# Measurement of the $^{160}$Gd(n, γ) cross section at n_TOF

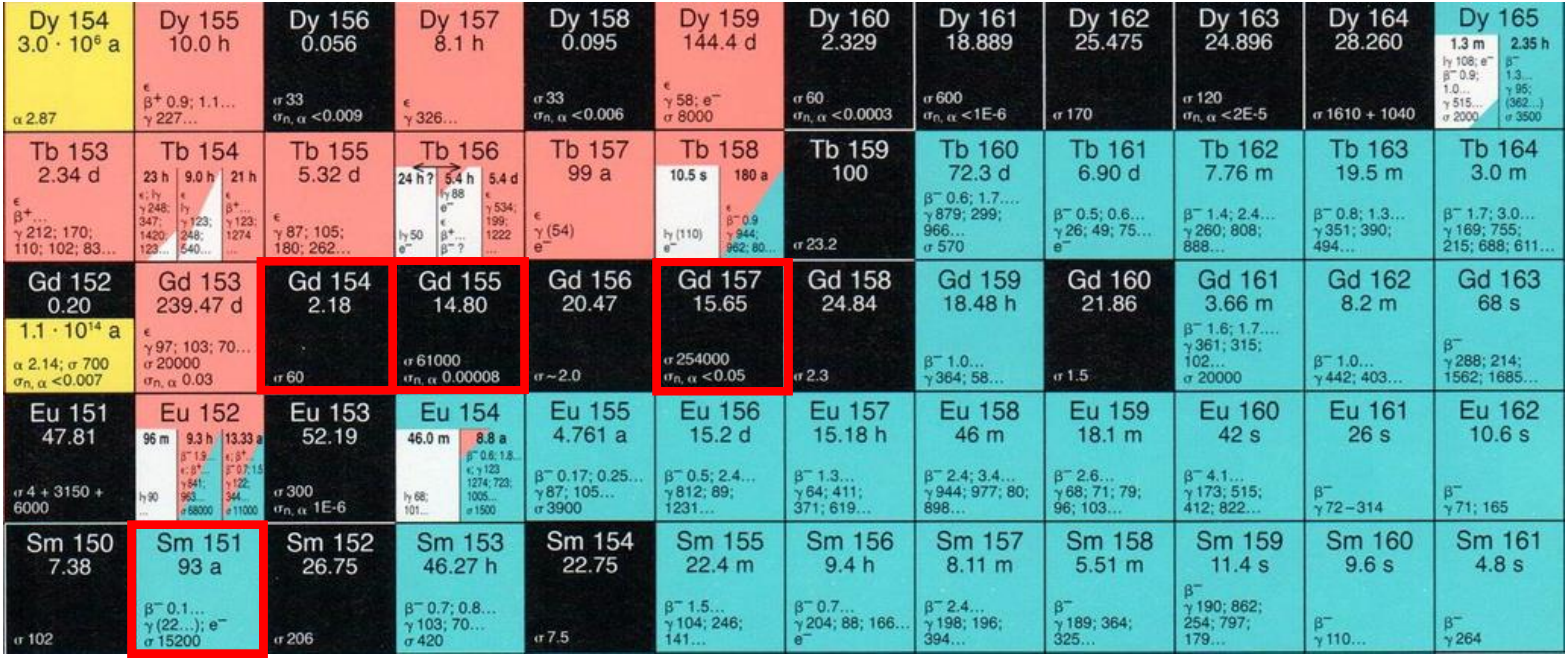
***M. Mastromarco,*** *A. Mazzone, A. Manna, S. Amaducci, A. Mengoni, C. Massimi, N. Colonna, G. Tagliente, S. Cristallo*

# Motivations

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)

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)



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**$^{161}$Tb is a clinically interesting isotope for theranostics**

# Motivations: Terbium-161

- Chemically similar to Lutetium-177 (used in theranostic as γ and $\beta^-$ emitter)

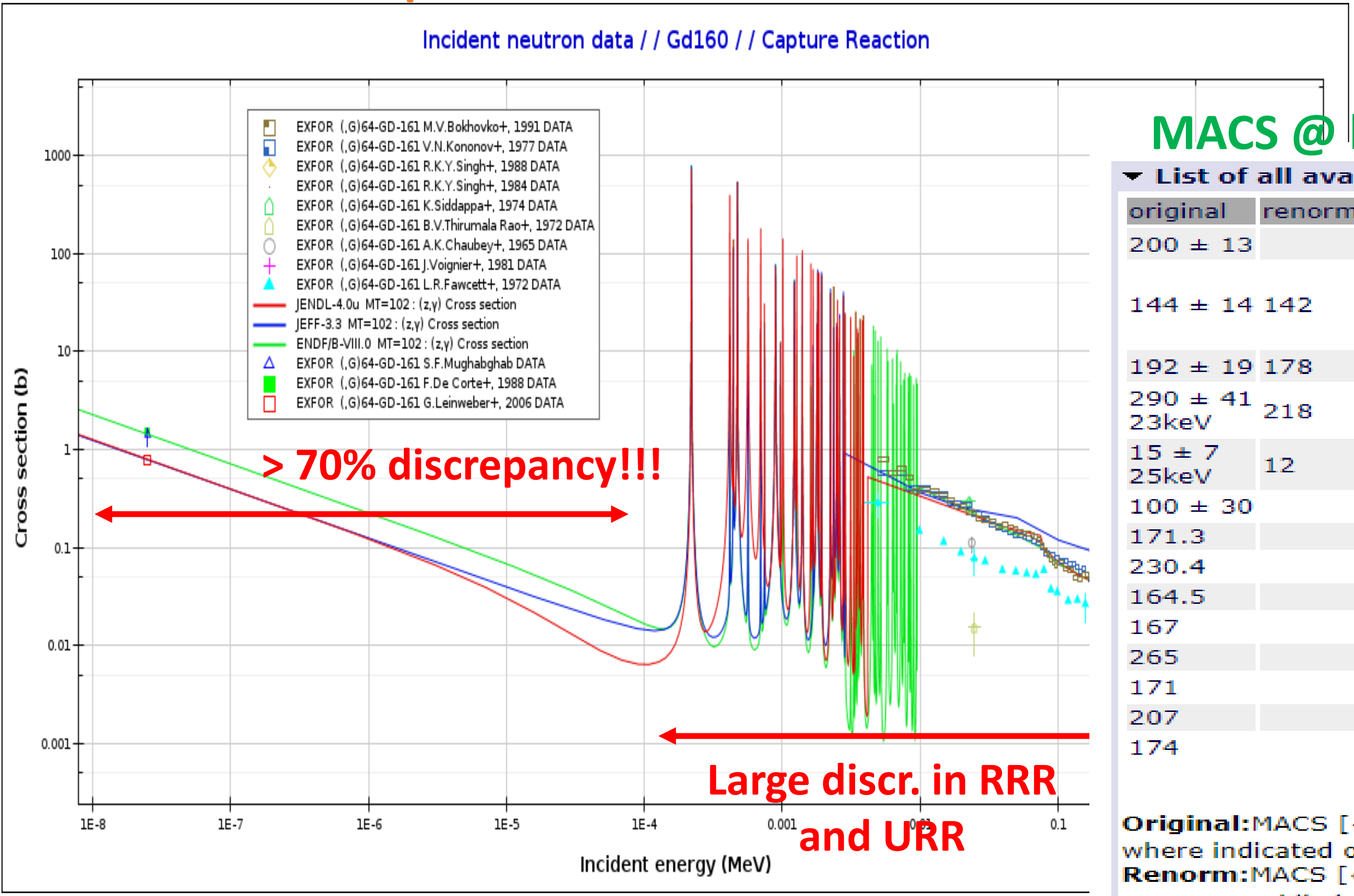
- Similar half-life $T_{1/2}$ = 6.9 d (against 6.7 d of Lu-177)

In addiction to being a γ 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




## 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, $^{6}$Li, $^{10}$B+Au:B-V | BKP92 |
| 144 ± 14 | 142 | 1984 | c | VdG, Act., 1/v(kT), Au:657mb(25keV)$^{160}$Gd(n,gamma)$^{161}$Gd beta decay of $^{161}$Tb | BKY84 |
| 192 ± 19 | 178 | 1978 | b | VdG, TOF, $^{10}$B:Mag75, Au:628mb(kT=30keV) | KYP78 |
| 290 ± 41 23keV | 218 | 1973 | c | Sb-Be, Act., 1/v(E), $^{127}$I:836mb(23keV) | SSR73 |
| 15 ± 7 25keV | 12 | 1972 | c | Sb-Be, Act., 1/v(E), $^{127}$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 [<σ v>/$v_T$] (mb) for kT=30 keV, based on the published cross sections except where indicated otherwise.
**Renorm:** MACS [<σ v>/$v_T$] (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 + a1 ln(E) + a2 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 **deutered benzene: (C6D6 & STED)**

- Low neutron sensitivity
- Low γ-ray detection efficiency

**EAR1**

- Flight Path: **185 m**
- Flux: **$10^6$/cm$^2$/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)

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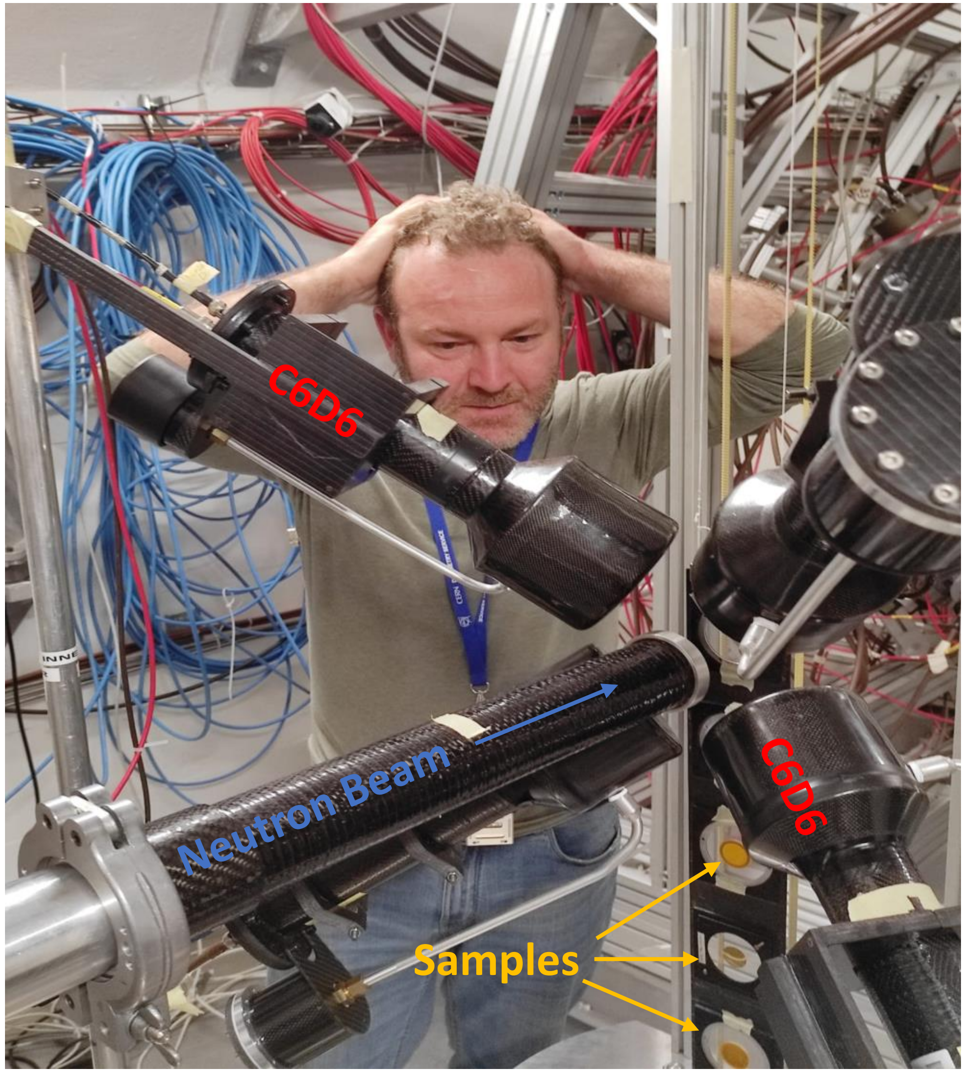
**EAR1: 4 C6D6 & me**



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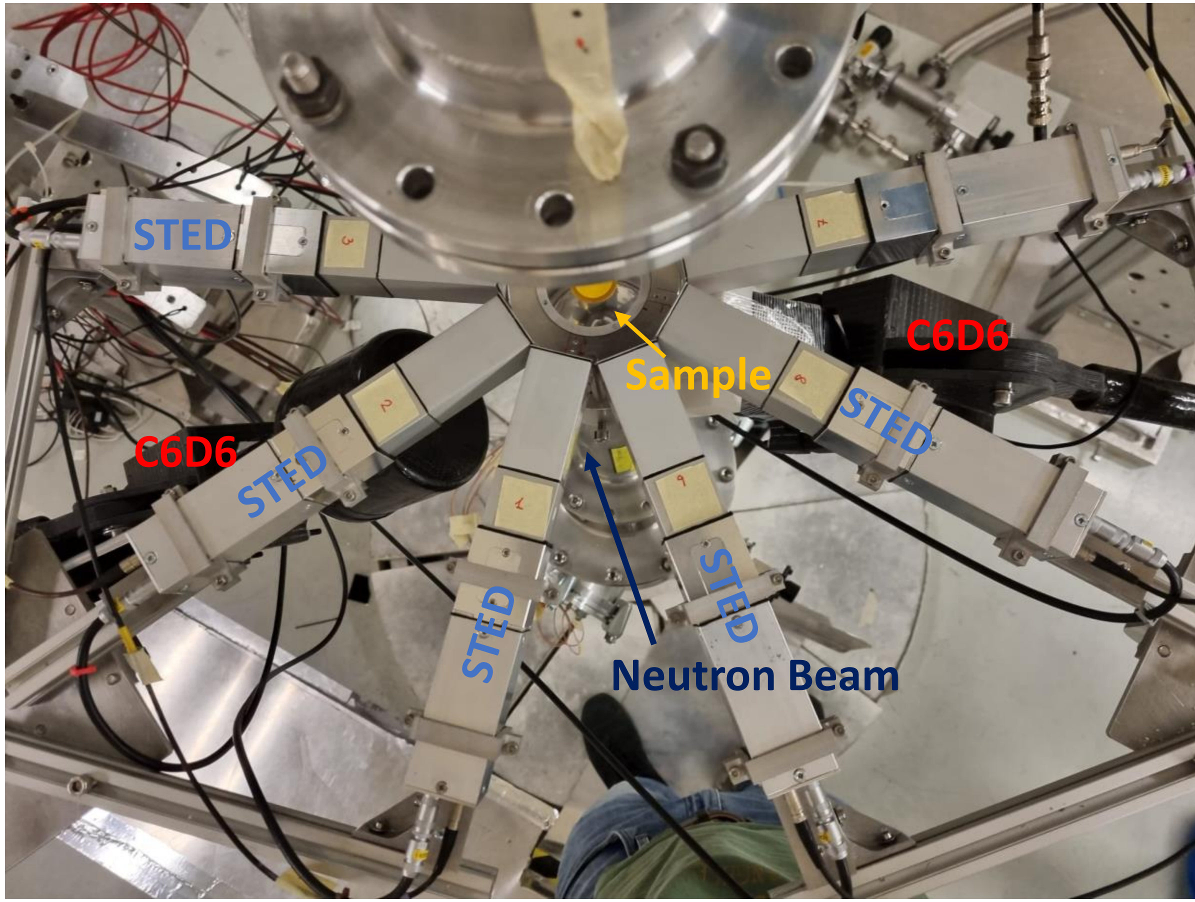
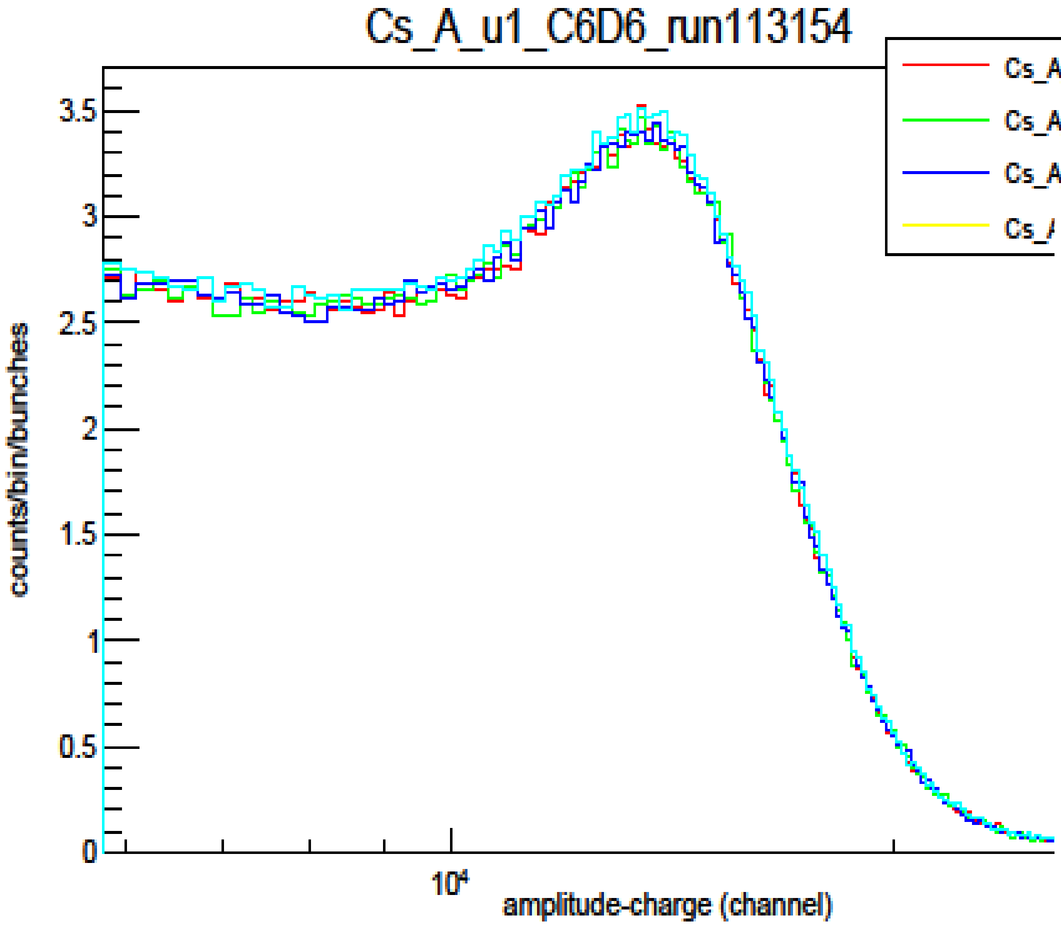
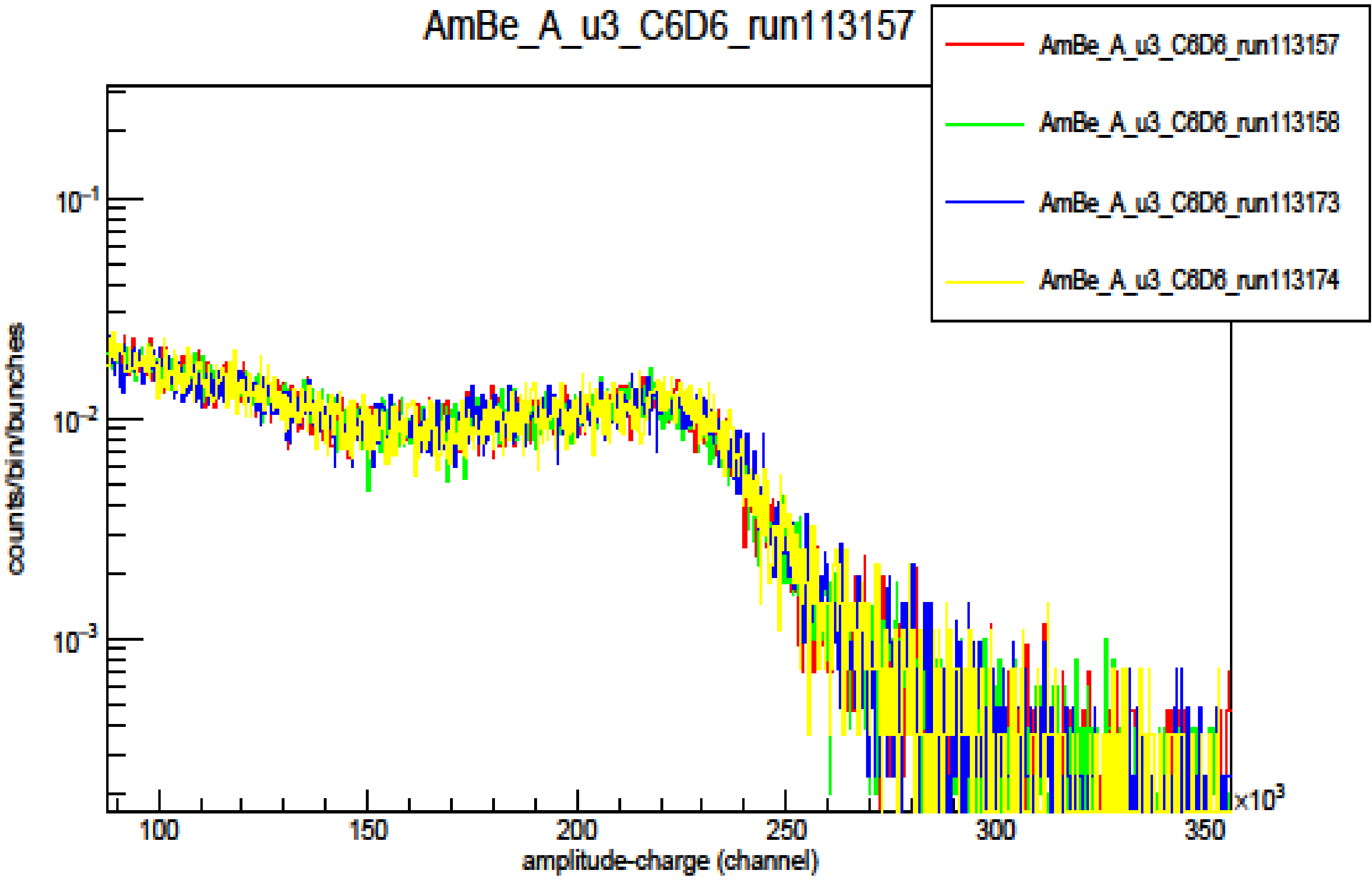
EAR2: 2 C6D6 + 9 STED



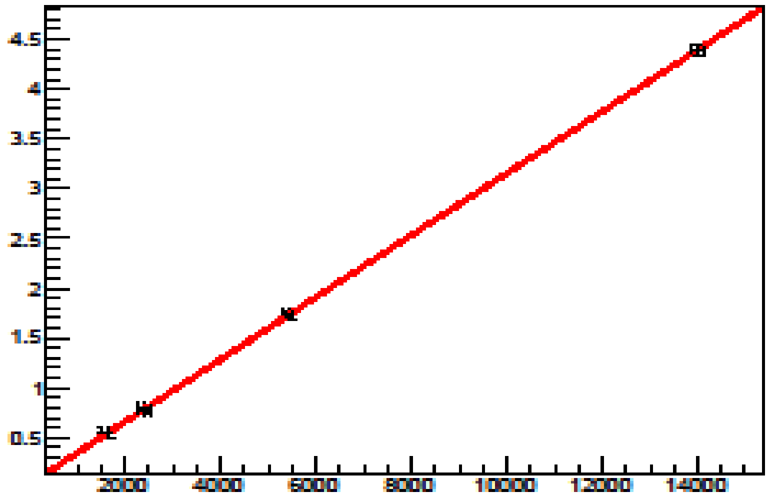
# EAR1: $C_6D_6$ Stability (Cs-137, Y-88, AmBe)



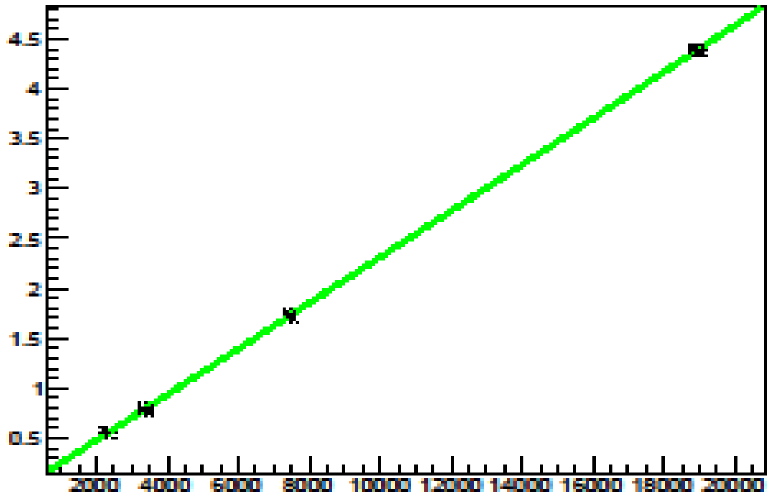



# Simulations: Setup geometry, Source simulations

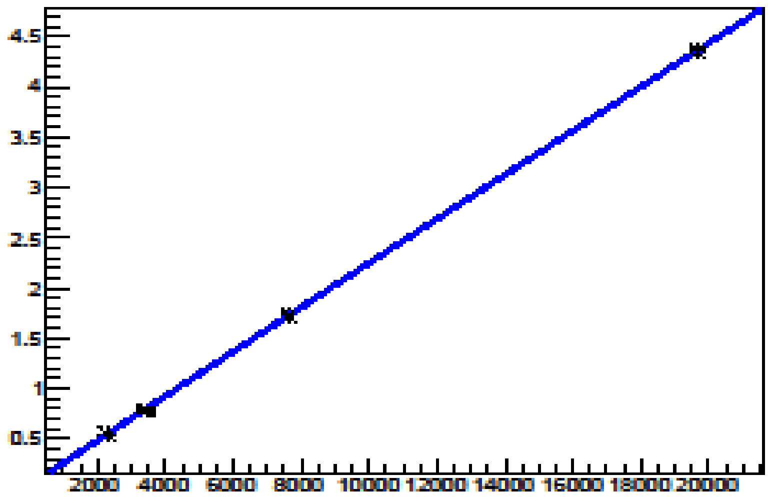
Calibration C6D6#1



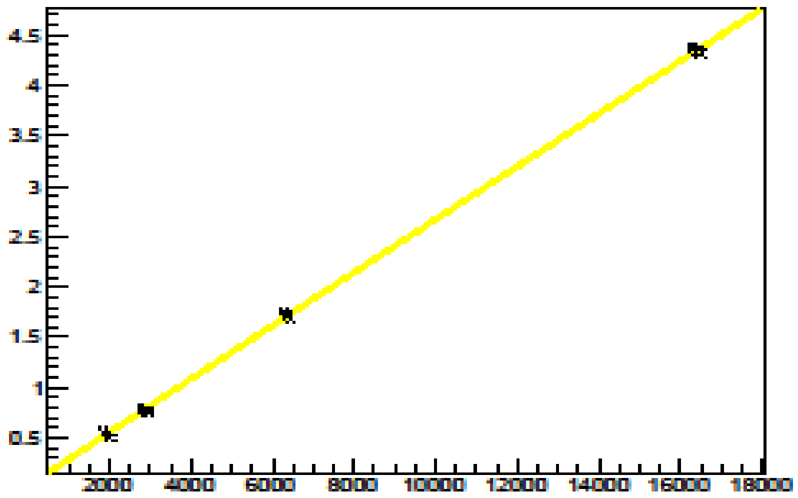

Calibration C6D6#2




Calibration C6D6#3

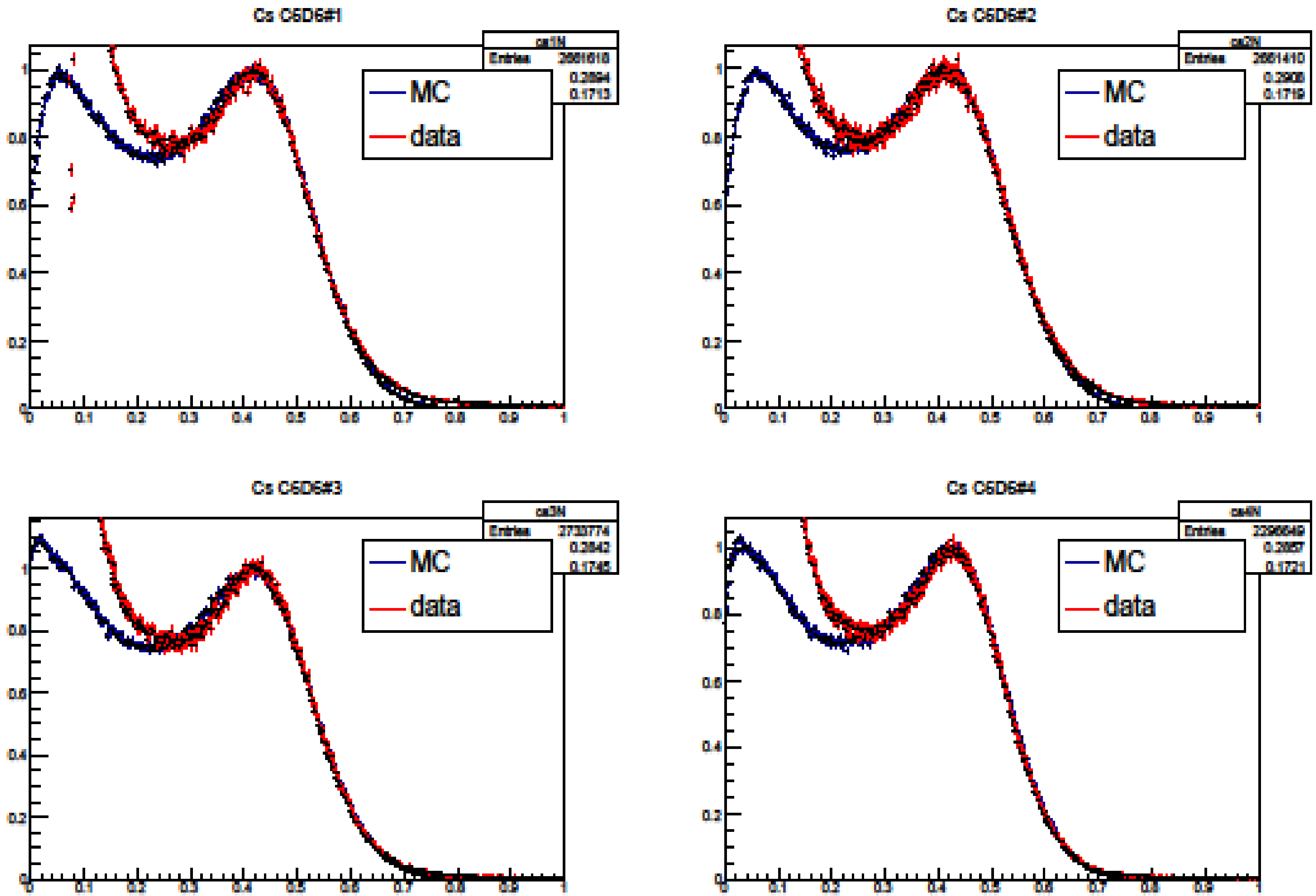



Calibration C6D6#4



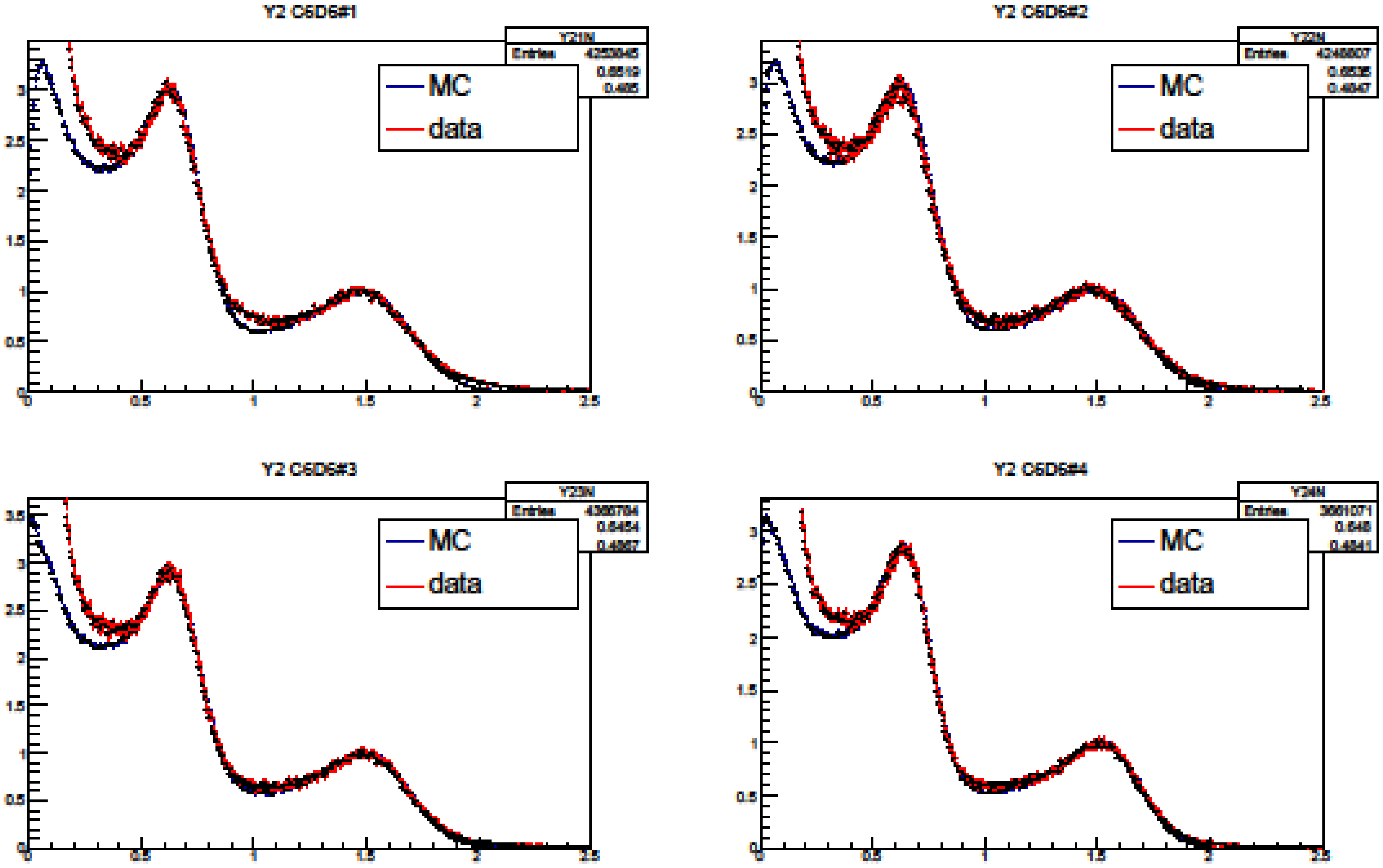
# Simulations: Setup geometry, Source simulations

**Cs-137**



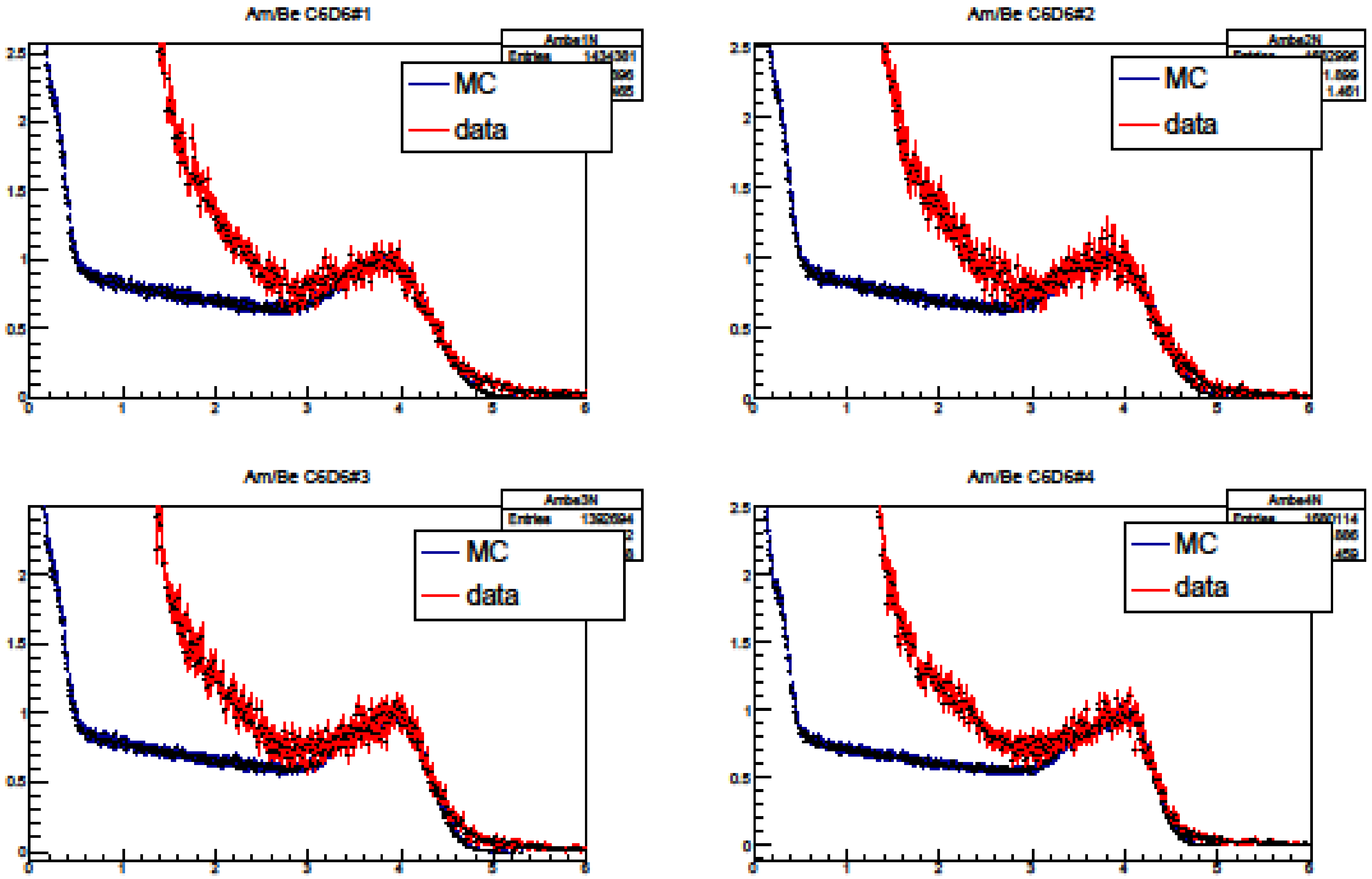
# Simulations: Setup geometry. Source simulations

**Y-88**



# Simulations: Setup geometry, Source simulations

**AmBe**



# MAM1: Last Results

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

# BaTMAN

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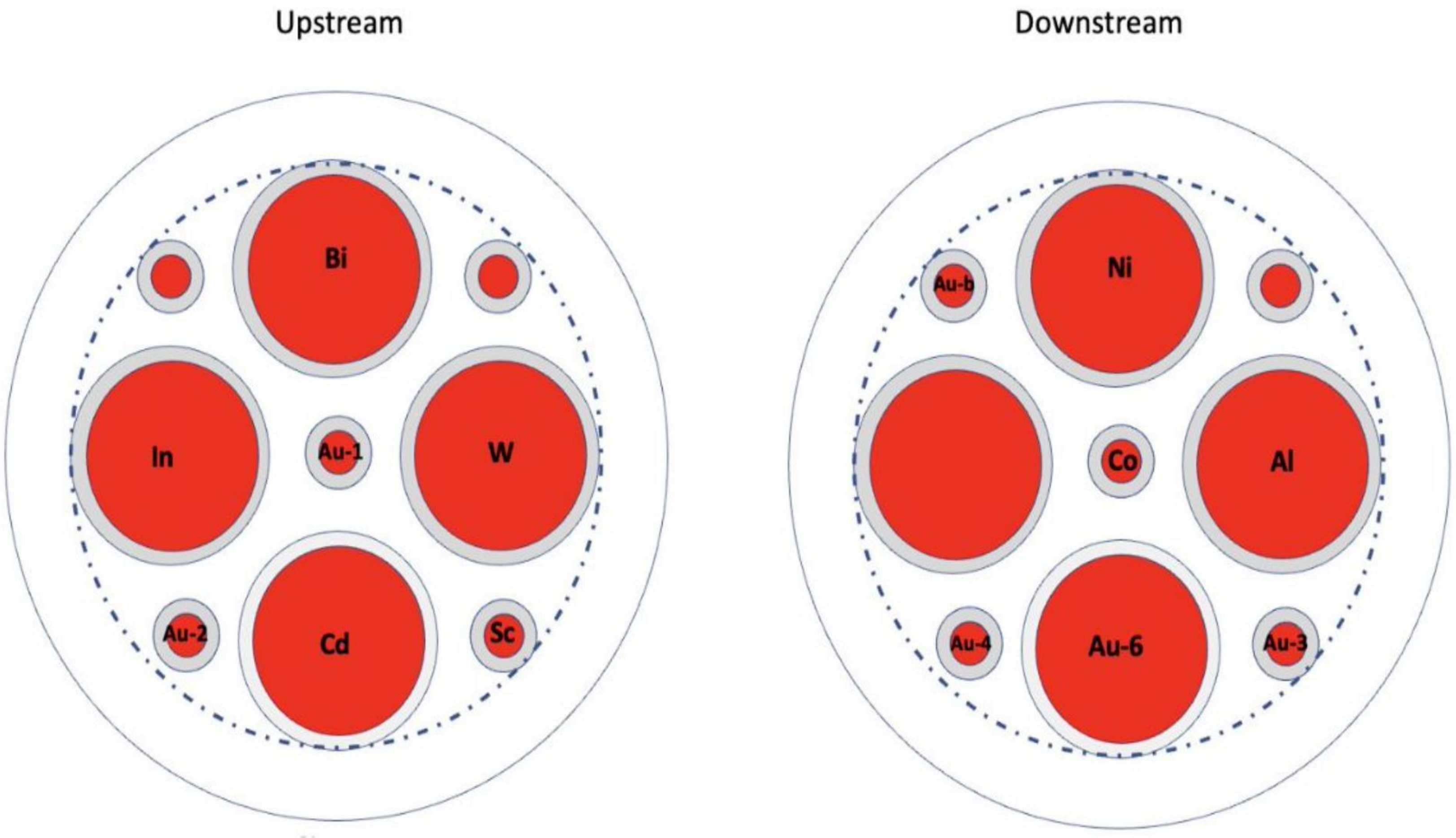
- Bayesian statistical approach to unfold the neutron flux
- Each flux group $\boldsymbol{\Phi_i}$ is determined by sampling the *Joint Posterior* PDF $\boldsymbol{p(\Phi_i \,/\, R_j\ \sigma_{ij})}$
- The JAGS tool for Bayiesian analysis to define the statistical model and sampling the *Posterior* PDF (Markoc 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**)

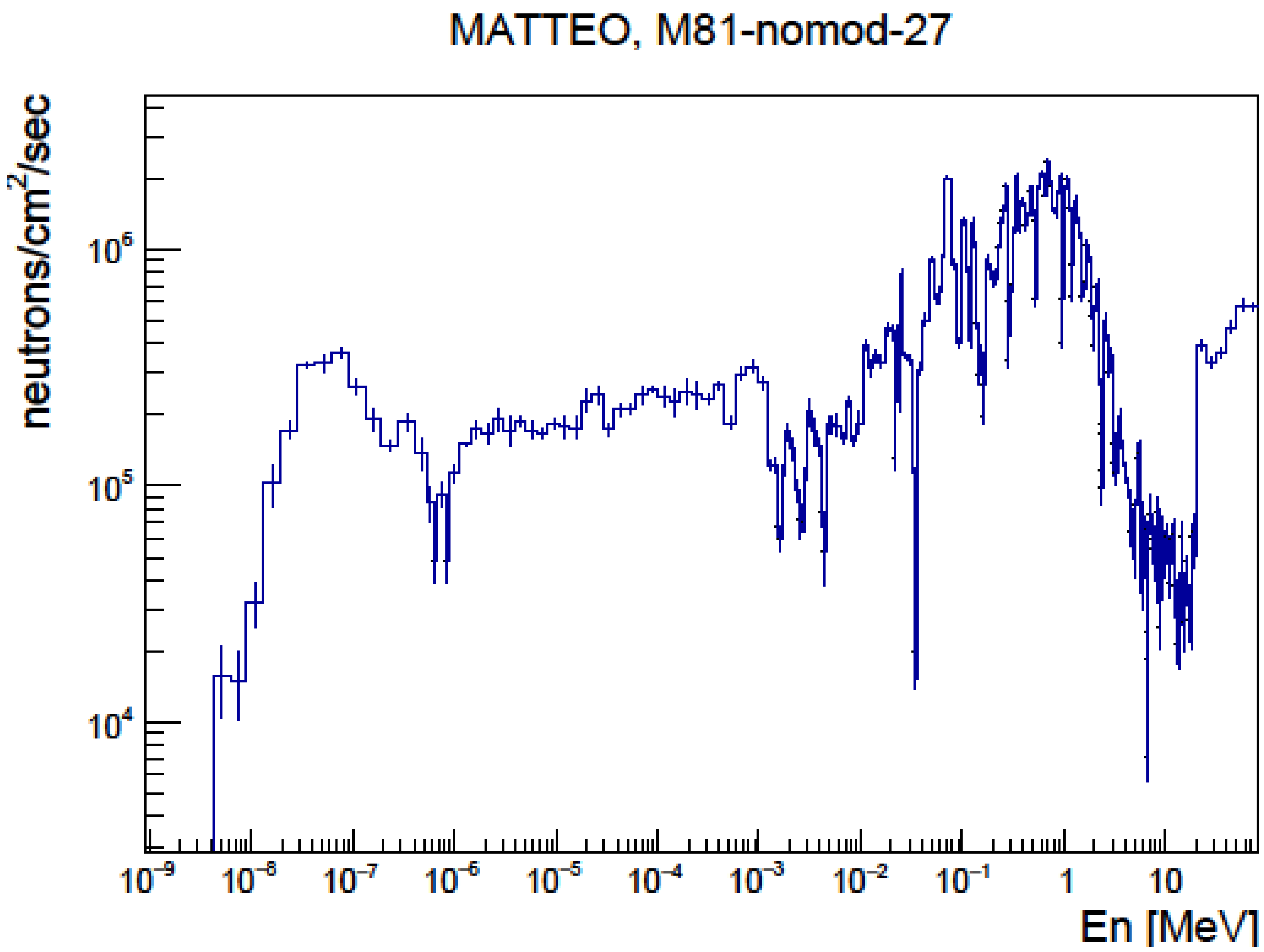
- Utilizzate correzioni di Self-Shielding calcolate (io) e simulate con MCNP (**S. Altieri e C. Beltrami**)

- 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



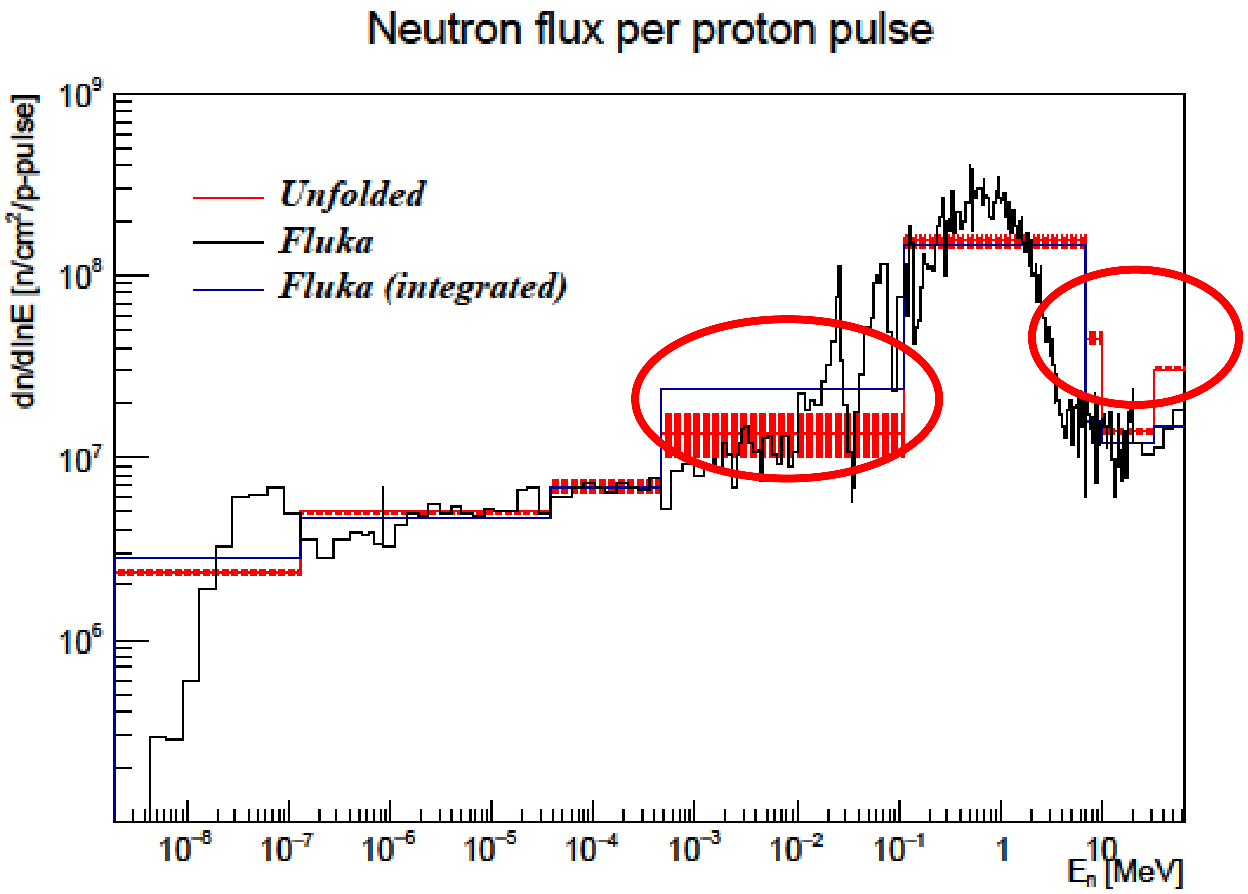
# 8 Energy Groups

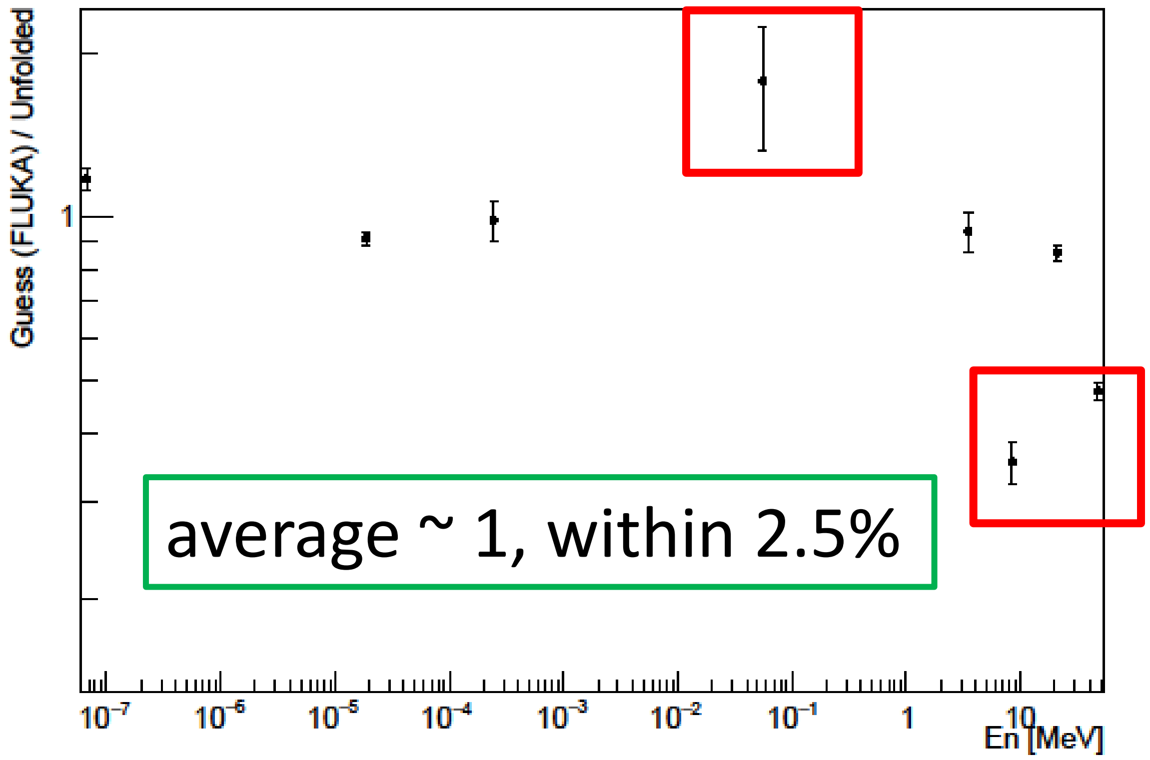
| Energy groups | |
|---|---|
| Group number | Energy range (MeV) |
| 1 | $2.0 \cdot 10^{-9} - 1.3 \cdot 10^{-7}$ |
| 2 | $1.3 \cdot 10^{-7} - 3.7 \cdot 10^{-5}$ |
| 3 | $3.7 \cdot 10^{-5} - 4.5 \cdot 10^{-4}$ |
| 4 | $4.5 \cdot 10^{-4} - 1.1 \cdot 10^{-1}$ |
| 5 | $1.1 \cdot 10^{-1} - 7$ |
| 6 | $7 - 10$ |
| 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 | $^{186}W(n,\gamma)^{187}W$ | 24.00 h | 685.77 | $(1.89 \pm 0.04) \cdot 10^5$ |
| Sc | $^{45}Sc(n,\gamma)^{46}Sc$ | 83.79 d | 1120.55 | $(4.32 \pm 0.09) \cdot 10^3$ |
| Au-1 | $^{197}Au(n,\gamma)^{198}Au$ | 2.6941 d | 411.80 | $(6.27 \pm 0.11) \cdot 10^4$ |
| Au-3 | $^{197}Au(n,\gamma)^{198}Au$ | 2.6941 d | 411.80 | $(1.22 \pm 0.02) \cdot 10^4$ |
| Au-4 | $^{197}Au(n,\gamma)^{198}Au$ | 2.6941 d | 411.80 | $(2.31 \pm 0.04) \cdot 10^4$ |
| Co | $^{59}Co(n,\gamma)^{60}Co$ | 1925.28 d | 1332.50 | $(2.68 \pm 0.05) \cdot 10^4$ |
| In | $^{113}In(n,\gamma)^{114m}In$ | 49.51 d | 190.29 | $(2.54 \pm 0.06) \cdot 10^4$ |
| Au-6 | $^{197}Au(n,\gamma)^{198}Au$ | 2.6941 d | 411.80 | $(2.14 \pm 0.04) \cdot 10^6$ |
| Cd | $^{114}Cd(n,\gamma)^{115}Cd$ | 53.46 h | 527.90 | $(2.24 \pm 0.05) \cdot 10^4$ |
| Ni | $^{58}Ni(n,p)^{58}Co$ | 70.86 d | 810.78 | $(1.57 \pm 0.03) \cdot 10^4$ |
| Ni | $^{58}Ni(n,2n)^{57}Ni$ | 35.60 h | 1377.63 | $(1.14 \pm 0.02) \cdot 10^3$ |
| Co | $^{59}Co(n,2n)^{58}Co$ | 70.86 d | 810.78 | $(6.40 \pm 0.11) \cdot 10^2$ |
| Au-4 | $^{197}Au(n,2n)^{196}Au$ | 6.1669 d | 355.68 | $(1.77 \pm 0.03) \cdot 10^2$ |
| Au-1 | $^{197}Au(n,2n)^{196}Au$ | 6.1669 d | 355.68 | $(7.73 \pm 0.13) \cdot 10^2$ |
| Au-3 | $^{197}Au(n,2n)^{196}Au$ | 6.1669 d | 355.68 | $(1.70 \pm 0.03) \cdot 10^2$ |
| Au-6 | $^{197}Au(n,2n)^{196}Au$ | 6.1669 d | 355.68 | $(6.59 \pm 0.14) \cdot 10^2$ |
| Al | $^{27}Al(n,\alpha)^{24}Na$ | 15.00 h | 1368.63 | $(1.13 \pm 0.02) \cdot 10^3$ |
| Bi | $^{209}Bi(n,3n)^{207}Bi$ | 31.55 y | 1063.66 | $(1.24 \pm 0.17) \cdot 10^4$ |
| Au-1 | $^{197}Au(n,4n)^{194}Au$ | 38.02 h | 328.46 | $(3.95 \pm 0.09) \cdot 10^2$ |
| Bi | $^{209}Bi(n,4n)^{206}Bi$ | 6.243 d | 803.10 | $(5.63 \pm 0.09) \cdot 10^3$ |

# Unfolding Results (C. Beltrami)



# 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)**