

# CHEMICAL ANALYSIS

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# Neutron Activation Analysis

D. De Soete

*Chief Assistant*

R. Gijbels

*Research Associate, Interuniversitair  
Instituut voor Kernwetenschappen*

J. Hoste

*Professor of Analytical Chemistry  
Institute for Nuclear Chemistry  
State University of Gent, Belgium*

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## PHYSICAL CONSTANTS

Symbol	Denomination	Magnitude
a.m.u.	atomic mass unit	931.48 MeV ( $^{12}\text{C}$ scale) 931.16 MeV ( $^{16}\text{O}$ scale)
$c$	light velocity in vacuum	$2.99793 \cdot 10^{10}$ cm $\text{s}^{-1}$
$e$	electron charge	$4.803 \cdot 10^{-10}$ esu
$h$	Planck's constant	$6.625 \cdot 10^{-27}$ erg s
$\hbar$	$= h/2\pi$	$1.0544 \cdot 10^{-27}$ erg s
$k$	Boltzmann's constant	$1.38047 \cdot 10^{-16}$ erg $\text{deg}^{-1}$
$m_n$	neutron mass	1.008665 a.m.u. ( $^{12}\text{C}$ scale) $1.6757 \cdot 10^{-24}$ g
$m_0$	electron rest mass	$5.486 \cdot 10^{-4}$ a.m.u. ( $^{12}\text{C}$ scale) $9.107 \cdot 10^{-28}$ g
$m_0 c^2$	electron rest energy	0.5110 MeV
$m_p$	proton rest mass	1.007273 ( $^{12}\text{C}$ scale) $1.6724 \cdot 10^{-24}$ g
$N_A$	Avogadro's number	$6.023 \cdot 10^{23}$ atoms $\text{mole}^{-1}$ ( $^{12}\text{C}$ scale)

## LIST OF SYMBOLS

<i>Symbol</i>	<i>Denomination</i>	<i>Symbol</i>	<i>Denomination</i>
$\alpha$	-alpha particle	$s$	-number of disintegrations
	-conversion coefficient		-distance
	-quotient of distribution coefficients	$s$	energy needed for a hole-electron pair creation (eV)
	-correction factor in the internal standard method	$s_x$	excitation energy of nucleus $x$ (MeV)
$A$	-mass number	$E$	energy (MeV, keV, eV, erg, . . .)
	-atomic weight	$E_b$	Coulomb barrier energy (MeV)
	-activity (rate or number of disintegrations, - counts)	$E_{Cd}$	cadmium cut-off energy (eV)
	-ampere	$E_{eff}$	effective threshold energy (MeV)
$\text{\AA}$	Angstrom ( $10^{-8}$ cm)	$E_{max}$	maximum energy in beta spectrum (MeV)
$\beta$	beta particle	$E_n$	energy corresponding to neutron velocity $v_n$ (0.025 eV)
$\beta^-$	negatron	$E_r$	energy at the maximum of a resonance peak (eV)
$\beta^+$	positron	$E_T$	threshold energy (MeV)
$B$	background	$E_x$	recoil energy of nucleus $x$ (MeV)
$b$	barn = unit of cross section ( $\text{cm}^2$ )	eV	electron volt ( $1.60 \cdot 10^{-12}$ erg)
$c$	number of counts	$\varphi$	neutron flux (beam or multidirectional) ( $\text{n cm}^{-2} \text{s}^{-1}$ )
cm	centimeter ( $10^{-2}$ m)	$\bar{\varphi}$	equivalent fission flux ( $\text{n cm}^{-2} \text{s}^{-1}$ )
$C$	-signal + background	$\varphi(E)$	$\varphi$ at neutron energy $E$ ( $\text{n cm}^{-2} \text{s}^{-1}$ )
	-capacity (Farad)	$\varphi_c$	epicadmium neutron flux per unit of lethargy = conventional epicadmium flux ( $\text{n cm}^{-2} \text{s}^{-1}$ )
	-compound nucleus	$\varphi_c(E)$	$\varphi_c$ at neutron energy $E$ ( $\text{n cm}^{-2} \text{s}^{-1}$ )
Ci	Curie ( $3.7 \cdot 10^{10}$ dps)		
$C_i$	convolution integer		
CR	cadmium ratio		
CR <sub>x</sub>	cadmium ratio of element (isotope) $x$		
CT	clock time		
$\delta$	-density ( $\text{g cm}^{-3}$ )		
	-residual standard deviation		
$D$	disintegration rate (dps, . . .)		
$D_A$	distribution coefficient for species $A$		
DT	total dead time		
$d$	-absorption thickness ( $\text{mg cm}^{-2}$ )		

## LIST OF SYMBOLS

xi

<i>Symbol</i>	<i>Denomination</i>	<i>Symbol</i>	<i>Denomination</i>
$\varphi_{cor}$	$\varphi$ , corrected for resonance absorption at finite dilution ( $\text{n cm}^{-2} \text{s}^{-1}$ )	$f_s$	self-absorption coefficient for beta rays
$\varphi_0$	conventional thermal neutron flux = $n v_0$ ( $\text{n cm}^{-2} \text{s}^{-1}$ )	$f_t$	comparative half-life of beta decay
$\varphi_{reactor}$	conventional reactor neutron flux ( $\text{n cm}^{-2} \text{s}^{-1}$ )	$f_{th}$	thermal neutron absorption factor in solids
$\varphi_{th}$	conventional thermal neutron flux below $E_{Cd}$ = $n_{th} v_0$ ( $\text{n cm}^{-2} \text{s}^{-1}$ )	$\Gamma$	nuclear level width (eV)
$\varphi_{th}(E)$	thermal neutron flux at energy $E$ ( $\text{n cm}^{-2} \text{s}^{-1}$ )	$\Gamma_x$	partial $\Gamma$ (eV)
$F$	-14 MeV neutron flux ( $\text{n cm}^{-2} \text{s}^{-1}$ )	$\gamma$	gamma ray
	-Fano factor	g	gram
	-decay correction factor for measurement of short lived activities (starting point of measuring interval)	h	-photopeak height (cm, activity)
$FDT$	fractional dead time		-height
$F_n$	fraction of the disintegration of the nuclides of the $n^{th}$ step, producing nuclides of the $(n+1)^{th}$ step in a disintegration chain	$I$	-hour
		$I$	resonance integral at infinite dilution (barn)
		$I'$	$I$ corrected for $1/v$ contribution (barn)
		$I_{abs}$	absorption resonance integral at infinite dilution (barn)
		$I_{act}$	activation resonance integral at infinite dilution (barn)
		$IDT$	instantaneous dead time
		$I^{eff}$	effective resonance integral = $I$ corrected for resonance absorption = $I$ at finite dilution (barn)
FWHM	full width at half maximum of a (photo)peak (eV, keV, . . .)	$I_n$	$I$ for the $n^{th}$ resonance peak (barn)
$f$	-total neutron absorption factor in solids	$I_{tot}$	= $\sum I_n$ (barn)
	-decay correction factor for the measurement of short lived activities (exact time within the measuring interval)	$I_x$	$I$ for the nuclear reaction of type $x$ (barn)
	-fission	$I'_x$	$I'$ for the nuclear reaction of type $x$ (barn)
	-fraction	$I_{1/v}$	resonance integral at infinite dilution obtained by integration of $\sigma_{1/v}$ (barn)
$f'$	total neutron absorption factor in solution	$\kappa$	-linear absorption coefficient for pair production ( $\text{cm}^{-1}$ )
$f(E)$	fission neutron flux at energy $E$ ( $\text{n cm}^{-2} \text{s}^{-1}$ )		-dielectric constant
$f_s$	epicadmium neutron absorption factor in solids		

Symbol	Denomination	Symbol	Denomination
$K_D$	distribution constant	mCi	milli-Curie ( $10^{-3}$ Curie)
$k$	-reactor reproduction factor	mg	milligram ( $10^{-3}$ gram)
	-constant	ml	milliliter = $10^{-3}$ liter
keV	kilo electron volt ( $10^3$ eV)	m $\mu$	milli micron = $10^{-7}$ cm ( $10^{-3}$ micron)
kg	kilogram ( $10^3$ g)	mm	millimeter ( $10^{-3}$ m)
$\lambda$	-radioactive decay constant ( $s^{-1}$ )	ms	milli second ( $10^{-3}$ second)
	-wave length ( $m\mu$ , $\text{\AA}$ )	mV	-milli electron volt ( $10^{-3}$ eV)
$l$	mean free path (cm)		-millivolt ( $10^{-3}$ volt)
L	-liter	$\nu$	-frequency ( $s^{-1}$ )
	-ligand		-neutrino
$L_c$	critical limit		-number of neutrons liberated per fission
$L_D$	detection limit		-number of neutrons in the nucleus
$L_Q$	quantitative determination limit	N	-number of target nuclei per $cm^2$
LT	live time		-normality (g eq. $L^{-1}$ )
$\mu$	-total mass absorption coefficient ( $cm^2 mg^{-1}$ )	n	-thermal neutron density from energy 0 to $\infty$ ( $n cm^{-3}$ )
	-micron ( $10^{-4}$ cm)		-neutron
$\mu'$	total linear absorption coefficient ( $cm^{-1}$ )	$n(E)$	neutron density at energy $E$ ( $n cm^{-3}$ )
$\mu A$	micro ampere ( $10^{-6}$ A)	ng	nano gram ( $10^{-9}$ gram)
$\mu b$	microbarn ( $10^{-6}$ barn)	ns	nano second ( $10^{-9}$ second)
$\mu Ci$	micro Curie ( $10^{-6}$ Curie)	$n_{th}$	thermal neutron density below $E_{cut}$ ( $n cm^{-3}$ )
$\mu g$	micro gram ( $10^{-6}$ gram)	$\bar{n}_{th}$	average $n_{th}$ in the sample at finite dilution ( $n cm^{-3}$ )
$\mu l$	micro liter ( $10^{-6}$ liter)	$n(v)$	neutron density at velocity $v$ ( $n cm^{-3}$ )
$\mu_n$	mobility of electrons in $n$ -type semiconductor material ( $cm^2 V^{-1} s^{-1}$ )	P	-probability
			-peak to total ratio
$\mu_p$	mobility of holes in $p$ -type semiconductor material ( $cm^2 V^{-1} s^{-1}$ )	p	proton
		Q	-reaction energy (MeV, a.m.u., ...)
$\mu s$	micro second ( $10^{-6}$ second)		-quality criterion of a counter
M	-molarity (mole $L^{-1}$ )	q	branching factor
	-factor of merit of a counter = $S/2\sqrt{B}$	$\rho$	resistivity (ohm $cm^{-1}$ )
MeV	million electron volt ( $10^6$ eV)	R	-reaction rate ( $s^{-1}$ )
m	-minute		count rate (cps, cpm, ...)
	-mass		
	-meter		
mA	milli ampere		
meq	milli equivalent		
mb	millibarn ( $10^{-3}$ barn)		

Symbol	Denomination	Symbol	Denomination
	-particle range	$\sigma_c$	cross section for compound nucleus formation (= $\sigma_{c,b}$ ) (barn)
	-resolution	$\sigma_{coh}$	coherent scatter cross section (barn)
	-radius	$\sigma_{col}$	collision cross section (barn)
	-distance	$\sigma(D)$	standard deviation for a signal equal to the detection limit
	-resistance (ohm)	$\sigma(E)$	cross section at neutron energy $E$ (barn)
$R_A$	-nuclear radius (Fermi unit = $10^{-13}$ cm)	$\sigma_{el}$	effective cross section (barn)
	-recovery factor of species $A$	$\sigma_{el}$	elastic scatter cross section (barn)
$R(V, E)$	response function of a detector	$\sigma_f$	fractional standard deviation (= coefficient of variation) = $\sigma_f/100$
$r$	-distance	$\sigma_{fa}$	free atom scatter cross section (barn)
	-radius	$\sigma_{inel}$	inelastic scatter cross section (barn)
$\Sigma$	macroscopic cross section = $\sigma N$ ( $cm^{-1}$ )	$\sigma_{14 MeV}$	cross section for 14 MeV neutrons (barn)
$\Sigma_R$	macroscopic removal cross section of sample for 14 MeV neutrons ( $cm^{-1}$ )	$\sigma_{n.e.}$	non elastic scatter cross section (barn)
$\Sigma_{R(i)}$	macroscopic removal cross section of element $i$ for 14 MeV neutrons ( $cm^{-1}$ )	$\sigma_{n,r}$	reaction cross section (barn)
$\sigma$	-effective microscopic target area ( $cm^2$ )	$\sigma(0)$	standard deviation of background for zero signal
	-cross section (barn)	$\sigma_0$	cross section at neutron velocity $v_0$ (barn)
	-linear absorption coefficient for Compton effect ( $cm^{-1}$ )	$\bar{\sigma}_0$	average elemental cross section at neutron velocity $v_0$ (barn)
	-standard deviation for an infinite population	$\sigma_p$	potential scattering cross section (= $4\pi R_A^2$ ) (barn)
$\bar{\sigma}$	average cross section in a fission neutron spectrum (barn)	$\sigma(Q)$	standard deviation for a signal at the quantitative determination limit
$\sigma\%$	percentage standard deviation (= percentage coefficient of variation)	$\sigma_r$	resonance cross section (barn)
$\sigma_{abs}$	absorption cross section (= $\sigma_c$ ) (barn)		
$\sigma_{act}$	isotopic activation cross section (barn)		
$\bar{\sigma}_{act}$	average elemental activation cross section (barn)		

Symbol	Denomination	Symbol	Denomination
$\sigma_r(E)$	resonance cross section at neutron energy $E$ (barn)	$T_{1/2}$	-total time = $\Delta t_o + \Delta t_p$ half-life = $\ln 2/\lambda$ (y, h, m, s, . . .)
$\sigma_{\text{reactor}}$	cross section for a reactor neutron spectrum (barn)	$T_m$	Maxwellian temperature ( $^{\circ}\text{K}$ )
$\sigma_{\text{reactor}}^{\text{eff}}$	effective $\sigma_{\text{reactor}} = \sigma_{\text{reactor}}$ corrected for absorption at finite dilution (barn)	$T_0$	293.6 $^{\circ}\text{K}$
$\sigma_{2(i)}$	microscopic elemental removal cross section for 14 MeV neutrons ( $\text{cm}^2$ )	$T_R$	reactor period
$\bar{\sigma}_s$	average scatter cross section (barn)	$t$	-decay time (h, m, s, . . .)
$\sigma_T$	total cross section (barn)	$t_{1/2}$	-thickness (cm)
$\sigma_{\text{th}}$	average cross section for neutron energies up to $E_{\text{Cd}}$ (barn)		-temperature ( $^{\circ}\text{C}$ )
$\sigma(v)$	cross section at neutron velocity $v$ (barn)		time necessary to establish half of the equilibrium distribution in isotopic exchange
$\sigma(\bar{v})$	cross section at neutron velocity $\bar{v}$ (barn)	$t_p$	irradiation time (h, m, s, . . .)
$\sigma_{1/\nu}$	cross section in the episcadmium region, disregarding resonance peaks (barn)	$t_{\text{eff}}$	effective thickness for resonance neutron absorption (cm)
$S$	-saturation factor -surface, area -signal	$u$	number of standard deviations
$S_{B/A}$	separation factor of species $B$ from $A$ = enrichment factor of $A$ = depletion factor for $B$	$V$	-volume (L, ml, $\mu\text{l}$ , . . .)
$s$	-standard deviation for a finite population -second	$V(d)$	-tension (volt)
$\theta$	-isotopic abundance -angle (degree, radian)	$v$	-volt electrical field
$\tau$	-mean life (s, . . .) -dead time ( $\mu\text{s}$ , . . .) -resolving time ( $\mu\text{s}$ , . . .) -linear absorption coefficient for photoelectric effect ( $\text{cm}^{-1}$ )	$\bar{v}$	-neutron velocity ( $\text{cm s}^{-1}$ )
$T$	-absolute temperature ( $^{\circ}\text{K}$ )	$v_1$	average neutron velocity in a Maxwell-Boltzmann distribution ( $\text{cm s}^{-1}$ )
		$v_0$	neutron velocity at $E_{\text{Cd}}$ ( $\text{cm s}^{-1}$ )
		$W_i$	most probable neutron velocity in a Maxwell-Boltzmann distribution (2200m/s at $20^{\circ}\text{C}$ = 0.025 eV)
		$w$	statistical weight
		$y$	weight (g, mg, . . .)
		$\zeta$	-year -fission yield
		$Z$	Fermi potential in a semiconductor (eV)
		$z$	-atomic number -residual counting efficiency

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