Study of ^{25}Mg+n reactions: Towards a deeper understanding of the s process

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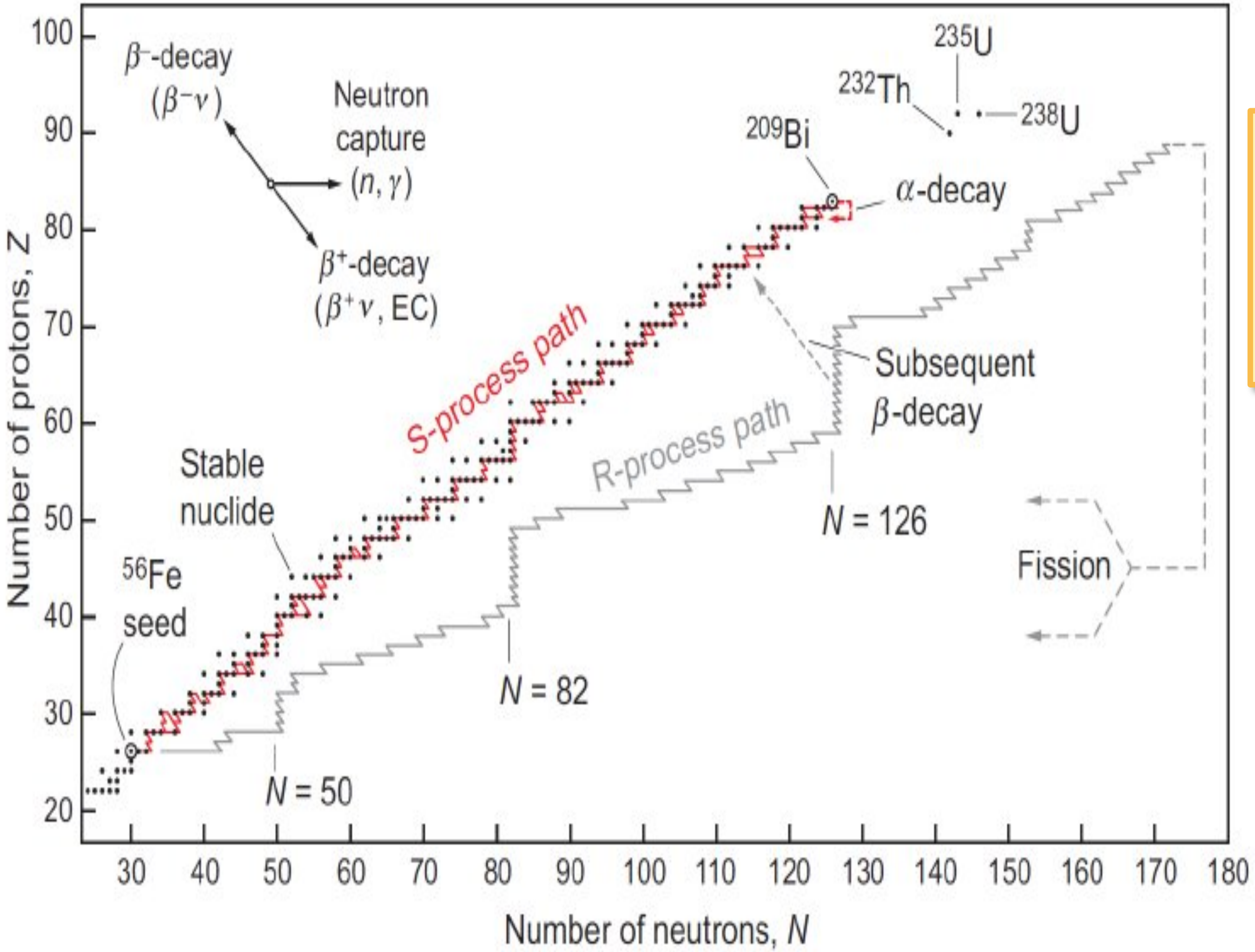
outline

- Motivations
- New measurements:
  - ^{25}Mg(n, γ) @ n_TOF
  - ^{25}Mg(n, tot) @ GELINA
- Preliminary results
- An idea for the future
  - ^{25}Mg(n, α)^{22}Ne @ EAR2 - n_TOF

Motivations



The s process

nucleosynthesis of heavy elements

E. M. Burbidge, G.R. Burbidge, W.A. Fowler, F. Hoyle
Rev. Mod. Phys. **29** (1957) 547

Motivations

The s process

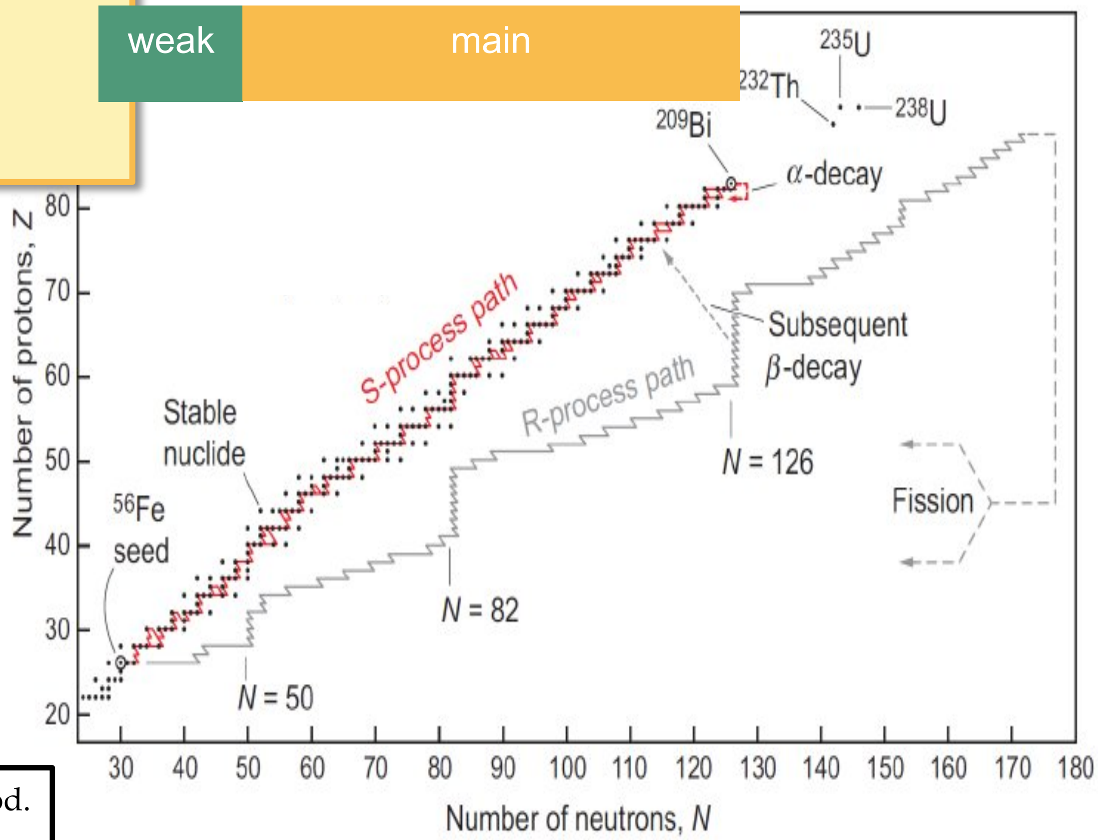
Identified neutron sources:

$^{13}C(\alpha, n)^{16}O$ and $^{22}Ne(\alpha, n)^{25}Mg$

and 2 different components:

1. **Main component**
   → AGB stars
   $^{22}Ne(\alpha, n)^{25}Mg$ partially activated

2. **Weak component**
   → Massive stars
   $^{22}Ne(\alpha, n)^{25}Mg$ main source



F. Käppeler, R. Gallino, S. Bisterzo, and Wako Aoki, Rev. Mod. Phys. **83** (2011) 157

M. Pignatari, R. Gallino, M. Heil, M. Wiescher, F. Käppeler, F. Herwig, S. Bisterzo, ApJ. **710** (2010) 155

Motivations

1. NEUTRON POISON:

^{25,26}**Mg** are the most important **neutron poisons** due to neutron capture on Mg stable isotopes in competition with neutron capture on ^{56}Fe (the basic s-process seed for the production of heavy isotopes).

2. CONSTRAINTS for ^{22}Ne(α, n)^{25}Mg:

It is one of the most important **neutron source in Red Giant stars.** Its **reaction rate** is very **uncertain** because of the **poorly known property of the states in ^{26}Mg**. From neutron measurements the **J**$^{\pi}$ of ^{26}Mg states can be deduced.

$^{25}Mg(n,\gamma)$

Motivation 1

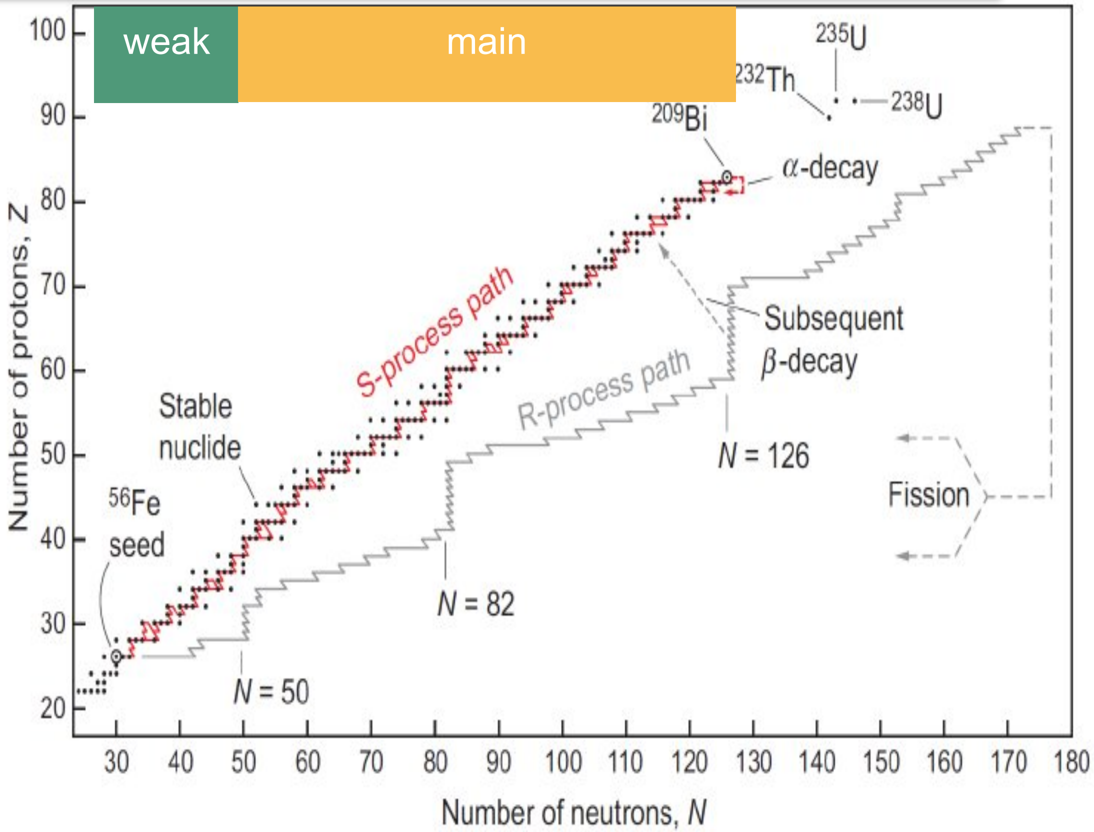
^{25,26}Mg isotopes: neutron poison of the s process

Main component - AGB stars

- kT = 8 keV (t = 10^4 years)
  - Mg density = 0
  - Neutron density ≈ 10^7 / cm^3
- kT = 23 keV (t < 10 years)
  - Mg density ≈ $10^{9\div10}$ / cm^3
  - Neutron density ≈ $10^{9\div10}$ / cm^3

Weak component - Massive stars

- kT = 25 keV
  - Mg density ≈ 10^7 / cm^3
  - Neutron density ≈ 10^7 / cm^3
- kT=90 keV
  - Mg density ≈ $10^{11\div12}$ / cm^3
  - Neutron density ≈ $10^{11\div12}$ / cm^3



^{25}Mg(n, γ)

Motivation 1

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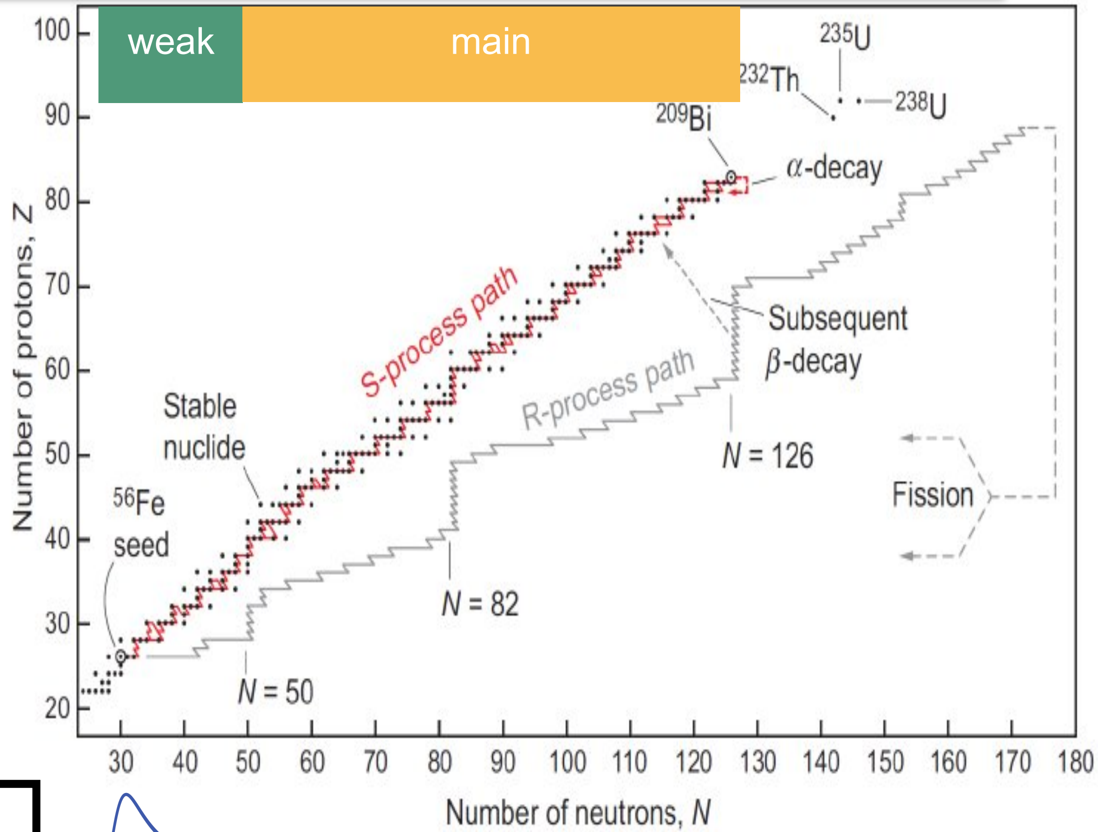


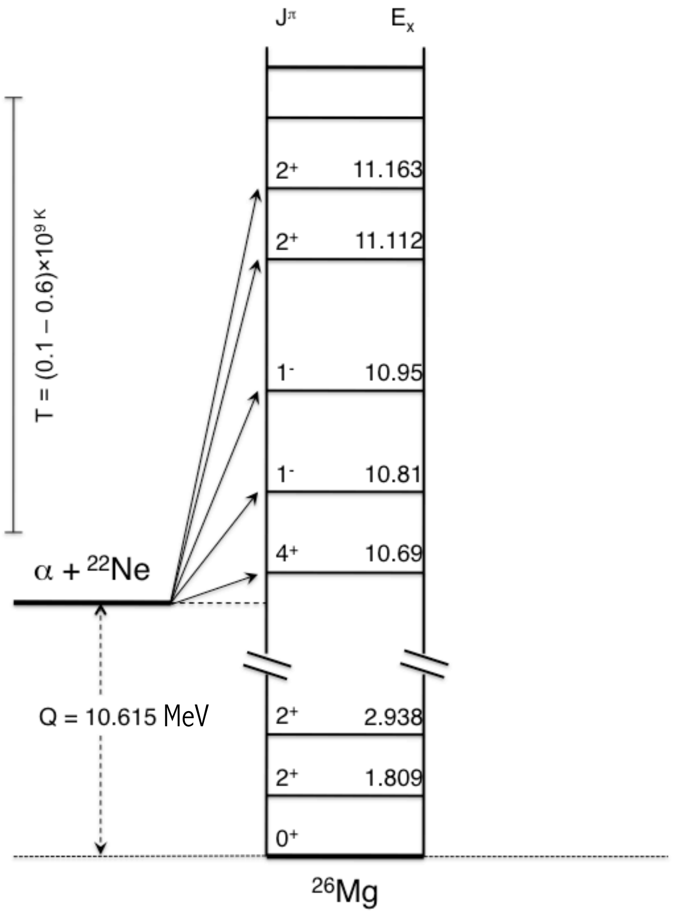
From neutron TOF measurements:
→ **^{25}Mg(n, γ) cross section**

Motivation 2

Constraints for the $^{22}Ne(\alpha, n)^{25}Mg$ reaction

Element	Spin/ parity
^{22}Ne	0^+
^{4}He	0^+

Only **natural-parity states in ^{26}Mg** can participate in the $^{22}Ne(\alpha ,n)^{25}Mg$ reaction



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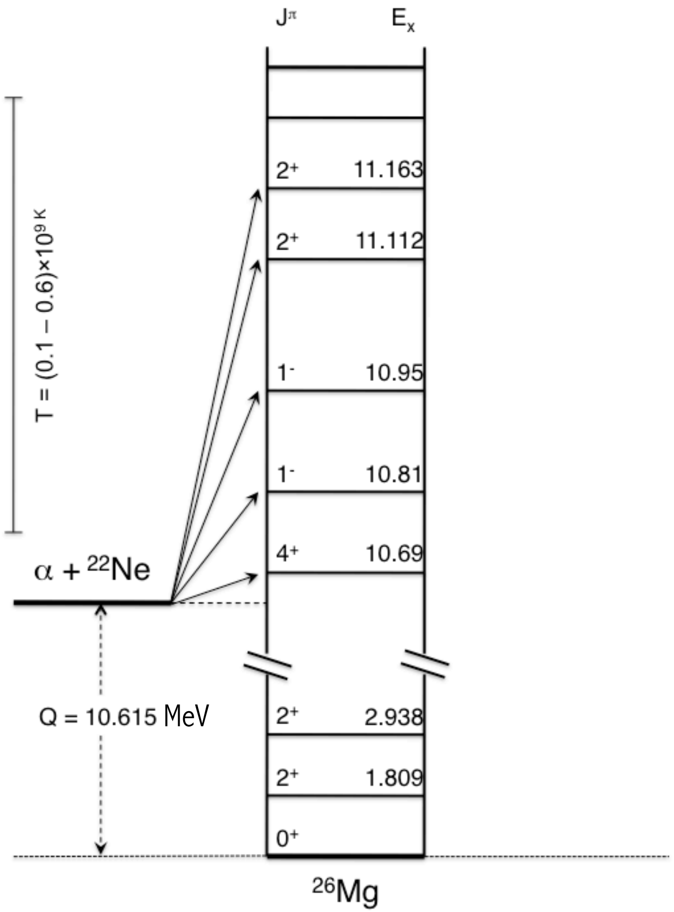
$$\vec{J} = \underbrace{\vec{I} + \vec{i}}_{} + \vec{\ell}$$

$$\vec{J} = 0 + \vec{\ell}$$

$$\pi = (-1)^{\ell}$$

$J^{\pi} = 0^+, 1^-, 2^+, 3^-, 4^+ \ldots$



^{25}Mg(n, tot)
^{25}Mg(n, γ)

Motivation 2

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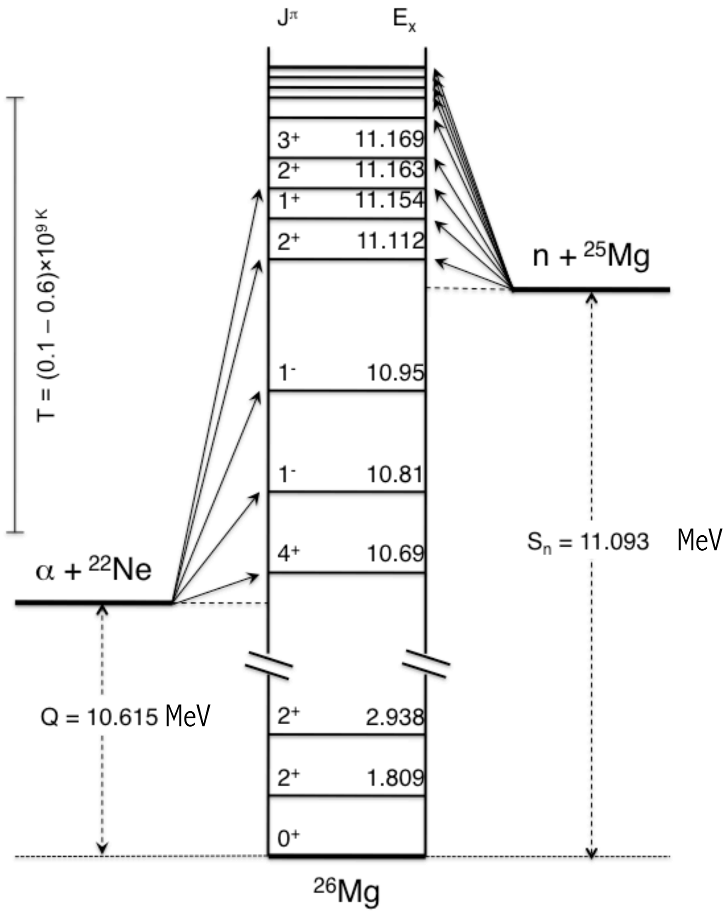
Constraints for the ^{22}Ne(α, n)^{25}Mg reaction

Element	Spin/ parity
^{25}Mg	$5/2^+$
neutron	$1/2^+$

$$\vec{J} = \underbrace{\vec{I} + \vec{i}}\; + \vec{\ell}$$

$$\vec{J} = 2 + \vec{\ell} \qquad \vec{J} = 3 + \vec{\ell}$$

s-wave → J^π= **2⁺**, 3^+
p-wave → J^π= **1⁻**, 2^-, **3⁻**, 4^-
d-wave → J^π= **0⁺**, 1^+, **2⁺**, 3^+, **4⁺**, 5^+
States in ^{26}Mg populated by ^{25}Mg+n reaction



Motivation 2

$^{25}Mg(n, tot)$
$^{25}Mg(n, \gamma)$

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neutron	$1/2^+$
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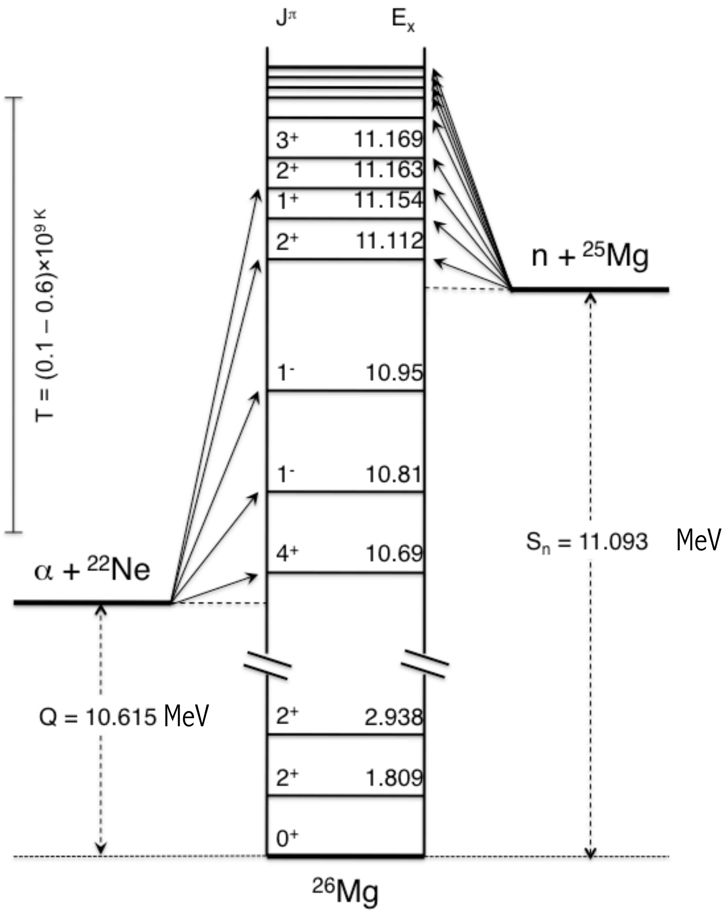
^{4}He	0^+



From neutron TOF measurements:
→ **J^π for the ^{26}Mg states**

$^{25}Mg(n, \gamma)$ @ n_TOF

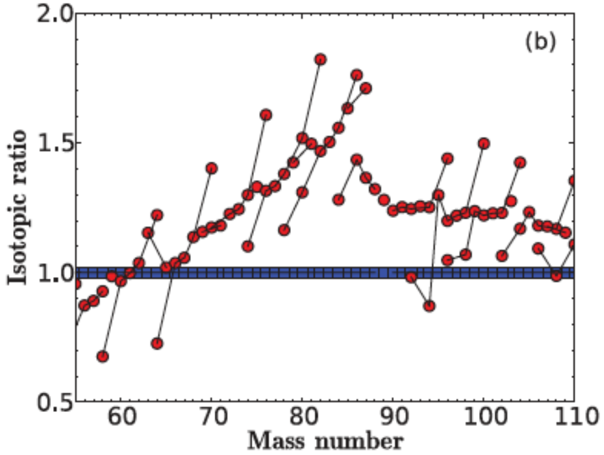
Motivations

Results from previous (2003) measurement:

PHYSICAL REVIEW C **85**, 044615 (2012)

Resonance neutron-capture cross sections of stable magnesium isotopes and their astrophysical implications

C. Massimi,[1,2,*] P. Koehler,[3] S. Bisterzo,[4] N. Colonna,[5] R. Gallino,[4] F. Gunsing,[6] F. Käppeler,[7] G. Lorusso,[5] A. Mengoni,[8,9] M. Pignatari,[10] G. Vannini,[1,2] U. Abbondanno,[11] G. Aerts,[6] H. Álvarez,[12] F. Álvarez-Velarde,[13] S. Andriamonje,[6] J. Andrzejewski,[14] P. Assimakopoulos,[15,†] L. Audouin,[16] G. Badurek,[17] M. Barbagallo,[5] P. Baumann,[18] F. Bečvář,[19] F. Belloni,[11] M. Bennett,[20] E. Berthoumieux,[6] M. Calviani,[9] F. Calviño,[21] D. Cano-Ott,[13] R. Capote,[8,22] C. Carrapiço,[23,6] A. Carrillo de Albornoz,[23] P. Cennini,[9] V. Chepel,[24] E. Chiaveri,[9] G. Cortes,[25] A. Couture,[26] J. Cox,[26] M. Dahlfors,[9] S. David,[16] I. Dillmann,[7] R. Dolfini,[27] C. Domingo-Pardo,[28] W. Dridi,[6] I. Duran,[12] C. Eleftheriadis,[29] M. Embid-Segura,[13] L. Ferrant,[16,†] A. Ferrari,[9] R. Ferreira-Marques,[24] L. Fitzpatrick,[9] H. Frais-Koelbl,[8] K. Fujii,[11] W. Furman,[30] I. Goncalves,[23] E. González-Romero,[13] A. Goverdovski,[31] F. Gramegna,[32] E. Griesmayer,[8] C. Guerrero,[13] B. Haas,[33] R. Haight,[34] M. Heil,[35] A. Herrera-Martinez,[9] F. Herwig,[36] R. Hirschi,[20] M. Igashira,[37] S. Isaev,[16] E. Jericha,[17] Y. Kadi,[9] D. Karadimos,[15] D. Karamanis,[15] M. Kerveno,[18] V. Ketlerov,[30] V. Konovalov,[29] S. Kopecky,[38] E. Kossionides,[39] M. Krtička,[19] C. Lampoudis,[29,6] H. Leeb,[17] C. Lederer,[40] A. Lindote,[24] I. Lopes,[24] R. Losito,[9] M. Lozano,[22] S. Lukic,[18] J. Marganiec,[14] L. Marques,[23] S. Marrone,[5] T. Martínez,[13] P. Mastinu,[32] E. Mendoza,[13] P. M. Milazzo,[11] C. Moreau,[11] M. Mosconi,[7] F. Neves,[24] H. Oberhummer,[17] S. O'Brien,[26] M. Oshima,[41] J. Pancin,[6] C. Papachristodoulou,[15] C. Papadopoulos,[42] C. Paradela,[12] N. Patronis,[15] A. Pavlik,[40] P. Pavlopoulos,[43] L. Perrot,[6] M. T. Pigni,[17] R. Plag,[7] A. Plompen,[38] A. Plukis,[6] A. Poch,[25] J. Praena,[22] C. Pretel,[25] J. Quesada,[22] T. Rauscher,[10] R. Reifarth,[34] G. Rockefeller,[34] M. Rosetti,[44] C. Rubbia,[27] G. Rudolf,[18] J. Salgado,[23] C. Santos,[23] L. Sarchiapone,[9] R. Sarmento,[23] I. Savvidis,[29] C. Stephan,[16] G. Tagliente,[5] J. L. Tain,[28] D. Tarrío,[12] L. Tassan-Got,[16] L. Tavora,[23] R. Terlizzi,[5] P. Vaz,[23] A. Ventura,[44] D. Villamarin,[13] V. Vlachoudis,[9] R. Vlastou,[42] F. Voss,[7] S. Walter,[7] H. Wendler,[9] M. Wiescher,[26] and K. Wisshak[7]



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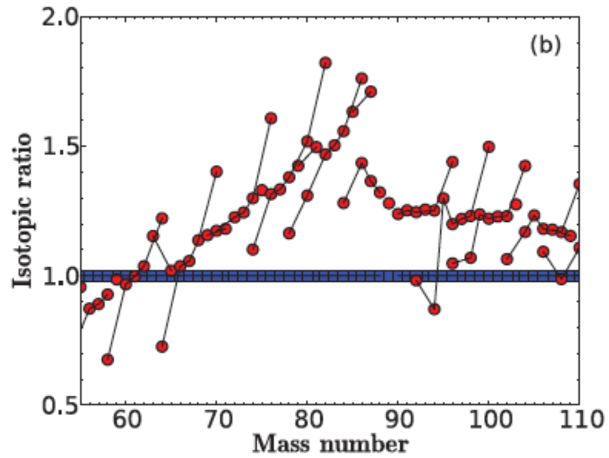

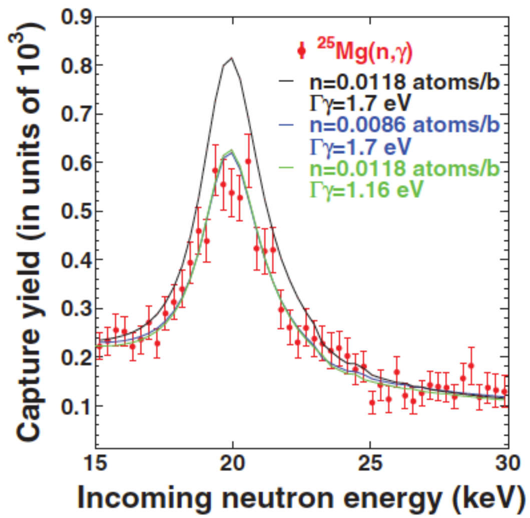

Oxide Sample → **Large uncertainty** in the mass of the Mg sample

Motivations

New measurement: improvements

1. **Sample**
   - Capture on a **metal** ^{25}Mg-enriched sample → **no data in literature**
   - Transmission on the **^{25}Mg-enriched** sample → **no data in literature**

2. **n_TOF facility Phase-II**:
   - **Borated water** as neutron moderator → **γ-ray background reduced**

$^{25}Mg(n, \gamma)$ @ n_TOF

New Measurement

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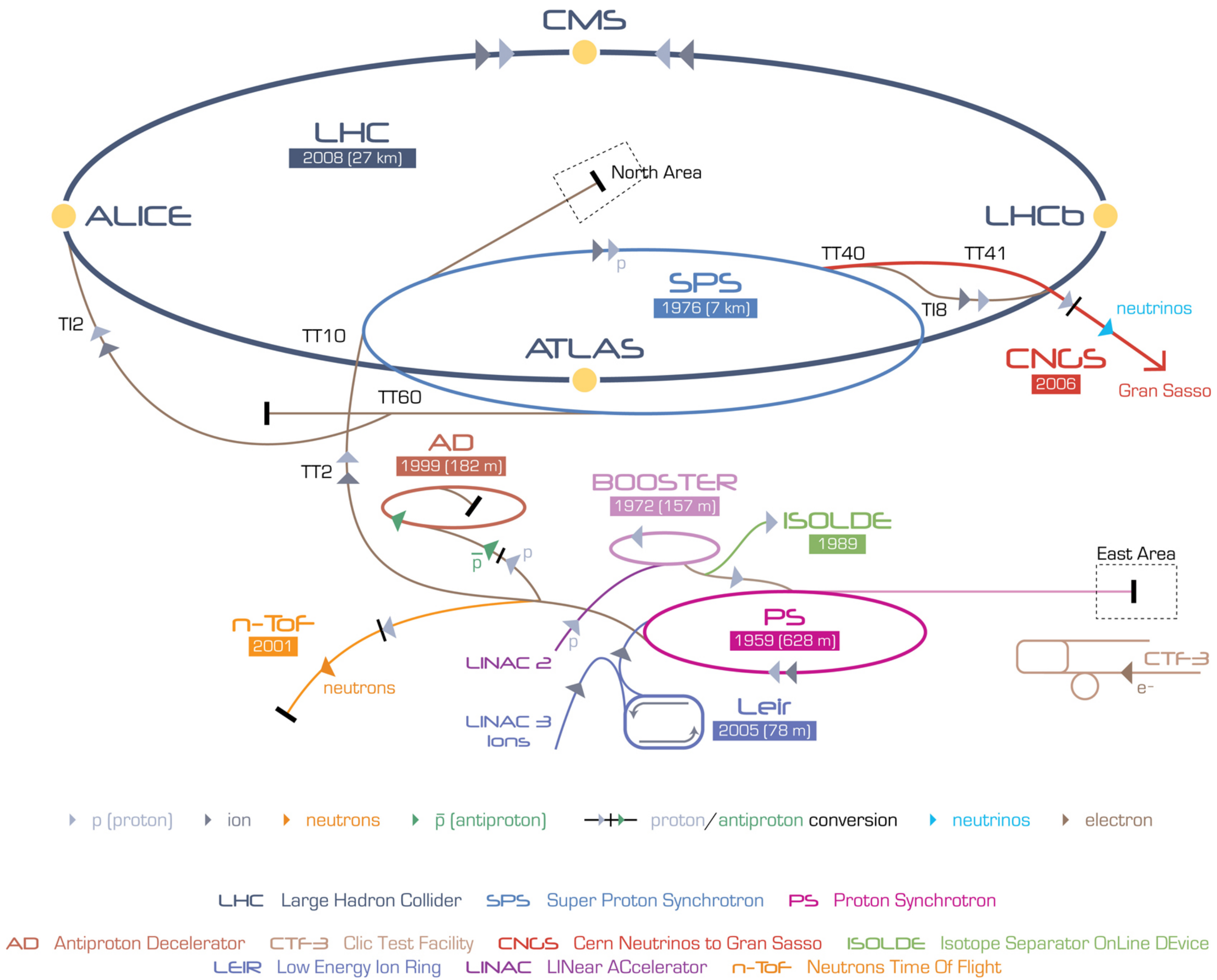

$^{25}Mg(n, \gamma)$ @ n_TOF

New Measurement

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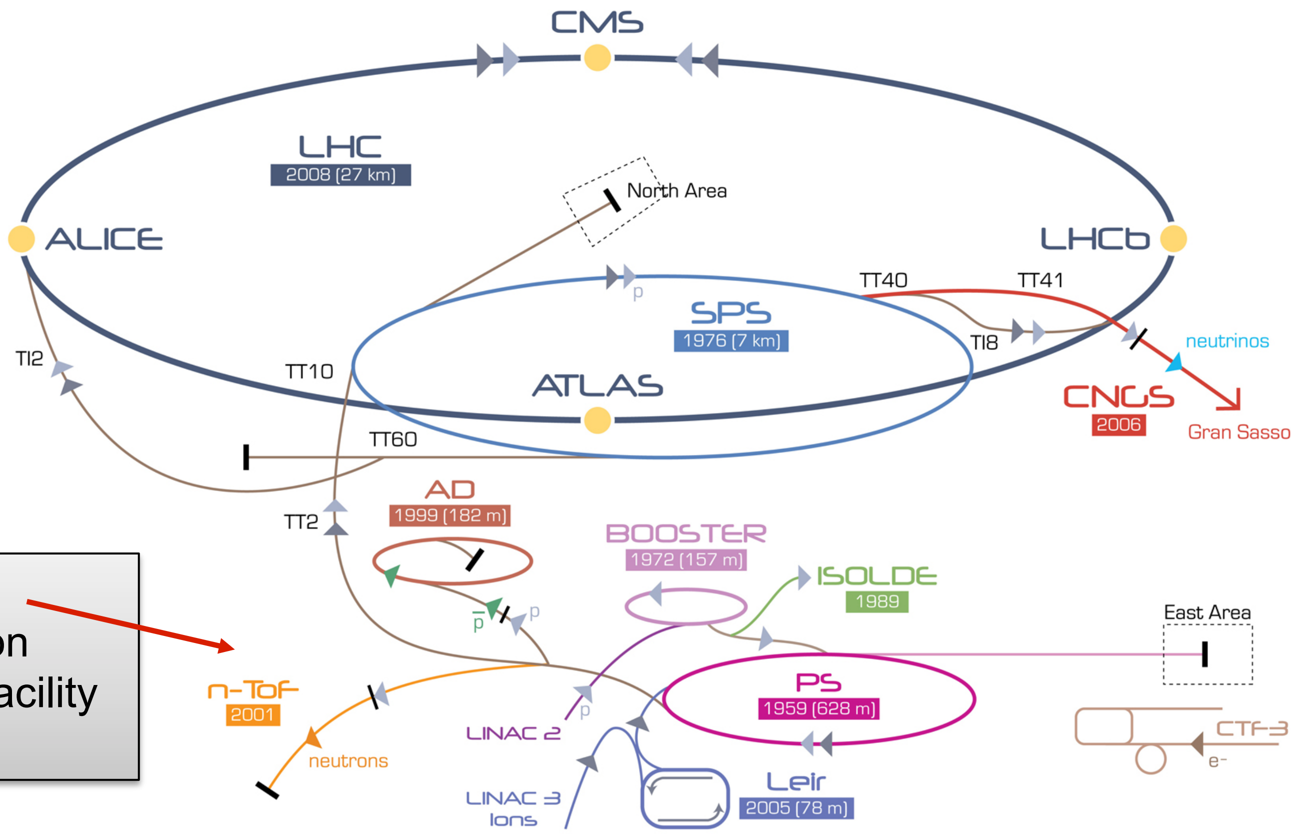
CERN

n_TOF
the neutron
time-of-flight facility
at **CERN**



p (proton) ion neutrons p̄ (antiproton) proton/antiproton conversion neutrinos electron

LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron

AD Antiproton Decelerator CTF3 Clic Test Facility CNGS Cern Neutrinos to Gran Sasso ISOLDE Isotope Separator OnLine DEvice
LEIR Low Energy Ion Ring LINAC LINear ACcelerator n-ToF Neutrons Time Of Flight

$^{25}Mg(n, \gamma)$ @ n_TOF

New Measurement

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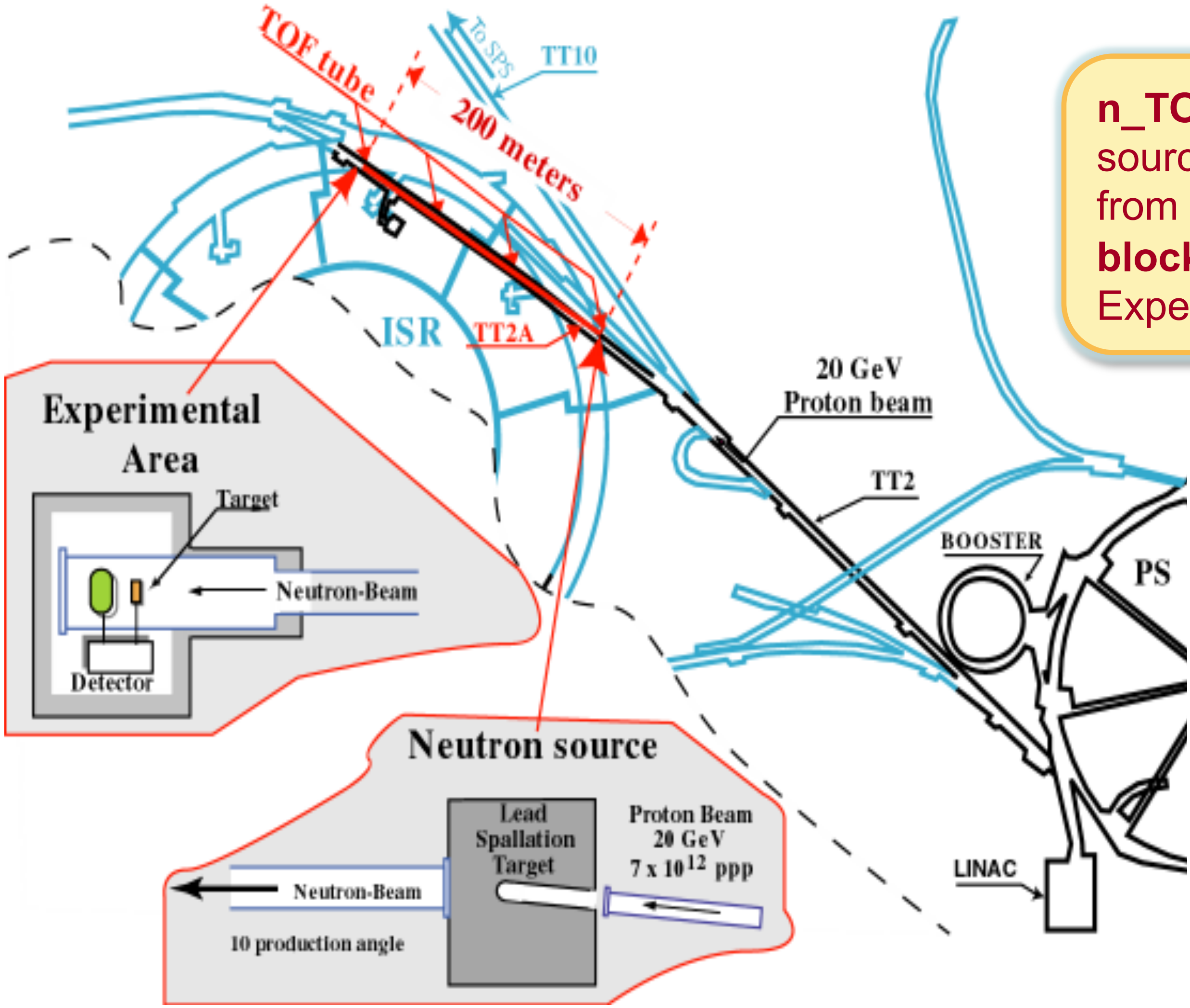

n_TOF is a neutron **spallation** source based on **20 GeV/c protons** from the CERN PS hitting a **Pb block** (~360 neutrons per proton). Experimental area at **200 m**.

Neutron flux	10^5 n/cm^2/pulse
Neutron energy	30 meV – 1 GeV
Energy resolution	DE/E ~ 10^{-4}
Repetition rate	~ 0.8 Hz

$^{25}Mg(n, \gamma)$ @ n_TOF

New Measurement

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2003

OLD sample (powder)

Science-Technical Centre "Stable Isotopes" (Obninsk, Russia)

Property	Value
Mass MgO	3.19 g
Diameter	22 mm
Thickness	2.3 mm
Areal density	1.234×10^{-2} at/b

Enrichment 95.75%
$^{24}Mg \sim 3\%$,
$^{26}Mg \sim 1.2\%$

Neutrons ≈ 1.1×10^{10}
1 eV < E_n < 1 MeV

2012

New sample (metal)

National Isotope Development Center (ORNL, USA)

Property	Value
Mass Mg	3.94 g
Diameter	20 mm
Thickness	7 mm
Areal density	3.00×10^{-2} at/b

Enrichment 97.86 %
$^{24}Mg \sim 1.83\ \%$
$^{26}Mg \sim 0.31\ \%$

Neutrons ≈ 1.9×10^{10}
0.03 eV < E_n < 1 MeV

$^{25}Mg(n, \gamma)$ @ n_TOF

New Measurement

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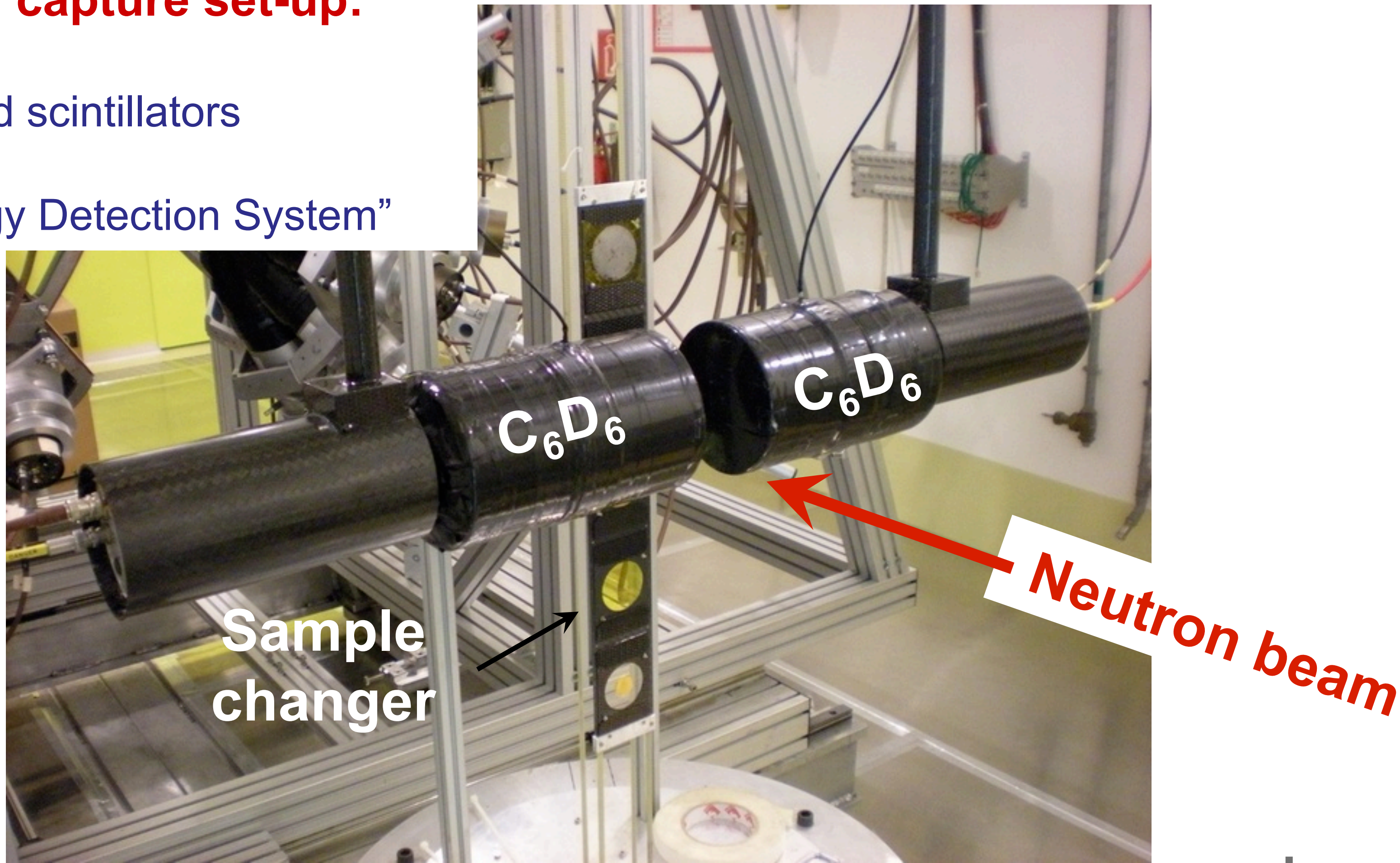
Typical capture set-up:

- 2 C_6D_6 liquid scintillators
- "Total Energy Detection System"



Data Analysis

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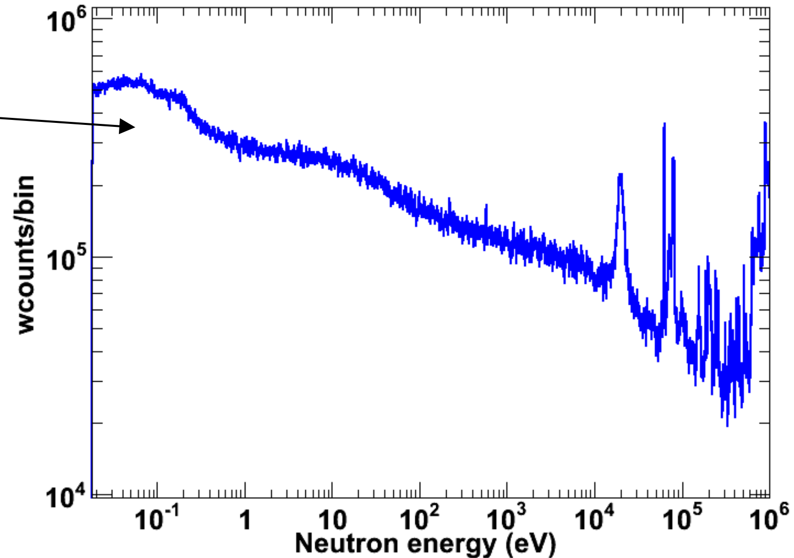
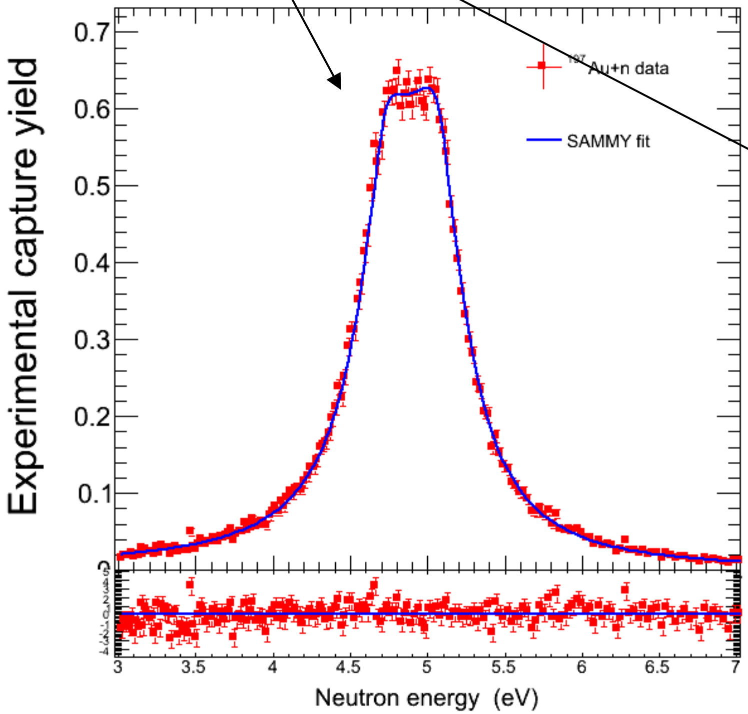
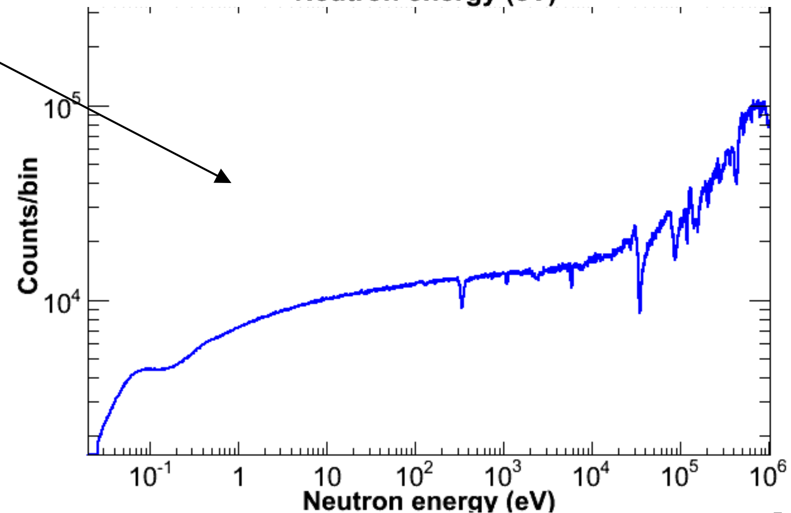
Experimental capture yield

$$Y(E_n) = N \frac{C_w(E_n)}{\varphi_n(E_n)} \propto (1 - e^{-n\sigma_{tot}}) \frac{\sigma_\gamma}{\sigma_{tot}}$$



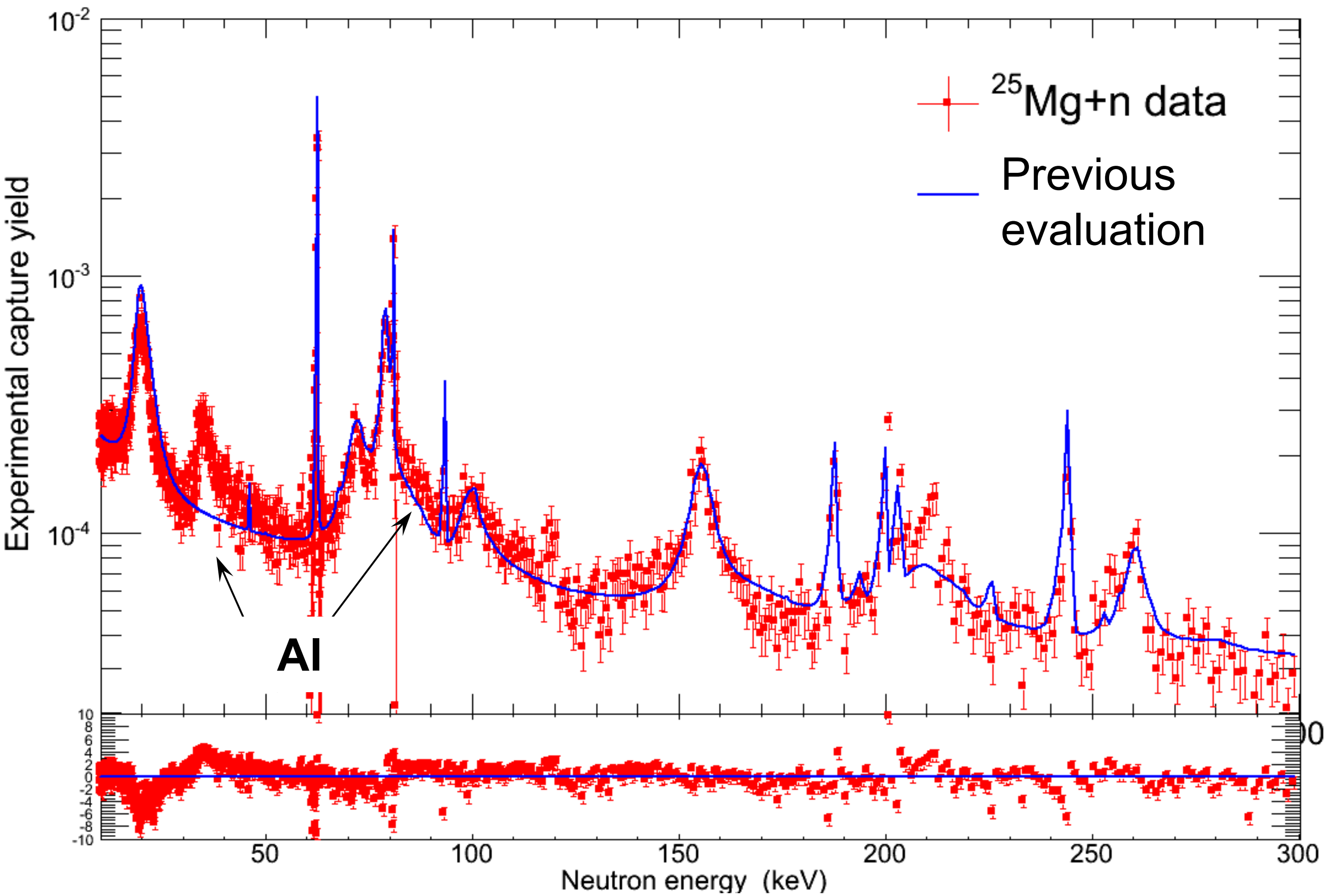




^{25}Mg(n, γ) @ n_TOF

Preliminary Results

2012 data



$^{25}Mg(n, \gamma)$ @ n_TOF

Preliminary Results

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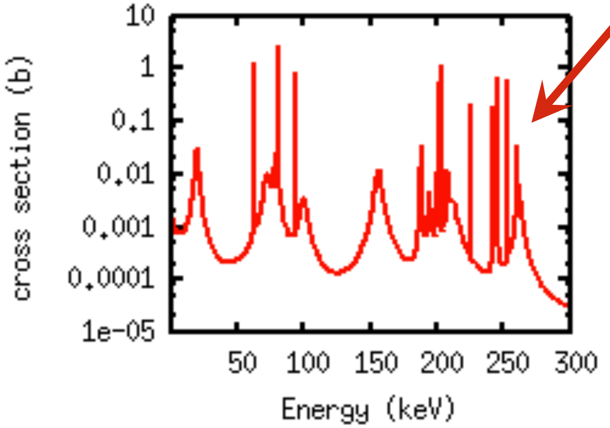
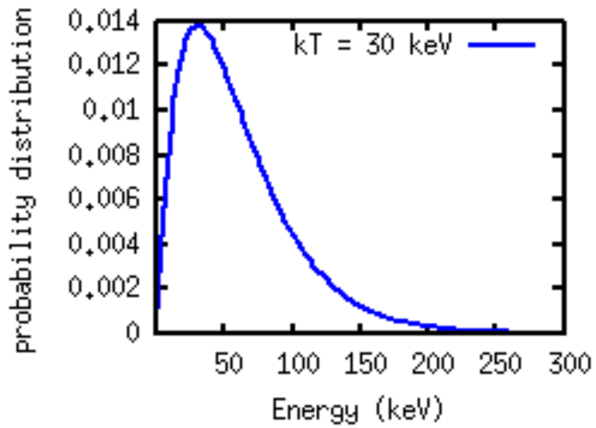
$^{25}Mg(n, \gamma)^{26}Mg$ resonances → **R-matrix** parameterization of the **cross section**

E_n (keV)	ℓ	J^π	Γ_γ (eV)	Γ_n (eV)
-154.25	0	2^+	6.5	30000
19.86 ± 0.05	0	2^+	1.7 ± 0.2	2310 ± 30
62.727 ± 0.003	1^a	$1^{+\,a}$	4.1 ± 0.7	28 ± 5
72.66 ± 0.03	0	2^+	2.5 ± 0.4	5080 ± 80
79.29 ± 0.03	0	3^+	3.3 ± 0.4	1560 ± 80
81.117 ± 0.001	0^b	$(2)^+$	3 ± 2	0.8 ± 0.7
93.60 ± 0.02	(1)	(1^-)	2.3 ± 2	0.6 ± 0.2
100.03 ± 0.02	0	3^+	1.0 ± 0.1	5240 ± 40
$[101.997 \pm 0.009]$	[1]	$[2^-]$	$[0.2 \pm 0.1]$	$[4 \pm 3]$
$[107.60 \pm 0.02]$	$[0]^b$	$[3^+]$	$[0.3 \pm 0.1]$	$[2 \pm 1]$
156.34 ± 0.02	(1)	(2^-)	6.1 ± 0.4	5520 ± 20
188.347 ± 0.009	0	$(2)^+$	1.7 ± 0.2	590 ± 20
194.482 ± 0.009	(1)	$4^{(-)}$	0.2 ± 0.1	1730 ± 20
200.20 ± 0.03	1^b	1^-	0.3 ± 0.3	1410 ± 60
200.944 ± 0.006	(2)	(2^+)	3.0 ± 0.3	0.7 ± 0.7
203.878 ± 0.001	(1)	(2^-)	0.8 ± 0.3	2 ± 1
208.27 ± 0.01	(1)	(1^-)	1.2 ± 0.5	230 ± 20
211.14 ± 0.05	(1)	(2^-)	3.1 ± 0.7	12400 ± 100
226.255 ± 0.001	(1)	(1^-)	4 ± 3	0.4 ± 0.2
242.47 ± 0.02	(1)	(1^-)	6 ± 4	0.3 ± 0.2
244.60 ± 0.03	1	$1^{-\,c}$	3.5 ± 0.6	50 ± 20
245.552 ± 0.002	(1)	(1^-)	2.3 ± 2	0.5 ± 0.2
253.63 ± 0.01	(1)	(1^-)	3.1 ± 2.7	0.1 ± 0.1
261.84 ± 0.03	(1)	$4^{(-)}$	2.6 ± 0.4	3490 ± 60
279.6 ± 0.2	(0)	(2^+)	1.9 ± 0.7	3290 ± 50
311.57 ± 0.01	(2)	(5^+)	(0.84 ± 0.09)	(240 ± 10)



Convoluted with **neutron** stellar **flux**



MACS and reaction rate

$^{25}Mg(n, \gamma)$ @ n_TOF

Preliminary Results

INFN Istituto Nazionale di Fisica Nucleare

Stellar site	Temperature keV	MACS (this work)	MACS (KADoNiS)
He - AGB	8	**4.9±0.6 mb**	4.9 mb
He - AGB	23	**3.2±0.2 mb**	6.1 mb
30	30	**4.1±0.6 mb**	6.4±0.4 mb
He – Massive	25	**3.4±0.2 mb**	6.2 mb
C - Massive	90	**2.6±0.3 mb**	4.0 mb

s-process abundances

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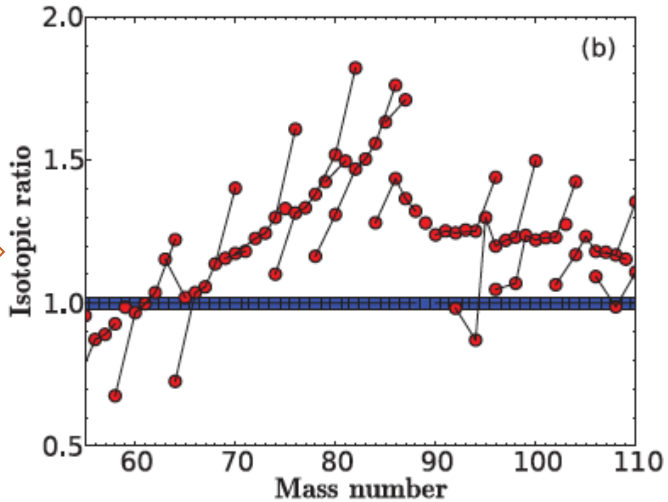

Reduced poisoning effect in Massive Stars

$^{25}Mg(n, \gamma)$ @ n_TOF

Preliminary Results

INFN Istituto Nazionale di Fisica Nucleare

$^{25}Mg(n, \gamma)^{26}Mg$ resonances

E_n (keV)	ℓ	J^π	Γ_γ (eV)	Γ_n (eV)
−154.25	0	2^+	6.5	30000
19.86 ± 0.05	0	2^+	1.7 ± 0.2	2310 ± 30
62.727 ± 0.003	1^a	$1^{+\ a}$	4.1 ± 0.7	28 ± 5
72.66 ± 0.03	0	2^+	2.5 ± 0.4	5080 ± 80
79.29 ± 0.03	0	3^+	3.3 ± 0.4	1560 ± 80
81.117 ± 0.001	0^b	$(2)^+$	3 ± 2	0.8 ± 0.7
93.60 ± 0.02	(1)	(1^-)	2.3 ± 2	0.6 ± 0.2
100.03 ± 0.02	0	3^+	1.0 ± 0.1	5240 ± 40
$[101.997 \pm 0.009]$	[1]	$[2^-]$	$[0.2 \pm 0.1]$	$[4 \pm 3]$
$[107.60 \pm 0.02]$	$[0]^b$	$[3^+]$	$[0.3 \pm 0.1]$	$[2 \pm 1]$
156.34 ± 0.02	(1)	(2^-)	6.1 ± 0.4	5520 ± 20
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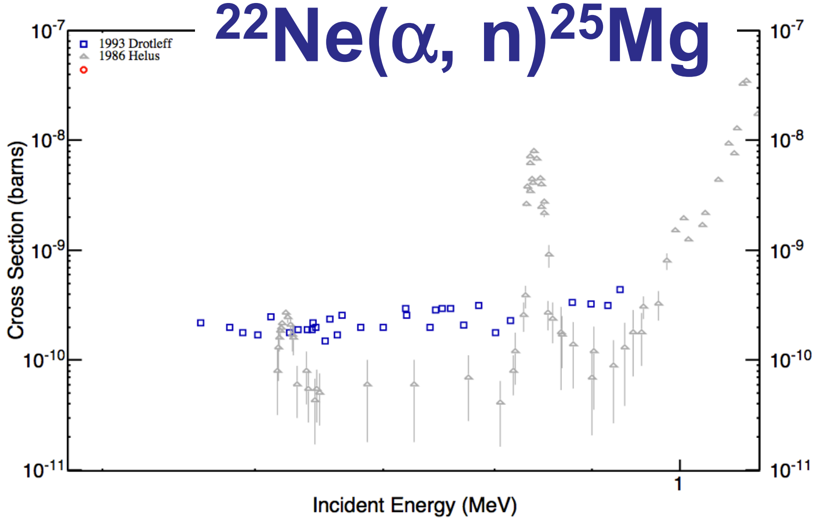
261.84 ± 0.03	(1)	$4^{(-)}$	2.6 ± 0.4	3490 ± 60
279.6 ± 0.2	(0)	(2^+)	1.9 ± 0.7	3290 ± 50
311.57 ± 0.01	(2)	(5^+)	(0.84 ± 0.09)	(240 ± 10)

$^{22}Ne(\alpha, n)^{25}Mg$



Constraints for the $^{22}Ne(\alpha, n)^{25}Mg$ reaction

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INFN Istituto Nazionale di Fisica Nucleare

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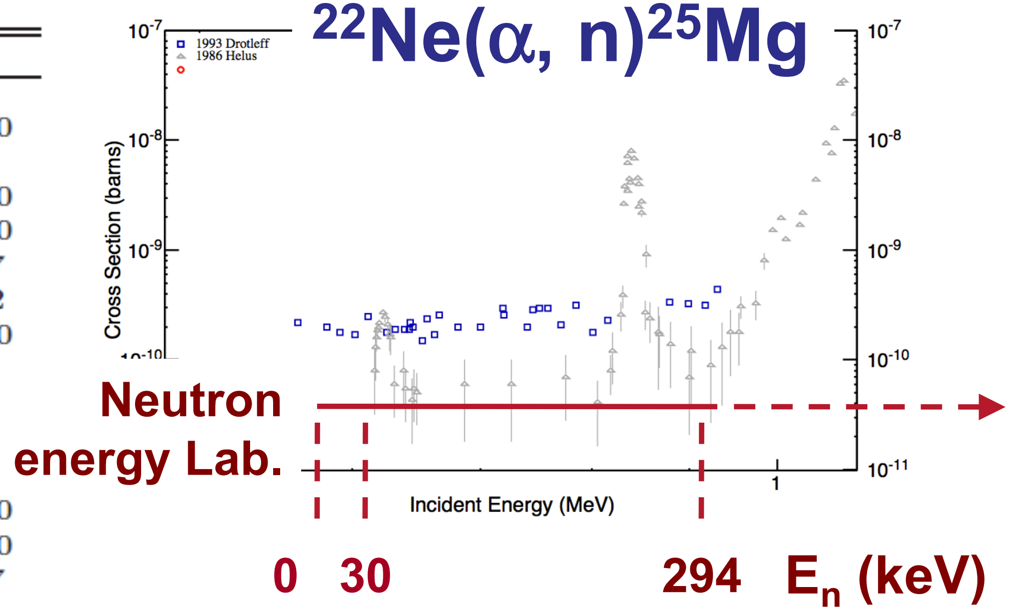


Constraints for the $^{22}Ne(\alpha, n)^{25}Mg$ reaction

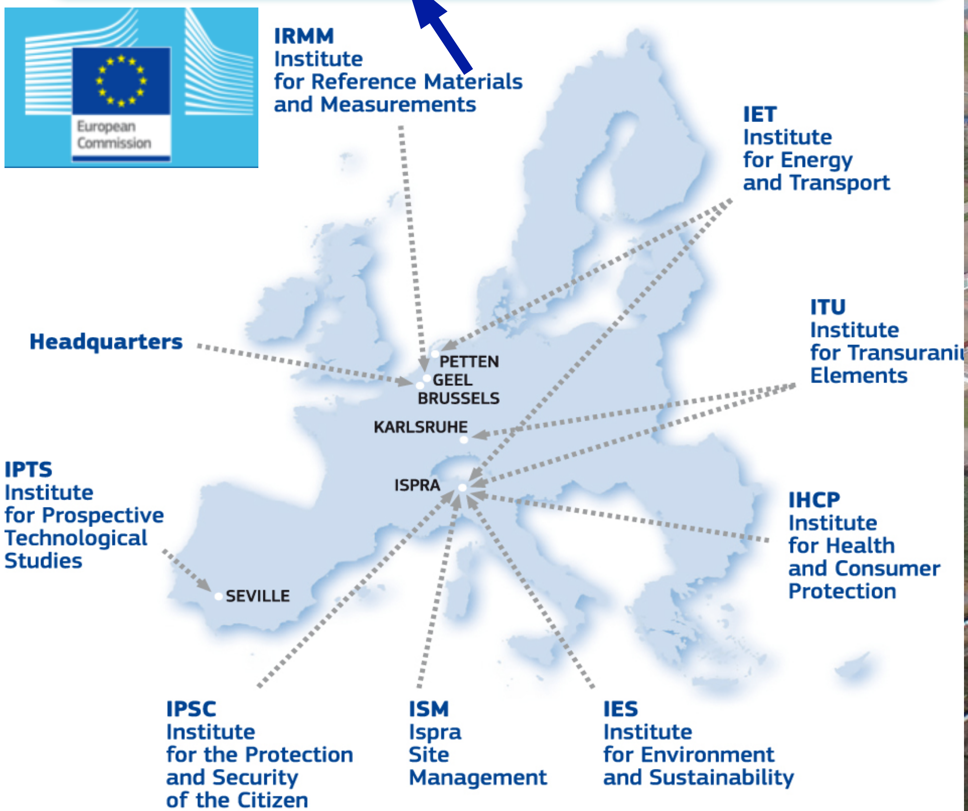
Observed ~ 30 resonances in the energy region of interest

$^{25}Mg(n, tot)$ @ GELINA

New Measurement

Istituto Nazionale di Fisica Nucleare

GELINA is a photonuclear **neutron source** based on **140 MeV e⁻** impinging on a **U target**. 10 Experimental areas at different flight paths (10 m - 400 m).



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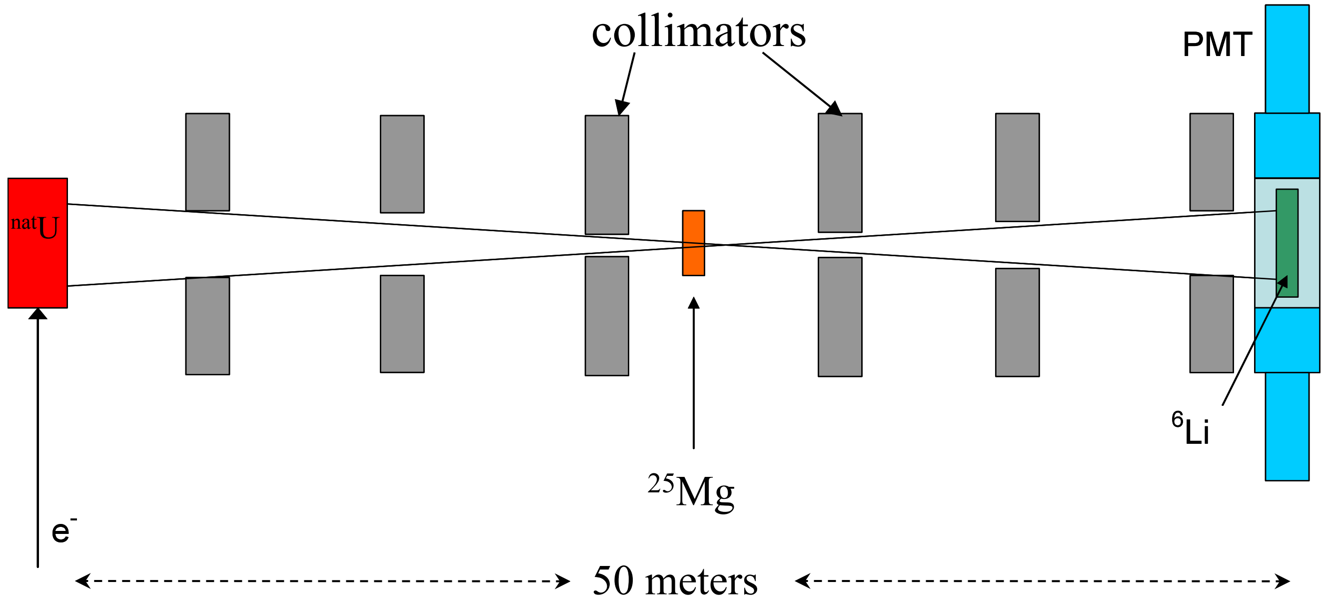
New Measurement

Istituto Nazionale di Fisica Nucleare

Experimental set up



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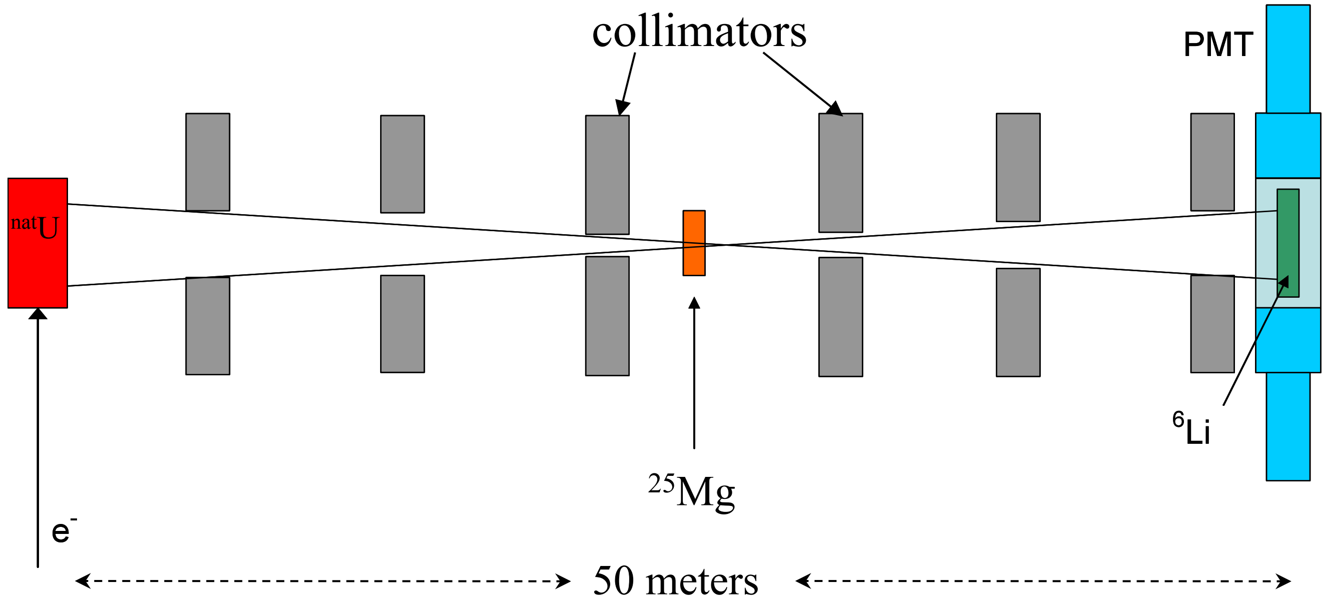
Istituto Nazionale di Fisica Nucleare



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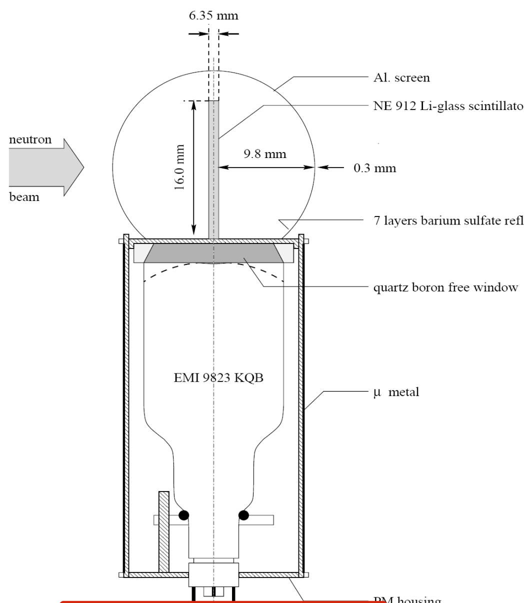
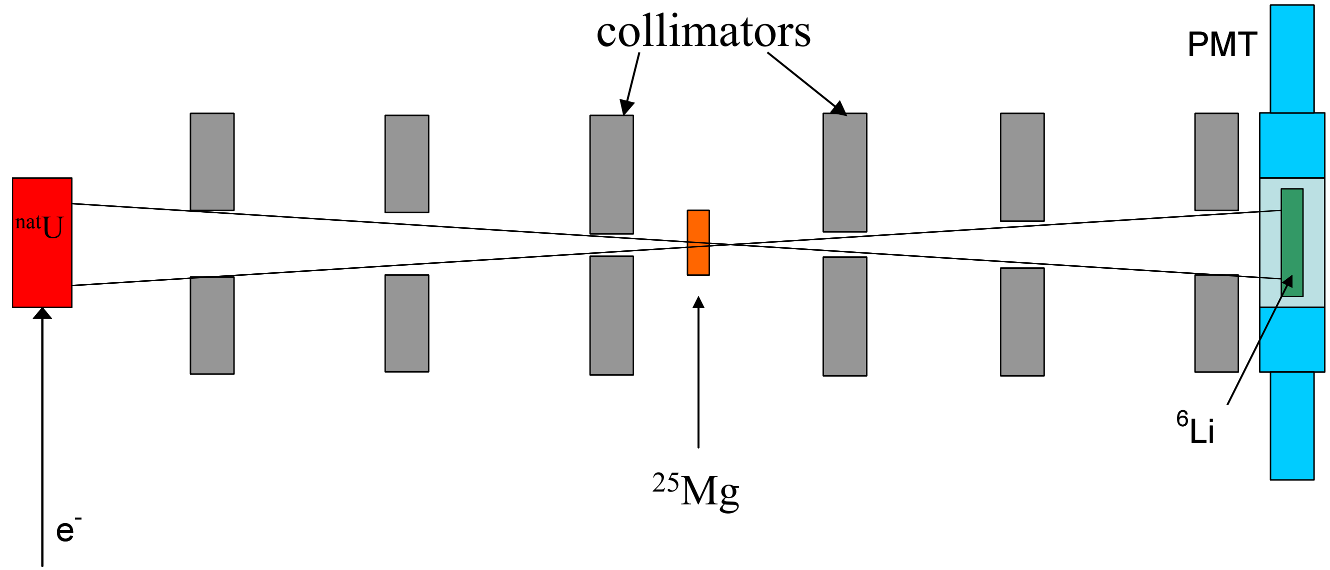


Litium glass scintillator

$^{25}Mg(n, tot)$ @ GELINA

New Measurement



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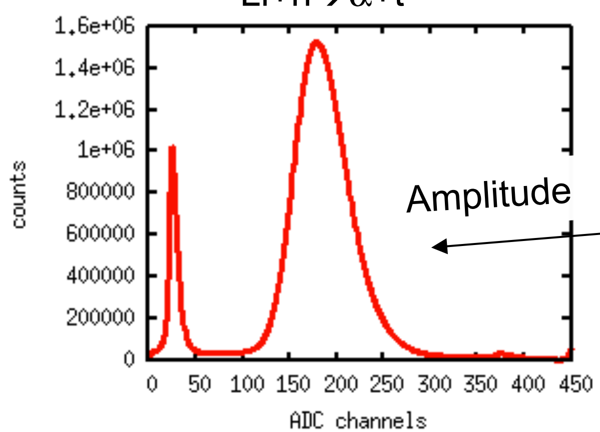

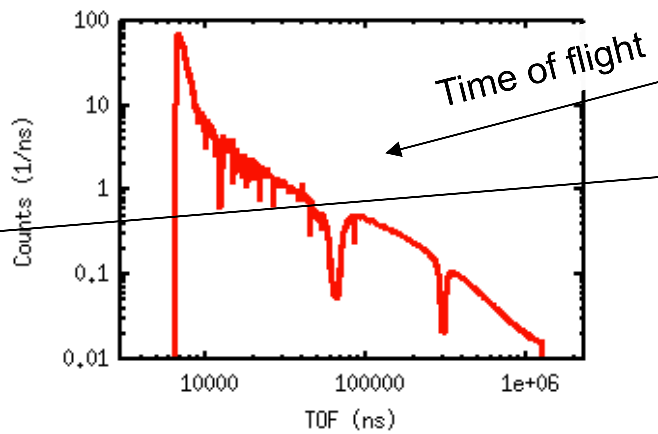

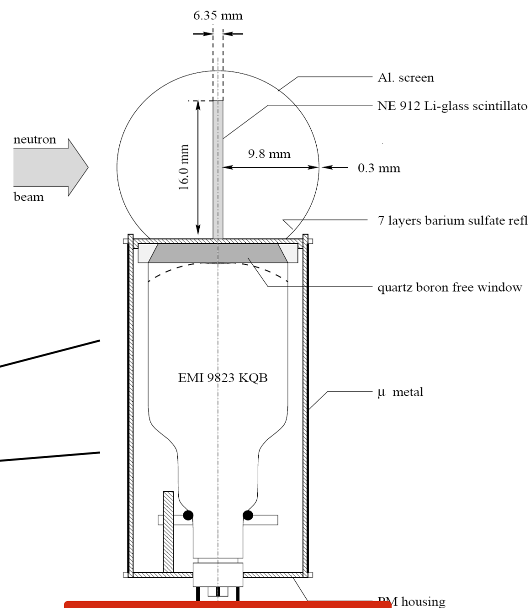

Litium glass scintillator

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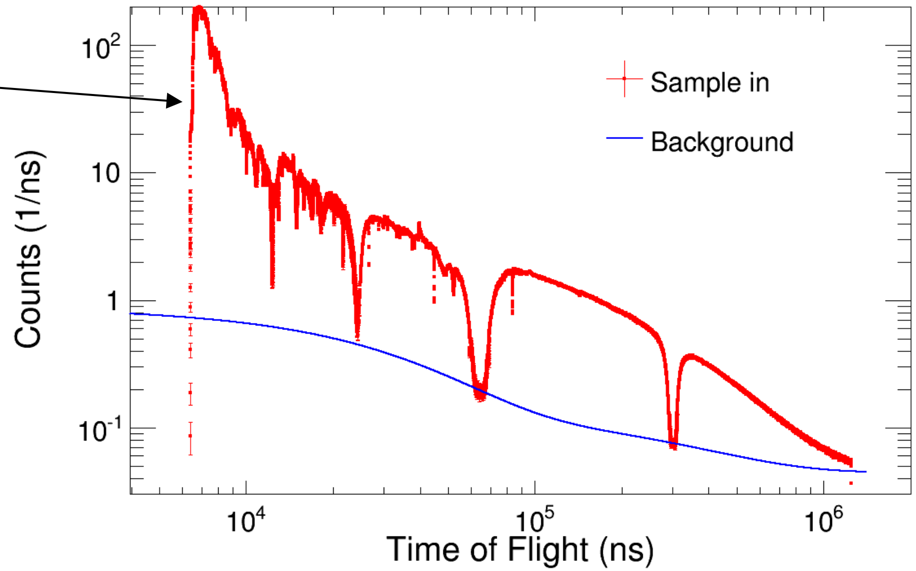
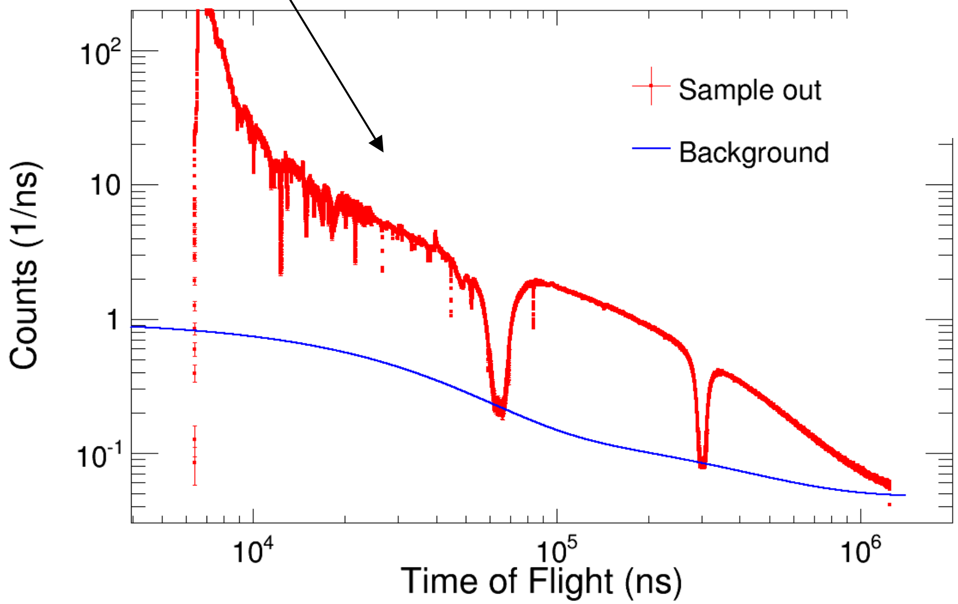
New Measurement

$$T = \frac{C_{in}}{C_{out}} \propto e^{-n\,\sigma_{tot}}$$





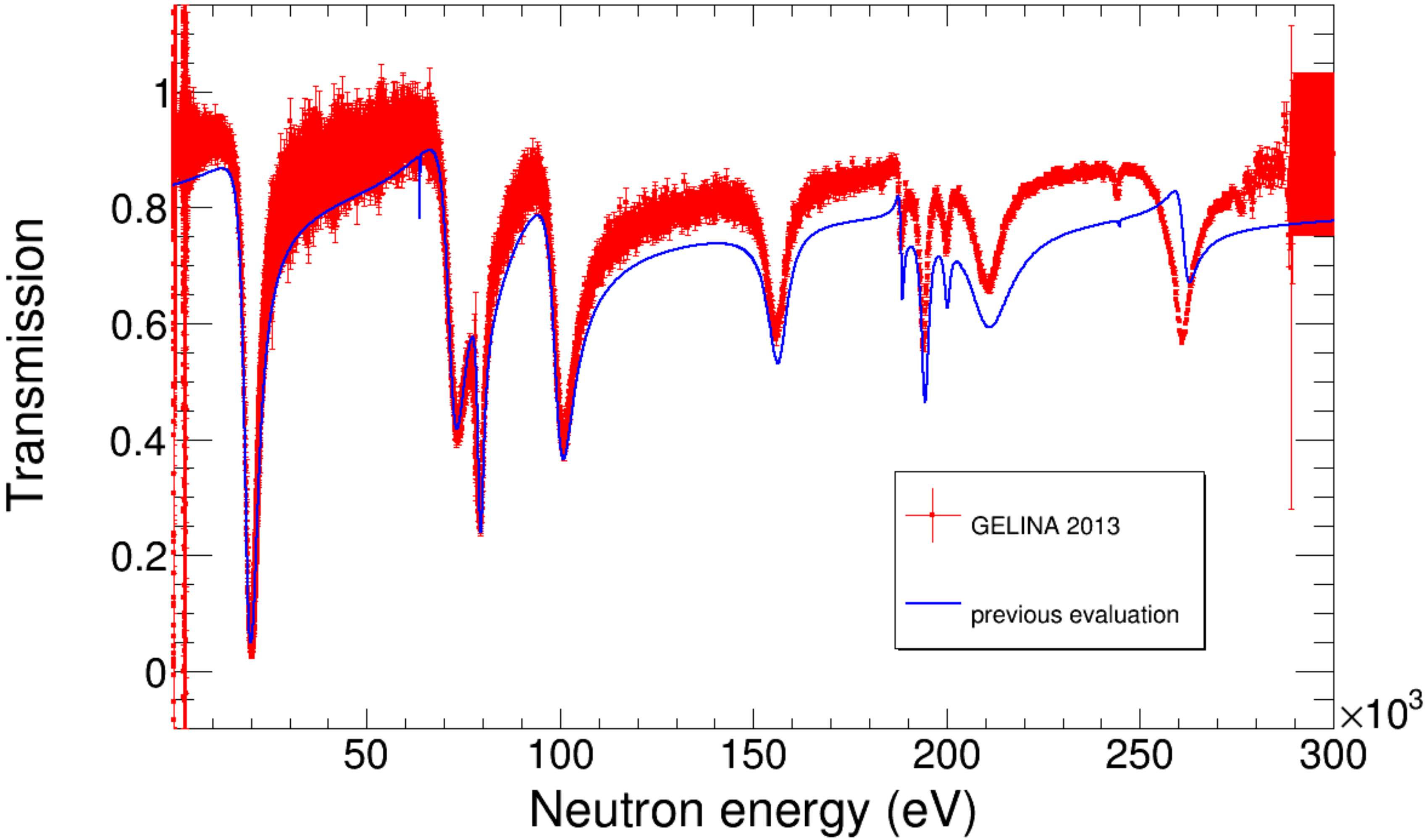
Background determined by **black resonance** technique:

$$B(t) = b_0 + b_1 e^{-\lambda_1 t} + b_2 e^{-\lambda_2 t} + b_3 e^{-\lambda_3 (t+t_0)}$$

$^{25}Mg(n, tot)$ @ GELINA

New Measurement

INFN Istituto Nazionale di Fisica Nucleare



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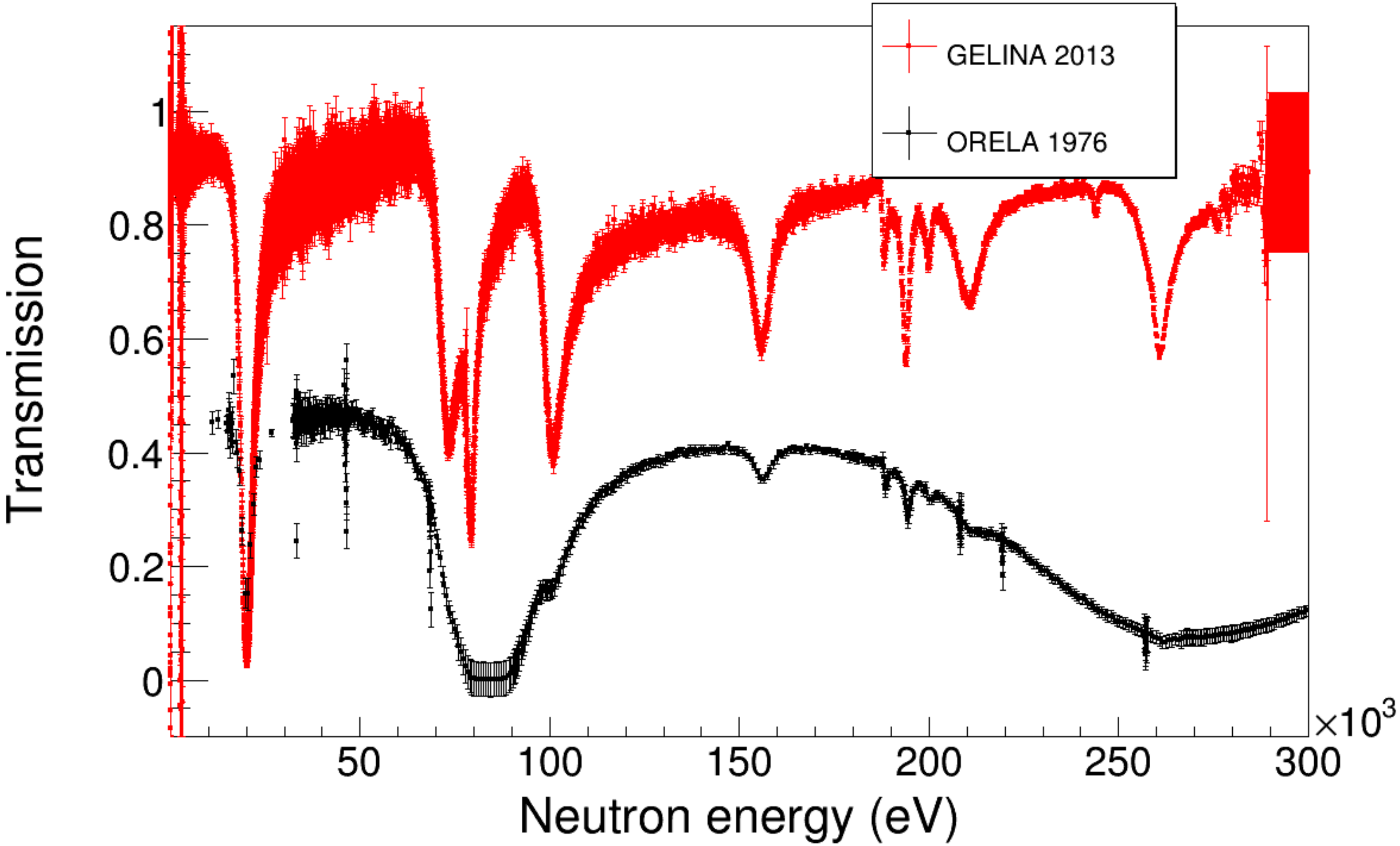

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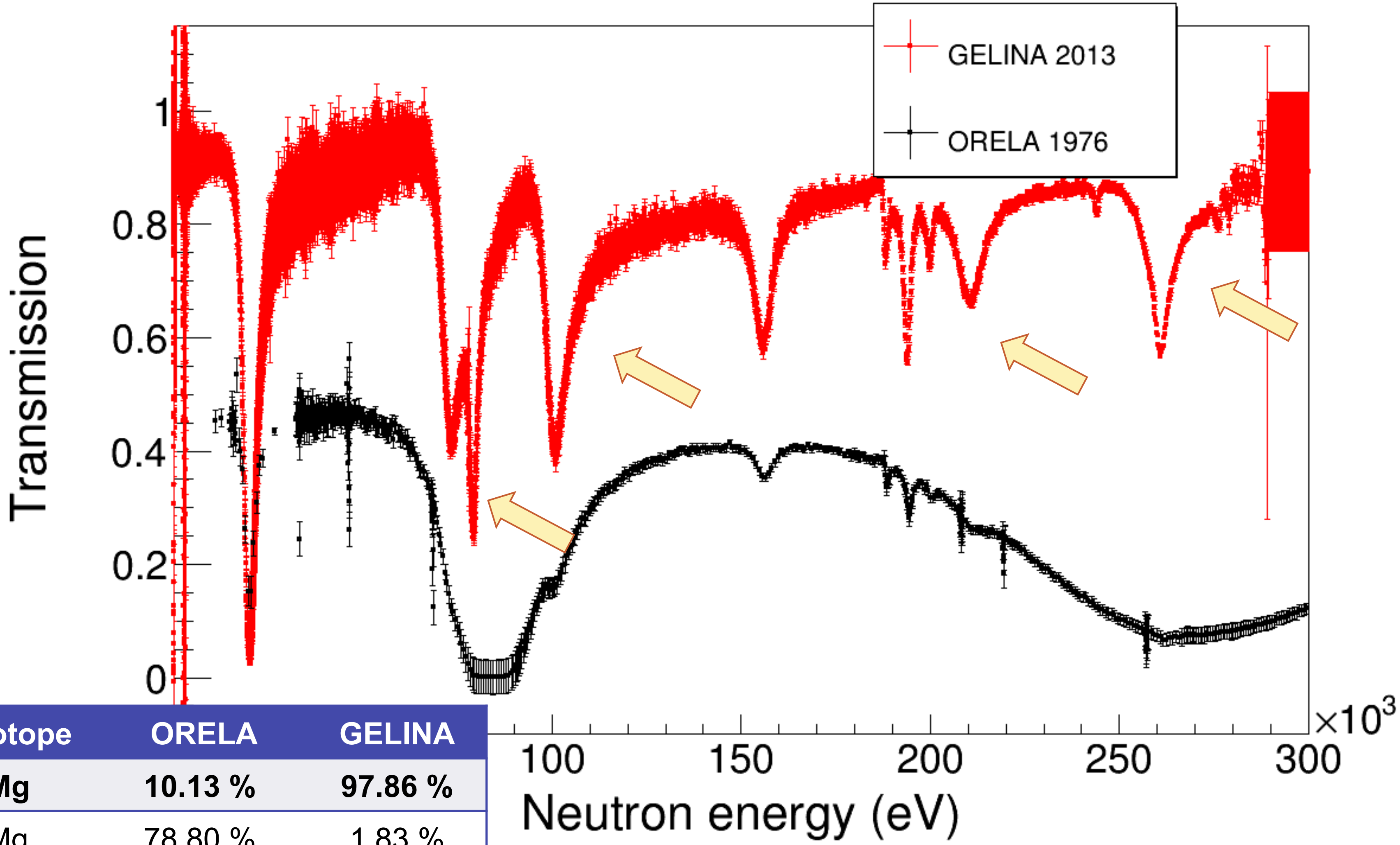
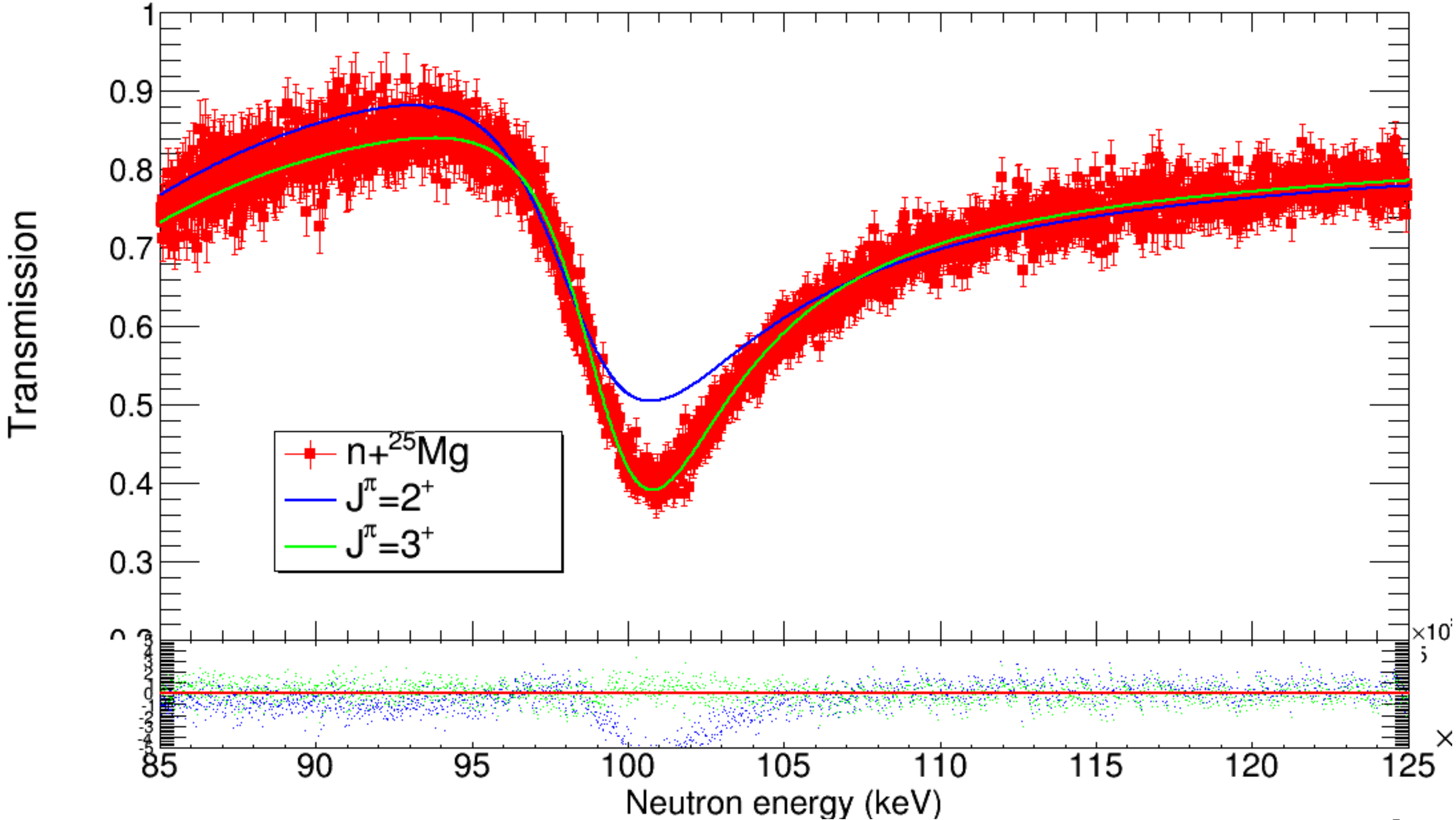


Isotope	ORELA	GELINA
^{25}Mg	**10.13 %**	**97.86 %**
^{24}Mg	78.80 %	1.83 %
^{26}Mg	11.17 %	0.31 %

New Measurement

Istituto Nazionale di Fisica Nucleare

Example of sensitivity to J^{π}



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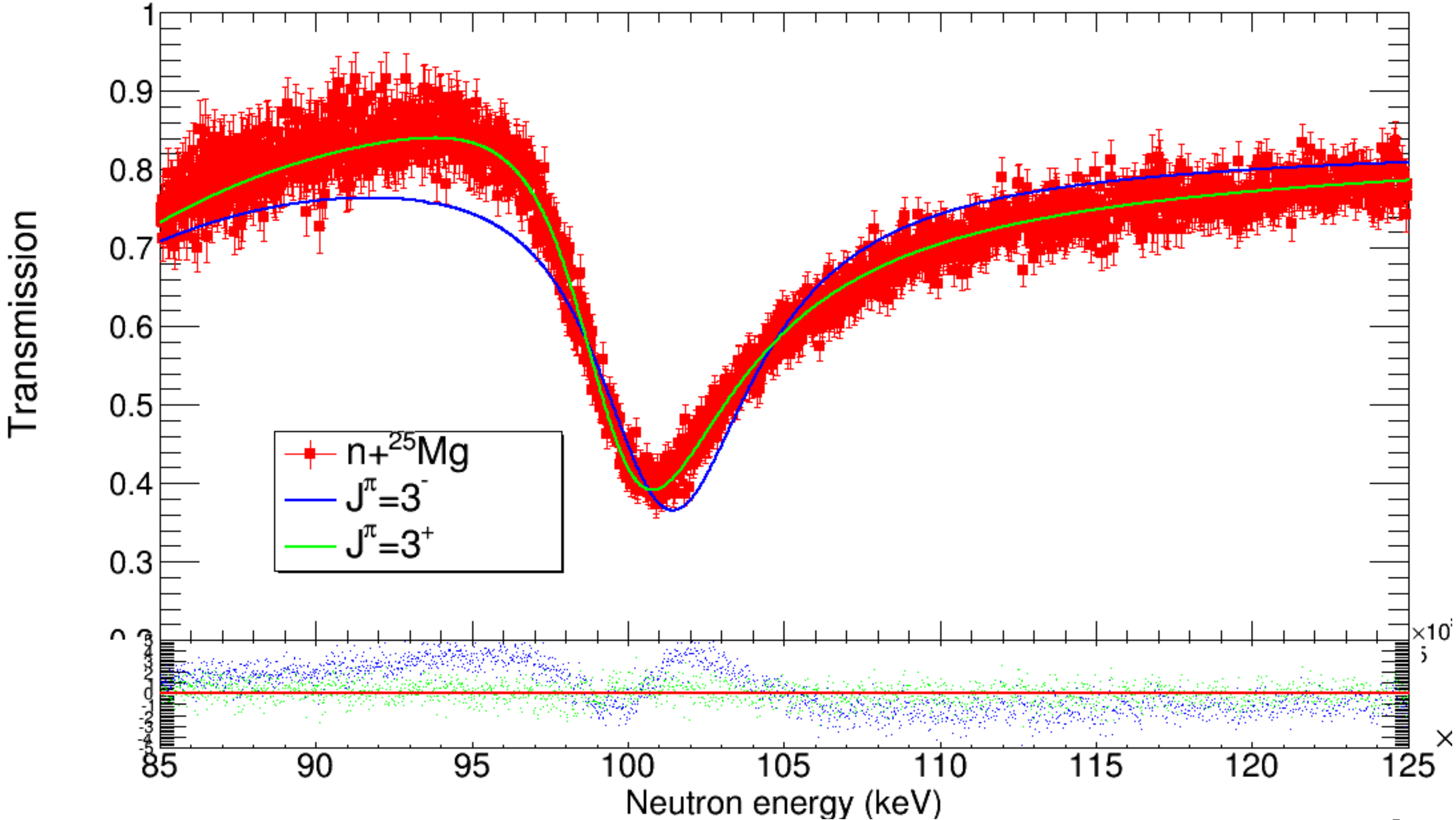

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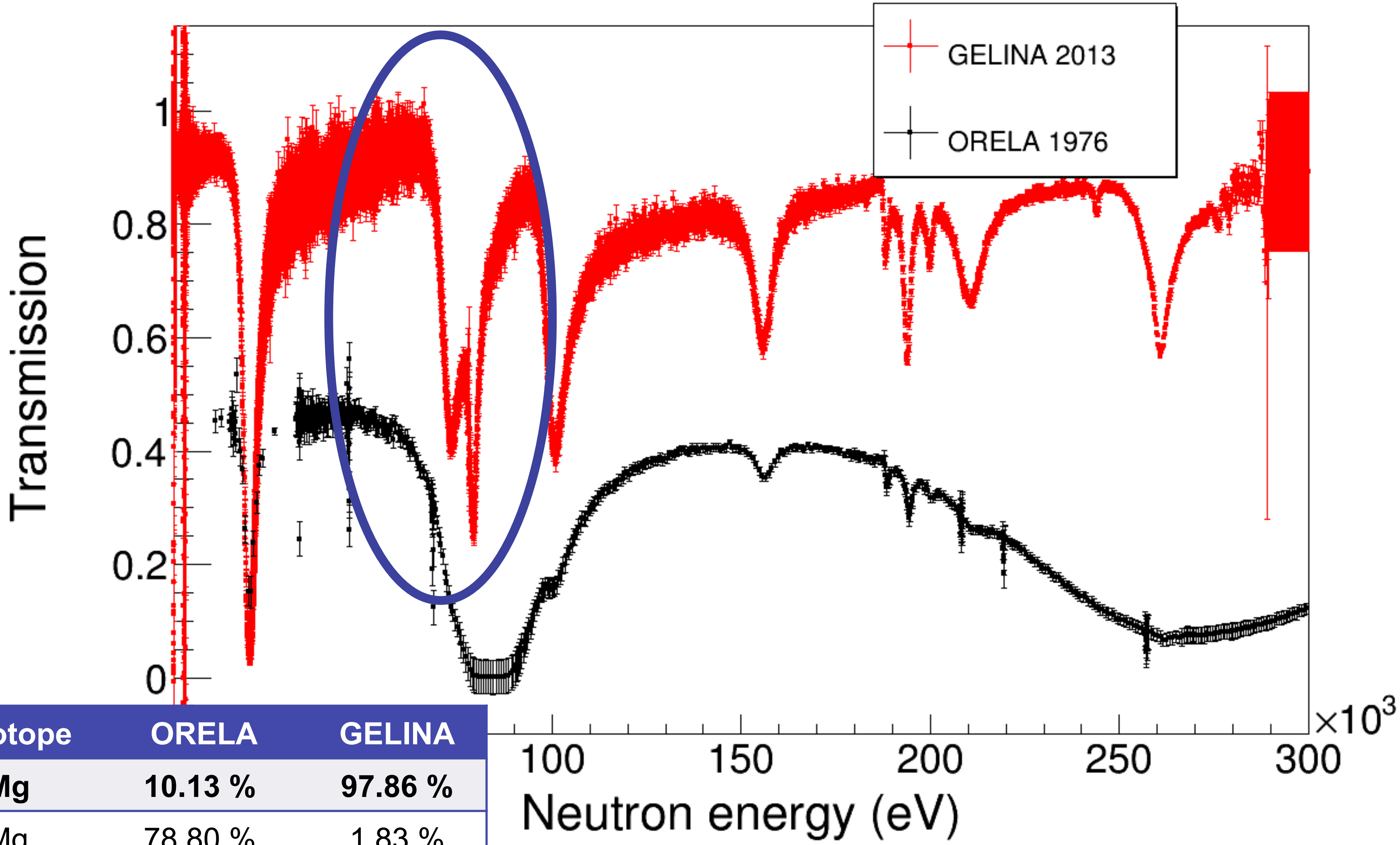

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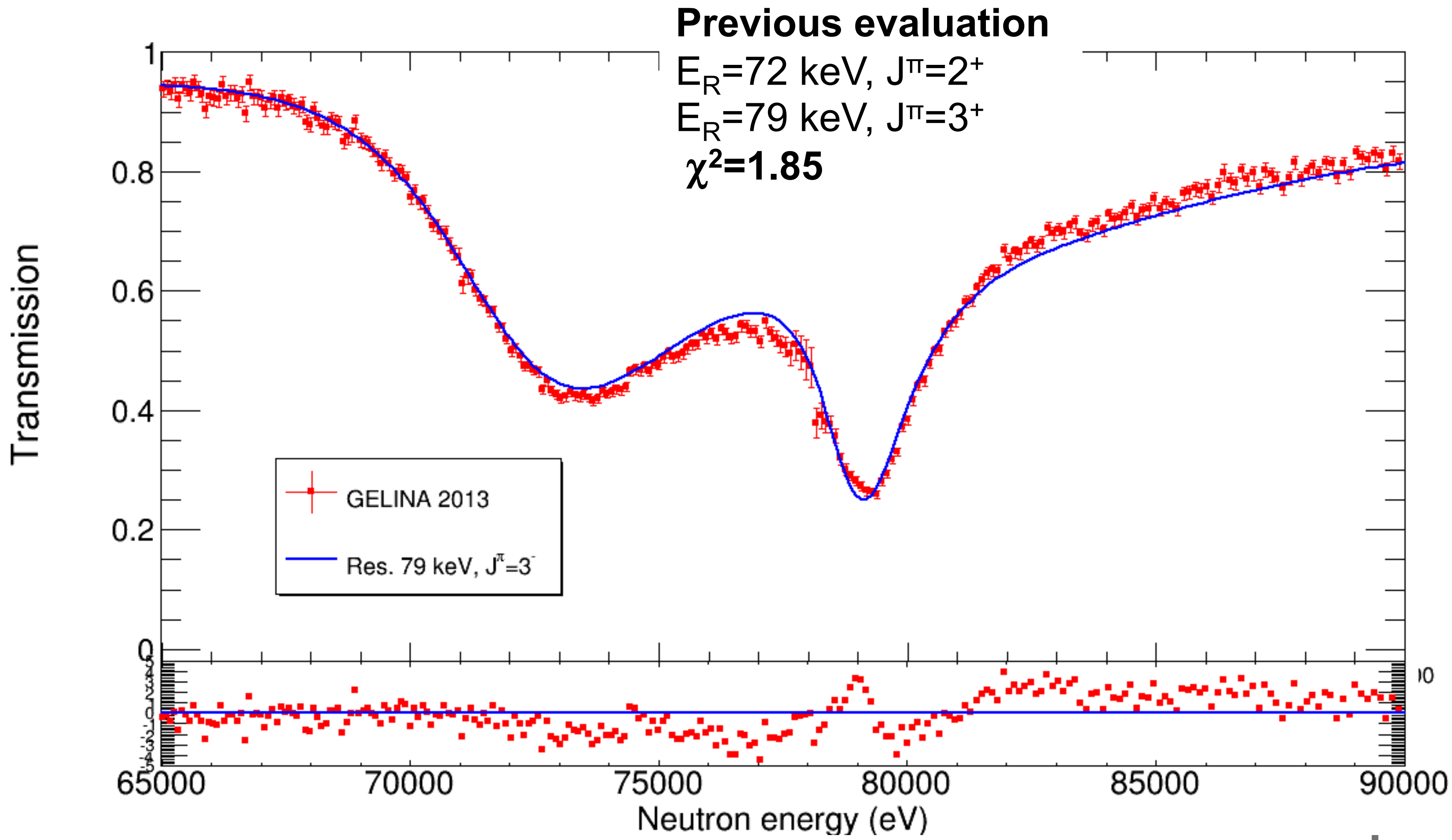

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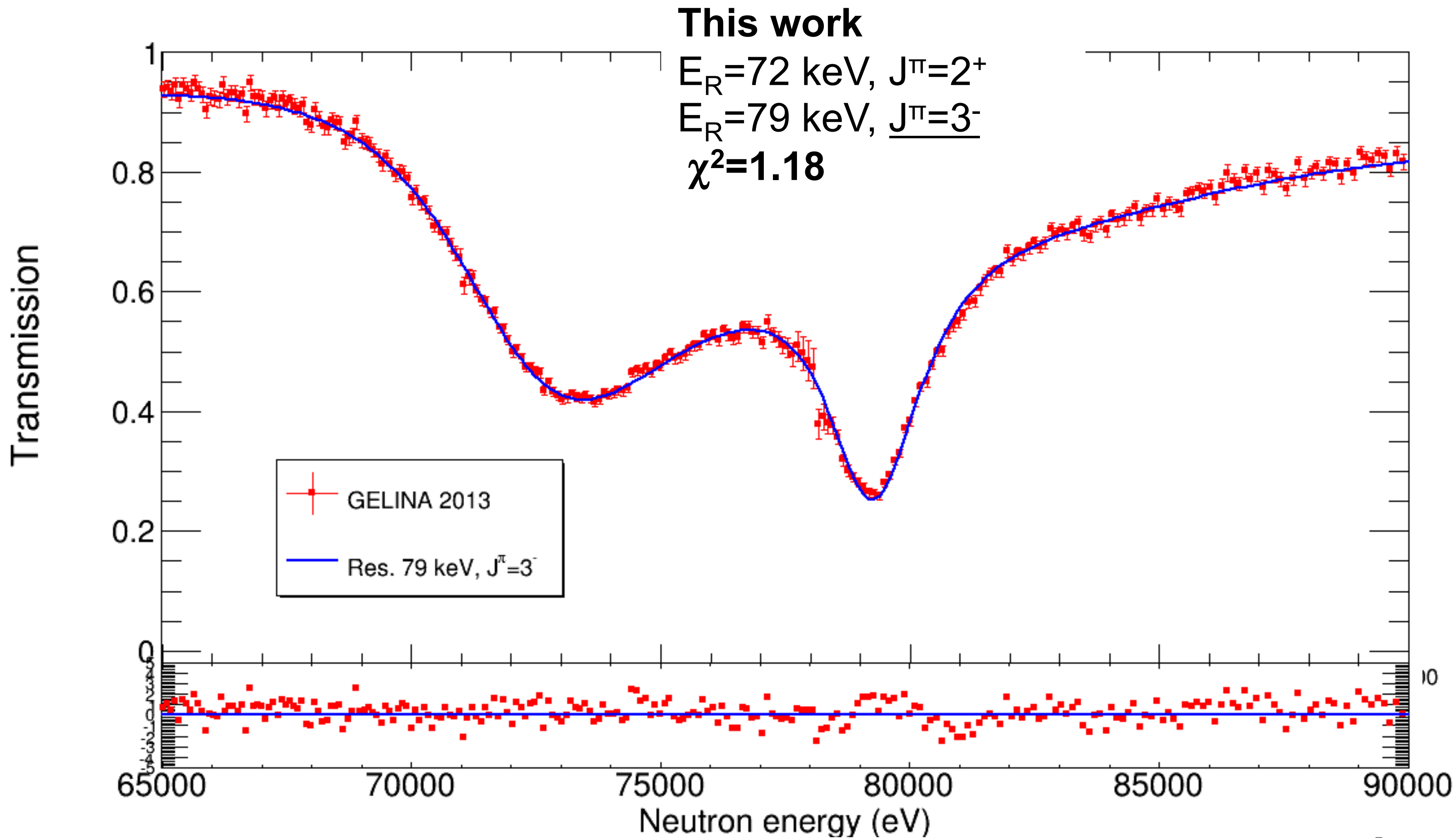

Conclusion

- ^{25}Mg(n, γ) reaction cross-section was measured at n_TOF in 2003 and in 2012 with an improved measurement set up.

- The ^{25}Mg(n, tot) measurement was performed at the GELINA facility in 2013.

- Final analysis - simultaneous resonance shape analysis of capture and transmission - is ongoing:
  - accurate ^{25}Mg(n,γ) cross section ≈ confirms previous n_TOF data;
  - J^{π} information on ^{26}Mg → evidence for more natural states than previously thought →**HIGHER ^{22}Ne(α, n) reaction rate;**

- An idea for the future: ^{25}Mg(n, α)^{22}Ne at n_TOF EAR2, **to complete the study of the key isotope ^{25}Mg**

An idea for the future

Complete the study of the most important neutron source in Red Giants by **measuring $^{25}Mg(n, \alpha)^{22}Ne$** reaction **cross-section**

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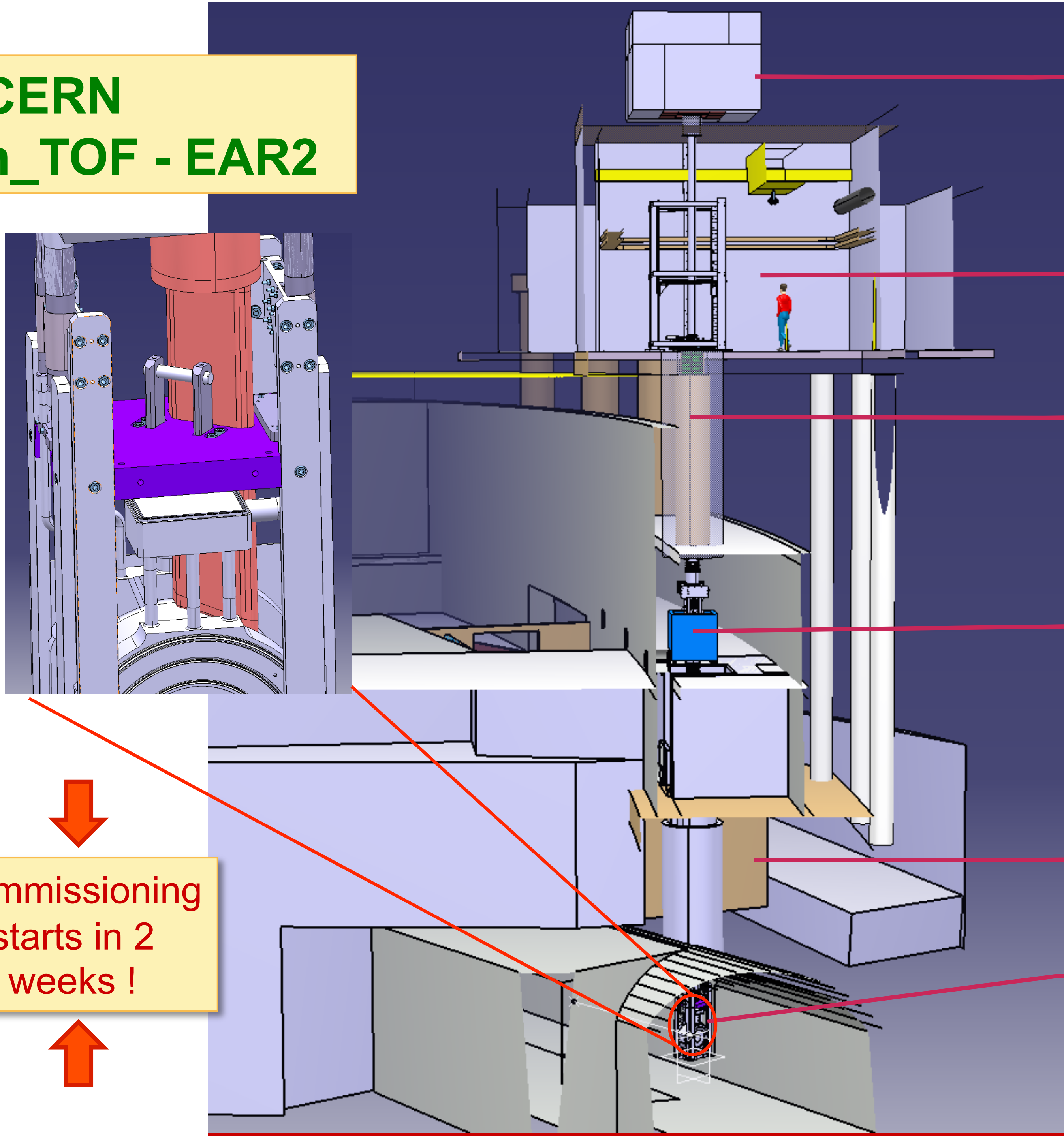
Solution:

a) High neutron flux

b) Flux delivered in a short time interval

a) + b) = n_TOF new experimental area (**EAR2**)

CERN n_TOF - EAR2



Commissioning starts in 2 weeks !

Acknowledgement

- EC-JRC-IRMM, GELINA team
- The n_TOF Collaboration
- **Paul Koehler (**partially funded the experiment when he was at **ORNL)**
- **Italian Institute of Nuclear Physics – INFN:** partially funded the experiment.

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SPIN & PARITY

Istituto Nazionale di Fisica Nucleare

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SPIN & PARITY

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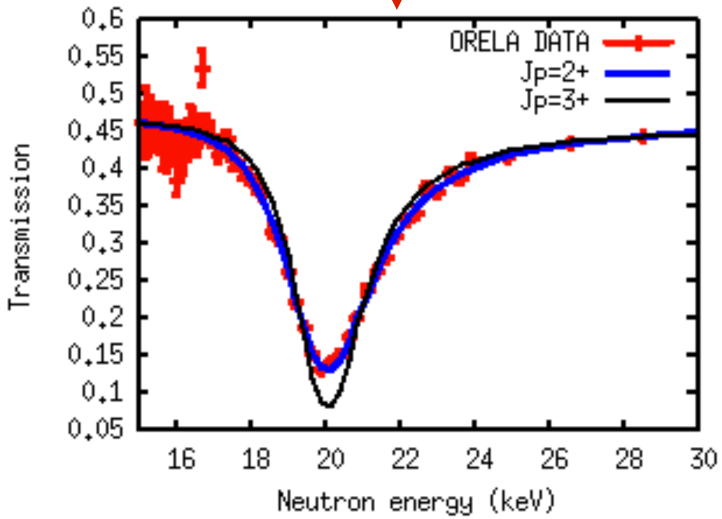

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[illegible]	[illegible]	[illegible]	[illegible]	± 3]
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EXAMPLE Of SPIN ASSIGNMENT

Principles

Transmission : σ(n,tot)

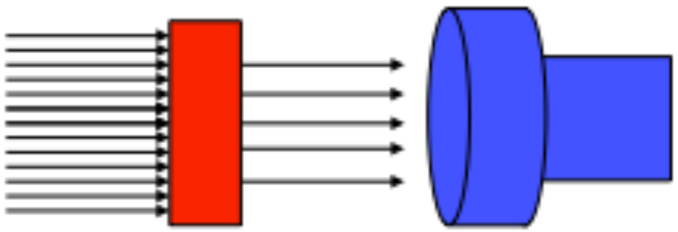
$$T \cong e^{-n\sigma_{tot}}$$

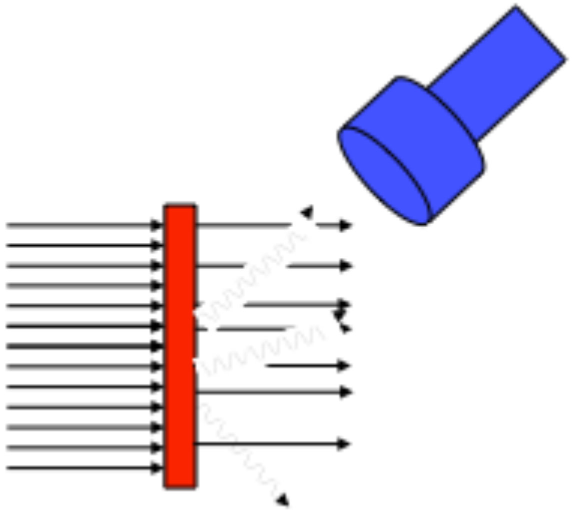
T : transmission
Fraction of the neutron beam traversing the sample without any interaction

Reaction yield : σ(n,r)

$$Y_r \approx (1 - e^{-n\sigma_{tot}})\frac{\sigma_r}{\sigma_{tot}}$$

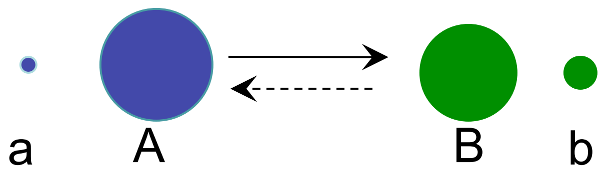
Y_r : reaction yield
Fraction of the neutron beam creating a (n,r) reaction in the sample





Time reversal invariance

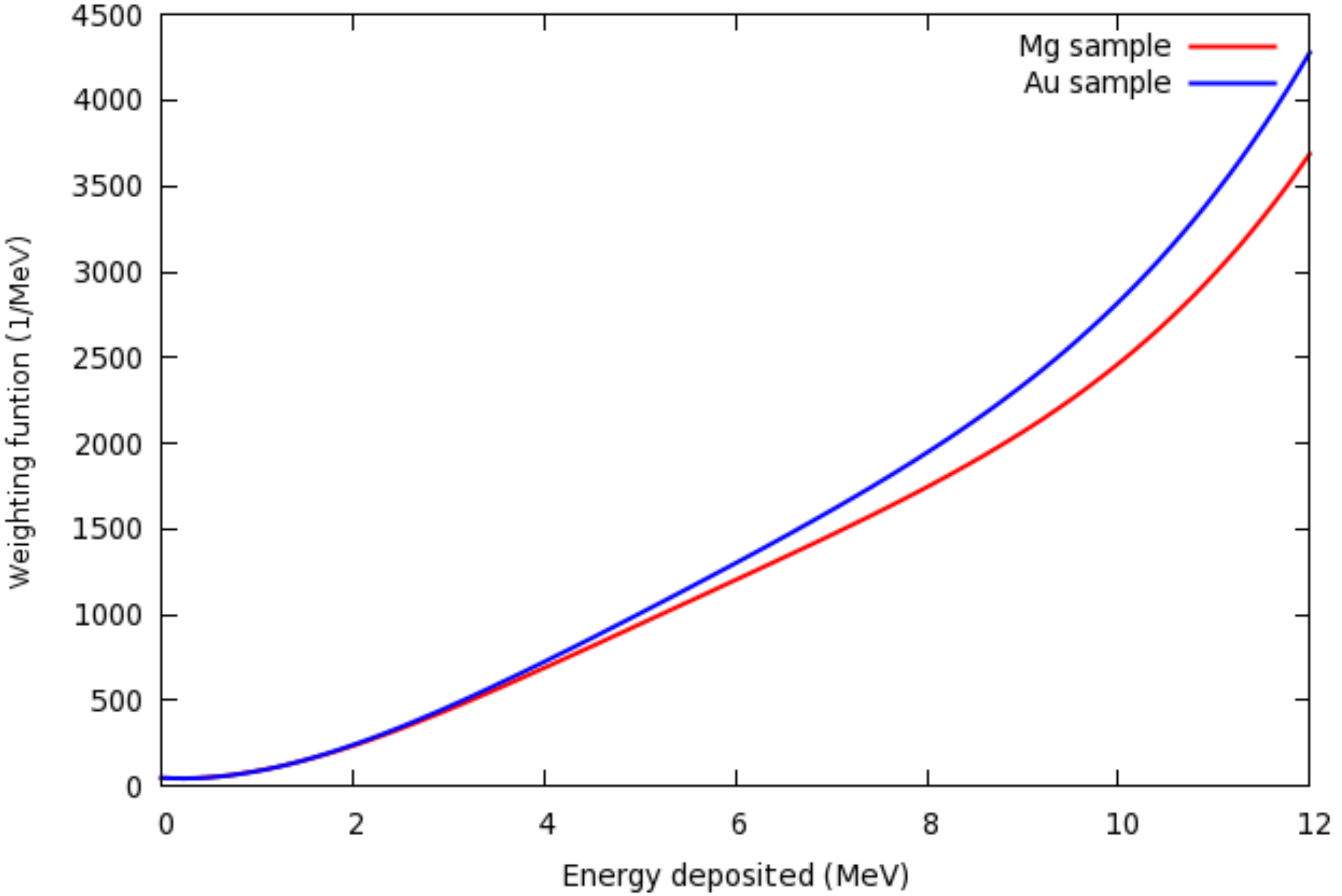
Relation between the **^{25}Mg(n,a)^{22}Ne** and the **^{22}Ne(a,n)^{25}Mg** cross-section by "*detailed balance technique*"



$$\frac{\sigma_{(a,b)}}{\sigma_{(b,a)}} = \frac{m_b m_B E_{bB} (2J_b + 1)(2J_B + 1)}{m_a m_A E_{aA} (2J_a + 1)(2J_A + 1)}$$

Energy region of interest:
$0 < E_n <$ few MeV

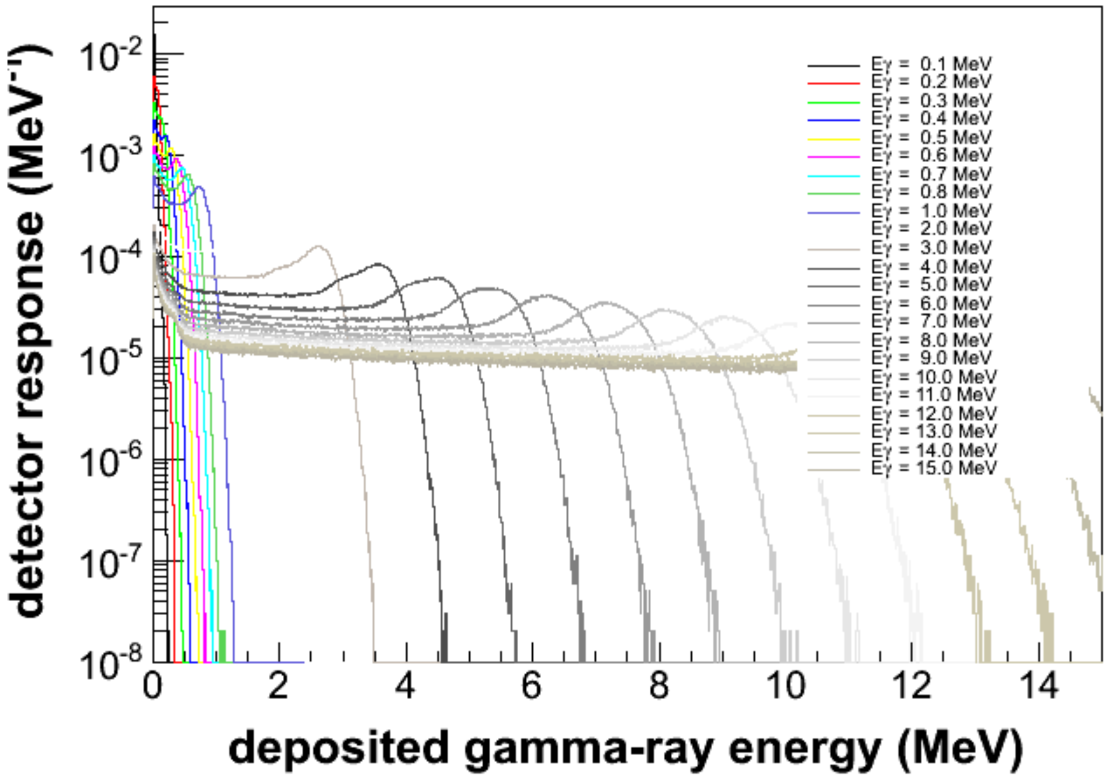
Weighting functions

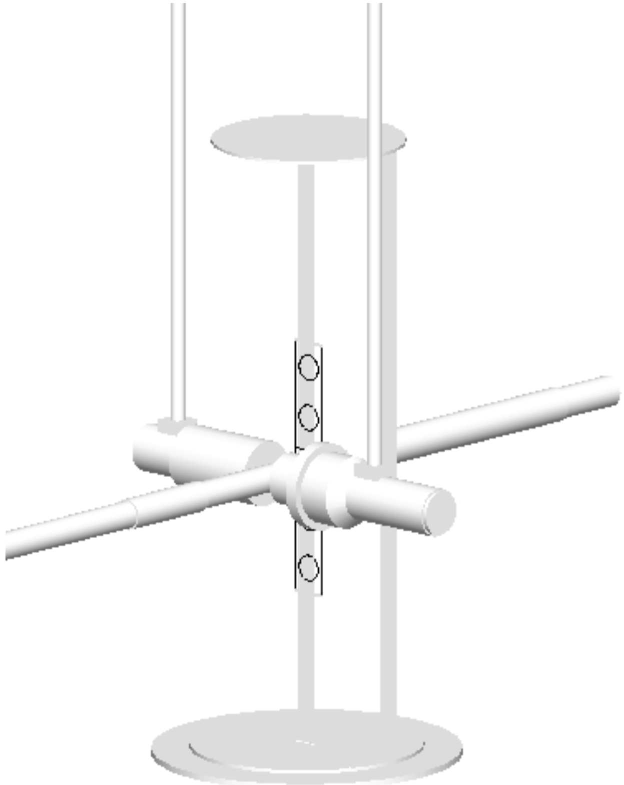


Monte Carlo Simulation

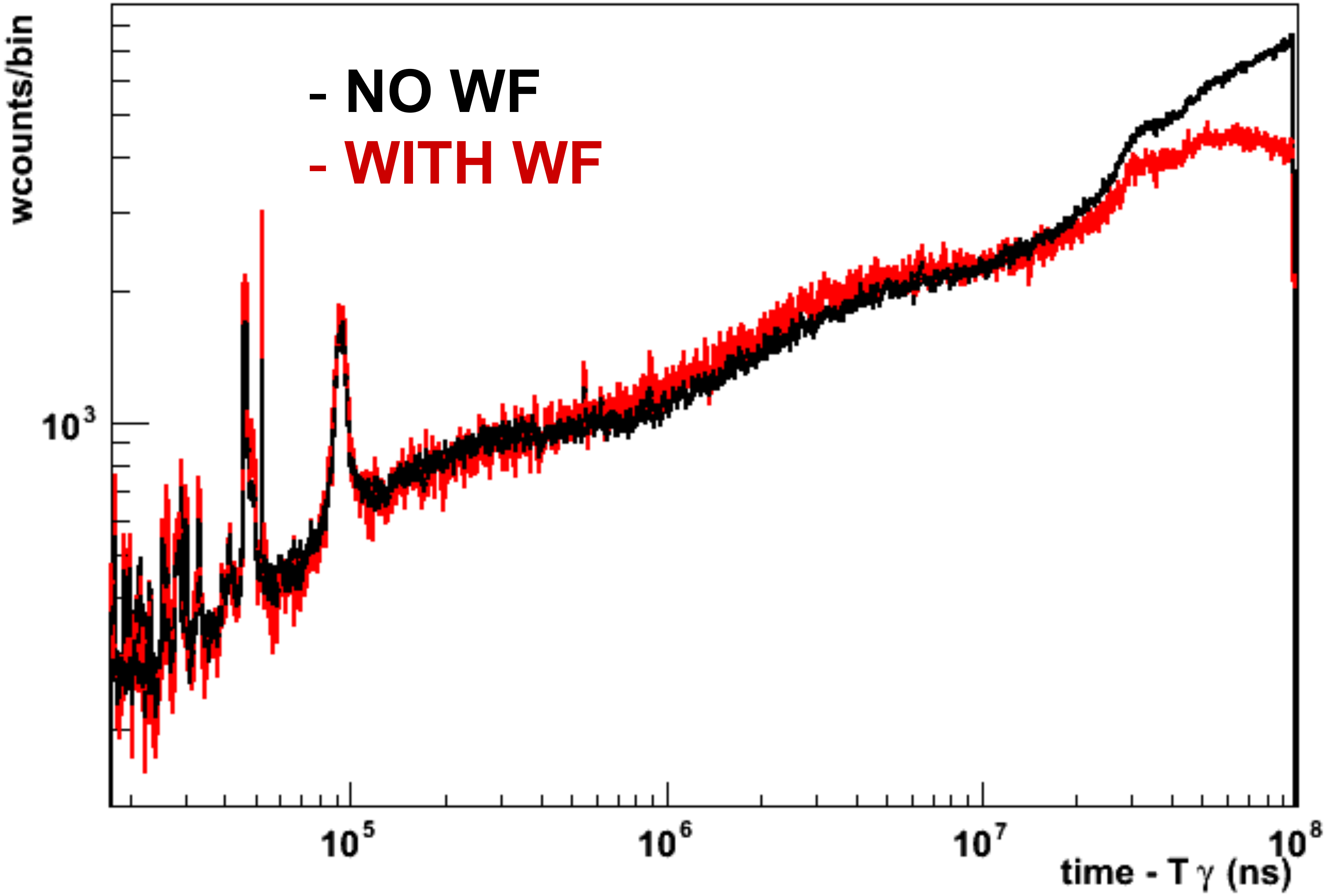
Detailed Monte Carlo simulation

Pulse Height Weighting Function





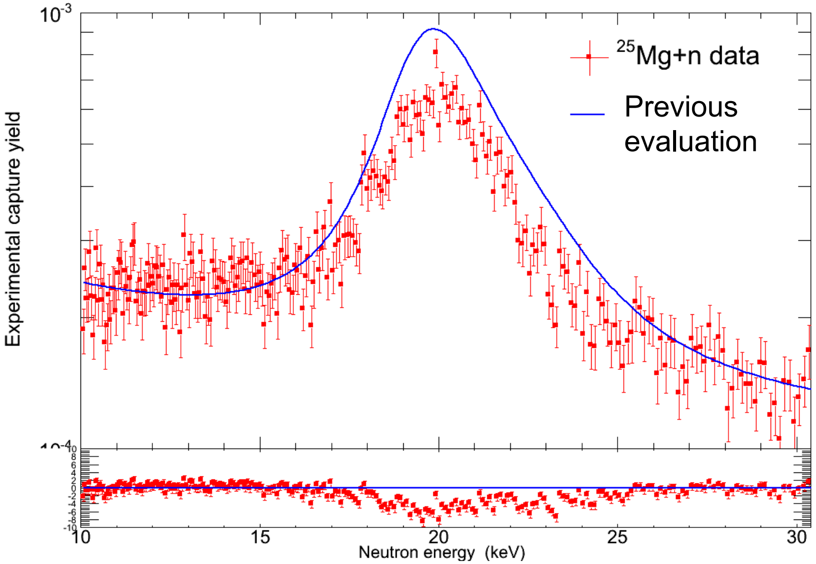
Weighting Function



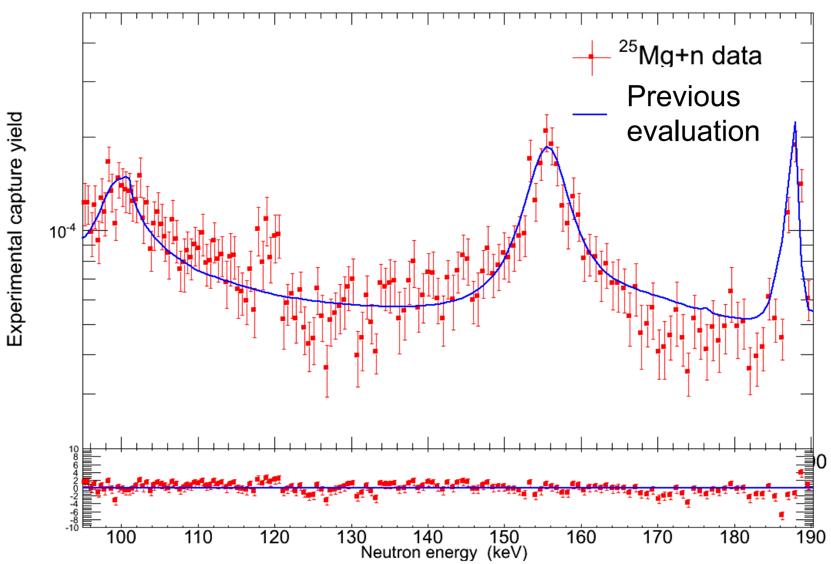
Preliminary Results

2012 data

First s-wave resonance at ~ 20 keV

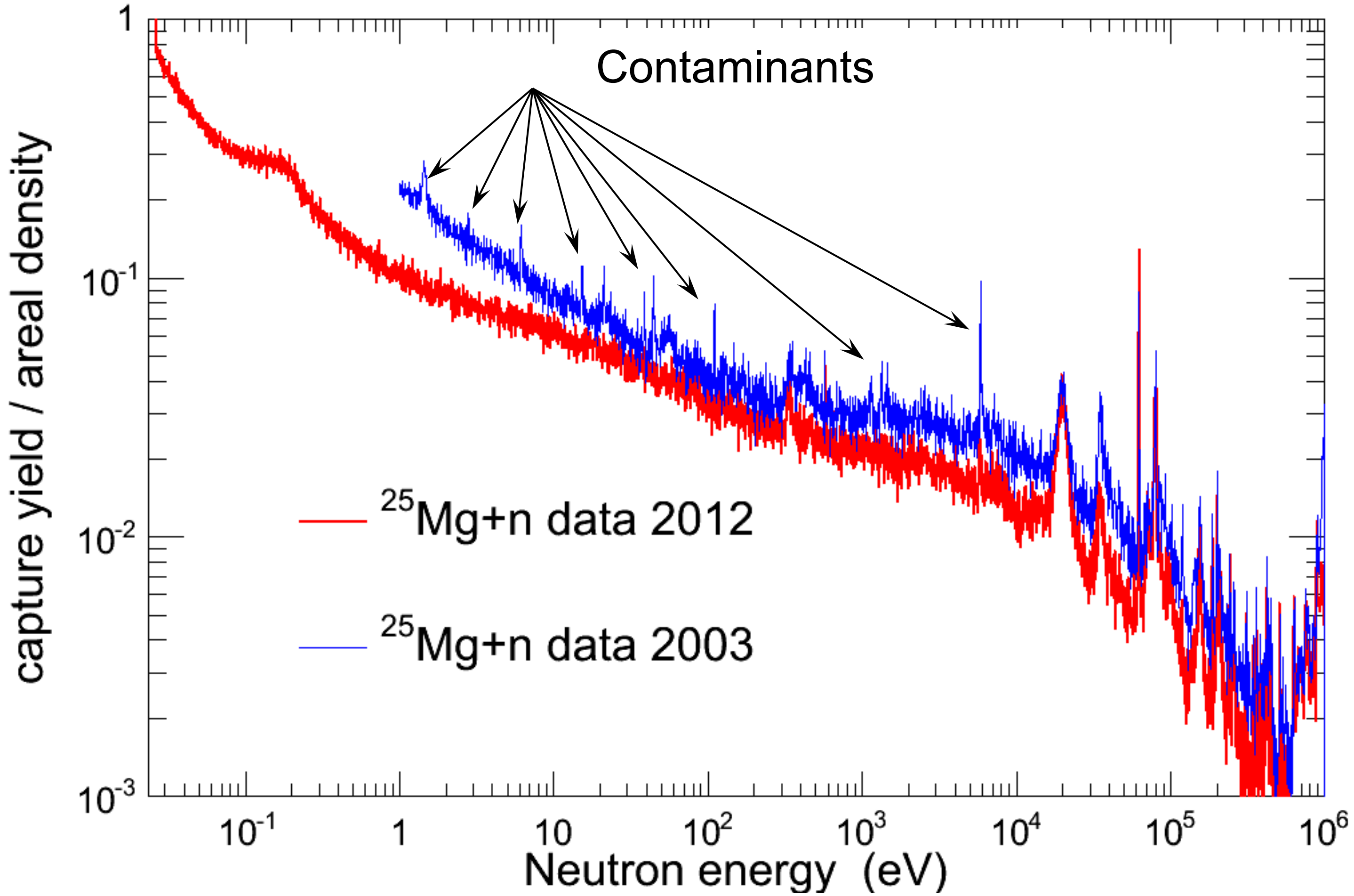


Other resonances at ~ 150 keV

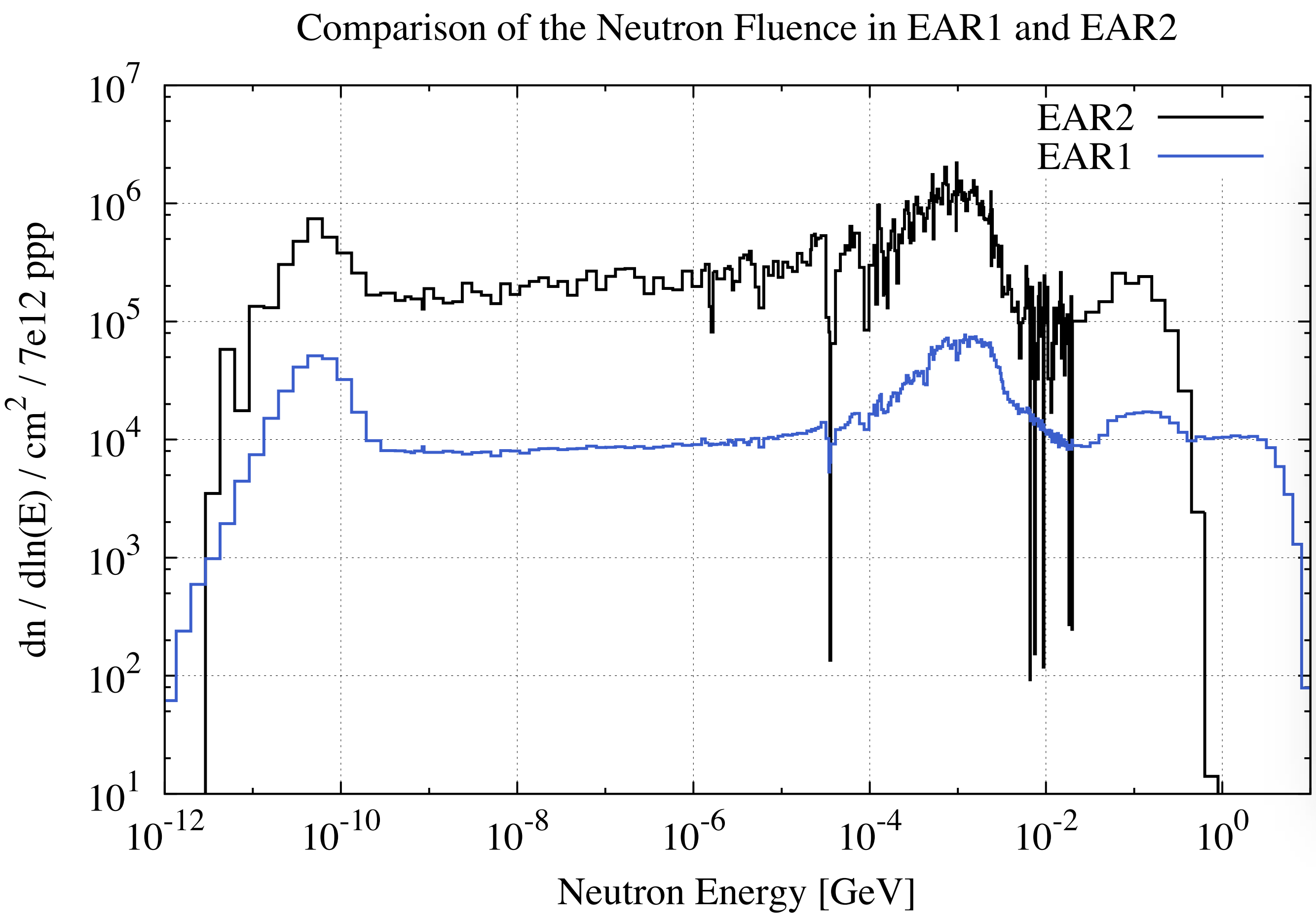


Energies relevant to s process

Quality of the sample



n_TOF EAR2



Higher fluence,
by a factor of 25, relative to EAR1.

The **shorter flight path** implies a factor of 10 smaller time-of-flight.

Global gain by a factor of **250 in the signal/ background ratio**