



# Measurement of the $^{160}\text{Gd}(n, \gamma)$ cross section at n\_TOF

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N. Colonna, G. Tagliente, S. Cristallo*

U Abbondanno *et al.* (The n\_TOF Collaboration), [Phys. Rev. Lett. 93, 161103 \(2004\)](#)

S. Marrone *et al.*, (The n\_TOF Collaboration) [Phys. Rev. C 73, 034604 \(2006\)](#)

# Motivations

A. Mazzone *et al.* (The n\_TOF Collaboration), [Physics Letters B 804, 135405 \(2020\)](#)

M. Mastromarco *et al.* (The n\_TOF Collaboration), [EPJA 55, 9 \(2019\)](#)

<b>Dy 154</b> 3.0 · 10 <sup>6</sup> a α 2.87	<b>Dy 155</b> 10.0 h ε β <sup>+</sup> 0.9; 1.1... γ 227...	<b>Dy 156</b> 0.056 σ <sub>n, α</sub> 33 σ <sub>n, α</sub> < 0.009	<b>Dy 157</b> 8.1 h ε γ 326...	<b>Dy 158</b> 0.095 σ <sub>n, α</sub> 33 σ <sub>n, α</sub> < 0.006	<b>Dy 159</b> 144.4 d ε γ 58; e <sup>-</sup> σ 8000	<b>Dy 160</b> 2.329 σ <sub>n, α</sub> 60 σ <sub>n, α</sub> < 0.0003	<b>Dy 161</b> 18.889 σ <sub>n, α</sub> 600 σ <sub>n, α</sub> < 1E-6	<b>Dy 162</b> 25.475 σ 170	<b>Dy 163</b> 24.896 σ <sub>n, α</sub> 120 σ <sub>n, α</sub> < 2E-5	<b>Dy 164</b> 28.260 σ 1610 + 1040	<b>Dy 165</b> 1.3 m 2.35 h Iy 108; e <sup>-</sup> β <sup>-</sup> 0.9; 1.3... 1.0... γ 95; γ 515... (362...) σ 2000 σ 3500
<b>Tb 153</b> 2.34 d ε β <sup>+</sup> ... γ 212; 170; 110; 102; 83...	<b>Tb 154</b> 23 h 9.0 h 21 h ε; Iy 248; 347; 1420; 123... Iy 123; 248; 540... ε; β <sup>+</sup> ... γ 123; 1274	<b>Tb 155</b> 5.32 d ε γ 87; 105; 180; 262...	<b>Tb 156</b> 24 h? 5.4 h 5.4 d Iy 88 ε; γ 534; 199; 1222 Iy 50 β <sup>+</sup> ... β <sup>-</sup> ?	<b>Tb 157</b> 99 a ε γ (54) e <sup>-</sup>	<b>Tb 158</b> 10.5 s 180 a Iy (110) ε β <sup>-</sup> 0.9 γ 944; 962; 80...	<b>Tb 159</b> 100 σ 23.2	<b>Tb 160</b> 72.3 d β <sup>-</sup> 0.6; 1.7... γ 879; 299; 966... σ 570	<b>Tb 161</b> 6.90 d β <sup>-</sup> 0.5; 0.6... γ 26; 49; 75... e <sup>-</sup>	<b>Tb 162</b> 7.76 m β <sup>-</sup> 1.4; 2.4... γ 260; 808; 888...	<b>Tb 163</b> 19.5 m β <sup>-</sup> 0.8; 1.3... γ 351; 390; 494...	<b>Tb 164</b> 3.0 m β <sup>-</sup> 1.7; 3.0... γ 169; 755; 215; 688; 611...
<b>Gd 152</b> 0.20 1.1 · 10 <sup>14</sup> a α 2.14; σ 700 σ <sub>n, α</sub> < 0.007	<b>Gd 153</b> 239.47 d ε γ 97; 103; 70... σ 20000 σ <sub>n, α</sub> 0.03	<b>Gd 154</b> 2.18 σ 60	<b>Gd 155</b> 14.80 σ 61000 σ <sub>n, α</sub> 0.00008	<b>Gd 156</b> 20.47 σ ~ 2.0	<b>Gd 157</b> 15.65 σ 254000 σ <sub>n, α</sub> < 0.05	<b>Gd 158</b> 24.84 σ 2.3	<b>Gd 159</b> 18.48 h β <sup>-</sup> 1.0... γ 364; 58...	<b>Gd 160</b> 21.86 σ 1.5	<b>Gd 161</b> 3.66 m β <sup>-</sup> 1.6; 1.7... γ 361; 315; 102... σ 20000	<b>Gd 162</b> 8.2 m β <sup>-</sup> 1.0... γ 442; 403...	<b>Gd 163</b> 68 s β <sup>-</sup> γ 288; 214; 1562; 1685...
<b>Eu 151</b> 47.81 σ 4 + 3150 + 6000	<b>Eu 152</b> 96 m 9.3 h 13.33 a β <sup>-</sup> 1.9; ε; β <sup>+</sup> ... γ 841; 122; 963; 344... σ 68000 σ 11000	<b>Eu 153</b> 52.19 σ 300 σ <sub>n, α</sub> 1E-6	<b>Eu 154</b> 46.0 m 8.8 a β <sup>-</sup> 0.6; 1.8... ε; γ 123; 1274; 723; 1005... Iy 68; 101... σ 1500	<b>Eu 155</b> 4.761 a β <sup>-</sup> 0.17; 0.25... γ 87; 105... σ 3900	<b>Eu 156</b> 15.2 d β <sup>-</sup> 0.5; 2.4... γ 812; 89; 1231...	<b>Eu 157</b> 15.18 h β <sup>-</sup> 1.3... γ 64; 411; 371; 619...	<b>Eu 158</b> 46 m β <sup>-</sup> 2.4; 3.4... γ 944; 977; 80; 898...	<b>Eu 159</b> 18.1 m β <sup>-</sup> 2.6... γ 68; 71; 79; 96; 103...	<b>Eu 160</b> 42 s β <sup>-</sup> 4.1... γ 173; 515; 412; 822...	<b>Eu 161</b> 26 s β <sup>-</sup> γ 72-314	<b>Eu 162</b> 10.6 s β <sup>-</sup> γ 71; 165
<b>Sm 150</b> 7.38 σ 102	<b>Sm 151</b> 93 a β <sup>-</sup> 0.1... γ (22...); e <sup>-</sup> σ 15200	<b>Sm 152</b> 26.75 σ 206	<b>Sm 153</b> 46.27 h β <sup>-</sup> 0.7; 0.8... γ 103; 70... σ 420	<b>Sm 154</b> 22.75 σ 7.5	<b>Sm 155</b> 22.4 m β <sup>-</sup> 1.5... γ 104; 246; 141...	<b>Sm 156</b> 9.4 h β <sup>-</sup> 0.7... γ 204; 88; 166... e <sup>-</sup>	<b>Sm 157</b> 8.11 m β <sup>-</sup> 2.4... γ 198; 196; 394...	<b>Sm 158</b> 5.51 m β <sup>-</sup> γ 189; 364; 325...	<b>Sm 159</b> 11.4 s β <sup>-</sup> γ 190; 862; 254; 797; 179...	<b>Sm 160</b> 9.6 s β <sup>-</sup> γ 110...	<b>Sm 161</b> 4.8 s β <sup>-</sup> γ 264

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## <sup>161</sup>Tb is a clinically interesting isotope for theranostics

<b>Dy 154</b> 3.0 · 10 <sup>6</sup> a α 2.87	<b>Dy 155</b> 10.0 h ε β <sup>+</sup> 0.9; 1.1... γ 227...	<b>Dy 156</b> 0.056 σ <sub>n, α</sub> 33 σ <sub>n, α</sub> < 0.009	<b>Dy 157</b> 8.1 h ε γ 326...	<b>Dy 158</b> 0.095 σ <sub>n, α</sub> 33 σ <sub>n, α</sub> < 0.006	<b>Dy 159</b> 144.4 d ε γ 58; e <sup>-</sup> σ 8000	<b>Dy 160</b> 2.329 σ <sub>n, α</sub> 60 σ <sub>n, α</sub> < 0.0003	<b>Dy 161</b> 18.889 σ <sub>n, α</sub> 600 σ <sub>n, α</sub> < 1E-6	<b>Dy 162</b> 25.475 σ 170	<b>Dy 163</b> 24.896 σ <sub>n, α</sub> 120 σ <sub>n, α</sub> < 2E-5	<b>Dy 164</b> 28.260 σ 1610 + 1040	<b>Dy 165</b> 1.3 m 2.35 h I <sub>γ</sub> 108; e <sup>-</sup> β <sup>-</sup> β <sup>-</sup> 0.9; 1.3... 1.0... γ 95; γ 515... (362...) σ 2000 σ 3500
<b>Tb 153</b> 2.34 d ε β <sup>+</sup> ... γ 212; 170; 110; 102; 83...	<b>Tb 154</b> 23 h 9.0 h 21 h ε; I <sub>γ</sub> 248; 347; 1420; 123... ε; I <sub>γ</sub> 123; 248; 540... ε β <sup>+</sup> ... γ 123; 1274	<b>Tb 155</b> 5.32 d ε γ 87; 105; 180; 262...	<b>Tb 156</b> 24 h? 5.4 h 5.4 d I <sub>γ</sub> 88 ε; I <sub>γ</sub> 534; 199; 1222 ε β <sup>+</sup> ... γ 50 β <sup>+</sup> ... e <sup>-</sup> β <sup>-</sup> ?	<b>Tb 157</b> 99 a ε γ (54) e <sup>-</sup>	<b>Tb 158</b> 10.5 s 180 a I <sub>γ</sub> (110) ε β <sup>-</sup> 0.9 e <sup>-</sup> γ 944; 962; 80...	<b>Tb 159</b> 100 σ 23.2	<b>Tb 160</b> 72.3 d β <sup>-</sup> 0.6; 1.7... γ 879; 299; 966... σ 570	<b>Tb 161</b> 6.90 d β <sup>-</sup> 0.5; 0.6... γ 26; 49; 75... e <sup>-</sup>	<b>Tb 162</b> 7.76 m β <sup>-</sup> 1.4; 2.4... γ 260; 808; 888...	<b>Tb 163</b> 19.5 m β <sup>-</sup> 0.8; 1.3... γ 351; 390; 494...	<b>Tb 164</b> 3.0 m β <sup>-</sup> 1.7; 3.0... γ 169; 755; 215; 688; 611...
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# Motivations: Terbium-161

- Chemically similar to Lutetium-177 (used in theranostic as  $\gamma$  and  $\beta^-$  emitter)
  - Similar half-life  $T_{1/2} = 6.9$  d (against 6.7 d of Lu-177)

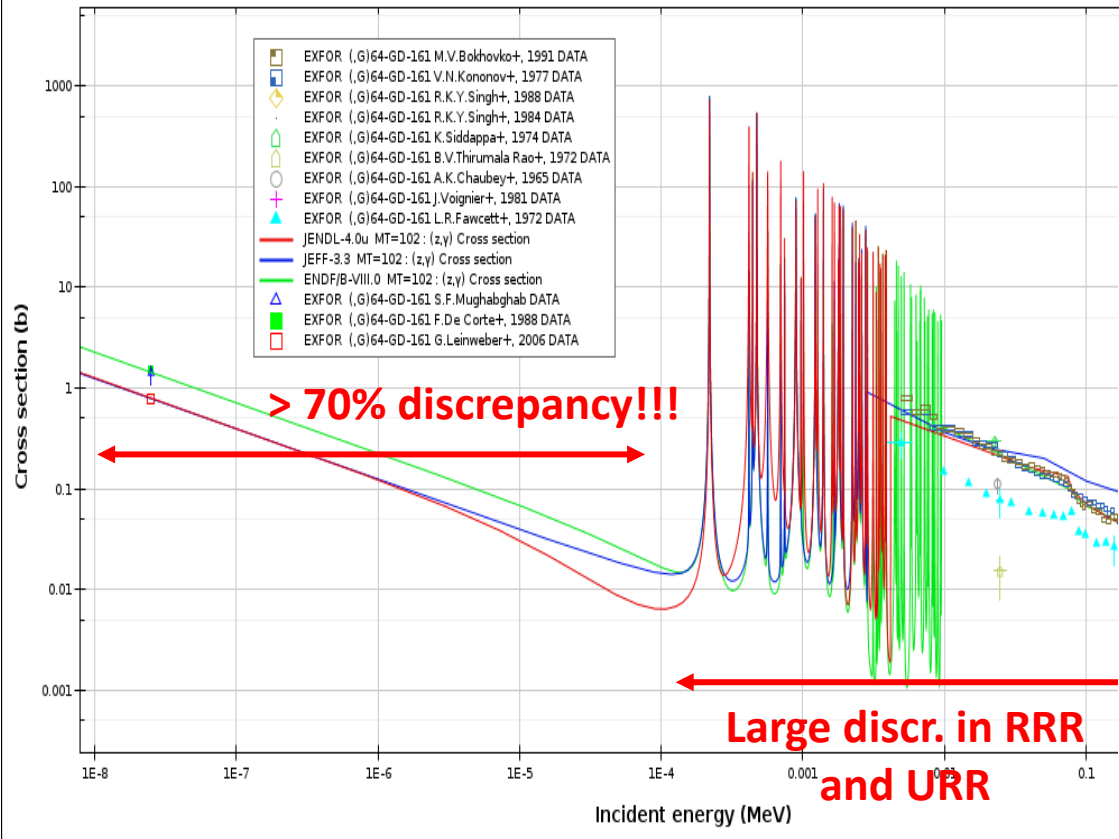
In addition to being a  $\gamma$  and  $\beta^-$  emitter (like Lu-177), Terbium-161 is also an emitter of Auger and conversion electrons;

The higher LET (compared to Lu-177) can be effective in reducing the survival probability of tumors cells.

# Motivations: State of the Art

## Exp. Data and Main Evaluations

Incident neutron data // Gd160 // Capture Reaction



## MACS @ kT=30 keV

source: <https://exp-astro.de/kadonis1.0/>

### List of all available values

original	renorm.	year	type	Comment	Ref
200 ± 13		1992	c	VdG, TOF, <sup>6</sup> Li, <sup>10</sup> B+Au:B-V	BKP92
144 ± 14	142	1984	c	VdG, Act., 1/v(kT), Au:657mb(25keV) <sup>160</sup> Gd(n,gamma) <sup>161</sup> Gd beta decay of <sup>161</sup> Tb	BKY84
192 ± 19	178	1978	b	VdG, TOF, <sup>10</sup> B:Mag75, Au:628mb(kT=30keV)	KYP78
290 ± 41	218	1973	c	Sb-Be, Act., 1/v(E), <sup>127</sup> I:836mb(23keV)	SSR73
15 ± 7	12	1972	c	Sb-Be, Act., 1/v(E), <sup>127</sup> I:832mb(25keV)	TRK72
100 ± 30		1971	e		AGM71
171.3		2006	e		endfb7
230.4		2004	e		jeff31
164.5		2002	e		jendl33
167		2000	t		RaT99
265		1981	t		Har81
171		1976	t		HWF76
207		2002	t	MOST 2002	Gor02
174		2005	t	MOST 2005	Gor05

> 30% discrepancy

**Original:** MACS [ $\langle \sigma v \rangle / v_T$ ] (mb) for kT=30 keV, based on the published cross sections except where indicated otherwise.

**Renorm:** MACS [ $\langle \sigma v \rangle / v_T$ ] (mb) for kT=30 keV for which the reference or standard cross section was meanwhile improved.

**Type:** The letters and numbers in the column labelled 'type' give information on how the cross section has been obtained:

c Directly quoted from the reference itself

b Calculated from smooth cross sections with model fit:  $\ln(\sigma) = a + a_1 \ln(E) + a_2 \ln^2(E)$

e Evaluated value taken directly from the reference

t Theoretical value

# Experimental Setup @ EAR1 and EAR2 (n\_TOF)

Liquid scintillation detectors with **deuterated benzene: (C6D6 & STED)**

- Low neutron sensitivity
- Low  $\gamma$ -ray detection efficiency

## EAR1

- Flight Path: **185 m**
- Flux:  **$10^6/\text{cm}^2/\text{Proton Bunch}$**
- Very High Resolution:  **$< 10^{-3}$**

The **total energy detection principle** by combining the detection system with the so-called **Pulse Height Weighting Technique (PHWT)**

P. Schillebeeckx *et al.*, Nucl. Data Sheets **113**, 3054 (2012)

A. Borella, G. Aerts, F. Gunsing *et al.*, Nucl. Instr. Meth. A **577**, 626 (2007)

# Experimental Setup @ EAR1 and EAR2 (n\_TOF)

Liquid scintillation detectors with **deuterated benzene: (C6D6 & STED)**

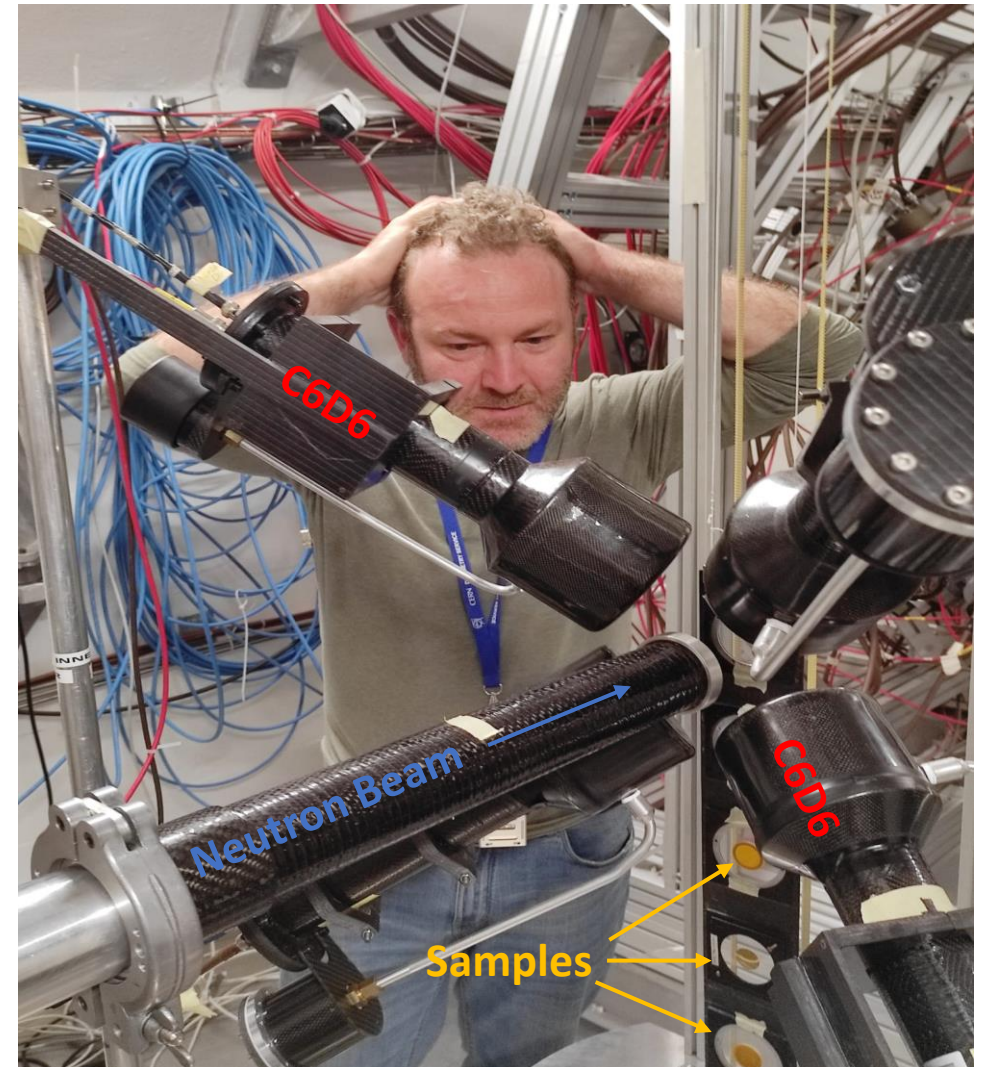
- Low neutron sensitivity
- Low  $\gamma$ -ray detection efficiency

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EAR1: 4 C6D6 & me



# Experimental Setup @ EAR1 and EAR2 (n\_TOF)

Liquid scintillation detectors with **deuterated benzene:**  
**(C6D6 & STED)**

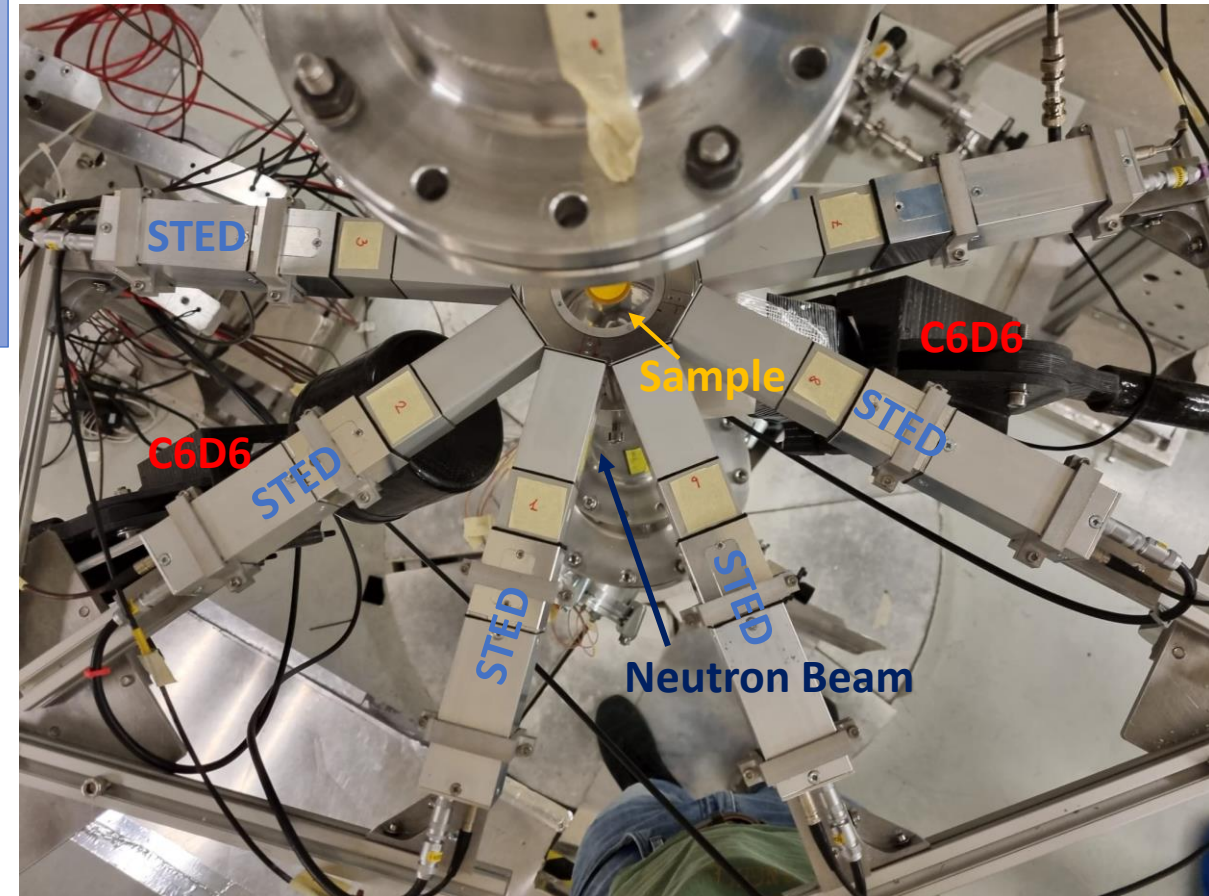
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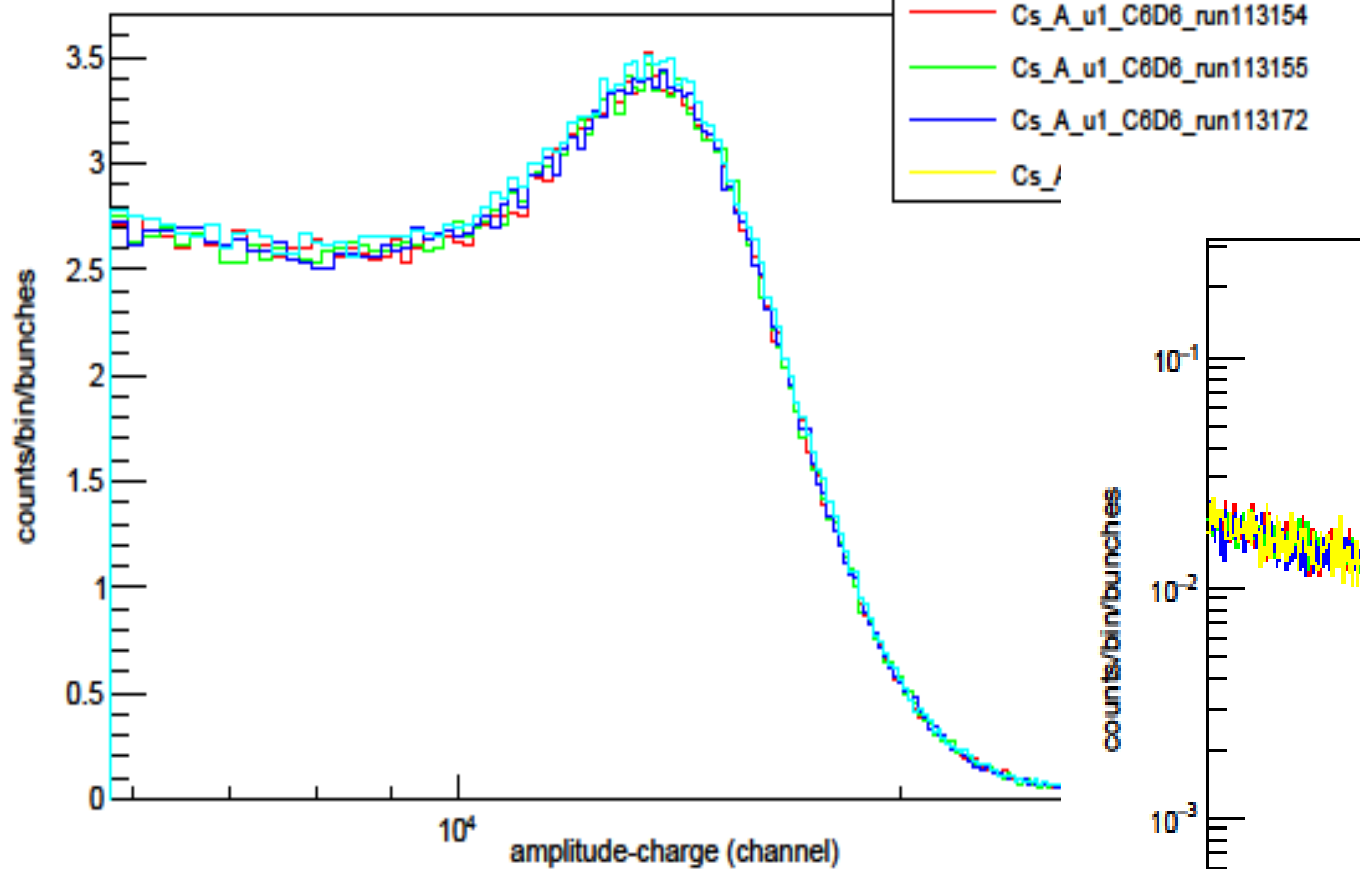
EAR2: 2 C6D6 + 9 STED



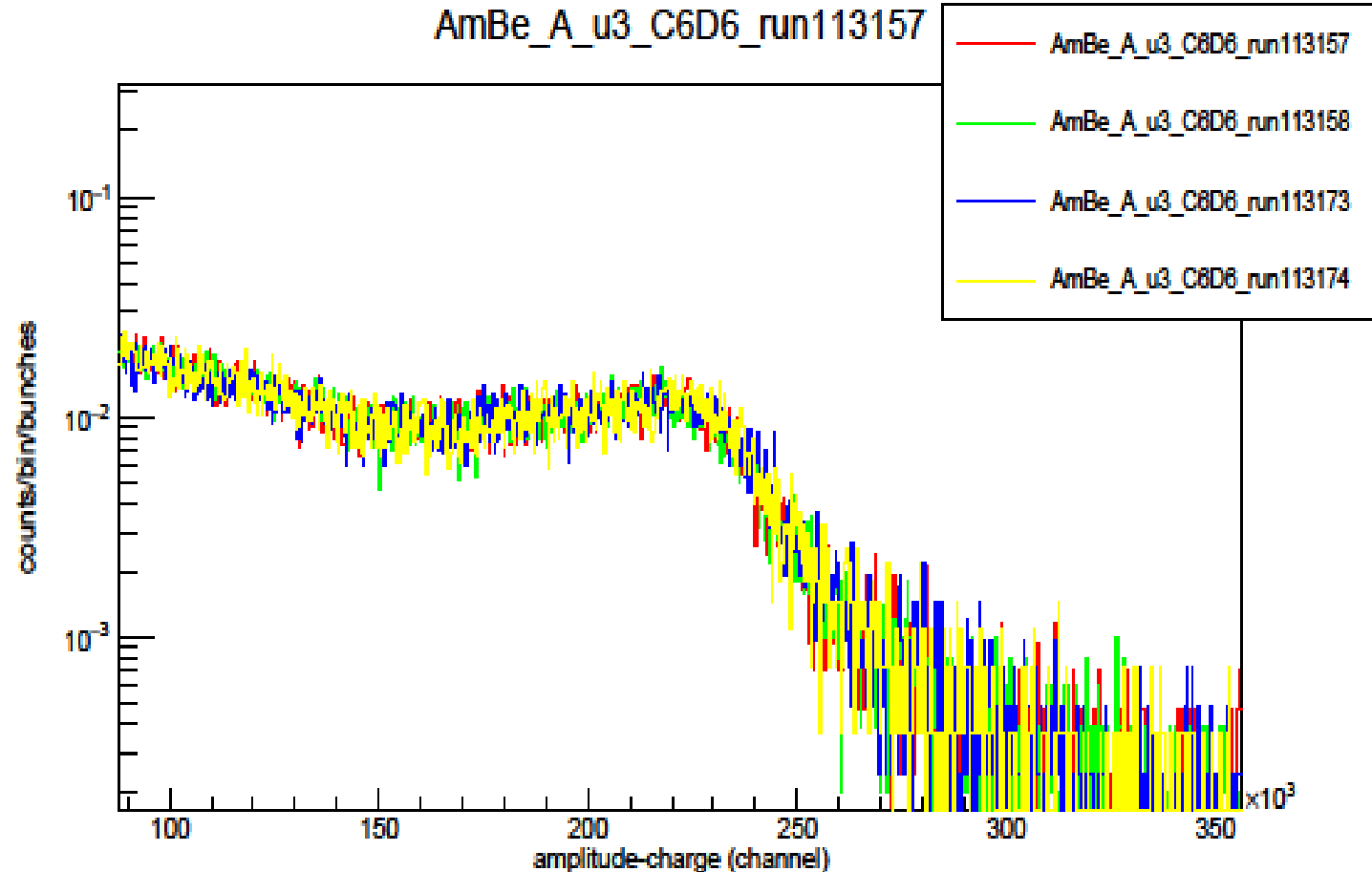


# EAR1: C<sub>6</sub>D<sub>6</sub> Stability (Cs-137, Y-88, AmBe)

Cs\_A\_u1\_C6D6\_run113154

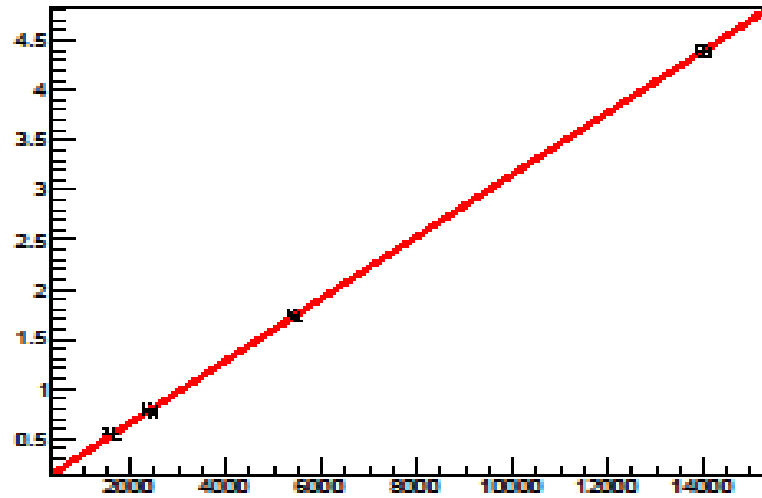


AmBe\_A\_u3\_C6D6\_run113157

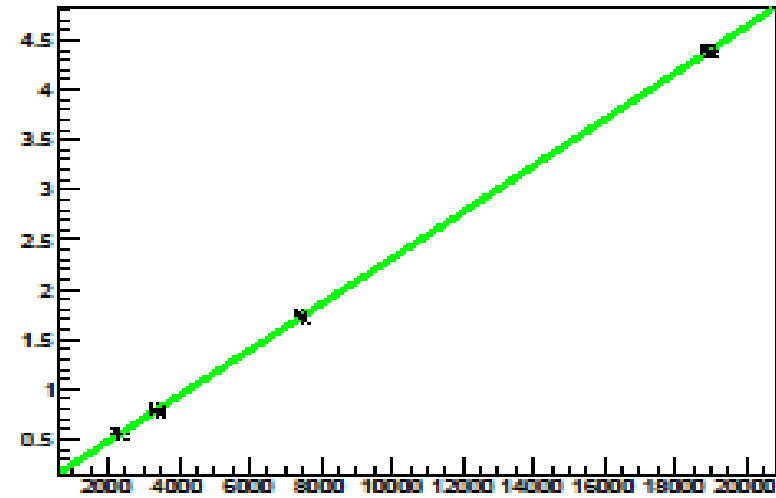


# Simulations: Setup geometry, Source simulations

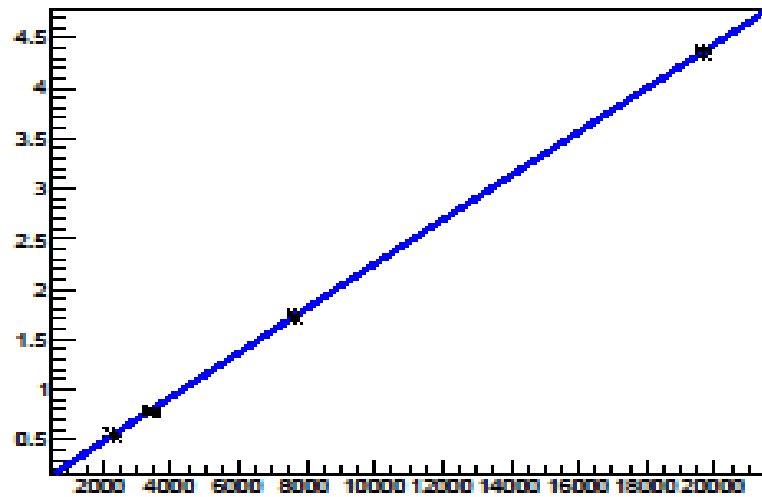
Calibration C6D6#1



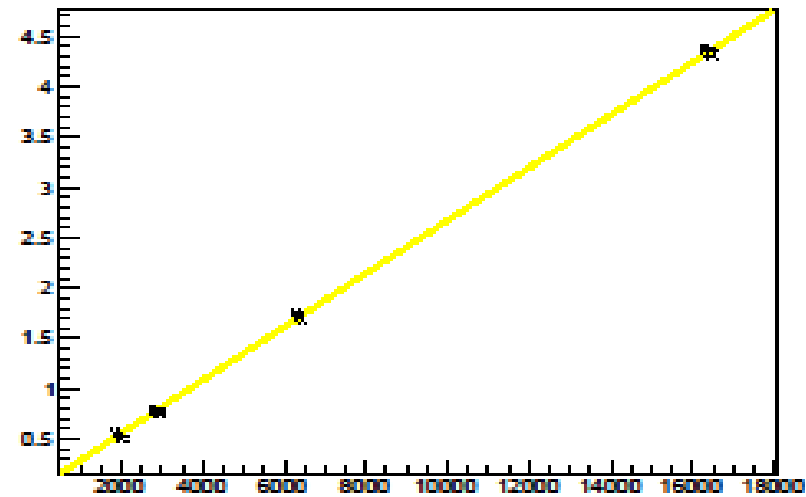
Calibration C6D6#2



Calibration C6D6#3

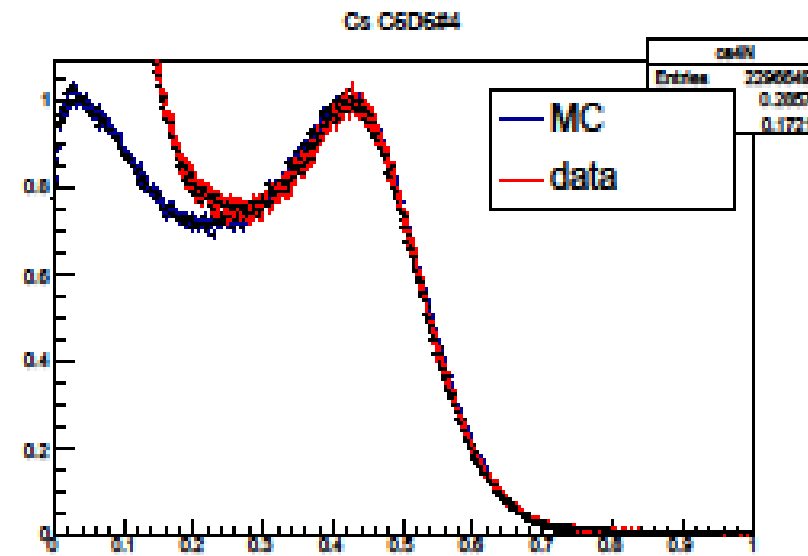
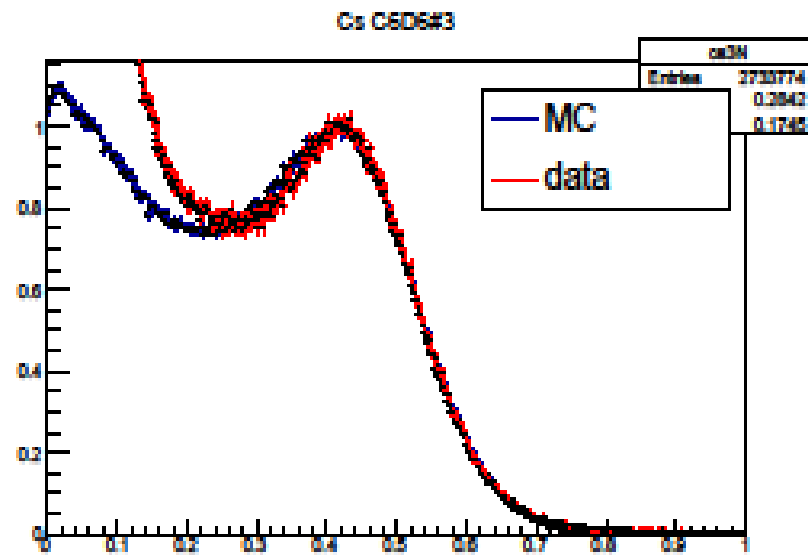
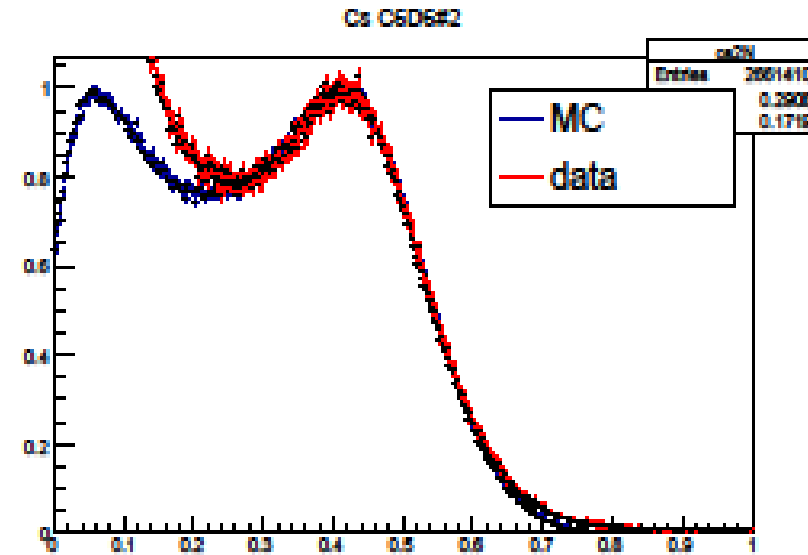
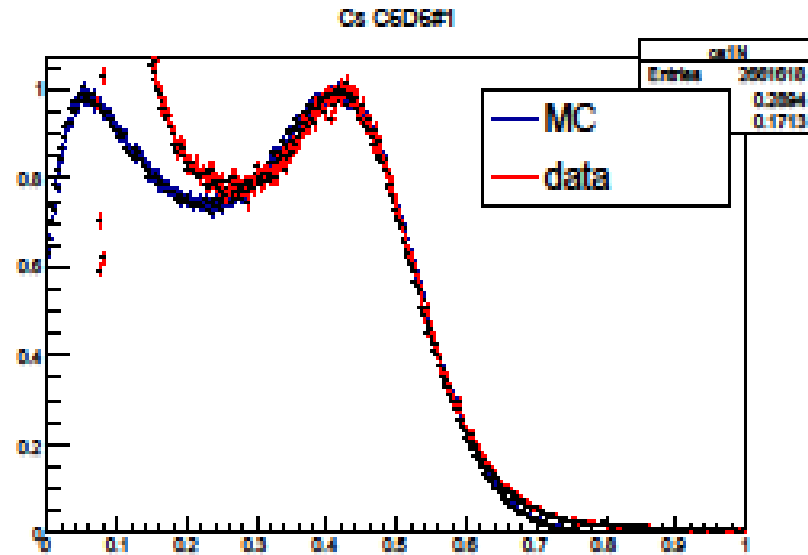


Calibration C6D6#4



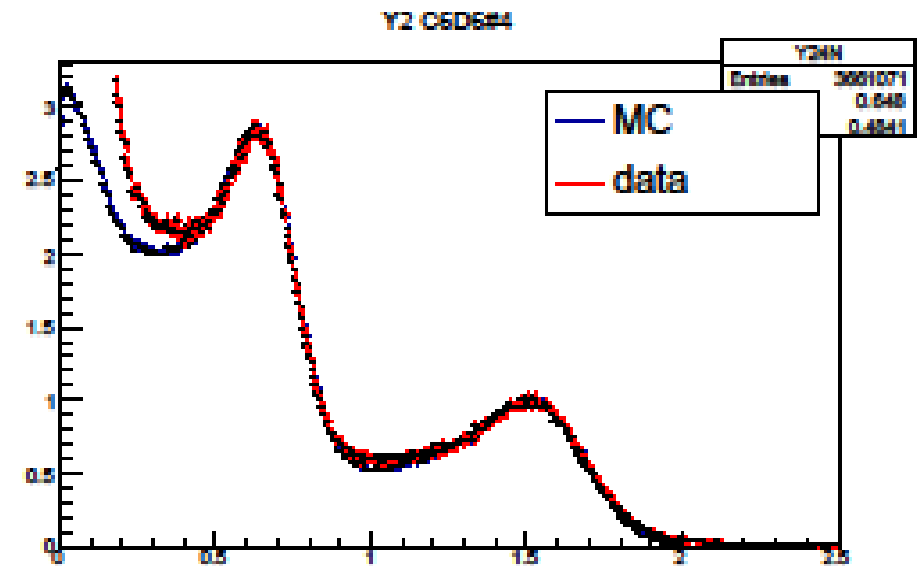
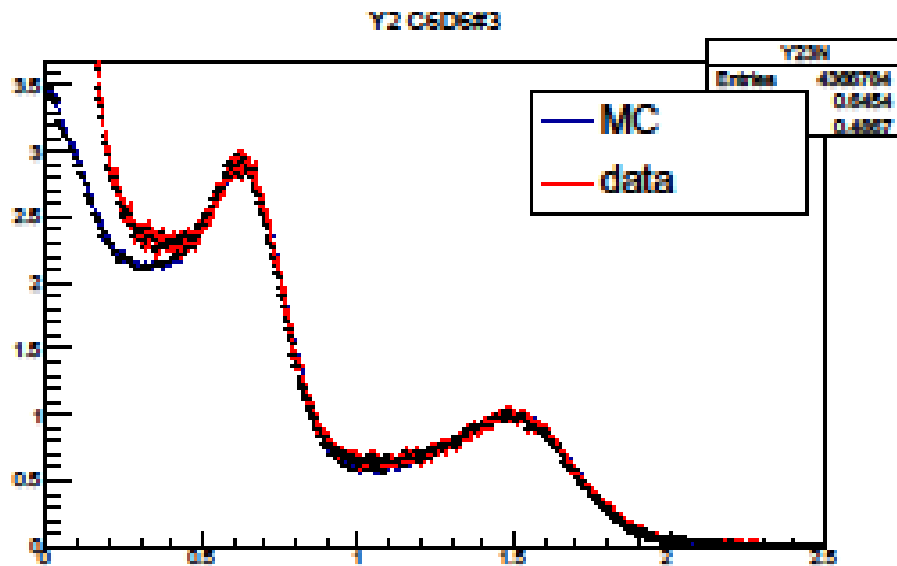
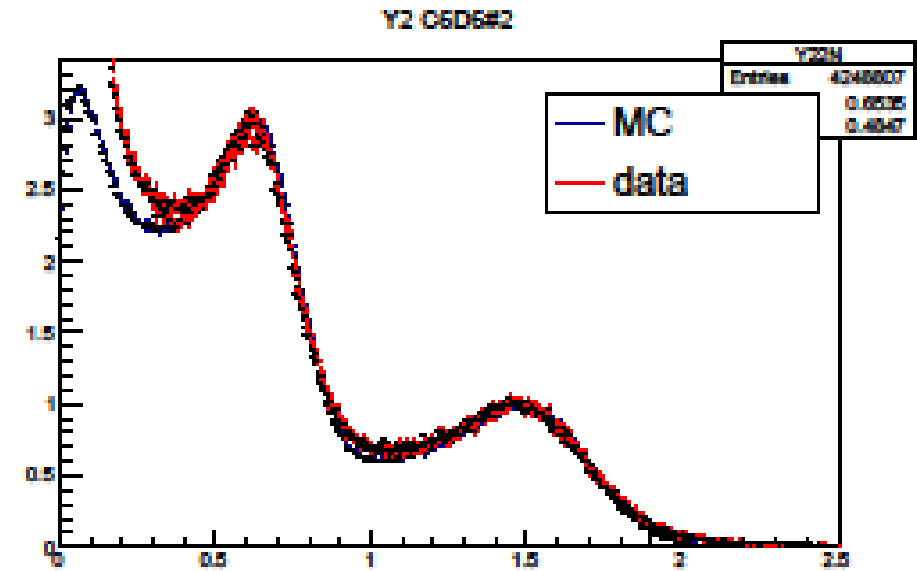
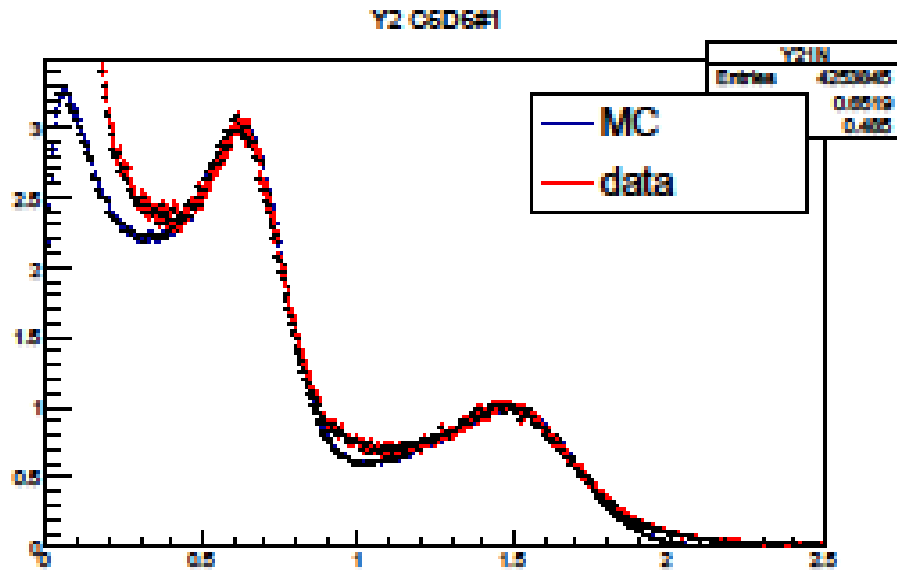
# Simulations: Setup geometry, Source simulations

Cs-137



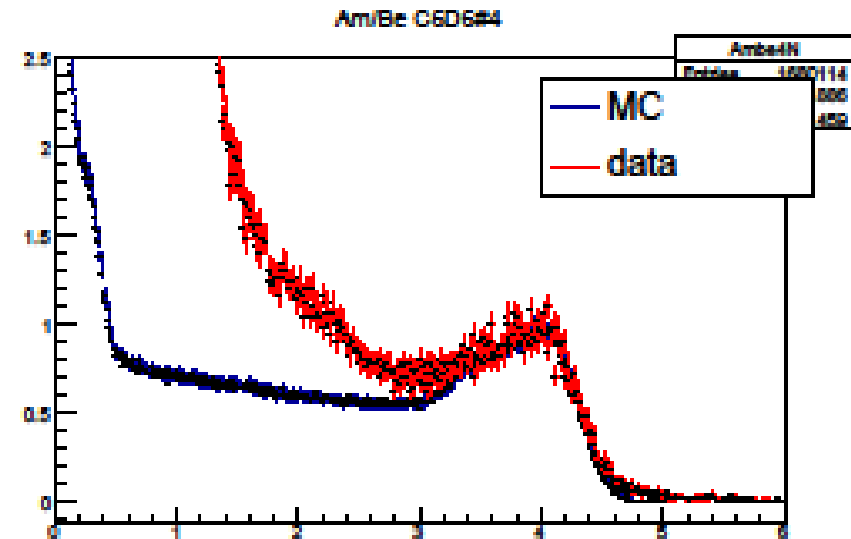
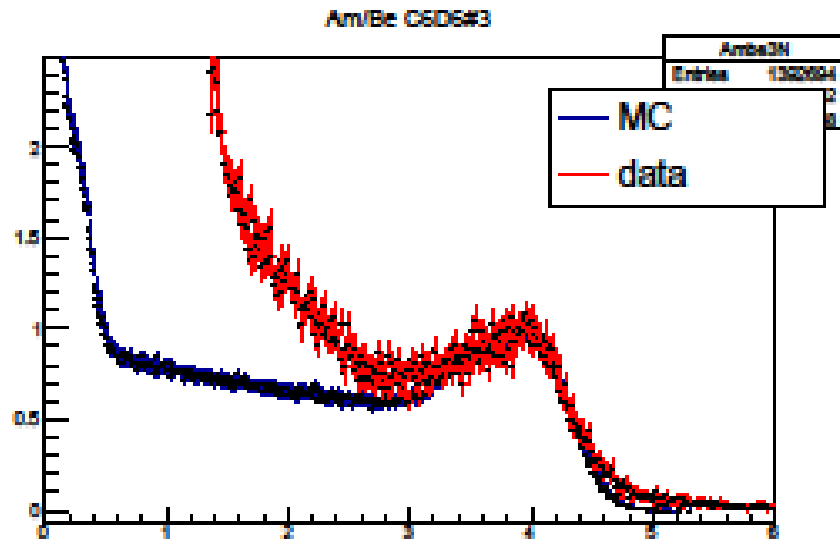
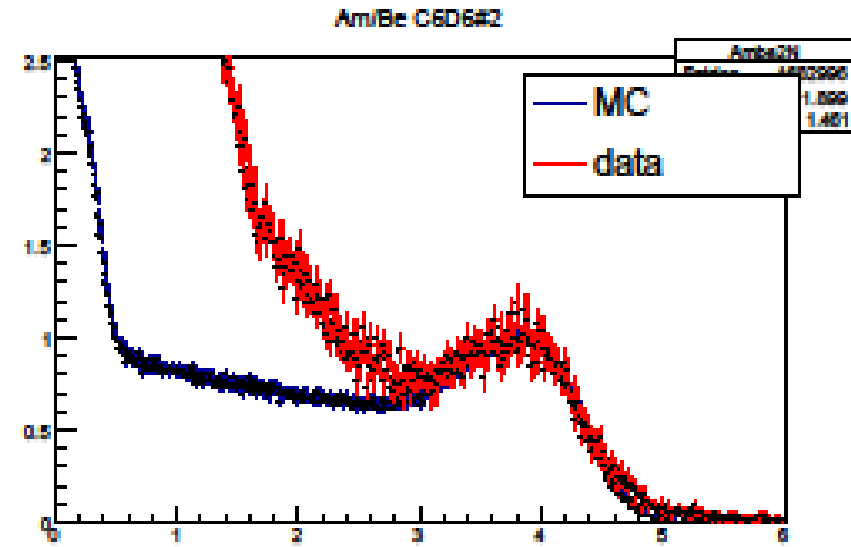
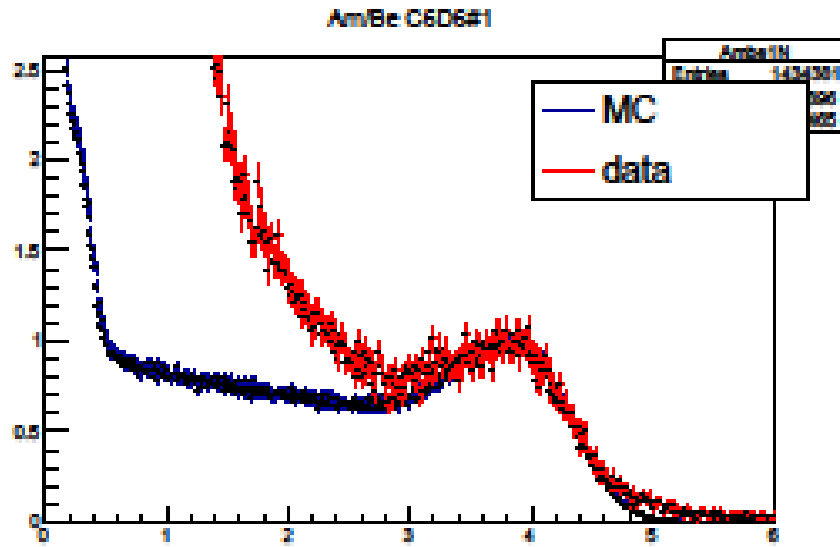
# Simulations: Setup geometry. Source simulations

Y-88



# Simulations: Setup geometry, Source simulations

AmBe



# MAM1: Last Results

*Chiara Beltrami, M. Mastromarco, S. Altieri, N. Colonna*

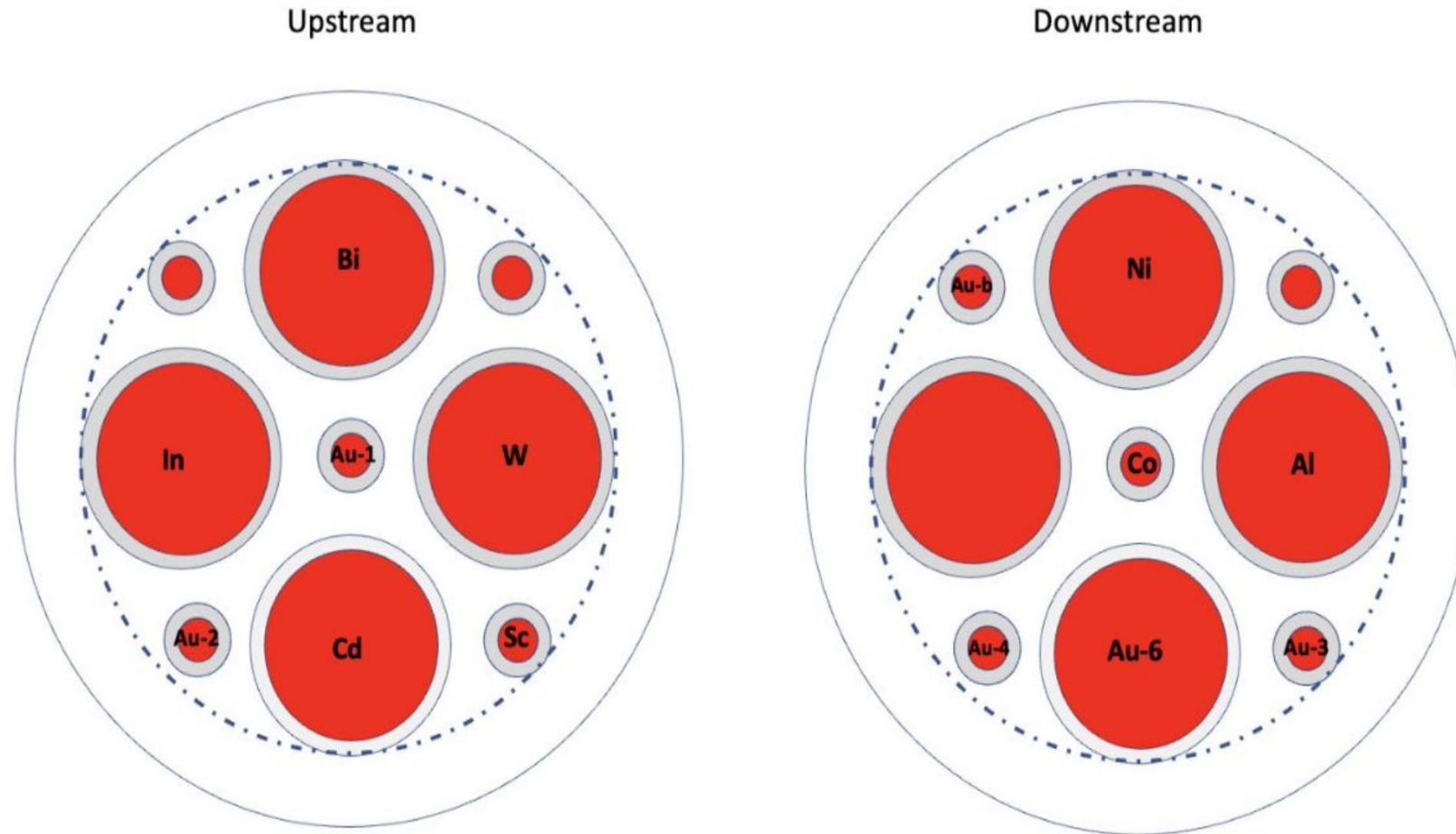
# BaTMAN

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- Bayesian statistical approach to unfold the neutron flux
- Each flux group  $\Phi_i$  is determined by sampling the *Joint Posterior* PDF  $p(\Phi_i / R_j \sigma_{ij})$
- The **JAGS** tool for Bayesian analysis to define the statistical model and sampling the *Posterior* PDF (Markov Chains Monte Carlo simulations).

Program available here: <https://github.com/davidechiesa/BaTMAN>

# Apparato MAM1





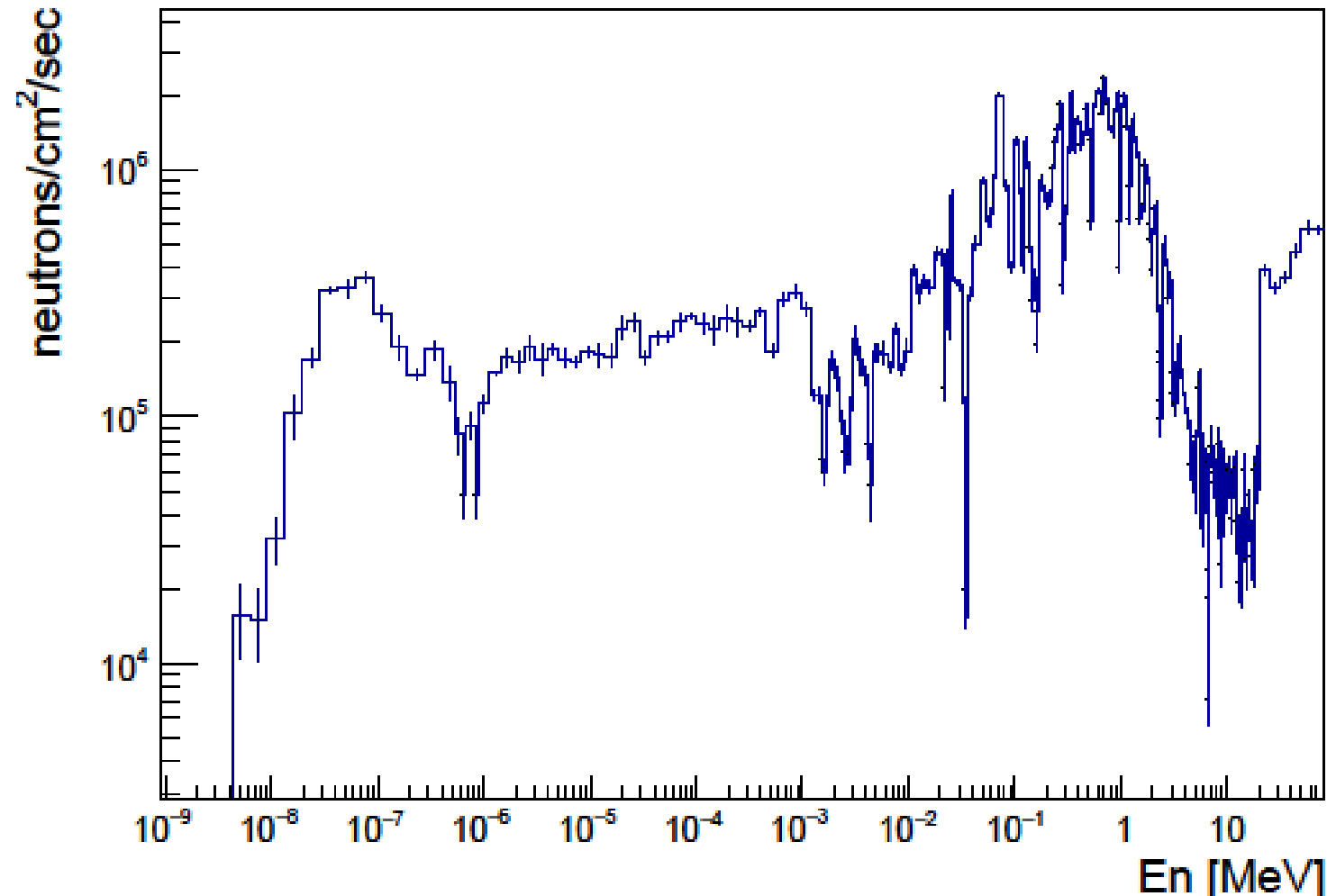
- Utilizzati i risultati finali delle misure di attivazione dei target (**Elisso**)
- Utilizzate correzioni di Self-Shielding calcolate (io) e simulate con MCNP (**S. Altieri e C. Beltrami**)
- Utilizzate sezioni d'urto ENDF (fino a 20 MeV) e TENDL ad alte energie con diverse estrapolazioni (**Elisso**)

# Input Data/Parameters

# XS_name	SSA (Bq/g)	Err (Bq/g)	g/mol	I.A.	Selfshielding
Cd114_ng_endf.dat	2.1443E+04	4.9936E+02	112.41	0.2873	Cd_ss.dat
Sc45_ng_endf.dat	5.3808E+05	1.7393E+04	44.96	1.0000	Sc_ss.dat
Au197_ng_endf.dat	9.4344E+05	1.9072E+04	196.97	1.0000	Au_ss.dat
W186_ng_endf.dat	1.6077E+05	4.1008E+03	183.84	0.2843	W_ss.dat
In113_ng_endf.dat	5.3850E+04	1.3178E+03	114.82	0.0429	In_ss.dat
Co59_ng_endf.dat	6.9178E+05	1.4334E+04	58.93	1.0000	Co59_ss.dat
Au197_n2n_tendl.dat	1.1890E+04	2.4211E+02	196.97	1.0000	NoSelfShield
Au197_n4n_tendl.dat	6.0226E+03	1.7010E+02	196.97	1.0000	NoSelfShield
Ni58_np_tendl.dat	2.6686E+04	5.4590E+02	58.69	0.6808	NoSelfShield
Ni58_n2n_tendl.dat	1.9417E+03	7.2903E+01	58.69	0.6808	NoSelfShield
Al27_na_tendl.dat	6.5584E+03	1.4804E+02	26.98	1.0000	NoSelfShield
Co59_n2n_tendl.dat	1.8362E+04	3.7727E+02	58.93	1.0000	NoSelfShield
#Co59_n3n_tendl.dat	6.8103E+03	3.7408E+02	58.93	1.0000	NoSelfShield
Bi209_n3n_tendl.dat	1.1242E+04	1.5384E+03	208.98	1.0000	NoSelfShield
Bi209_n4n_tendl.dat	5.1545E+03	1.0299E+02	208.98	1.0000	NoSelfShield
Bi209_n5n_tendl.dat	3.5429E+03	1.8338E+02	208.98	1.0000	NoSelfShield

# FLUKA Simulations by M. Cecchetto

MATTEO, M81-nomod-27



# 8 Energy Groups

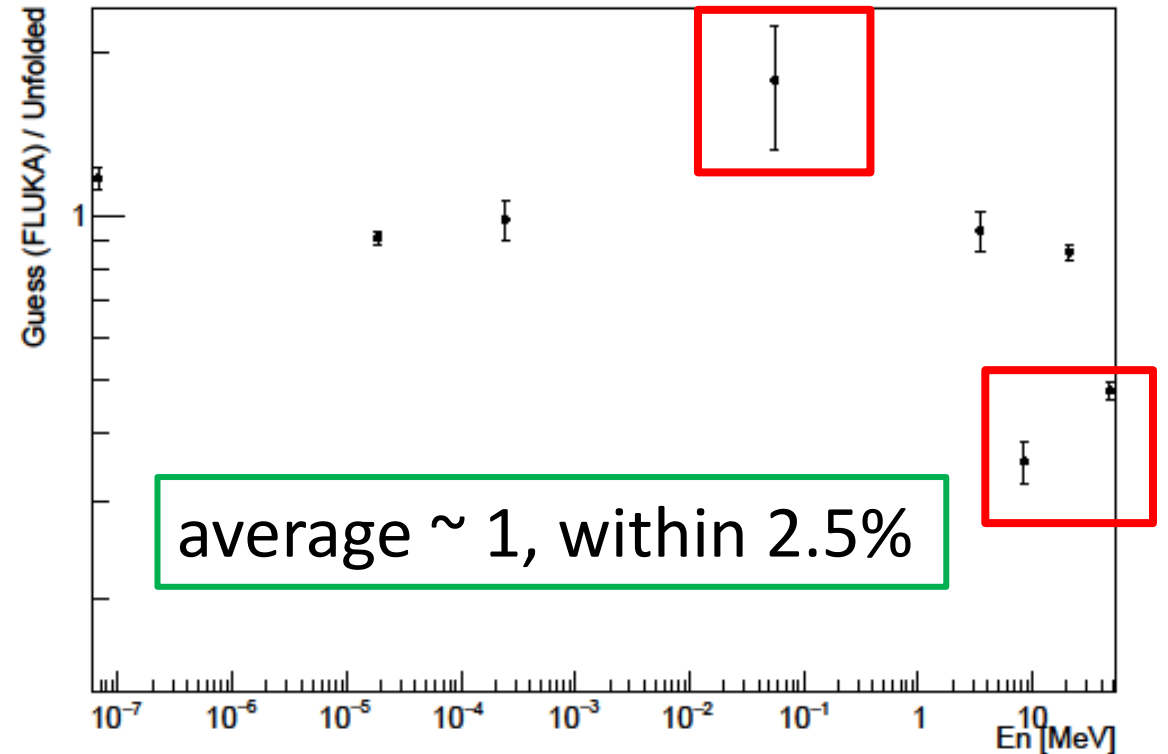
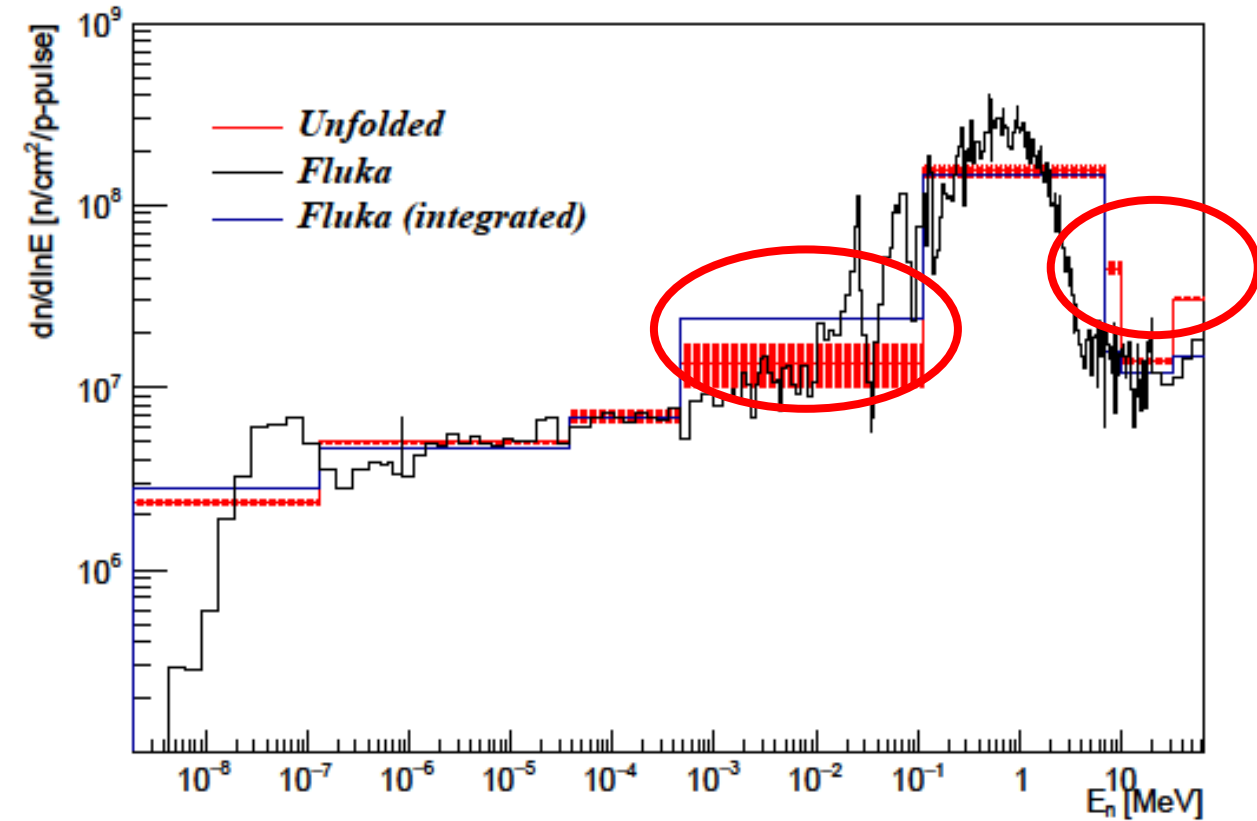
Energy groups	
Group number	Energy range (MeV)
1	$2.0 \cdot 10^{-9} - 1.3 \cdot 10^{-7}$
2	$1.3 \cdot 10^{-7} - 3.7 \cdot 10^{-5}$
3	$3.7 \cdot 10^{-5} - 4.5 \cdot 10^{-4}$
4	$4.5 \cdot 10^{-4} - 1.1 \cdot 10^{-1}$
5	$1.1 \cdot 10^{-1} - 7$
6	7 – 10
7	10 – 32
8	32 – 63

# Reaction for Group

Saturation Activity of radiative capture reactions and treshold reactions				
Foil	Reaction	$T_{\frac{1}{2}}$	$E_{\gamma}$ (keV)	SA(Bq)
W	$^{186}\text{W}(n, \gamma)^{187}\text{W}$	24.00 h	685.77	$(1.89 \pm 0.04) \cdot 10^5$
Sc	$^{45}\text{Sc}(n, \gamma)^{46}\text{Sc}$	83.79 d	1120.55	$(4.32 \pm 0.09) \cdot 10^3$
Au-1	$^{197}\text{Au}(n, \gamma)^{198}\text{Au}$	2.6941 d	411.80	$(6.27 \pm 0.11) \cdot 10^4$
Au-3	$^{197}\text{Au}(n, \gamma)^{198}\text{Au}$	2.6941 d	411.80	$(1.22 \pm 0.02) \cdot 10^4$
Au-4	$^{197}\text{Au}(n, \gamma)^{198}\text{Au}$	2.6941 d	411.80	$(2.31 \pm 0.04) \cdot 10^4$
Co	$^{59}\text{Co}(n, \gamma)^{60}\text{Co}$	1925.28 d	1332.50	$(2.68 \pm 0.05) \cdot 10^4$
In	$^{113}\text{In}(n, \gamma)^{114m}\text{In}$	49.51 d	190.29	$(2.54 \pm 0.06) \cdot 10^4$
Au-6	$^{197}\text{Au}(n, \gamma)^{198}\text{Au}$	2.6941 d	411.80	$(2.14 \pm 0.04) \cdot 10^6$
Cd	$^{114}\text{Cd}(n, \gamma)^{115}\text{Cd}$	53.46 h	527.90	$(2.24 \pm 0.05) \cdot 10^4$
Ni	$^{58}\text{Ni}(n, p)^{58}\text{Co}$	70.86 d	810.78	$(1.57 \pm 0.03) \cdot 10^4$
Ni	$^{58}\text{Ni}(n, 2n)^{57}\text{Ni}$	35.60 h	1377.63	$(1.14 \pm 0.02) \cdot 10^3$
Co	$^{59}\text{Co}(n, 2n)^{58}\text{Co}$	70.86 d	810.78	$(6.40 \pm 0.11) \cdot 10^2$
Au-4	$^{197}\text{Au}(n, 2n)^{196}\text{Au}$	6.1669 d	355.68	$(1.77 \pm 0.03) \cdot 10^2$
Au-1	$^{197}\text{Au}(n, 2n)^{196}\text{Au}$	6.1669 d	355.68	$(7.73 \pm 0.13) \cdot 10^2$
Au-3	$^{197}\text{Au}(n, 2n)^{196}\text{Au}$	6.1669 d	355.68	$(1.70 \pm 0.03) \cdot 10^2$
Au-6	$^{197}\text{Au}(n, 2n)^{196}\text{Au}$	6.1669 d	355.68	$(6.59 \pm 0.14) \cdot 10^2$
Al	$^{27}\text{Al}(n, \alpha)^{24}\text{Na}$	15.00 h	1368.63	$(1.13 \pm 0.02) \cdot 10^3$
Bi	$^{209}\text{Bi}(n, 3n)^{207}\text{Bi}$	31.55 y	1063.66	$(1.24 \pm 0.17) \cdot 10^4$
Au-1	$^{197}\text{Au}(n, 4n)^{194}\text{Au}$	38.02 h	328.46	$(3.95 \pm 0.09) \cdot 10^2$
Bi	$^{209}\text{Bi}(n, 4n)^{206}\text{Bi}$	6.243 d	803.10	$(5.63 \pm 0.09) \cdot 10^3$

# Unfolding Results (C. Beltrami)

Neutron flux per proton pulse



# TO DO:

- Ottimizzazione della scelta gruppi di energia
- Correzioni campioni periferici
- Correzioni per stati metastabili per alcuni isotopi
- Ottimizzazione sezioni d'urto ad alte energie
- Confronto risultati con gli altri apparati (MAM2 E ANTILOPE)

# Conclusions:

- Discrepancy at the 4° group is mainly due to the small contribution of the (n,γ) cross section reactions
- A possible attempt to improve the unfolding procedure is to try to extend the number of the energy groups in which dividing the neutron spectrum
- Try to improve the extraction of the cross section at higher energy

**Molto probabilmente le discrepanze ad alte energia sono dovute alle simulazioni del flusso con FLUKA (vedasi flusso in EAR1 e EAR2)**