International Atomic Energy Agency

Neutron Kerma factors in EXFOR: actual status and missing published results

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Workshop of
International Network of Nuclear Reaction Data Centres
6 – 10 October 2014, Vienna

Neutron KERMA factors: Definitions and Units

- **Definition of Quantity:**

  KERMA (*K*) = **K**inetic **E**nergy **R**eleased in **Ma**tter per mass unit: ***K* = *dE/dm***

  K accounts for energy deposition from all **charged ejectiles** (*p, d, α,* … *e(?)*) of nuclear reaction including **recoils** (which deposit energy **locally**) however **excludes** neutral reaction products (*n, γ,* …) (which deposit energy **non-locally** or at "large" distance from collision)

- KERMA **Factors** k_f is a ***K*** per particle fluence ***Φ* = *N/Area*:**

$$k_f = {}^{K}/_{\Phi}$$

- k_f is a product of mean ejectile energy E_j and production cross section σ_j summed over all reaction channels ***j*** and normalized per target mass *M*

total k_f

$$k_f(E) = \sum_j k_j = \sum_j E_j\, \sigma(n,xj)\,/M$$

partial k_j

- KERMA Factors **Unit** is *[Energy/Mass*Area]* and could be expressed as:
  - *in SI base units:* J/kg m^2 = Gy m^2 = *10^{+15} fGy m^2 (most often used units)*
  - *in CGS base units:* erg/g cm^2 = rad cm^2

    inter-conversion: *1 fGy m^2 = 10^{+9} rad cm^2 (1 J = 10^{+7}erg, 1 Gy = 100 rad)*

What do KERMA factors serve for

- **Reactor and Radiation Material Physics**: Kerma Factors being partitioned between *Electron Ionization losses* and *Atom Recoils Energies* gives the **Damage Energy** that defines the Number of Primary Kick-off Atoms (PKA) shifted from the lattice sites and finally the displacement-per-atom rate, i.e. **dpa-cross-sections** *(this is a point of interest for the IAEA CRP on "Primary Radiation Damage Cross Sections": https://www-nds.iaea.org/CRPdpa/)*

- **Medicine**: Neutron Kerma factors are used in Medicine to predict the ionization coursed by secondary charged particles from neutron reactions in human tissue or Tissue Equivalent Plastics (TEP, e.g. A-150 …)

- More Generally: the measured Kerma factors are used for **Validation of Evaluated cross section Libraries** that gives a confidence for their predictions

KERMA definitions and data from ICRU http://www.icru.org/

- **International Commission on Radiation Units and Measurements (ICRU)** develops internationally recommendations on radiation quantities/units, reference data for ionizing radiation to medical, science/technology, protection…
- **ICRU collaborates** with:

  professional societies, government agencies, national labs …
  US National Council on Radiation Protection (NCRP)
  International Atomic Energy Agency (IAEA) http://www-naweb.iaea.org/nahu/index.html
  World Health Organization (WHO)
  International Commission on Radiological Protection (ICRP)
  United Nations Scientific Committee on Effects of Atomic Radiation (UNSCEAR)
  International Organization for Standardization (ISO)
  International Bureau and Committee of Weights and Measures (BIPM, CIPM)

- **ICRU current members** (15) :

  H.-G. Menzel (Switzerland, *Chairman);* P.M. DeLuca, Jr (USA, *Vice Chairman)* ...
  (they are Authors of papers proposed to compile – Entries can be sent for approval)

- **ICRU Report 13 “**Neutron Fluence, Neutron Spectra and Kerma” (1969)
  19 “Radiation Quantities and Units (1971) ?
  63 “Nuclear Data for Neutron and Proton Radiotherapy and for Radiation Protection”, 2000, ISBN 0-913394-62-9 (*Kf* up to 150 MeV)

What EXFOR Policy Documents say about KERMA factors

- **LEXFOR** (IAEA-NDS-208, rev 2011/01) has

  No Information about **KERMA (factors) at all**

- **EXFOR Basics** (IAEA-NDS-206, June 2008) defines in Dictionary 236 the reaction Parameter (SF6) as:

  ,KER - *Kerma factor*

- **EXFOR Protocol** (IAEA-NDS-0215, rev 2014/05) categories a compilation scope for Kerma as:

  B - Voluntary compilation …. Kerma factors (integral data only)

EXFOR actual status: 3 measurements are compiled so far

- **U.J. Schrewe et al. - Entry** 22507 contains Kerma Factors for
  - **Elements**

    ^{12}C, ^{14}N, ^{16}O, ^{00}Mg, ^{27}Al, ^{00}Si, ^{00}Fe, ^{00}Zr
  - **Materials**

    C-CMP (A-150 = tissue-equivalent plastic)

    Al-CMP (Aluminium nitrate AlN), AL-OXI (Aluminium oxide Al_2O_3)

    SI-OXI (Silicon oxide SiO_2), ZR-OXI (Zirconium oxide ZiO_2)

    (*my comments: - data in EXFOR are from (C,97TRIEST,2,1643,199705)*

    *- authors' data were wrongly converted into fGy*m2 !*

    - likely have to be superseded by Phys. Med. Biol. 45(2000)651)

- **U.J. Benck et al. - Entries** 22811 & 22807 **:** Total and Partial K_f for:
  - **Elements** ^{27}Al, ^{00}Si

    (*my comments: main reference (J,PMB,44,(1),1,1999) in Entry 22811.001*

    seems is incorrect, should be J,PMB,45(1),29,2000)

- **E. Raeymackers et al. - Entry** 22942 **:** Total and partial Kf
  - **Elements** ^{209}Bi, U

Current List of missing published experimental results (1)

current list is here: https://www-nds.iaea.org/CRPdpa/DataMissed.pdf

Reaction	Source Lab	Reference	EXFOR
C Mg Fe TEP	D-T 14.7 MeV Univ. of Kansas	C. Wuu and L. Milavickas, Determination of the Kerma Factors in Tissue-equivalent Plastic. C, Mg, and Fe for 14.7 MeV Neutrons **Med. Phys. 14(6), 1007 (1987)**	compile
C Mg Fe	D-T 15.0 MeV LLNL	E. Goldberg, D.R. Slaughter, R.H. Howell, Experimental Determination of Kerma Factors at E ≈ 15 MeV, **LLL Report UCID-17789, 1978**	compile
C	RTNS-I 14.1, 15, 17.9 MeV	P.M. DeLuca, Jr., H.H. Barschall, R.C. Haight, and J.C. McDonald, ‘‘Kerma factor of carbon for 14.1 MeV neutrons’, **Radiation Research 100, 78–86 (1984)**	compile
		P.M. DeLuca, Jr., H.H. Barschall, R.C. Haight, J.C. McDonald, ‘‘Measured neutron carbon kerma factors from 14.1 MeV to 18 MeV,’’ *Proc. of 5th Symp. Neutron Dos., v I:* Luxembourg, 1985, **No. EUR 9762 EN, p.193**.	
	LLNL	P.M. DeLuca, Jr., H.H. Barschall, M. Burhoe, and R.C. Haight, ‘‘Carbon kerma factor for 18- and 20-MeV neutrons,’’ **Nucl. Sci. Eng. 94 (1986) 192-198**	compile

Current List of missing published experimental results (2)

current list is here: https://www-nds.iaea.org/CRPdpa/DataMissed.pdf

Reaction	Source Lab	Reference	EXFOR
O, Al, Si	RTNS-I 14.1, 15, 17.9 MeV LLNL	P.M. DeLuca, H.H. Barschall, H.H. Sun, R.C. Haight, ‘Kerma factor of Oxygen Aluminium and Silicon for 15 and 20 MeV Neutrons **Radiat. Protect. Dosimetry 23 (1988) 27**	compile
C	D-T LLNL	R.C. Haight, S.M. Grimes et al. **NSE 87 (1984) 41**	compile
H at C, N,O at	^{7}Li(p,n) Crocker lab. CA	J.L. Romero, F.P. Brady, T.S. Subramanian, ‘‘Neutron induced charged particle spectra and kerma from 25 to 60 MeV,’’ **Santa Fe - 1985, v. 1, pp. 687–699**	compile
C, O, Si	T(d,n) Uni of Wisconsin	C.L. Hartmann, P.M. DeLuca, Jr., and D.W. Pearson, ‘Measurement of neutron kerma factors in C, O, and Si at 18, 23, and 25 MeV,’ **Radiat. Protect. Dosim. 44, 25 (1992)**	compile
C, Mg, Fe		C.L. Hartmann, P.M. DeLuca Jr., D.W. Pearson, ‘Measurement of C, Mg and Fe Kerma Factors and the ^{19}F(n,2n)^{18}F Cross Section for 18 to 27 MeV Neutrons’ **ND-1991, Jülich, pp. 589-591** C.L. Hartmann, Measurements of Neutron Kerma Factors at 18, 23 and 25 MeV, **Ph.D. Thesis, Uni of Wisconsin, 1991**	

Current List of missing published experimental results (3)

current list is here: https://www-nds.iaea.org/CRPdpa/DataMissed.pdf

Reaction	Source Lab	Reference	EXFOR
Mg, Si, Fe O	WNR by ToF LANL PSI	W.D. Newhauser, "Neutron Kerma Factor Measurements in the 25 MeV to 85 MeV Neutron Energy Range", **Ph.D. Thesis, University of Wisconsin, Madison, 1995 here** **Abstract: Medical Physics 22(1995)2128**	compile
C total and partial	Cyclotron Li(p,n) Louvain-la-Neuve	I. Slypen, V. Corcalciuc, and J.P. Meulders, 'Kerma values deduced from neutron-induced charged-particle spectra of carbon from 40-MeV to 75-MeV' **Phys. Med. Biol. 40, 73–82 (1995)**	Compile
C		I. Slypen, S. Benck, J.P. Meulders, V. Corcalciuc, 'Experimental partial and total kerma coefficients for carbon deduced from microscopic cross sections at incident neutron energies below 75 MeV" **Phys. in Med. and Biol. 45 (2000) 577**	???
H		V. Corcalciuc, S. Benck, R. Malu, J.P. Meulders, I. Slypen, "Experimental hydrogen kerma factors for incident neutron energies from 25 to 75 MeV, **Phys. in Med. and Biololgy 44(1999)719**	???
H, C, O, N, *A-150, TEM, TE-P, H_2O, muscle*	Cyclotron Li(p,n) Louvain-la-Neuve	J.P. Meulders, S. Benck, I. Slypen, V. Corcalciuc, 'Experimental kerma coefficients of biologically important materials at neutron energies below 75 MeV', **Medical Physics 27, 2541 (2000)**	compile
^{12}C(n,n'3α)	^{9}Be(d,n) Louvain-la-Neuve	B. Antolkovic, L. Slaus and D. Plenkovic, **"**Experimental Determination of the Kerma Factors for the Reaction ^{12}C(n,n'3a) at En = 10-35 MeV", **Radiation Research 97(1984)253**	compile
^{12}C(n,n'3α)	D(d,n) T(d,n) PTB	B.Antolkovic, G.Dietzes, H.Klein, "Secondary alpha particle spectra and partial Kerma factors of the reaction n+^{12}C->n+3α", **Radiation Protect. Dosimetry 44(1992)31**	compile

Current List of missing published experimental results (4)

current list is here: https://www-nds.iaea.org/CRPdpa/DataMissed.pdf

Reaction	Source Lab	Reference	EXFOR
C, N, O, Mg, Al, Si, Fe, Zr, AlN, Al_2O3, $Si0_2$, A-150	D(d,n) T(d,n) E=5-17MeV at PTB ^{9}Be(p,xn) E=34-66MeV at PSI	U.J. Schrewe, W.D. Newhauser, H.J. Brede, P.M. DeLuca, “Experimental kerma coefficients and dose distributions of C, N, O, Mg, Al, Si, Fe, Zr, A-150 plastic, Al_2O_3, AlN, SiO_2 and ZrO_2 for neutron energies up to 66 MeV”, **Phys. Med. Biol. 45, 651 (2000)**	compile
C and A-150 plastic	^{9}Be(p,xn) PSI, Switzerland	H. Schuhmacher, H.J. Brede, R. Henneck, A. Kunz, J.P. Meulders, P. Pihet, U.J. Schrewe, ‘Measurement of neutron kerma factors for carbon and A-150 plastic at neutron energies of 26.3 and 37.8 MeV’ **Phys. Med. Biol. 37, 1265–1281 (1992)** U.J. Schrewe, H.J. Brede et al. ‘Determination of Kerma Factors for A-150 plastic and Carbon for neutron energies above 20 MeV’ **ND-1991, Jülich, p. 586-594**	compile

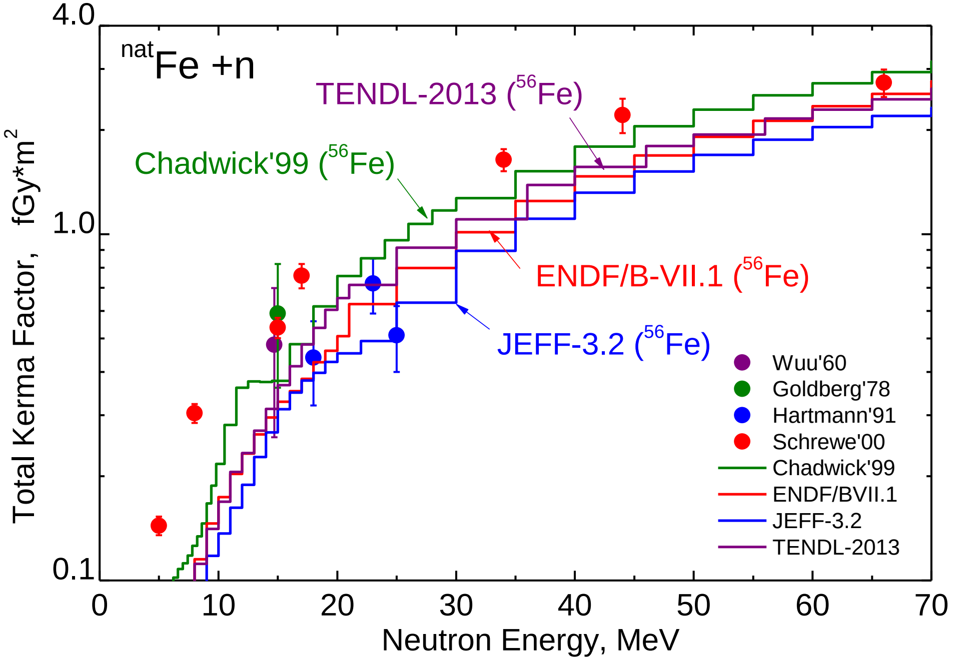
Current List of missing published experimental results (5)

current list is here: https://www-nds.iaea.org/CRPdpa/DataMissed.pdf

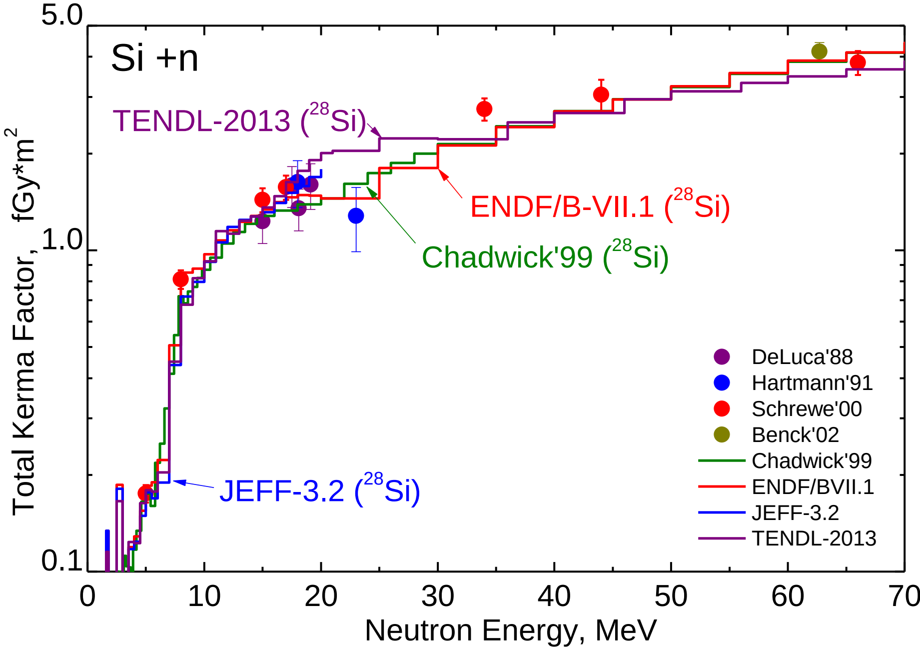
Reaction	***Source Lab***	***Reference***	***EXFOR***
Mg, Al C	T(d,n) at PTB 15 MeV 17 MeV	G. Buhler, H.G. Menzel, H. Schuhmacher, 'Neutron kerma factors for magnesium and aluminium measured with low-pressure proportional counters' **Phys. Med. Biol. 31 (1986) 601** G. Buhler, H.G. Menzel, H. Schuhmacher, S. Guldbakke, 5th Symp Neutr Dos, Munich, EUR-9762, p. 309 (1985)	compile
C, A-150	T(d,n) PTB Germany	P. Pihet, S. Guldbakke, H.G. Menzel and H. Schuhmacher, 'Measurement of kerma factors for carbon and A-150 plastic: neutron energies from 13.9 to 20.0 MeV' **Phys. Med. Biol. 37, 1957 (1992)**	compile
N, O, Ca	?? Ohio Univ.	M.S.Islam, R.W.Finlay, J.S.Petler, J.Rapaport, R.Alarcon, J. Wierzbicki, Neutron scattering cross sections and partial kerma values for oxygen, nitrogen and calcium at1 8<E_n<60MeV **Phys. Med. Biol. 33, 315 (1988)**	compile
C	T(d,n) PNNL	J.C. McDonald, ''Calorimetric measurements for the carbon kerma factor for 14.6-MeV neutrons,'' **Radiation Research 109 (1987) 28–35**	compile
C total and partial kf	7Li(p,n) TSL Uppsala.	B.E. Bergenwall, A. Atac and S. Kullander, 'Experimental kerma coefficients for carbon deduced from microscopic cross sections at 96 MeV incident neutron energy", **Phys. Med. Biol. 49 (2004)4523**	compile
?	???	L.S. August, P. Shapiro, R.B. Theus, Cross Sections and Yields for High Energy Neutron Source Reactions. **National Bureau of Standards, NBSIR 77-1279, p.31, 1977**	???

Neutron KERMA factors: Measurements and Evaluations

Fe Kerma factor



Si Kerma factor



In Figures:

- Experimental data from are proper papers
- Evaluated data from: (i) M. Chadwick et al., “A consistent set of neutron kerma coefficients from thermal to 150 MeV for biologically important materials”, Med. Phys. 26(12999)974

  (ii) Evaluated Libraries processed by NJOY (course groups)

Example (1): direct measurement by micro-dosimeter

Paper: C. Wuu, L. Milavickas, "Determination of the Kerma Factors in Tissue-equivalent Plastic, C, Mg, and Fe for 14.7 MeV Neutrons“, Med. Phys. 14(6), 1007 (1987)

Neutron Source:

T(d,n) reaction produce E = 14.1-14.9 MeV at 0 deg, <E> = 14.7 MeV

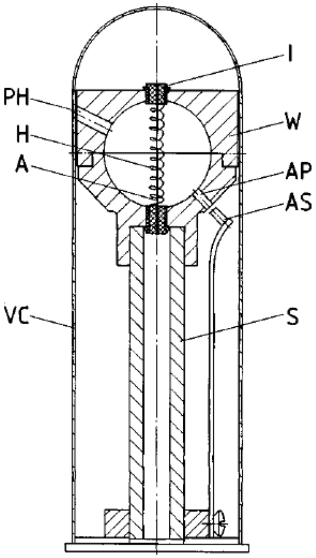


Fig. from U.Schrewe et al. PMB45(2000)651

Neutron Fluence, contribution of D(d,n), room return were measured

- by associated α-particles method
- by ^{63}Cu(n,2n) activation technique having threshold 11.9 MeV

Radiation Detector:

Rossi-type proportional counter (micro-dosimeter) of dia. 1.0 -1.5 μm

- walls made of studied materials: Tissue-equivalent Plastic (TEP), C, Mg, Fe
- filled with gas propan-based Tissue-equivalent (TE) gas and Argon

Proportional counters were calibrated (before and after Experim.) with ^{244}Cm α-source

Contribution of gamma to neutron Kerma were measured with ^{60}Co γ-source, the obtained spectrum was normalized and subtracted

Example (2): derivation from measured DDX of the reaction secondaries

Paper: J.P.Meulders, S.Benck, I.Slypen, V.Corcalciuc "Experimental kerma coefficients of biologically important materials at neutron energies below 75 MeV"
Medical Physics 27, 2541 (2000) *(summaries of published results)*

Neutron Source: "Li(p,n) reaction produces at 0° angle a quasi-monoenergetic neutron spectrum consisting of a high-energy well-defined peak, containing about 50% of all the neutrons, followed by a flat continuum of lower energy neutrons"

Neutron Fluence

- by integration of *proton beam charge* by Faraday cup
- relative to *H(n,p)* by telescope which detect protons at 45 deg

Detector: Δ*E*-*E* telescopes simultaneously detected the light charged particle

Extrapolation below detector threshold and to other angles
to get partial and total Kerma Factors

Proposals

Compile:

~ 15 articles with Neutron Kerma Factors

Revisit and eventually correct:

Entry 22507 (data from later publication, units …)
Entry 22811 (main reference)