** **N:**
- = **Z** = = **A** = = **N** =
- Any Z, Any A, Any N

Decay Mode condition: enabled / disabled — **Decay Mode** ANY

E(level) condition: enabled / disabled — 0 = **E(level) (MeV)** = 40

Jπ(level) condition: enabled / disabled — **J** = **Parity :** ANY

$T_{1/2}$(level) condition: enabled / disabled — 0 fs = $T_{1/2}$ = 1E10 Gy

Neutron Data condition: enabled / disabled — **Reaction Type:** Any
- 0 = **Cross Section (b)** = 10E+6
- 0 = **Resonance Integral (b)** = 10E+6

Output: Web Page / Formatted File

Search   Clear

NuDat2 - Nuclear Wallet Cards database version of 12/10/2004

http://www.nndc.bnl.gov/nudat2/indx_sigma.jsp

Nuclear Wallet Cards Search

Search parameters:
Nucleus:197AU, Reaction Type:ANY, 0 <=Cross Section<= 10E+6, 0 <=Reaction Int.<= 10E+6

Results:

Nucleus	E(level) (MeV)	Jπ	Δ(MeV)	$T_{1/2}$	Abundance	Decay Modes	Reaction type	Product State	σ(b)	Resonance Integral (b)
$^{197}_{79}Au$	0.0000	3/2+	-31.1570	STABLE			Capture		98.65 *9*	1.55E+3 *3*
							Scattering		7.84 *13*	

NUCLEAR DATA SERVICES

Nuclear Data from NuDat

Tables of nuclear data will be produced for the specified type of nuclear data and the nuclides specified by the user. A brief description may be found in the Abstract and a full desciption including examples may be found in the document "The NuDat Program for Nuclear Data on the Web".

Data Base Last Updated On January 15, 2003

	Type of Nuclear Data
LEVELS	Adopted levels from ENSDF
GAMMAS	Adopted gammas rays from ENSDF
LEVELS AND GAMMAS	Adopted levels and gamma rays from ENSDF
WALLET CARDS	Ground and Metastable State Properties
DECAY RADIATIONS	ENSDF decay data processed by RADLIST
NEUTRON DATA	Thermal Data and Resonance Integrals from BNL325

Updated by: TWB (May 17, 2002).

NuDat

Thermal Cross Sections and Resonance Integral Retrieval Parameters

Thermal Cross Sections and Resonance Integral Retrieval Parameters

Mass Number: 197

Element: Au

Half-Life:

Reaction: c

Sigma:

Resonance Int:

Table Format: Narrow

Submit | Clear Form

Levels | Gammas | Levels & Gammas | Wallet Cards | Decay Radiations | Neutron Data

Nuclear Data Services

Nuclear Level Density Parameters based on new values for the spin dispersion parameter are available here.

Nuclear Data (NuDat) Retrieval

Neutron Data (Thermal Cross Sections and Resonance Integrals)

Mass Number: 197 **Reaction:** C
Element: AU **Sigma:**
$T_{1/2}$: **Resonance Integral:**

A	ELEMENT	Half-Life	Sigma Type	Product State	Sigma (barns)	Sigma Uncertainty (barns)	RI (barns)	RI Uncertainty (barns)
197	AU	STABLE	C		98.65	0.09		
197	AU	STABLE	C				1550.	28.

This program and the accompanying data base has been produced by the National Nuclear Data Center located at the Brookhaven National Laboratory Upton, N.Y., USA, with funding from the U.S. Department of Energy. Neither the BNL nor the USDOE make any warranty or assume any legal responsibility for the contents of the data base.

Generated at the IAEA NDS by NUDAT Wed Feb 9 13:11:59 2005

Westcott s_0

F. DE CORTE et al:
JRNC, 179 (1994) 93 -103

mainly from

C.H. WESTCOTT: Effective cross section values
for well-moderated thermal reactor spectra
Report CRRP-960 of the AECL, Nov 1, 1960 (reprinted 1962)

J.I. KIM, E.M. GRYNTAKIS, H.J. BORN:
Radiochim. Acta, 22 (1975) 20

Table 1

Status of the relevant nuclear data of the analytically interesting nuclides and monitors

Target nuclide	$g(T_n, {}^oC)$[29]	W'	F_{Cd}	$\bar{E}_r$,eV	s_o	Formed nuclide (Activation-decay type)[27]	Half life T	Notes
^{103}Rh	1.025 (20) 1.044 (100)	-	-	1.45	7.26*	^{104}Rh (IV/a)	42.3 s	k_o in Ref.[28] via HØGDAHL convention; * : from Ref.[6]
^{115}In	1.020 (20) 1.036 (100)	-	0.93	1.56	18.5*	^{116m}In (IV/b)	54.15 min	k_o's in Ref.[28] via HØGDAHL convention; * : calc. from Q_o
^{151}Eu	0.901 (20) 0.831 (100)	-	-	0.448	1.20*	^{152m}Eu (I)	9.32 h	k_o's in Ref.[8] via WESTCOTT convention; * : from Ref.[31]
					1.25*	^{152}Eu (I)	13.51 a	
^{164}Dy	0.988 (20) 0.978 (100)	-	1	224	-0.20*	^{165m}Dy (I)	1.258 min	k_o's in Ref.[28] via HØGDAHL convention; * : calc. from Q_o
					-0.27*	^{165}Dy (IV/b)	2.334 h	

F. De Corte et al:
JRNC, 179 (1994) 93 -103

Pure Appl. Chem., Vol. 71, No. 12, pp. 2309–2315, 1999.
Printed in Great Britain.

INTERNATIONAL UNION OF PURE AND APPLIED CHEMISTRY

ANALYTICAL CHEMISTRY DIVISION
COMMISSION ON RADIOCHEMISTRY AND NUCLEAR TECHNIQUES*

TEMPERATURE DEPENDENCE OF THE WESTCOTT *g*-FACTOR FOR NEUTRON REACTIONS IN ACTIVATION ANALYSIS

(Technical Report)

Prepared for publication by
NORMAN E. HOLDEN
Reactor Division, Brookhaven National Laboratory (BNL), Upton, New York, 11973, USA

Holden, PAC 1999

Table 2 Westcott *g*-factors for neutron capture reactions

T (°C)	E_n (eV)	^{151}Eu	^{152}Eu	^{153}Eu	^{154}Eu	^{155}Eu	^{155}Gd	^{157}Gd
0	0.0236	0.9225	0.9469	0.9799	1.1839	1.0462	0.8586	0.8642
20	0.0253	0.9014	0.9272	0.9741	1.2278	1.0573	0.8443	0.8521
40	0.0270	0.8817	0.9083	0.9685	1.2736	1.0688	0.8296	0.8393
60	0.0287	0.8634	0.8902	0.9630	1.3212	1.0807	0.8147	0.8259
80	0.0305	0.8464	0.8729	0.9576	1.3701	1.0929	0.7996	0.8122
100	0.0322	0.8307	0.8562	0.9523	1.4201	1.1057	0.7845	0.7983
120	0.0339	0.8164	0.8402	0.9471	1.4707	1.1189	0.7695	0.7843
140	0.0356	0.8033	0.8248	0.9421	1.5218	1.1326	0.7547	0.7703
160	0.0374	0.7915	0.8099	0.9372	1.5730	1.1470	0.7400	0.7563
180	0.0391	0.7810	0.7956	0.9323	1.6239	1.1620	0.7256	0.7425
200	0.0408	0.7717	0.7819	0.9276	1.6744	1.1778	0.7115	0.7288
220	0.0425	0.7637	0.7686	0.9230	1.7243	1.1945	0.6976	0.7154
240	0.0443	0.7569	0.7557	0.9185	1.7732	1.2122	0.6841	0.7022
260	0.0460	0.7514	0.7434	0.9141	1.8211	1.2310	0.6708	0.6892
280	0.0477	0.7471	0.7314	0.9097	1.8678	1.2511	0.6579	0.6765
300	0.0494	0.7440	0.7198	0.9055	1.9131	1.2726	0.6453	0.6640
320	0.0512	0.7421	0.7086	0.9014	1.9570	1.2957	0.6331	0.6519
340	0.0529	0.7414	0.6977	0.8973	1.9994	1.3206	0.6211	0.6400
360	0.0546	0.7419	0.6872	0.8933	2.0402	1.3474	0.6095	0.6284
380	0.0563	0.7435	0.6770	0.8894	2.0793	1.3764	0.5982	0.6170
400	0.0580	0.7463	0.6671	0.8856	2.1169	1.4078	0.5872	0.6060