

Fig. 1. C/E ratio in $^{252}\text{Cf}(\text{s.f.})$ field: obvious outliers: $^{59}\text{Co}(n,\gamma)$, $^{92}\text{Mo}(n,p)$, $^{60}\text{Ni}(n,p)$ and $^{46}\text{Ti}(n,2n)$.

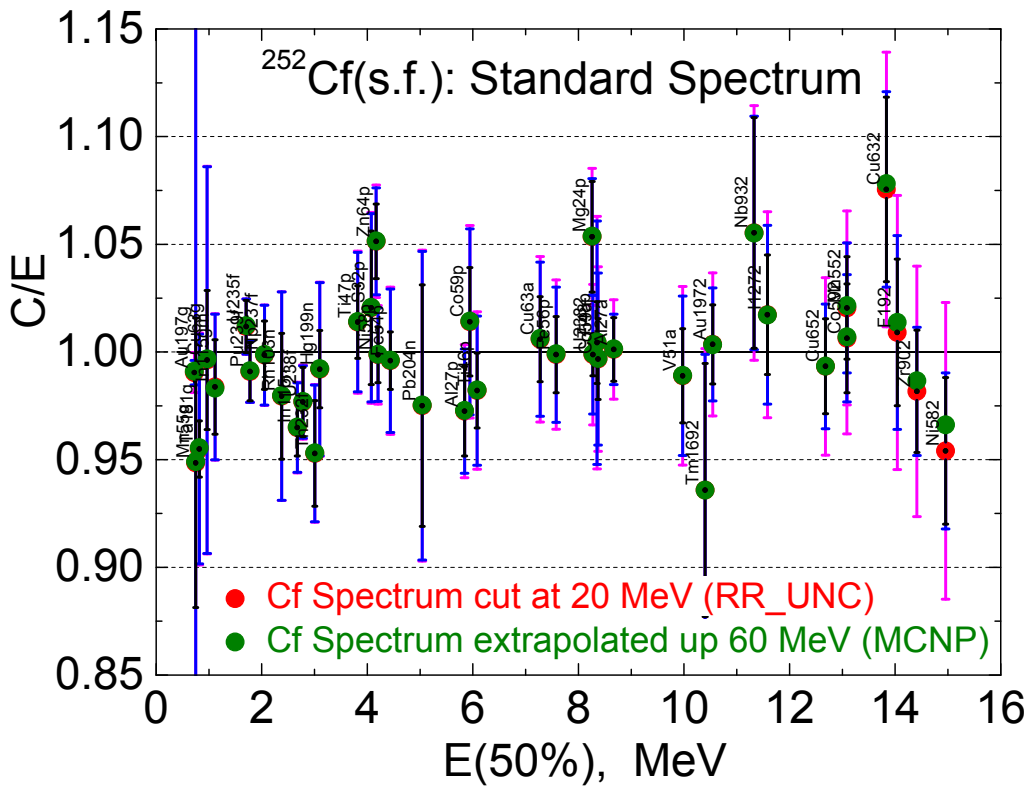


Fig. 2. C/E ratio in $^{252}\text{Cf}(\text{s.f.})$ field: all measured data but without obvious outliers. Error bars include only experimental (black), additionally IRDFF-1.03 evaluated XS (blue) and Cf(s.f.) spectrum (pink) uncertainties. C/E for outliers $^{59}\text{Co}(n,\gamma)$, $^{92}\text{Mo}(n,p)$, $^{60}\text{Ni}(n,p)$ and $^{46}\text{Ti}(n,2n)$ are located outside of Figure.

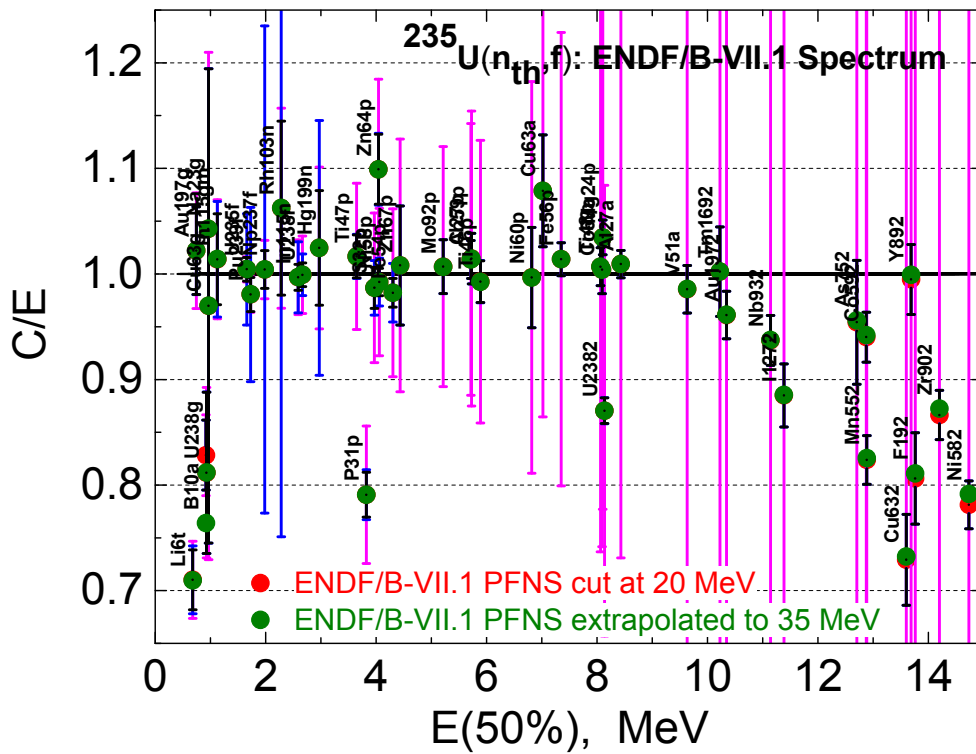


Fig. 3. C/E with IRDFFF-1.03 cross sections averaged in the $^{235}\text{U}(n_{th},f)$ PFNS from ENDF/B-VII.1 [1]. Uncertainties: experimental SPA (black bars), IRDFFF-1.03 cross sections (blue), evaluated spectra (pink) - not shown.

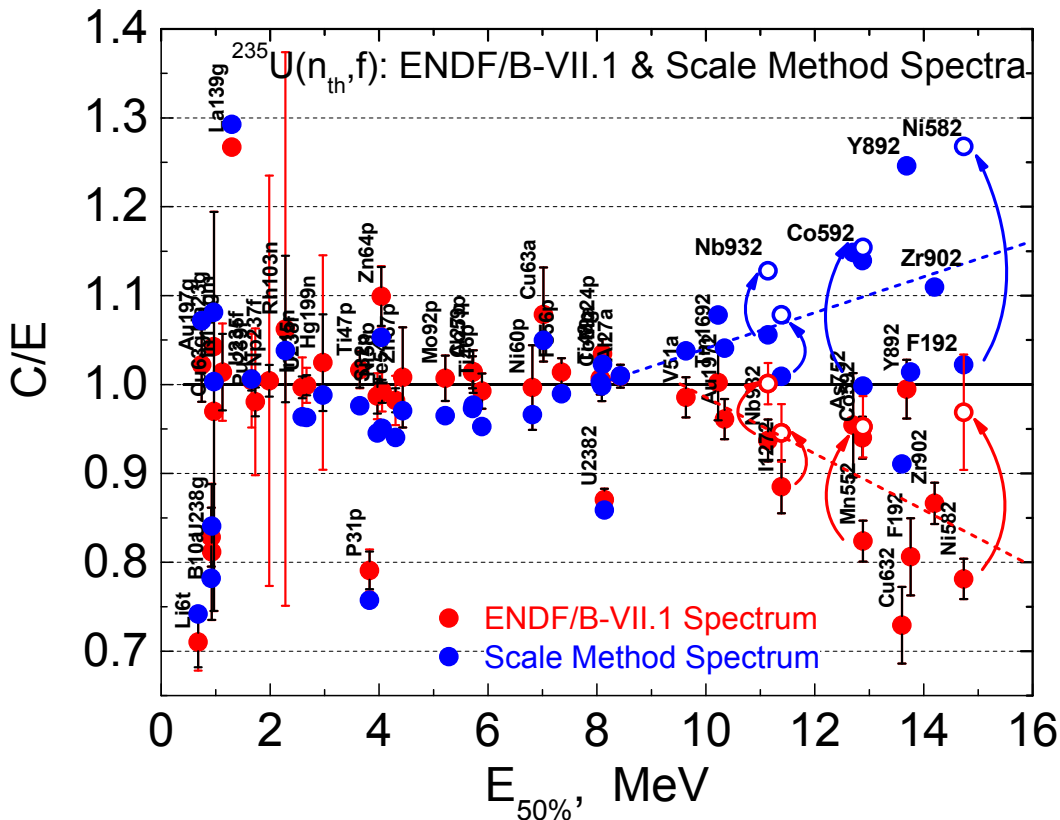


Fig. 4. C/E with IRDFFF-1.03 cross sections averaged in the $^{235}\text{U}(n_{th},f)$ PFNS from ENDF/B-VII.1 [1] and Scale method [2]. Uncertainties: experimental SPA (black bars), IRDFFF-1.03 cross sections (red), evaluated spectra - not shown. Three curved arrows show the change of C/E for $^{127}\text{I}(n,2n)$, $^{55}\text{Mn}(n,2n)$ and $^{58}\text{Ni}(n,2n)$ when SPA recommended by W. Mannhart are replaced with K. Zolotarev values.

Date: Jan 2014 – Sep 2014

Reference

1. M.B. Chadwick, M. Herman et al., Nuclear Data Sheets, **112**, 2887 (2011)
2. N.V. Kornilov, Nucl. Sci. Eng., **169**, 290 (2011)

The same but for [Cf-252 field](#)

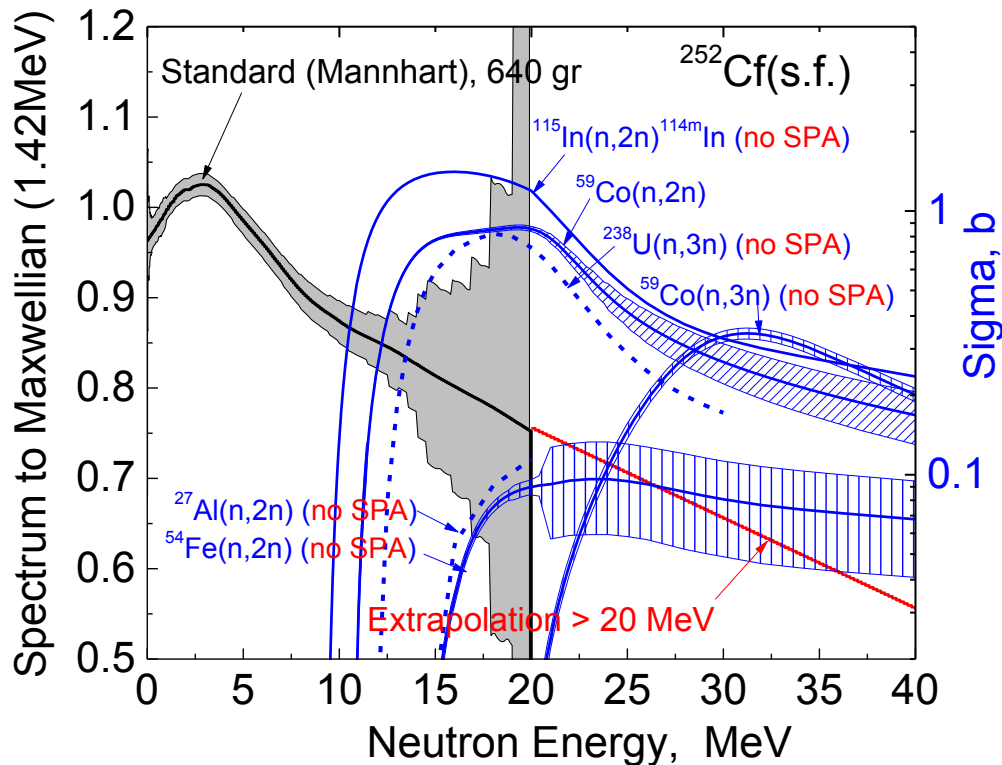
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**Spectrum averaged cross sections (SPA) for the high threshold dosimetry reactions:
feasibility of activation and other alternative experimental techniques for SPA at level of 1 - 1000 μb**

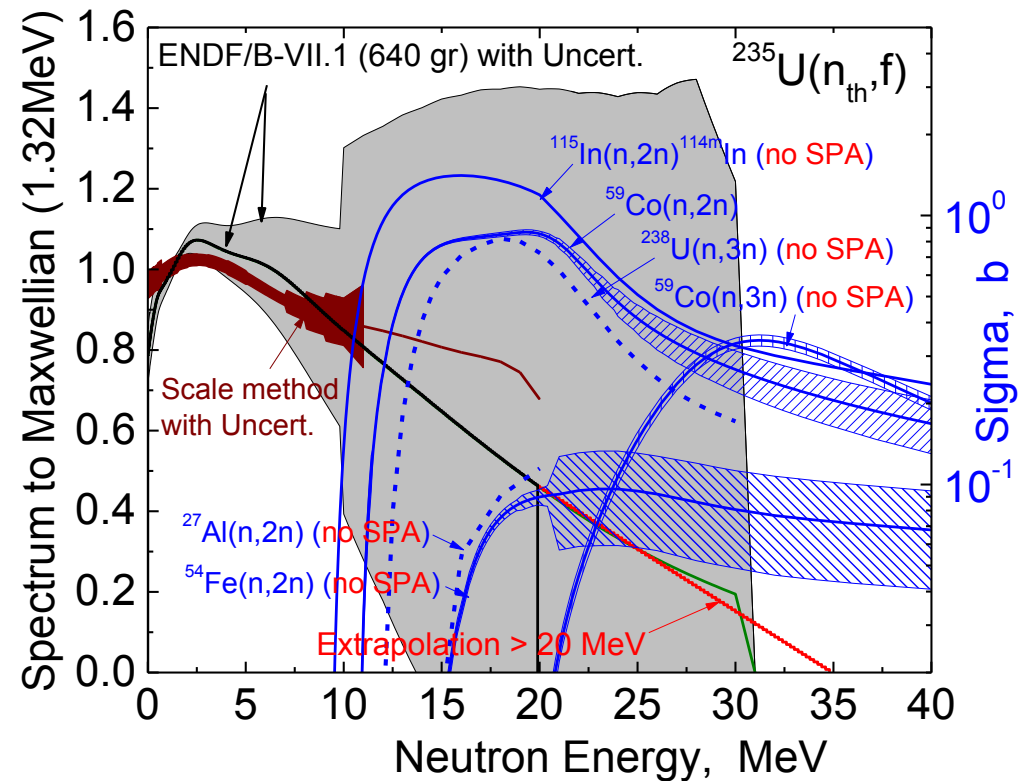
I. SPA cross sections for the high threshold dosimetry reactions

Following the recommendation of the IAEA Technical Meeting “Toward a New Evaluation of Neutron Standards”, 8-12 July 2013 ([INDC\(NDS\)- 0641](#)):
“... assessing the possibility of using the AMS technique for the measurement of the $^{235}\text{U}(n_{\text{th}},f)$ or $^{235}\text{U}(n_{\text{cold}},f)$ prompt fission neutron averaged cross sections which can be used for validation of the prompt fission neutron spectrum at energies above 8 MeV ($\langle E_{50\%} \rangle > 8 \text{ MeV}$)”

the **spectrum averaged cross sections (SPA)** were calculated for several high threshold IRDFD reactions in $^{252}\text{Cf}(s.f.)$ and $^{235}\text{U}(n_{\text{th}},f)$ fields:



$^{252}\text{Cf}(s.f.)$ PFNS (ratio to Maxwellian $T = 1.42 \text{ MeV}$) and IRDFD cross sections (only $^{59}\text{Co}(n,2n)$ SPA was measured).



$^{235}\text{U}(n_{\text{th}},f)$ PFNS (ratio to Maxwellian $T = 1.32 \text{ MeV}$) and IRDFD cross sections (only $^{59}\text{Co}(n,2n)$ SPA was measured).

Table 1. Dosimetry reactions, their stable products, kinematic threshold E_{thr} , effective energy $E_{50\%}$ and SPA in the $^{252}\text{Cf(s.f.)}$ field, sorted by increasing $E_{50\%}$.

IRDF reactions and their products	E_{thr} MeV	$E_{50\%}$ MeV	SPA, μb		$N_{product} / N_{target}$ if $10^8 \text{ n/cm}^2/\text{s}$, 1000h	Comments
			IRDF ¹	Experiment ²		
$^{252}\text{Cf(s.f.)}$ Spontaneous Fission Spectra: given ^{252}Cf produces Flux = $10^8 \text{ n/cm}^2/\text{s}$ (i.e. at $\approx 1 \text{ cm}$ from ^{252}Cf of 10^9 n/s intensity³) and Irradiation of sample = 1000 h = 4.17 weeks						
$^{54}\text{Fe}(n,\alpha)^{51}\text{Cr}$ (ϵ , 27.7 d) \rightarrow ^{51}V (stable)	0	7.430	1113 \pm 3.6%	No Exp	4007 10^{-16}	
$^{238}\text{U}(n,2n)^{237}\text{U}$ (β^- , 6.75 d) \rightarrow ^{237}Np (2.14 My)	6.180	8.276	20584 \pm 2.4%	19200 \pm 10% 12200 \pm 12%	74100 10^{-16}	Blinov vs. Shani: measurements discrepant !!!
$^{232}\text{Th}(n,2n)^{231}\text{Th}$ (β , 26 d) \rightarrow ^{231}Pa (3.28 kY)	6.448		24377 (B-VII.1)	No Exp	87757 10^{-16}	
$^{169}\text{Tm}(n,2n)^{168}\text{Tm}$ (ϵ , 93 d) \rightarrow ^{168}Er (stable)	8.082	10.400	6260 \pm 2.4%	6690 \pm 6.3%	22536 10^{-16}	
$^{130}\text{Te}(n,2n)^{129}\text{Te}$ (IT, β , 34 d) \rightarrow ^{129}I (stable)	8.484		3494 (B-VII.1)	No Exp	12578 10^{-16}	AMS threshold ^W = 10^{-14}
$^{141}\text{Pr}(n,2n)^{140}\text{Pr}$ (ϵ , 3.4 min) \rightarrow ^{140}Ce (stable)	9.464	11.85	1990 \pm 11.1%	No Exp.	7164 10^{-16}	
$^{75}\text{As}(n,2n)^{74}\text{As}$ (ϵ , 17.8 d) \rightarrow ^{74}Ge (stable)	10.383	12.91	621 \pm 5.8%	No Exp.	2236 10^{-16}	
$^{115}\text{In}(n,2n)^{114\text{m}}\text{In}$ (IT, 50 d; β^-) \rightarrow ^{114}Sn (stable)	10.633	13.09	1633 \pm 5.0%	No Exp.	5879 10^{-16}	
$^{59}\text{Co}(n,2n)^{58}\text{Co}$ (ϵ , 70 d) \rightarrow ^{58}Fe (stable)	10.633	13.09	410 \pm 0.0%	405 \pm 2.5%	1476 10^{-16}	
$^{238}\text{U}(n,3n)^{236}\text{U}$ (α , $2.34 \cdot 10^7 \text{ y}$) \rightarrow ^{232}Th (stable)	11.330		163 (B-VII.1)	No Exp.	567 10^{-16}	AMS threshold ^W = 10^{-11}
$^{56}\text{Fe}(n,2n)^{55}\text{Fe}$ (ϵ , 2.74 y) \rightarrow ^{55}Mn (stable)	11.40		170 (B-VII.1)	No Exp.	612 10^{-16}	AMS threshold ^W = 10^{-14}
$^{89}\text{Y}(n,2n)^{88}\text{Y}$ (ϵ , 107 d) \rightarrow ^{88}Sr (stable)	11.612	13.90	346 \pm 1.3%	No Exp.	1246 10^{-16}	
$^{52}\text{Cr}(n,2n)^{51}\text{Cr}$ (ϵ , 27.7 d) \rightarrow ^{51}V (stable)	12.272	14.71	97 \pm 2.7%	No Exp.	360 10^{-16}	
$^{23}\text{Na}(n,2n)^{22}\text{Na}$ (ϵ , 2.60 y) \rightarrow ^{22}Ne (stable)	12.419	15.40	8.6 \pm 1.2%	No Exp.	31 10^{-16}	
$^{46}\text{Ti}(n,2n)^{45}\text{Ti}$ (ϵ, 3.1 h) \rightarrow ^{45}Sc (stable)	13.479	16.03	12.2 \pm 3.1%	93 \pm 33% (?)	44 10^{-16}	C/E = 0.13 \pm 33% ???!!!
$^{27}\text{Al}(n,2n)^{26}\text{Al}$ (ϵ , $7.17 \cdot 10^5 \text{ y}$) \rightarrow ^{26}Mg (stable)	13.55		5.7 (B-VII.1)	No Exp.	21 10^{-16}	AMS threshold ^W = 10^{-13}
$^{54}\text{Fe}(n,2n)^{53}\text{Fe}$ (ϵ , 8.5 min) \rightarrow ^{53}Mn (3.7 My)	13.629	16.48	3.5 \pm 1.5%	No Exp.	13 10^{-16}	not for AMS^W due to impact of $^{54}\text{Fe}(n,np+d)^{53}\text{Mn}$

IRDFFF reactions and their products	E _{thr} MeV	E _{50%} MeV	SPA, μb		N _{product} / N _{target} if 10 ⁸ n/cm ² /s, 1000h	Comments
			IRDFFF ¹	Experiment ²		
²⁵²Cf(s.f.) Spontaneous Fission Spectra: given ²⁵²Cf produces Flux = 10⁸ n/cm²/s (i.e. at ≈1 cm from ²⁵²Cf of 10⁹ n/s intensity³) and Irradiation of sample = 1000 h = 4.17 weeks						
²⁰⁹ Bi(n,3n) ²⁰⁷ Bi (ε, 31.6 y) → ²⁰⁷ Pb (stable)	14.416	18.21	19 ± 6.0%	No Exp.	68 10 ⁻¹⁶	
¹⁶⁹ Tm(n,3n) ¹⁶⁷ Tm (ε, 9.3 d) → ¹⁶⁷ Er (stable)	14.963	18.49	14.7 ± 5.7%	No Exp.	54 10 ⁻¹⁶	
⁵⁹ Co(n,3n) ⁵⁷ Co (ε, 271 d) → ⁵⁷ Fe (stable)	19.352	22.36	0.097 ± 5.6%	No Exp.	0.35 10 ⁻¹⁶	

Example of calculation for ²⁷Al(n,2n)²⁶Al: Ratio ²⁶Al/²⁷Al = Flux × Time × Sigma = 1.E+8 n/cm²/s × 3.6E+6 s × 5.7E-30 cm² = 20.5E-16

Table 2. Dosimetry reactions, their stable products, kinematic threshold E_{thr}, effective energy E_{50%} and SPA in the ²³⁵U(n_{th},f) field, sorted by increasing E_{50%}.

IRDFFF reactions and their products	E _{thr} MeV	E _{50%} MeV	SPA, μb		N _{product} / N _{target} if 10 ⁹ n/cm ² /s, 100 h	Comments
			IRDFFF ¹	Experiment ²		
²³⁵U(n_{th},f) neutron induced Fission Spectra: given n-Source produce Flux = 10⁹ n/cm²/s (cp. 1.9 10⁹ n/cm²/s from fission plate in KUR facility⁴) and Irradiation of sample = 100 h = 0.417 weeks						
¹⁶⁹ Tm(n,2n) ¹⁶⁸ Tm (ε, 93 d) → ¹⁶⁸ Er (stable)	8.082	10.40	3744 ± 2.6%	3735 ± 4.2%	13478 10 ⁻¹⁶	
¹¹⁵ In(n,2n) ¹¹⁴ In (IT, 50 d; β ⁻) → ¹¹⁴ Sn (stable)	10.633	11.60	861 ± 5.5%	No Exp.	3100 10 ⁻¹⁶	
¹⁴¹ Pr(n,2n) ¹⁴⁰ Pr (ε, 3.4 min) → ¹⁴⁰ Ce (stable)	9.464	11.65	1043 ± 12.0%	No Exp.	3755 10 ⁻¹⁶	
⁶⁵ Cu(n,2n) ⁶⁴ Cu (ε, 12.7 h) → ⁶⁴ Ni (stable) ⁶⁴ Cu (β ⁻ , 12.7 h) → ⁶⁴ Zn (stable)	10.065	12.46	318 ± 2.0%	No Exp.	⁶⁴ Ni/ ⁶⁵ Cu = 704 10 ⁻¹⁶ ⁶⁴ Zn/ ⁶⁵ Cu = 441 10 ⁻¹⁶	
⁷⁵ As(n,2n) ⁷⁴ As (ε, 17.8 d) → ⁷⁴ Ge (stable)	10.383	12.70	295 ± 6.4%	No Exp.	1062 10 ⁻¹⁶	
⁵⁹ Co(n,2n) ⁵⁸ Co (ε, 70 d) → ⁵⁸ Fe (stable)	10.633	13.09	191 ± 1.8%	203 ± 2.5%	688 10 ⁻¹⁶	
²³⁸ U(n,3n) ²³⁶ U (α, 2.34 10 ⁷ y) → ²³² Th (stable)	11.330		682 (BVII.0)	No Exp.	2455 10 ⁻¹⁶	
⁵⁶ Fe(n,2n) ⁵⁵ Fe (ε, 2.74 y) → ⁵⁵ Mn (stable)	11.400		739 (BVII.1)	No Exp.	2660 10 ⁻¹⁶	AMS threshold ^w = 10 ⁻¹⁴
⁸⁹ Y(n,2n) ⁸⁸ Y (ε, 107 d) → ⁸⁸ Sr (stable)	11.612	13.90	149 ± 1.4%	150 ± 3.3%	536 10 ⁻¹⁶	

IRDFFF reactions and their products	E _{thr} MeV	E _{50%} MeV	SPA, μb		N _{product} / N _{target} if 10 ⁹ n/cm ² /s, 100 h	Comments
			IRDFFF ¹	Experiment ²		
²³⁵U(n_{th},f) neutron induced Fission Spectra: given n-Source produce Flux = 10⁹ n/cm²/s (cp. 1.9 10⁹ n/cm²/s from fission plate in KUR facility⁴) and Irradiation of sample = 100 h = 0.417 weeks						
⁵² Cr(n,2n) ⁵¹ Cr (ε, 27.7 d) → ⁵¹ V (stable)	12.272	14.71	38 ± 2.7%	No Exp.	137 10 ⁻¹⁶	
²³ Na(n,2n) ²² Na (ε, 2.60 y) → ²² Ne (stable)	12.419	15.40	3.2 ± 1.3%	No Exp.	12 10 ⁻¹⁶	
⁴⁶ Ti(n,2n) ⁴⁵ Ti (ε, 3.1 h) → ⁴⁵ Sc (stable)	13.479	15.81	4.3± 4.4%	No Exp.	15 10 ⁻¹⁶	
²⁷ Al(n,2n) ²⁶ Al (ε, 7.17 10 ⁵ y) → ²⁶ Mg (stable)	13.550		2.0 (BVII.1)	No Exp.	7 10 ⁻¹⁶	AMS threshold ^W = 10 ⁻¹³
⁵⁴ Fe(n,2n) ⁵³ Fe (ε, 8.5 min) → ⁵³ Mn (3.7 My)	13.629	16.48	1.2± 5.1%	No Exp.	4 10 ⁻¹⁶	not for AMS^W due to impact of ⁵⁴Fe(n,np+d)⁵³Mn
²⁰⁹ Bi(n,3n) ²⁰⁷ Bi (ε, 31.6 y) → ²⁰⁷ Pb (stable)	17.416	17.88	5.4 ± 5.9%	No Exp.	19 10 ⁻¹⁶	
¹⁶⁹ Tm(n,3n) ¹⁶⁷ Tm (ε, 9.3 d) → ¹⁶⁷ Er (stable)	14.963	18.20	4 ± 6.1%	No Exp.	14 10 ⁻¹⁶	
⁵⁹ Co(n,3n) ⁵⁷ Co (ε, 271 d) → ⁵⁷ Fe (stable)	19.352	21.92	0.017 ± 7.7%	No Exp.	0.06 10 ⁻¹⁶	

Example of calculation for ²⁷Al(n,2n)²⁶Al: Ratio ²⁶Al/²⁷Al = Flux × Time × Sigma = 1.E+9 n/cm²/s × 3.6E+5 s × 2.E-30 cm² = 7.2E-16

Comments for Tables 1 and 2:

Italic font - reactions currently not included in IRDFFF

1) Calculated SPA uncertainty includes only IRDFFF-1.05 cross section uncertainty.

2) The known measurements are carried out by activation technique.

3) The most intensive ²⁵²Cf sources known up to now:

K. Kobayashi et al. [JNST 19(1982)341] used 500 μg of ²⁵²Cf which produced ≈ 1 10⁹ n/s;

J. Czikai et al. [Antwerp (1982)418] used 40 μg (?) of ²⁵²Cf which produced ≈ 1 10⁸ n/s (given 1 μg = 2.3 10⁶ n/s);;

M. Blinov et al. [Atom. Energiya 65(1988)206] used 2-3 Cf sources of 18 - 50 μg total mass or 0.4 - 1.2 10⁸ n/s (given 1 μg = 2.3 10⁶ n/s);

4) The most intensive PFNS source:

KUR power fission plate: Ø27 × 1 cm, 1.1 kg of 90% ²³⁵U, incident thermal n-flux = 5.8 10⁸ n/cm² [I. Kimura and K. Kobayashi NSE106(1990)332]

W) - information from private communication with A. Wallner

N_{product} / N_{target} - looks to be feasible for AMS

For other high energy reactions see: Cf-252(s.f.) http://www-nds.iaea.org/IRDFftest/IRDF105_MCNP_Cf.pdf
U-235(n_{th},f) http://www-nds.iaea.org/IRDFftest/IRDF_MCNPtest_U5.pdf .

Tables 1 and 2 show that it was impossible to measure so far some high threshold SPA by traditional activation technique with SPA below 150 - 400 μ b.

SPA for these reactions, if they can be measured by activation or alternative methods, will probe the unknown high energy part (i.e. above 8-10 MeV where uncertainties \approx 100%) of the $^{252}\text{Cf}(s.f.)$ and $^{235}\text{U}(n,f)$ spectra, since the dosimetry and some other reaction cross sections are known there with much better accuracy (\leq 10%).

II. Techniques alternative to Activation

1. The Accelerator Mass Spectrometry (AMS) was shown is feasible to measure extremely small SPA.

The method sensitivity $N_{\text{product}} / N_{\text{target}} \sim 10^{-12} - 10^{-16}$.

For more details see A. Wallner et al.:

“Novel method to study neutron capture of ^{235}U and ^{238}U simultaneously at keV energies”, [Phys. Rev Lett.112\(2014\)192501](#)

“Precise measurement of the $^{27}\text{Al}(n,2n)^{26}\text{gAl}$ excitation function near threshold and its relevance for fusion-plasma technology”, [J.Eur.Phys. A7, 285 \(2003\)](#)

“Production of Long-lived Radionuclides ^{10}Be , ^{14}C , ^{53}Mn , ^{55}Fe , ^{59}Ni and ^{202}gPb in a Fusion Environment” [J. Korean Phys. Soc. 59, 1378](#)

“Nuclear Data from AMS & Nuclear Data for AMS – some examples”, [EPJ 35 \(2012\) 01003](#)

“Accelerator Mass Spectrometry & Neutron-induced Reactions”, presentation at the IAEA TM on Standards (July 2013) [here](#) .

A. Wallner pointed out on the following **high threshold non-dosimetry reactions accessible for AMS:**

$^{27}\text{Al}(n,2n)^{26}\text{Al}$ was measured by AMS up to 19 MeV with accuracy 10% by A. Wallner et al., [Eur. Phys. A17, 285 \(2003\)](#)

$^{56}\text{Fe}(n,2n)^{55}\text{Fe}$ was measured by AMS around 14 MeV by A. Wallner et al. [J. Korean Phys. Soc. 59, 1378](#));

$^{238}\text{U}(n,3n)^{236}\text{U}$ was measured by AMS at 14 MeV by X. Wang et al. [Phys. Rev. C87\(2013\)014612](#)).

The status of these reaction cross sections are shown in Figs. 3-5.

Al-27(n,2n)

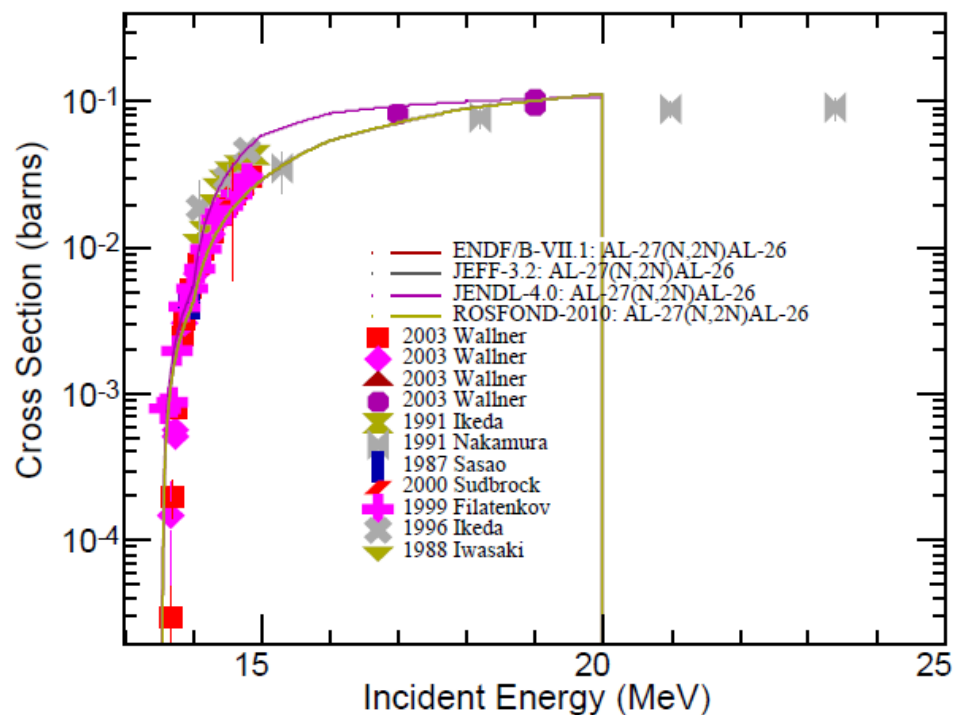


Fig 3. Available experimental and evaluated data for $^{27}\text{Al}(n,2n)^{26}\text{Al}$.

Fe-56(n,2n)

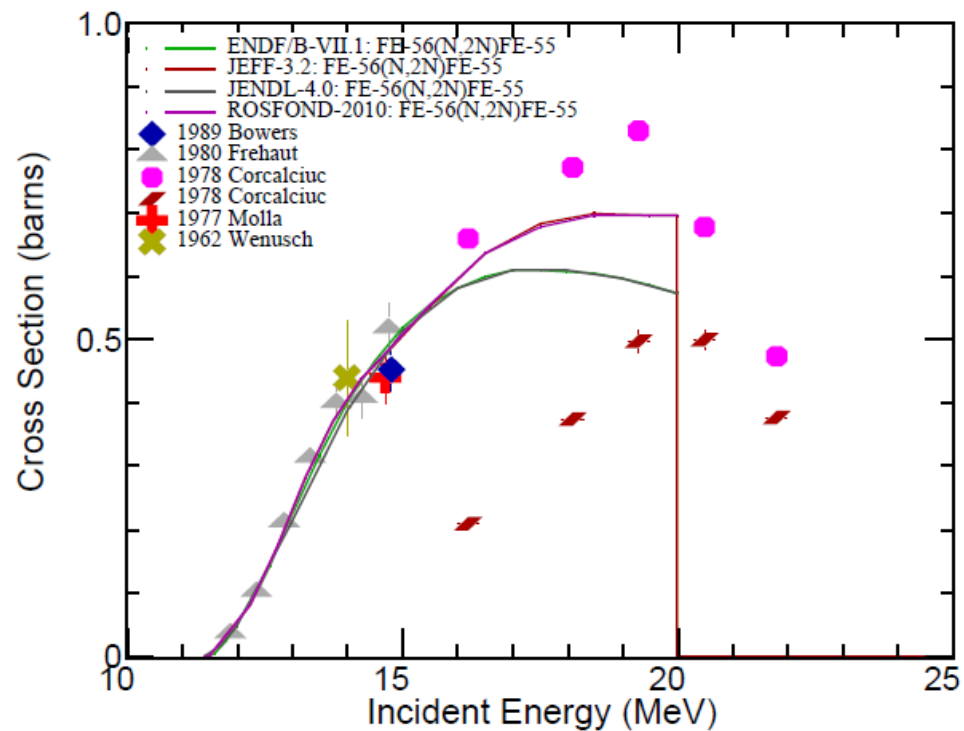


Fig 4. Available experimental and evaluated data for $^{56}\text{Fe}(n,2n)^{55}\text{Fe}$.

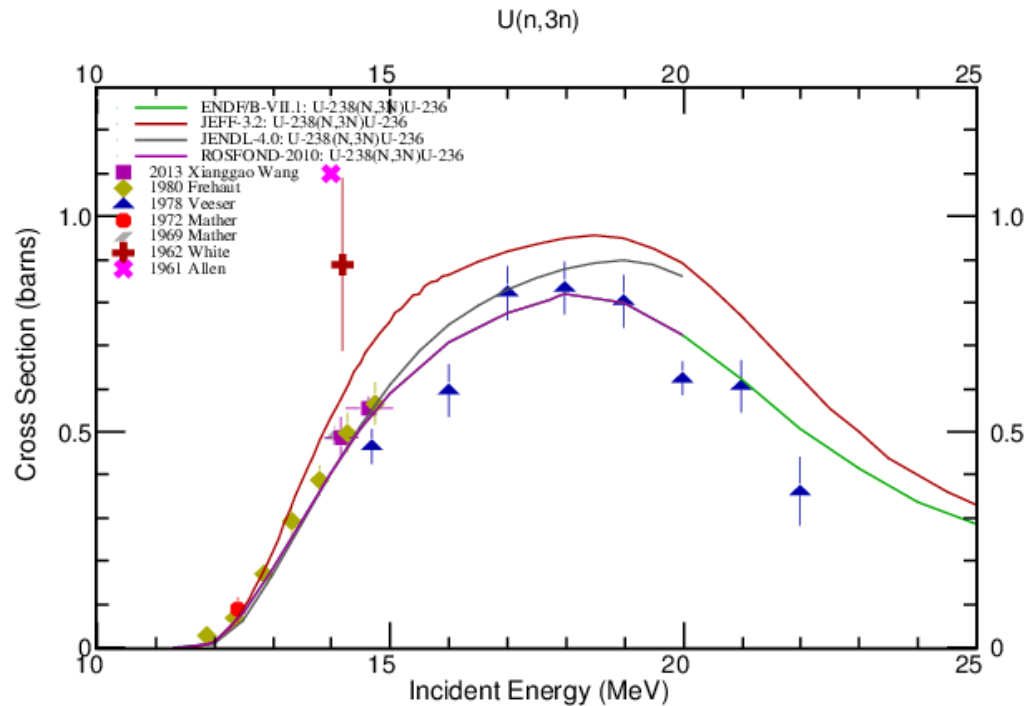


Fig. 5. Available experimental and evaluated data for $^{238}\text{U}(n,3n)^{236}\text{U}$.

2. Prompt Gamma Neutron Activation Analysis (PGNAA)

The method sensitivity $N_{\text{product}} / N_{\text{target}} \sim 100 \text{ ppm} = 10^{-4}$.

This technique was proved is capable to measure the non- threshold SPA cross sections

by employing the PGNAA facility of FRM-II after Ni foil irradiation in the LVR-15 reactor (fluence rate $3.10^{14} \text{ cm}^{-2}\text{s}^{-1}$) for reactions $^{62}\text{Ni}(n,\gamma)^{63}\text{Ni}$ ($T_{1/2} = 101.2 \text{ y}$, Atlas $\sigma(n_{\text{thermal}},\gamma) = 14.9 \text{ b}$) and $^{58}\text{Ni}(n,\gamma)^{59}\text{Ni}$ ($T_{1/2} = 7.6 \cdot 10^4 \text{ y}$, Atlas $\sigma(n_{\text{thermal}},\gamma) = 4.37 \text{ b}$).

For principles, first results and publications see:

V. Klupák, L. Viererbl, Z. Lahodová, J. Šoltés, I. Tomandl, P. Kudějová, “Nickel foil as transmutation detector for neutron fluence measurements”, [ISRD-15, EPJ Web of Conferences 106, 05013 \(2016\)](#).

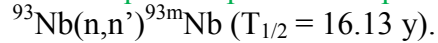
I. Tomandl, L. Viererbl, P. Kudějová, Z. Lahodová, V. Klupák, M. Fikrle, “Determination of trace concentrations of transmuted stable nuclides in TMD detectors using PGAA”, *J. of Radioanal. and Nuclear Chemistry*, [300 \(2014\) 1141](#).

3. Resonance Ionization Mass Spectroscopy (RIMS) - Isotope measurements based on Laser Spectroscopy.

The method sensitivity $N_{\text{product}} / N_{\text{target}} \sim ??$.

Currently under development for the trace analysis of short-lived and long-lived radioactive nuclei.

This technique was proved is capable to measure the cross section for dosimetry reaction



For principles, first results and publications see:

here: http://coe.nucl.nagoya-u.ac.jp/Measurement01_E.html and

H. Tomita, T. Takatsuka, T. Iguchi, Y. Adachi, Y. Furuta, T. Takamatsu, T. Noto, “Development of Neutron Dosimetry Technique with ${}^{93}\text{Nb}(n,n'){}^{93\text{m}}\text{Nb}$ Reaction by Resonance Ionization Mass Spectrometry”, [ISRD-15, EPJ 106, 05002 \(2016\)](#)

T. Takatsuka, H. Tomita, V. Sonnenschein, T. Sonoda, Y. Adachi et al. “Development of resonance ionization in a supersonic gas-jet for studies of short-lived and long-lived radioactive nuclei” , [NIM B 317 \(2013\)586](#)

4. Ion Beam Analysis (IBA) technique such as PIXE, PIGE etc.

The method sensitivity $N_{\text{product}} / N_{\text{target}} \sim 10^{-4}$ - 10^{-3} .

It seems will not be possible to use this technique to measure the high threshold SPA cross sections ($< 1 \text{ mb}$) because of its low sensitivity however it may work, as PGNA, for the non- threshold reactions with large SPA cross sections ($> 1 \text{ b}$).

5. Nuclear magnetic resonance (??).

The method sensitivity $N_{\text{product}} / N_{\text{target}} \sim ??$.