Measurement and EXFOR Compilation of Neutron-Induced Activation Cross Sections in the Energy Range up to 20 MeV

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Outline

- Activation data: needs and applications
- Activation method
- Main accelerator-based neutron source reactions
- Sample composition
- Neutron spectrum characterisation
- Coincidence summing effects
- Detector efficiency determination
- Nuclide identification by E_g and $T_{1/2}$
- Uncertainty analysis
- Constructing a covariance matrix from EXFOR uncertainties
- Isomeric ratio measurements
- ^{9}Be(d,n) thick target neutron spectrum
- Spectrum average cross section

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

Dates	May 1993 - present
Occupation or position held	Physicist 1993-1996; Research fellow 1996-2003; Assistant Professor 2003 - 2010, Associate Professor 2010-.
Main activities and responsibilities	- Nuclear research applying different experimental techniques, including: ○ (n,2n) cross section measurements based on neutron detection time distribution. ○ Reaction cross section measurements by activation method

International Atomic Energy Agency, Nuclear Data Section

Dates	October 2010 – October 2017
Occupation or position held	Nuclear Physicist
Main activities and responsibilities	- Survey of the scientific literature and compilation of the publications reporting experimental nuclear reaction data for the EXFOR database. - Organizing consultants' meetings and workshops.

European Commission, Institute for Reference Material and Measurements, Geel, BELGIUM

Dates	March 2005 – February 2009
Occupation or position held	National Seconded Expert
Main activities and responsibilities	- Neutron-induced activation cross section measurements on isotopes of Zr, Ta, W, Hf, Cr etc. - Development of a Monte-Carlo model of the HPGe detector. - ^{241}Am(n,2n) reaction study as part of broad collaboration between IRMM, ITU, and CEA (France).

Physikalisch-Technische Bandesanstalt (PTB)

Dates	April 2010 – September 2010
Occupation or position held	Visiting Scientist
Main activities and responsibilities	- Experimental study of neutron-induced reaction cross sections on Mo isotopes. - Re-establish the procedure for activation measurements after discontinuation of several years.

Institute of Experimental Physics, Debrecen, HUNGARY

Dates	January 1995 – January 1996
Main activities and responsibilities	- Study of reaction cross sections induced by quasy-monoenergetic neutrons and neutrons with spectral energy distribution from $^{9}Be(d,n)$ reaction by activation methods. - $^{2}H(d,n)^{3}He$ and $^{9}Be(d,n)^{10}B$ neutron flux determination using activation method and PHRS - (n,p) and (n,alpha) reaction cross section systematics at 14 MeV.

European Commission, Institute for Reference Material and Measurements, Geel, BELGIUM

Dates	February 2001 – January 2003
Principal subjects	Neutron-induced activation cross sections measurements on different isotopes of Co, Ni, Cu, Zr, and Pb from the threshold up to 20 MeV. $^{58}Ni(n,p)^{58m,g}Co$, the $^{60}Ni(n,p)^{60m,g}Co$ and $^{59}Co(n,2n)^{58m,g}Co$ isomeric ratio measurements.

Activation data: needs and applications

- Activation of materials : isotopes, activity
- Dose rates : handling limits, storage
- Heating : cooling , storage conditions
- Charge particle production : gas production, radiation damage
- Scattering cross sections (n,xn) x=1,2 .. : neutron transport
- Data for nuclear models development

Activation data in EXFOR

METHOD = ACTIV

Request #201
Access-Level=2 /pdf/

Attention: Huge data request

Found: Entries:3425; Subentries:30810; Datasets:28189 (Limit exceeded by factor of 5.7)

Go back, check and narrow your request

BACK

Continue your request with limited output:
produce list of Entries

LIST

EXFOR General Statistics
Information updated: 18-Oct-2016, 11:13:14
Database as of: 2016-10-18

Number of ENTRY	21424	experimental works
Number of SUBENT	149753	data tables (can contain data of more than one reaction)
Number of Datasets	166549	data tables of reactions
Number of Datapoints	13981410	total number of data points

Percent: [Counts]/[Number of ENTRY], i.e. = [Counts]/21424
Note. Σ[Percent] of a table below can be > 100% because one experimental work
can contain many data tables with data of many types

EXFOR Quantity

#	Code	Quantity	Counts	Percent
1	CS	Cross section data	10942	51
2	DAP	Partial differential data with respect to angle	4175	19.4
3	DA	Differential data with respect to angle	4152	19.3
4	RP	Resonance parameters	1924	8.98

ENTRY : 16%
SUBENT : 21 %
Datasets : 17 %

Activation method

$$\sigma_x = \sigma_{st} \frac{A_x}{A_{st}} \frac{[I\epsilon Fn]_{st}}{[I\epsilon Fn]_x} \frac{C_{flux,x}}{C_{flux,st}} \frac{C_{low,x}}{C_{low,st}} \frac{C_{coins,x}}{C_{coins,st}}$$

$$F = \frac{\lambda}{exp(-\lambda t_c)\left(1 - exp(-\lambda t_e)\right)\left(1 - exp(-\lambda t_m)\right)}$$

A - activity

I - gamma-ray emission probability

ε – detector efficiency

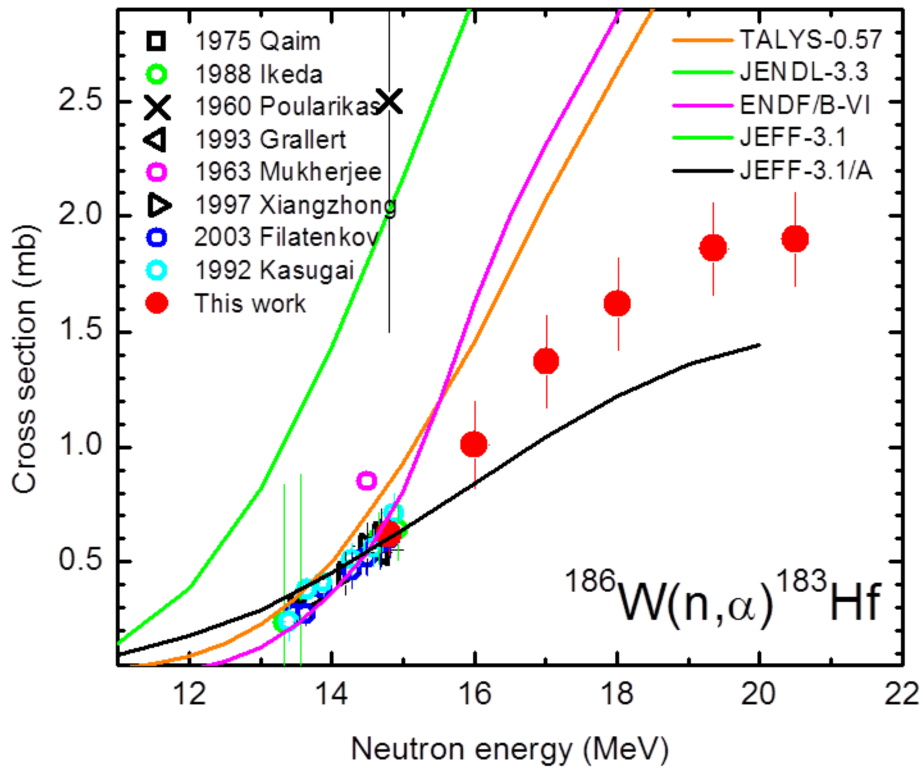
n – number of atoms in the target

C – correction factors

σ_{st} - *$^{27}Al(n,\alpha)^{24}Na$ standard reaction cross*

Employed mono- and quasymomo-energetic neutron source reactions

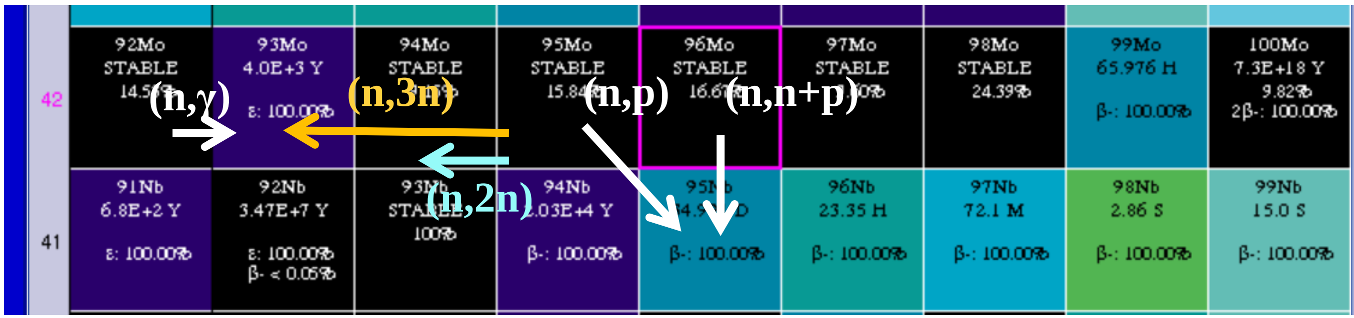
- Neutron generator (D-D: 2-3 MeV, D-T: 13.5-14.8 MeV): high intensity; low background; neutron emission in 4π; narrow energy range.
- Cyclotron (D-D: 4-13 MeV): neutron emission predominantly in forward direction; quasi-monoenergetic neutrons background of low-energy neutrons.
- Van de Graaff accelerator (D-D (gas target), D-T 13.8-20.5 MeV): wider energy range; neutron emission in 4π; quasi-monoenergetic neutrons background of low-energy neutrons; relatively low intensity.



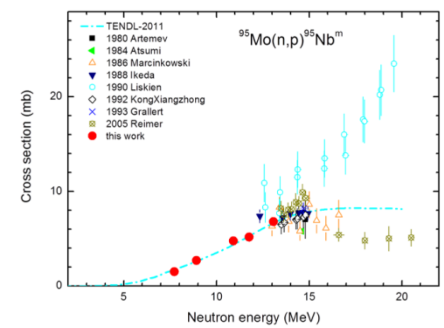
1975 Qaim
1988 Ikeda
1960 Poularikas
1993 Grallert
1963 Mukherjee
1997 Xiangzhong
2003 Filatenkov
1992 Kasugai
This work
TALYS-0.57
JENDL-3.3
ENDF/B-VI
JEFF-3.1
JEFF-3.1/A
$^{186}W(n,\alpha)^{183}Hf$
Cross section (mb)
Neutron energy (MeV)
2.5
2.0
1.5
1.0
0.5
12
14
16
18
20
22

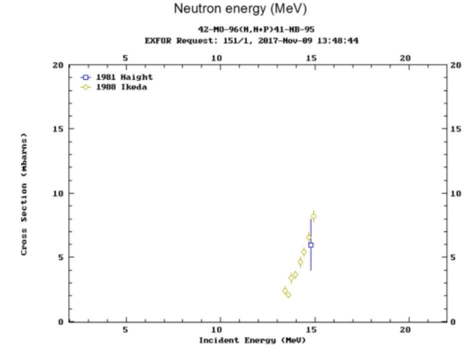
Sample composition

Interferences in production of the same radionuclide from different reactions on different isotopes in the sample.



samples with different isotopic composition





$$\sigma_1 = \frac{a_{y2}\sigma_x - a_{x2}\sigma_y}{a_{x1}a_{y2} - a_{x2}a_{y1}}$$

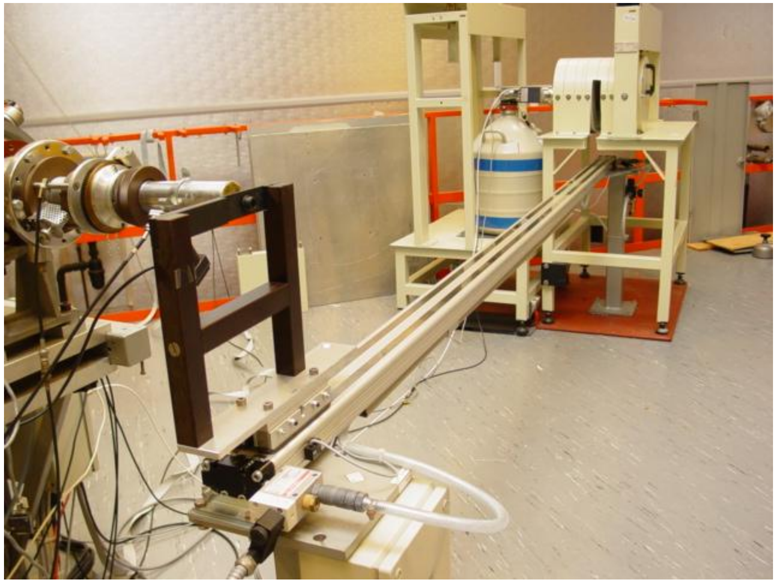
$$\sigma_2 = \frac{a_{x1}\sigma_y - a_{y1}\sigma_x}{a_{x1}a_{y2} - a_{x2}a_{y1}}$$

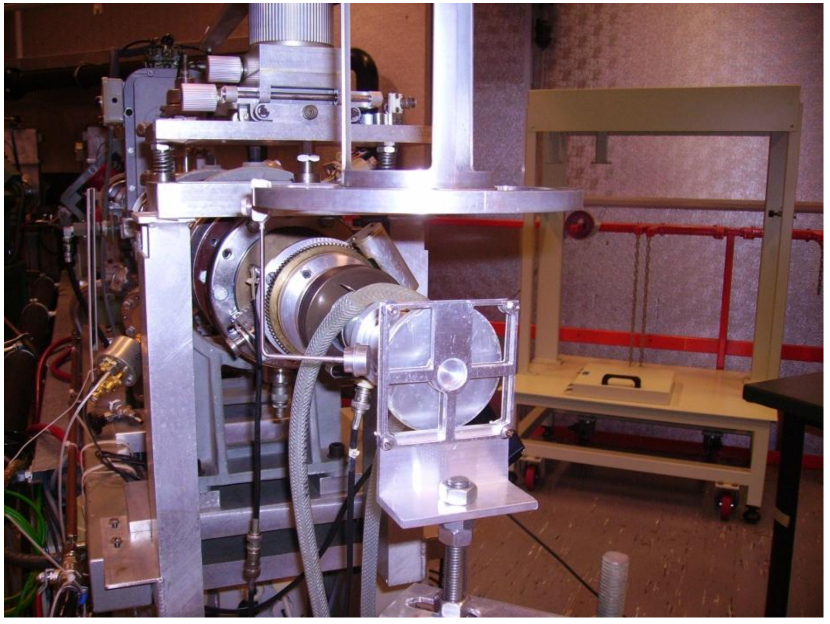
σ_i - i=1,2 reaction cross sections

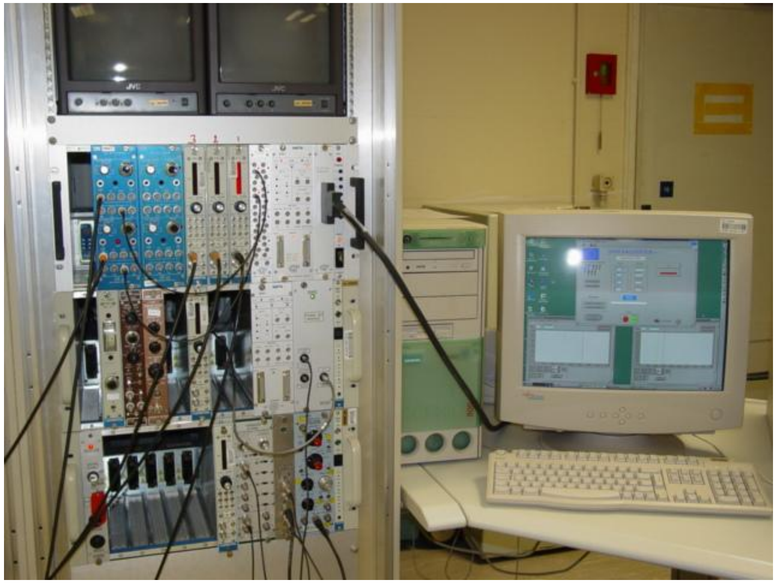
σ_s , effective cross sections for the sample $s = x,y$ isotopic composition

a_{si} - atom fraction of the target isotope in the sample

Irradiation geometry



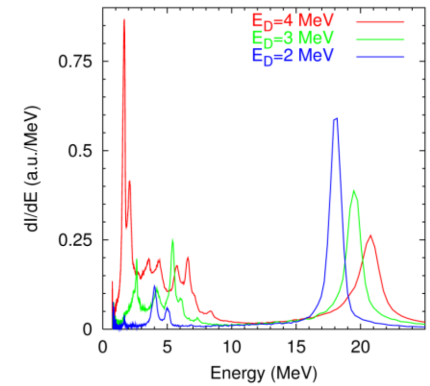


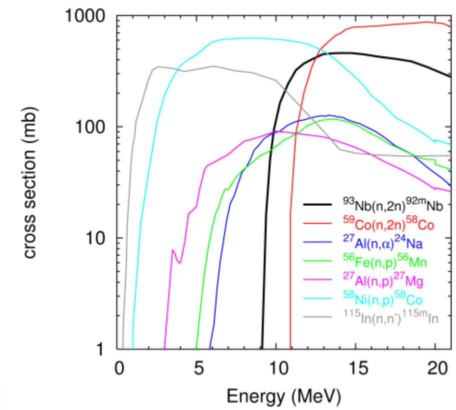


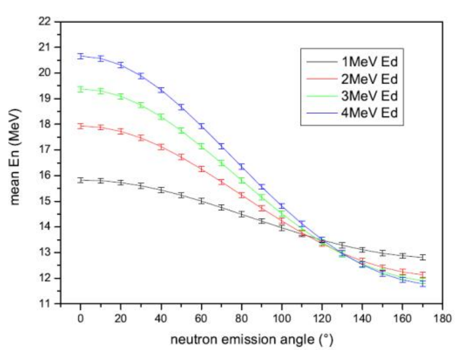
Neutron spectrum characterisation

- **Mean neutron energy** and energy distribution for the irradiation geometry : the reaction **kinematics**

- **Spectrum** unfolding : **time-of-flight** measurements in combination with threshold **activation** measurements







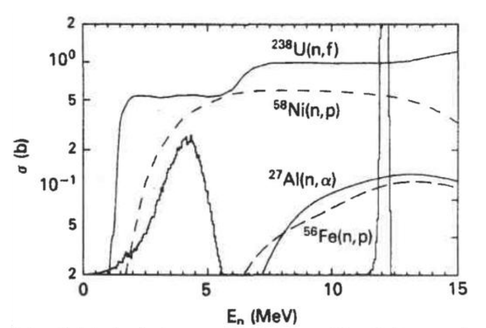


Fig. 1. Evaluated cross sections and the 0-deg neutron spectrum of the D(d,n)^{3}He reaction at 9.02 MeV. Cabral et al., Nucl. Sci. Eng. 106, 308-317 (1990).

Coincidence summing effects I

3 decays found: •1 100.0% β- 14.997 h $^{24}_{11}Na_{13}$ ⇨ $^{24}_{12}Mg_{12}$ •2 99.95% IT 20.18 ms $^{24m}_{11}Na_{13}$ ⇨ $^{24}_{11}Na_{13}$ •3 0.05% β- 20.18 ms $^{24m}_{11}Na_{13}$ ⇨ $^{24}_{12}Mg_{12}$

•1 **Evaluation**: R.B. FIRESTONE **Publication cut-off**: 3-Oct-2006 **ENSDF insertion**: 2007-10 **Publication**: Nuclear Data Sheets

Parent	$T_{1/2}$	E_x [keV]	Jp order	Decay	Q decay note on Q value	Daughter	Comments
$^{24}_{11}Na_{13}$	14.997 h *12*	0	4+	β- 100 %	5515.611 *39*	$^{24}_{12}Mg_{12}$	

see the ENSDF source

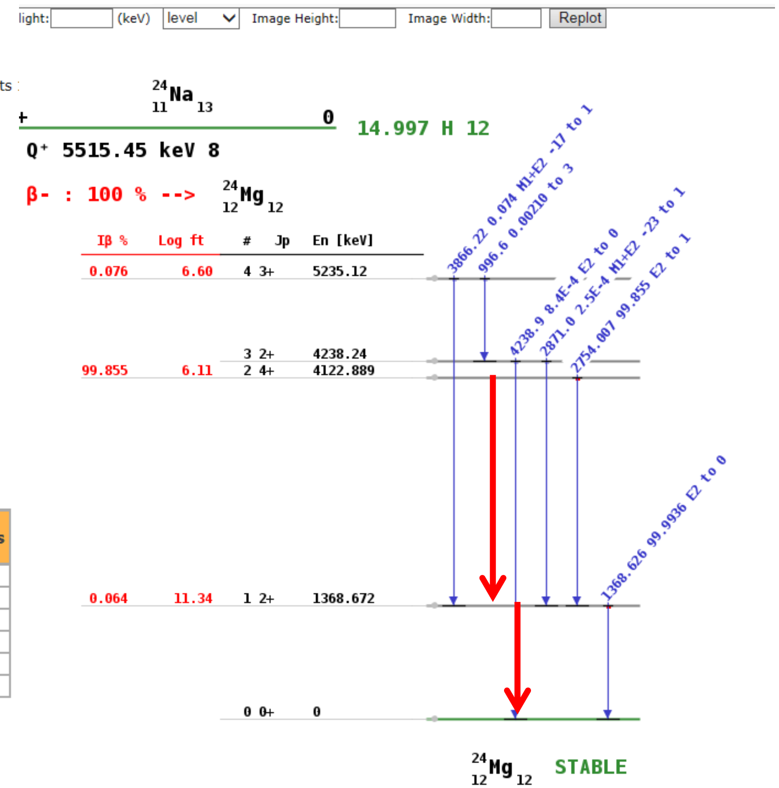
Note: Q-value used in ENSDF to determine displayed decay data is: 5515.61 *4* keV - see note on Q value

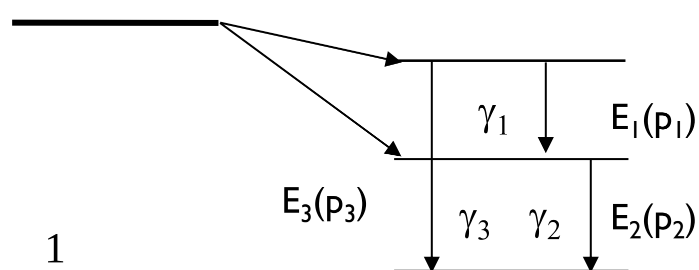
Beta - CSV

$<E_{\beta-}>$ [keV]	$I_{\beta-}$(abs) [%]	Daughter level [keV]	J^π	$E_{\beta-, max}$ [keV]	log*ft*	Transition type	Comments
89.24 *22*	0.076 *3*	5235.12 *4*	3+	280.33 *9*	6.60 *2*		
554.1 *3*	**99.855 *5***	4122.889 *12*	4+	1392.56 *8*	6.11 *1*		
1865.5 *3*	0.064 *6*	1368.672 *5*	2+	4146.78 *8*	11.34 *4*		

Gamma CSV

E_γ [keV]	I_γ(abs) [%]	Initial level [keV]	J^π	Final level [keV]	J^π	Mult.	δ	α_T	Comments
996.6 *10*	0.00210 *20*	5235.12 *4*	3+	4238.24 *3*	2+				
1368.626 *5*	**99.9936 *15***	1368.672 *5*	2+	0	0+	E2		1.3E-5	
2754.007 *11*	99.855 *5*	4122.889 *12*	4+	1368.672 *5*	2+	E2			
2871.0 *10*	2.5E-4 *4*	4238.24 *3*	2+	1368.672 *5*	2+	M1+E2	-23 *9*		
3866.22 *15*	0.074 *3*	5235.12 *4*	3+	1368.672 *5*	2+	M1+E2	-17 *4*		
4238.9 *10*	8.4E-4 *10*	4238.24 *3*	2+	0	0+	E2			





$$c_{coin1} = \frac{1}{1-\varepsilon_{t2}}$$

$$c_{coin2} = \frac{1}{1-(p_{\gamma1}/p_{\gamma2})\varepsilon_{t1}}$$

$$c_{coin3} = \frac{1}{1+p_{\gamma1}.\varepsilon_{peff\,1}.\varepsilon_{peff\,2}/\left(p_{\gamma3}.\varepsilon_{peff\,3}\right)}$$

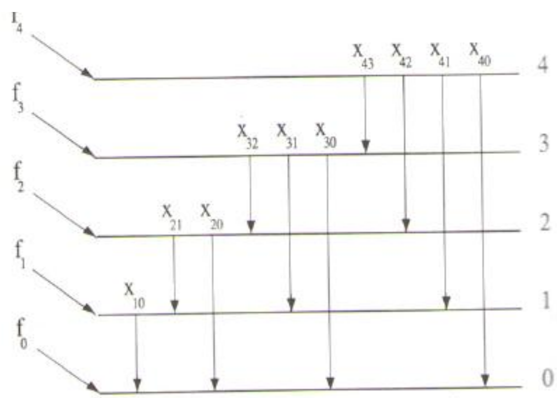
Coincidence summing effects II

Nuclear Instruments and Methods in Physics Research A290 (1990) 437–444 437
North-Holland

COINCIDENCE SUMMING IN GAMMA-RAY SPECTROSCOPY

Thomas M. SEMKOW [1,2)], Ghazala MEHMOOD [2)], Pravin P. PAREKH [1,2)] and Mark VIRGIL [1)]
[1)] *Wadsworth Center for Laboratories and Research, New York State Department of Health, Albany, NY 12201, USA*
[2)] *School of Public Health, State University of New York at Albany, Albany, NY 12201, USA*

Received 6 September 1989 and in revised form 9 January 1990



$$\mathbf{x} = \begin{pmatrix} 0 & & & & & \\ x_{10} & 0 & & & & \\ x_{20} & x_{21} & 0 & & & \\ \vdots & \vdots & \vdots & & & \\ x_{n0} & x_{n1} & x_{n2} & \cdots & x_{n\,n-1} & 0 \end{pmatrix}.$$

$$c_{ji} = \frac{x_{ji}}{1 + \alpha_{ji}},$$

$$a_{ji} = c_{ji}\epsilon^{\mathrm{p}}_{ji},$$

$$e_{ji} = c_{ji}\epsilon^{\mathrm{t}}_{ji},$$

$$b_{ji} = x_{ji} - e_{ji},$$

where

$$j > i = 0, \cdots, n-1.$$

$$\mathbf{A} = \sum_{k=1}^{n} \mathbf{a}^k,$$

$$\mathbf{B} = \mathbf{E} + \sum_{k=1}^{n} \mathbf{b}^k,$$

where

$$\mathbf{E} = \mathrm{diag}(1)$$

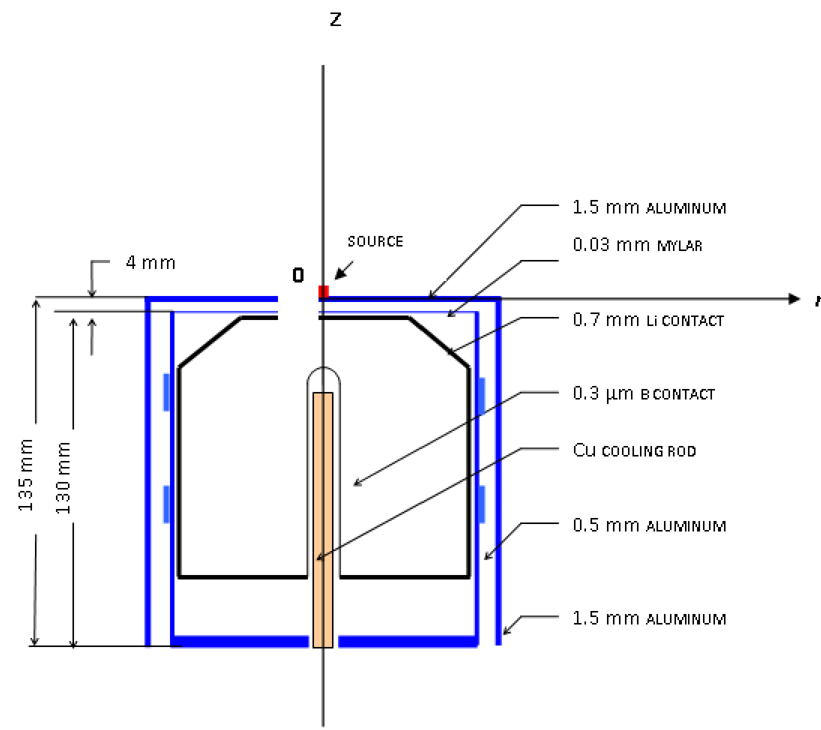
$$\mathbf{N} = \mathrm{diag}([\,f\mathbf{B}]_i),$$

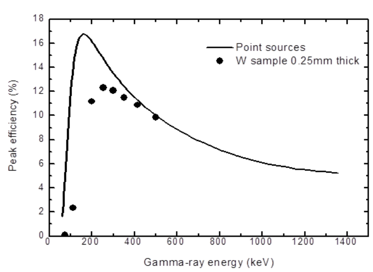
$$\mathbf{M} = \mathrm{diag}(B_{i0}),$$

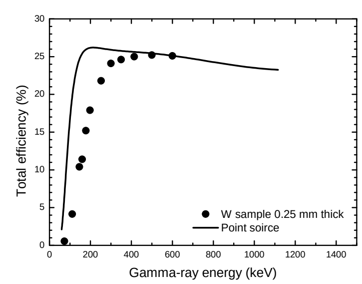
$$\mathbf{S} = R\mathbf{NAM}.$$

Detector efficiency

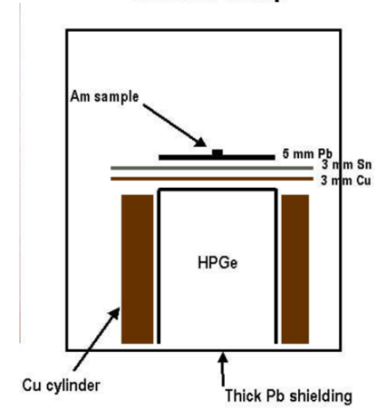
The Monte Carlo simulation of the detector response allows taking into account the detailed characteristics of the detector and samples (complex shape, sample matrix, γ-ray self-attenuation, volume activity distribution, coincidence summing effects, etc.







Detector setup

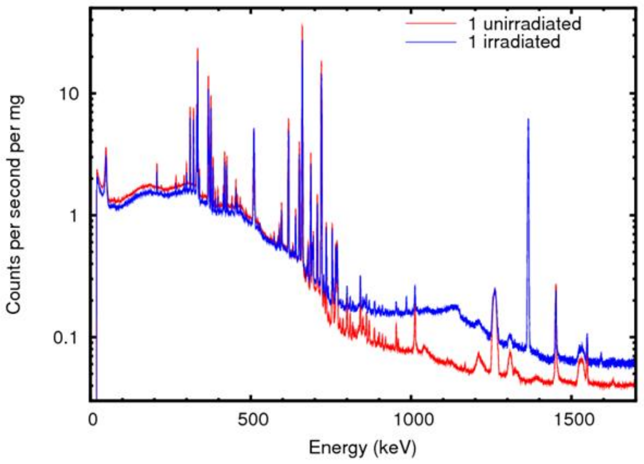


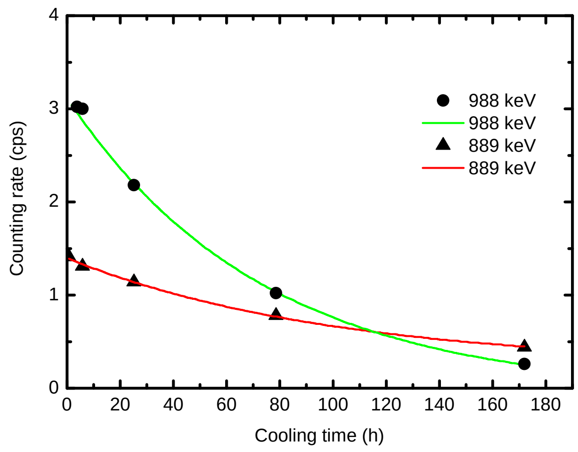
Self-attenuation correction:
standard formula 0.85
MCNP 0.65

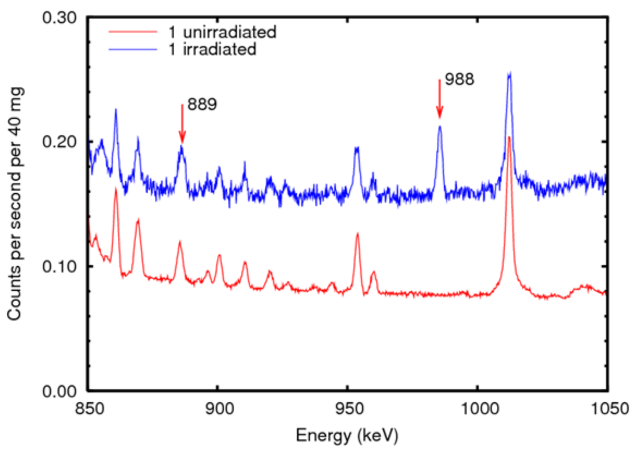
Nuclide identification by E_γ and $T_{1/2}$

^{240}Am decay data

$T_{1/2}$	50.8(3) h
E (keV)	I_γ (%)
988	73(4)
889	25.1(1.3)



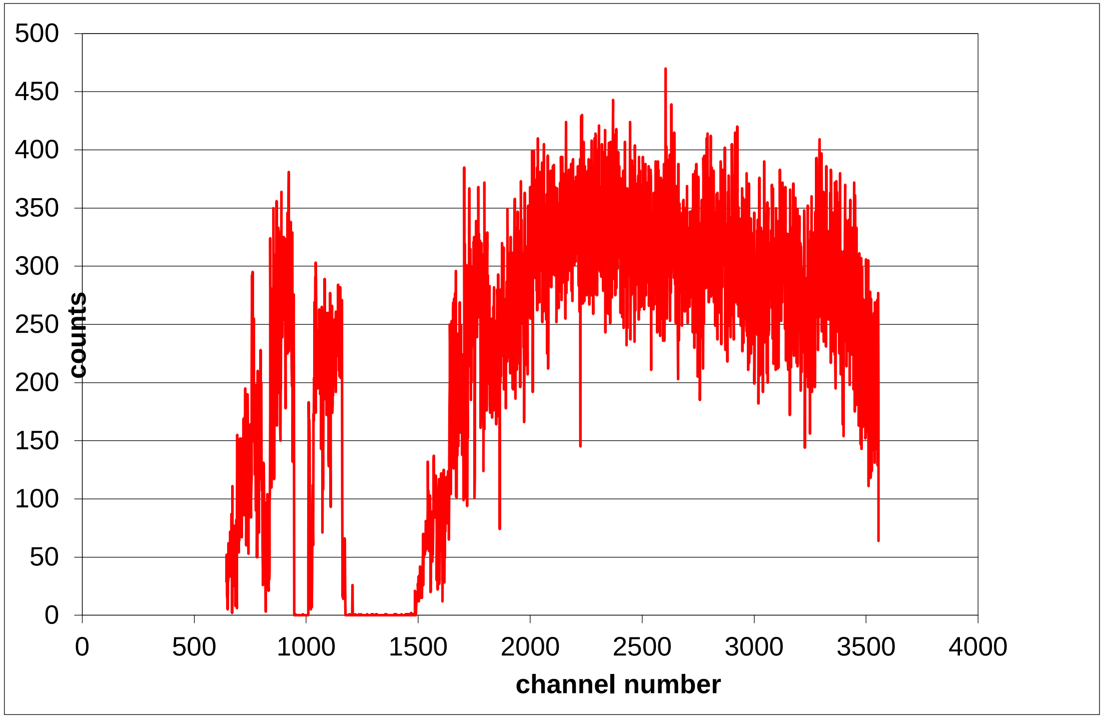




fitted $T_{1/2}$(988 keV) = 50.88 h

Neutron flux variation during irradiation

$$C_{\text{flux}} = \frac{\bar{\Phi}(1 - e^{-\lambda t_r})}{\sum_{i=1}^{m} \Phi_i (1 - e^{-\lambda \Delta t}) e^{-\lambda (m-i) \Delta t}}$$



Uncertainty analysis

$$\sigma_{\text{Am}} = f(a_k) = \prod_k a_k \qquad \mathbf{C}_{\sigma_{Am}} = \sum_k \left[\left(\frac{\partial \sigma_{Am}}{\partial a_k} \right) \mathbf{C}_{a_k} \left(\frac{\partial \sigma_{Am}}{\partial a_k} \right)^T \right]$$

$$F = \frac{\lambda}{exp(-\lambda t_c)(1 - exp(-\lambda t_e))(1 - exp(-\lambda t_m))}$$

The same sample employed in more than one irradiation

$$\mathbf{A}'_7 = \begin{pmatrix} 0.9^2 & & & & & & \cdots & & \\ 0.9\times0.6 & 0.6^2 & & & & & & & \\ 0.9\times0.4 & 0.6\times0.4 & 0.4^2 & & & & & & \\ 0.9\times0.6 & 0.6^2 & 0.4\times0.6 & 0.6^2 & & & & & \\ 0.9\times0.6 & 0.6^2 & 0.4\times0.6 & 0.6^2 & 0.6^2 & & & & \vdots \\ 0.9\times0.7 & 0.6\times0.7 & 0.4\times0.7 & 0.6\times0.7 & 0.6\times0.7 & 0.7^2 & & & \\ 0.9\times0.6 & 0.6^2 & 0.4\times0.6 & 0.6^2 & 0.6^2 & 0.7\times0.6 & 0.6^2 & & \\ 0.9\times0.6 & 0.6^2 & 0.4\times0.6 & 0.6^2 & 0.6^2 & 0.7\times0.6 & 0.6^2 & 0.6^2 & \\ 0.9\times0.6 & 0.6^2 & 0.4\times0.6 & 0.6^2 & 0.6^2 & 0.7\times0.6 & 0.6^2 & 0.6^2 & 0.6^2 \end{pmatrix}$$

$$\mathbf{A}'_5 = \begin{pmatrix} 0.3^2 & & & & & \cdots & & & \\ 0 & 0.3^2 & & & & & & & \\ 0 & 0.3^2 & 0.3^2 & & & & & & \\ 0 & 0.3^2 & 0.3^2 & 0.3^2 & & & & & \\ 0 & 0 & 0 & 0 & 0.3^2 & & & & \vdots \\ 0.3^2 & 0 & 0 & 0 & 0 & 0.3^2 & & & \\ 0 & 0 & 0 & 0 & 0.3^2 & 0 & 0.3^2 & & \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.3^2 & \\ 0.3^2 & 0 & 0 & 0 & 0 & 0.3^2 & 0 & 0 & 0.3^2 \end{pmatrix}$$

Table 4.2: Principal sources of uncertainty and their estimated magnitudes in %.

	Neutron energy (MeV)								
	8.34	9.15	13.33	16.1	17.16	17.9	19.36	19.95	20.61
σ_{Al}	1.9	1.9	1.6	2	2	2.2	3.1	4.1	5.4
S_{Am}	5.0	4.0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.4	5.7
S_{Al}	1.0	1.0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.0	1.6
I_{Am}	1.2	1.2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.2	1.2
n_{Al}	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
n_{Am}	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
$\epsilon_{\text{Al}}/\epsilon_{\text{Am}}$	3.0	3.0	3.[illegible]	[illegible]	[illegible]	[illegible]	3.0	3.0	3.0
$(f_\Sigma f_r)_{\text{Am}}$	0.9	0.6	0.[illegible]	[illegible]	[illegible]	[illegible]	0.6	0.6	0.6
$\frac{C_{\text{low,Am}}}{C_{\text{low,Al}}}$			0.[illegible]	[illegible]	[illegible]	[illegible]	1.3	1.4	1.4

not correlated

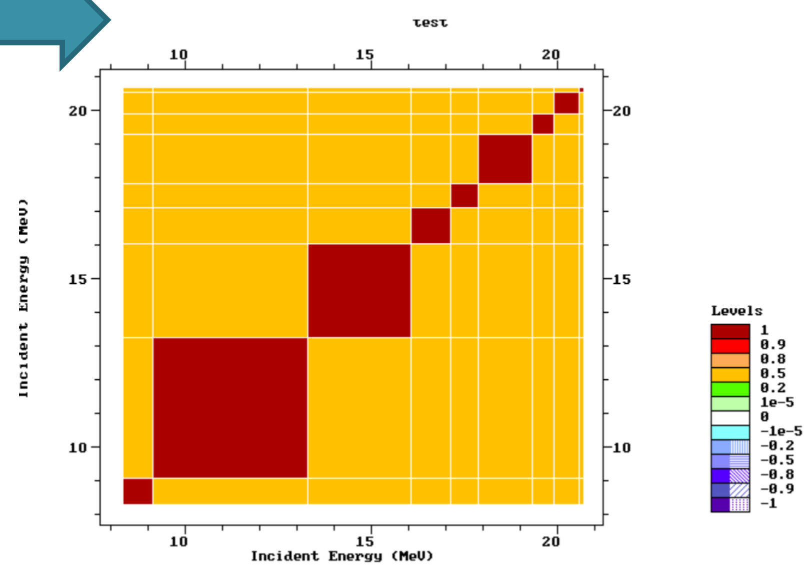
correlated

Energy (MeV)	σ_{Am} (mb)	Unc. (%)	Correlation matrix (x100)								
8.34(15)	96.8	6.5	100								
9.15(15)	162.9	5.7	35	100							
13.33(15)	241.8	4.6	37	42	100						
16.10(15)	152.4	4.6	38	43	53	100					
17.16 (3)	116.1	4.4	40	45	57	58	100				
17.90(10)	105.7	4.4	41	45	57	59	84	100			
19.36(15)	89.5	8.2	21	24	30	31	39	39	100		
19.95 (7)	102.1	5.8	30	34	44	45	58	59	51	100	
20.61 (4)	77.9	8.8	20	22	29	30	40	42	39	65	100

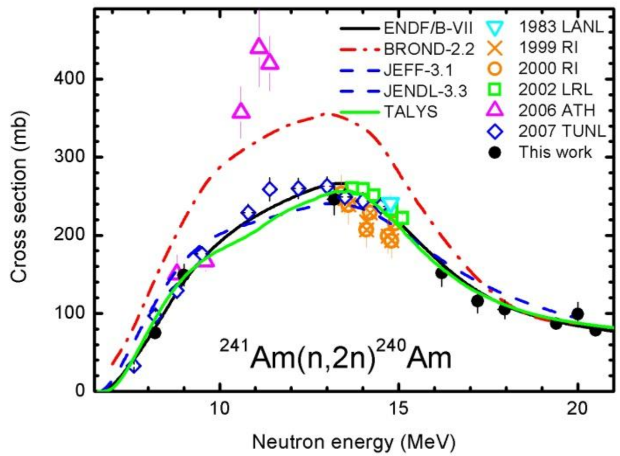
Constructing a covariance matrix from EXFOR uncertainties

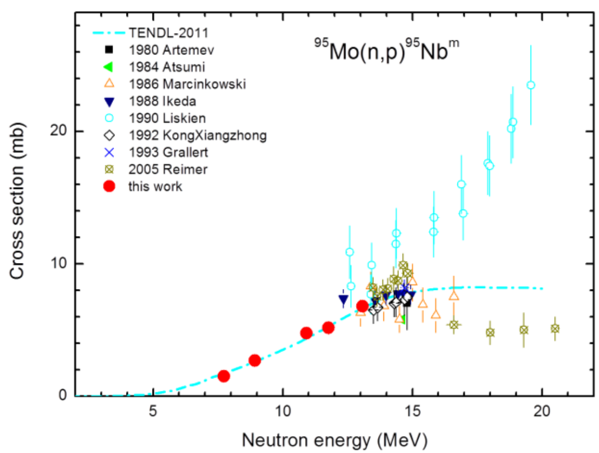
```
ERR-ANALYS (ERR-T,,,P) Total uncertainty
           (MONIT-ERR,,,P) 27Al(n,a) standard x-section (1.6-5.4%)
           (ERR-1,,,U) Counting of 240Am activity       (1.4-6.3%)
           (ERR-2,,,U) Counting of 24Na activity        (0.7-2.0%)
           (ERR-3,,,F) Intensity of 240Am gamma line        (1.2%)
           (ERR-4,,,U) Number of 27Al in sample             (0.1%)
           (ERR-5,,,P) Number of 241Am in sample            (0.3%)
           (ERR-6,,,F) 24Na/240Am efficiency ratio          (3.0%)
           (ERR-7,,,F) Correction for decay of 240Am    (0.4-0.9%)
           (ERR-8,,,U) Correction for secondary neutron    (<1.4%)
#/SUBENT 23114002
```

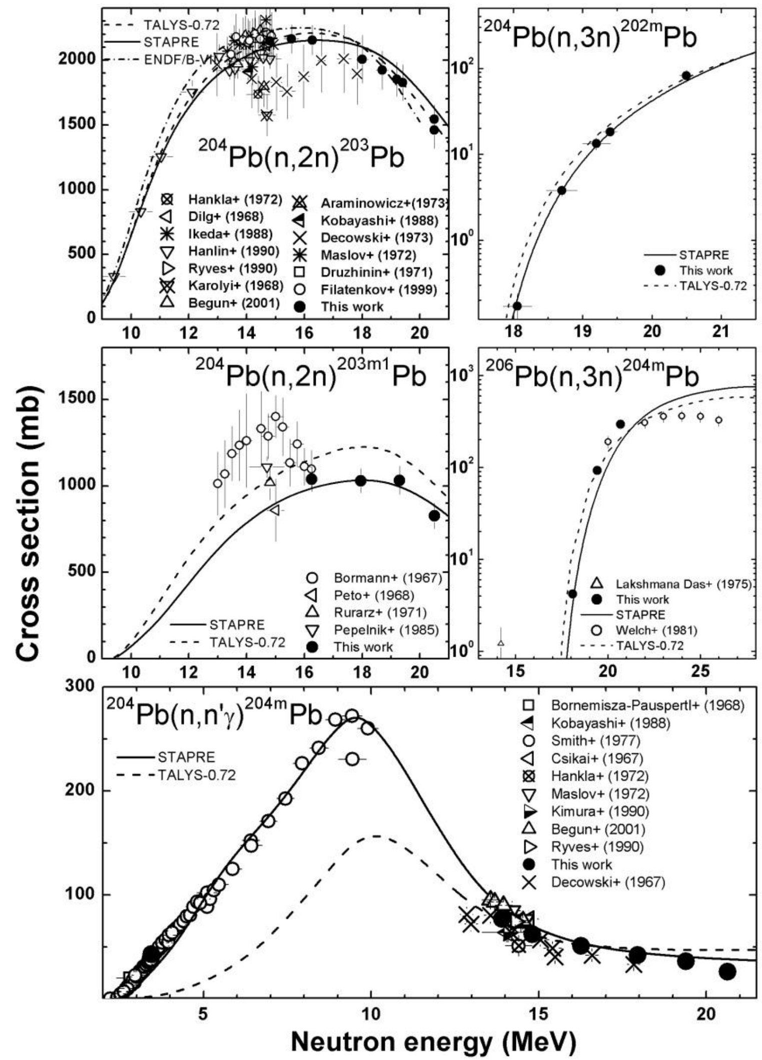
No.	1	2	3	4	5	6	7	8	9
Energy (eV) *0.001	8340.	9150.	13330.	16100.	17160.	17900.	19360.	19950.	20610.
Data (B) *1000.	96.8	162.9	241.8	152.4	116.1	105.7	89.5	102.1	77.9
Uncertainties defined in C5 (C4++)									
Total (%)	6.5	5.7	4.6	4.6	4.4	4.4	8.2	5.8	8.8
Statistical (%) *empty*	-	-	-	-	-	-	-	-	-
Systematic (%)	6.4	5.6	4.5	4.5	4.3	4.3	8.1	5.7	8.8
Uncertainties given in EXFOR									
ERR-T (%)	6.5	5.7	4.6	4.6	4.4	4.4	8.2	5.8	8.8
ERR-1 (%)	5.0	4.0	2.5	2.1	1.5	1.3	6.3	1.4	5.7
ERR-2 (%)	1.0	1.0	1.0	1.0	1.0	0.7	2.0	1.0	1.6
ERR-3 (%) *const*	1.2	=	=	=	=	=	=	=	=
ERR-4 (%) *const*	0.1	=	=	=	=	=	=	=	=
ERR-5 (%) *const*	0.3	=	=	=	=	=	=	=	=
ERR-6 (%) *const*	3.0	=	=	=	=	=	=	=	=
ERR-7 (%)	0.9	0.6	0.4	0.6	0.6	0.7	0.6	0.6	0.6
ERR-8 (%)	-	-	0.3	0.3	0.3	0.3	1.3	1.4	1.4
MONIT-ERR (%)	1.9	1.9	1.6	2.0	2.0	2.2	3.1	4.1	5.4



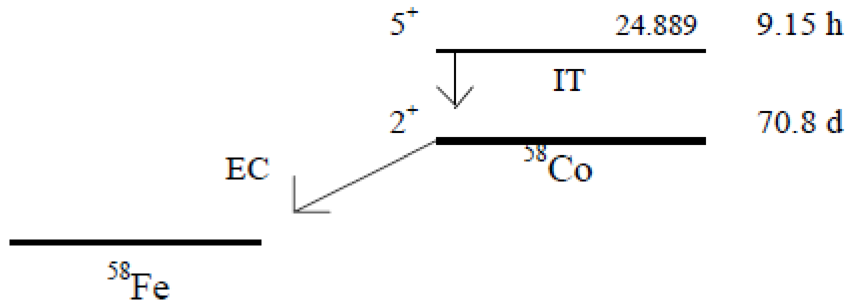
Some results







Isomeric ratio measurements



$$N_g(t_c) = n\Phi\left\{\left(\frac{p\sigma_m + \sigma_g}{\lambda_g} + \frac{p\sigma_m}{\lambda_m - \lambda_g}\right)\right\}\left(1 - e^{-\lambda_g T}\right)e^{-\lambda_g t_c} - \frac{p\sigma_m}{\lambda_m - \lambda_g}\left(1 - e^{-\lambda_m T}\right)e^{-\lambda_m t_c}$$

if we substitute

$$A = \left\{\left(\frac{p\sigma_m + \sigma_g}{\lambda_g} + \frac{p\sigma_m}{\lambda_m - \lambda_g}\right)\left(1 - e^{-\lambda_g T}\right)\right\}$$

$$B = \frac{p\sigma_m}{\lambda_m - \lambda_g}\left(1 - e^{-\lambda_m T}\right)$$

then

$$N_g(t_c) = n\Phi\left(Ae^{-\lambda_g t_c} + Be^{-\lambda_m t_c}\right).$$

The coefficients A and B can be determined by fitting the experimental data, and the isomeric cross section ratio is then given by:

$$\frac{\sigma_m}{\sigma_m + \sigma_g} = \frac{\left(\lambda_m - \lambda_g\right)}{\lambda_g}\frac{B}{\left(\left(\left(1 - e^{-\lambda_m T}\right)/\left(1 - e^{-\lambda_g T}\right)\right)A - B\right)}.$$

$^9Be(d,n)$ thick target neutron spectrum

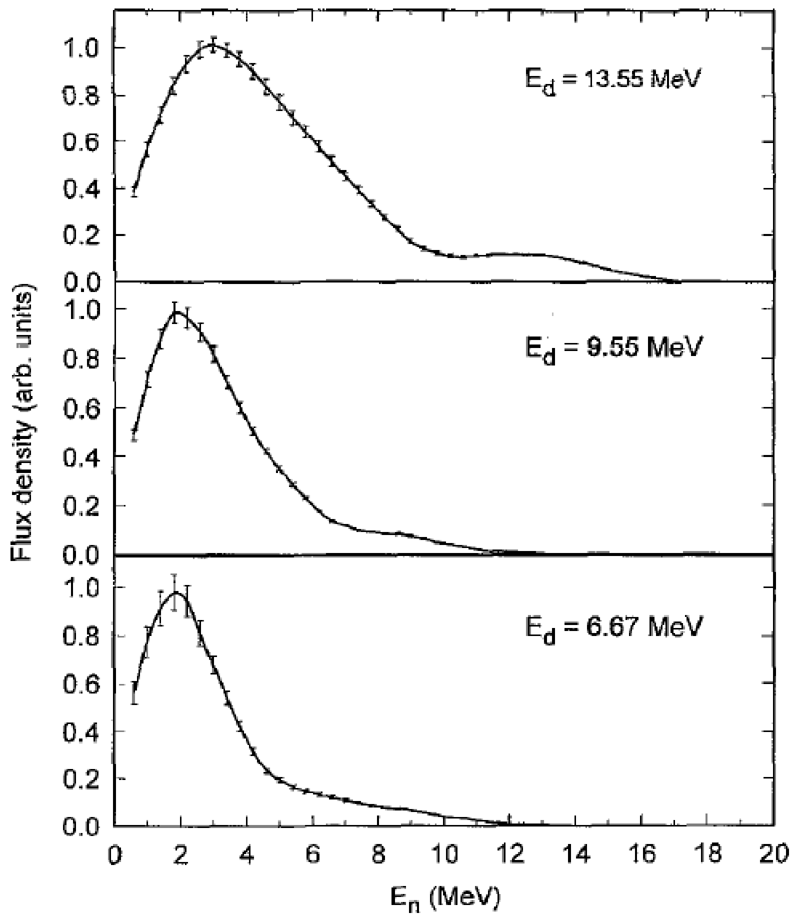


Fig. 7. Multiple foil activation unfolding of neutron spectra from a thick Be target at $E_d = 13.55$, 9.55 and 6.67 MeV.

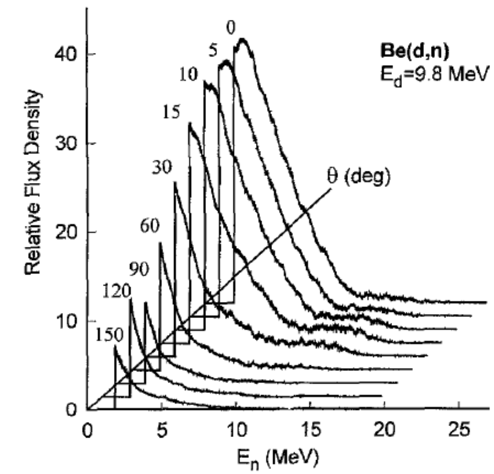
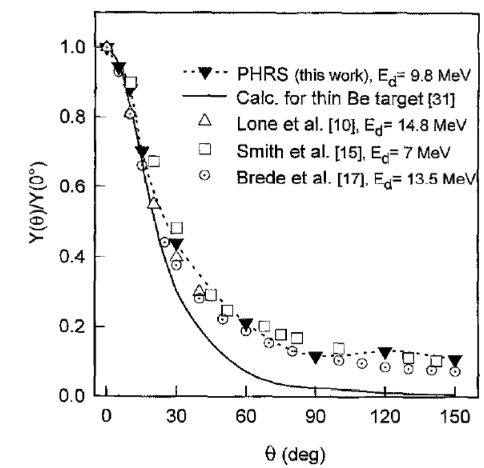


Fig. 9. Relative flux density of $^9Be(d, n)$ neutrons vs. emission angle measured by PHRS.



Spectrum average cross sections

$$\bar{\sigma} = \frac{\int_{E_1}^{E_2} \sigma(E)\Phi(E)dE}{\int_{E_1}^{E_2} \Phi(E)dE} = \int_{E_1}^{E_2} \sigma(E)\,\chi(E)$$

TABLE V

Measured and Calculated Be(d,n) Spectrum-Averaged Data for (n,p) Reactions

Reaction	Measured (mb)	ENDF-B/VI	IRDF90	JEF-2	JENDL3	CENDL2	SINCROS II.	ADL-3	BROND
$^{58}Ni(n,p)^{58m+g}Co$	325.65 ± 30	316.41	320.52	316.41	312.74			201.46	324.02[a]
$^{60}Ni(n,p)^{60m+g}Co$	18.54 ± 1.9	19.43[a]	19.81	19.43[a]	25.56			10.91	25.84
$^{64}Zn(n,p)^{64}Cu$	111.34 ± 10		119.00[a]	135.86			126.81	133.01	
$^{59}Co(n,p)^{59}Fe$	9.01 ± 0.9	9.01[a]		9.01[a]	9.02	8.77		13.55	
$^{90}Zr(n,p)^{90m}Y$	0.56 ± 0.05						0.48[a]	5.49	
$^{91}Zr(n,p)^{91m}Y$	0.86 ± 0.09						0.81[a]	2.99	
$^{92}Zr(n,p)^{92}Y$	0.59 ± 0.06	0.87		0.77	0.58[a]		0.63	0.41	0.52
$^{94}Zr(n,p)^{94}Y$	0.12 ± 0.02	0.30		0.29	0.14		0.11	0.12[a]	0.17
$^{92}Mo(n,p)^{92m}Nb$	34.42 ± 4.0						30.28[a]	40.21	
$^{96}Mo(n,p)^{96}Nb$	0.62 ± 0.07			0.84	0.64		0.66	0.62[a]	

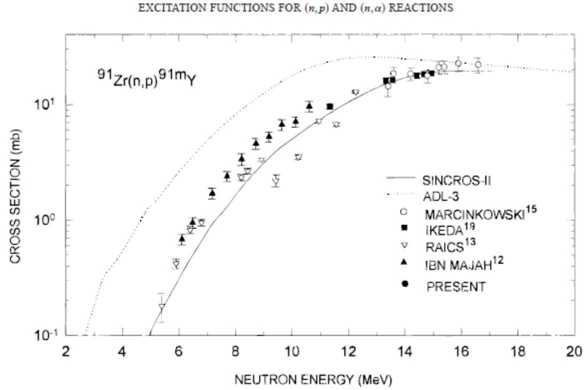


Fig. 8. Hydrogen production via the $^{91}Zr(n,p)^{91m}Y$ reaction.

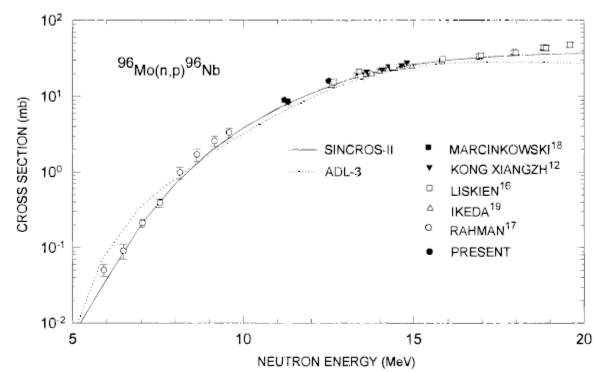


Fig. 4. Hydrogen production via the $^{96}Mo(n,p)^{96}Nb$ reaction.

TABLE IV

Measured and Calculated Be(*d*, *n*) Spectrum-Averaged Data for (*n*, *α*) Reactions

Reaction	Measured (mb)	ENDF-B/VI	IRDF90	JEF-2	JENDL3	CENDL2	SINCROS II.	ADL-3	BROND
$^{54}Fe(n,\alpha)^{51}Cr$	7.80 ± 0.80	9.96		10.11	9.62			11.24	7.25[a]
$^{51}V(n,\alpha)^{48}Sc$	0.61 ± 0.06		0.62[a]		0.67		0.52	0.47	
$^{59}Co(n,\alpha)^{56}Mn$	2.10 ± 0.18	2.35	2.40	2.35	2.45	2.40		2.13[a]	
$^{68}Zn(n,\alpha)^{65}Ni$	0.67 ± 0.07						0.86[a]	0.42	
$^{90}Zr(n,\alpha)^{87m}Sr$	0.12 ± 0.02						0.08[a]	0.18	

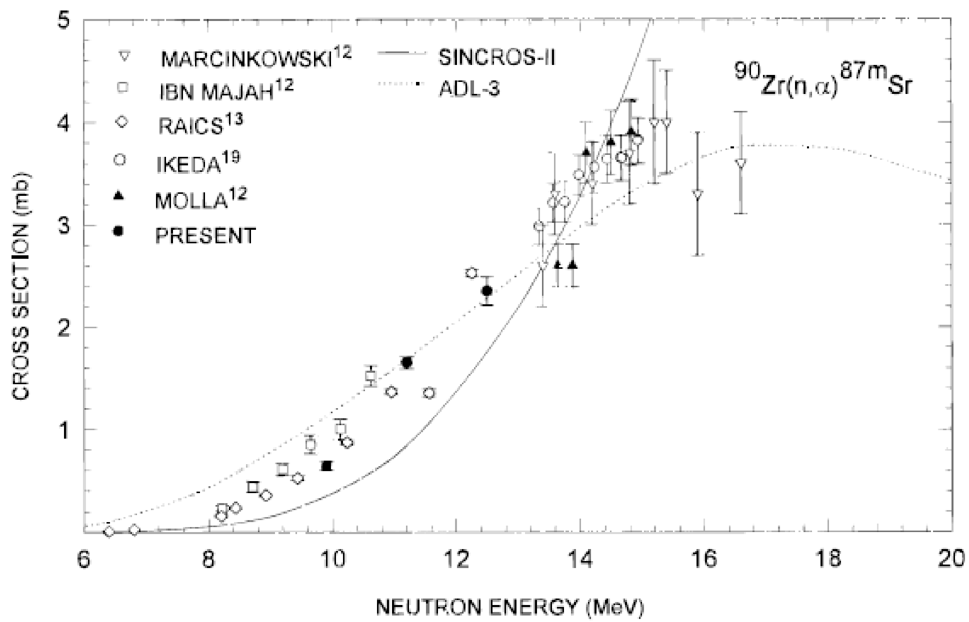


Fig. 7. Helium production via the $^{90}Zr(n,\alpha)^{87m}Sr$ reaction.