Study of ^{25}Mg+n reactions

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Roma, 21-25 settembre 2015

The n_TOF Collaboration

outline

- Motivations
- Measurements:
  - ^{25}Mg(n, tot) @ GELINA
  - ^{25}Mg(n, γ) @ n_TOF
- Results

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

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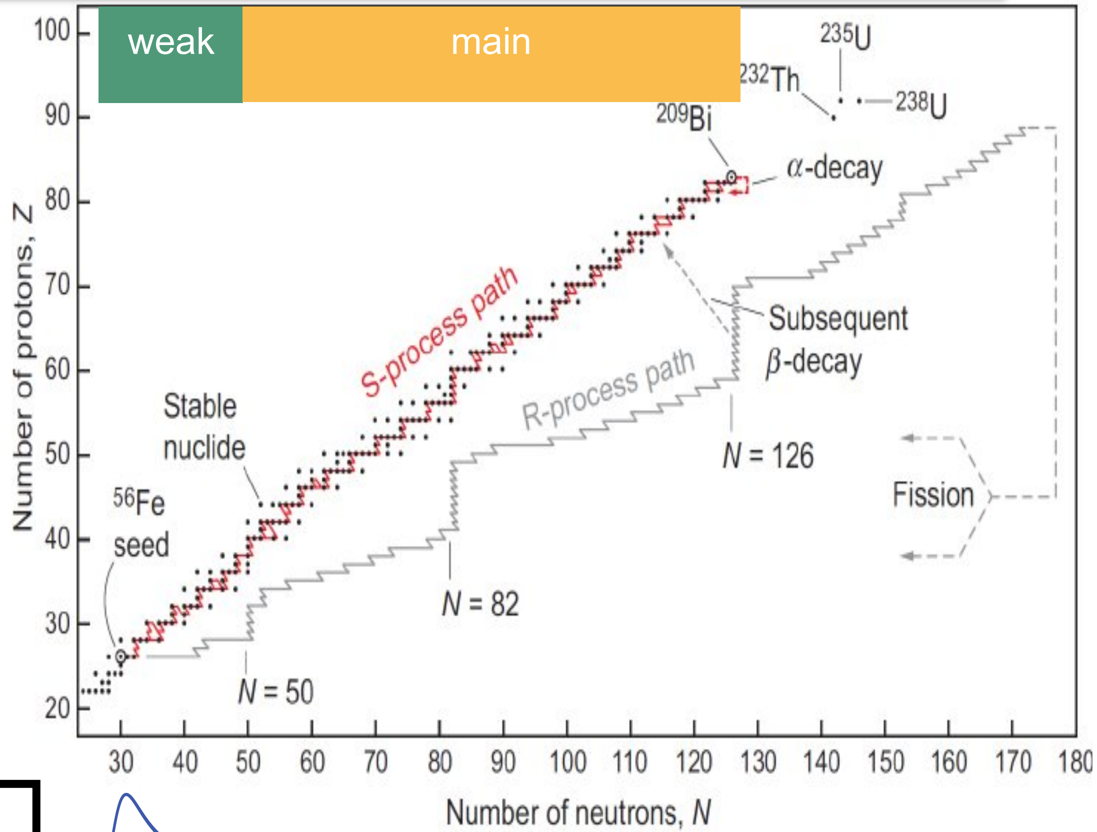
^{25,26}Mg isotopes: neutron poison of the s process

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 ≈ $10^{9÷10}$ / cm^3
  - Neutron density ≈ $10^{9÷10}$ / 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 ≈ $10^{11÷12}$ / cm^3
  - Neutron density ≈ $10^{11÷12}$ / cm^3



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

nTOF

nTOF

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

Motivation 2

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

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

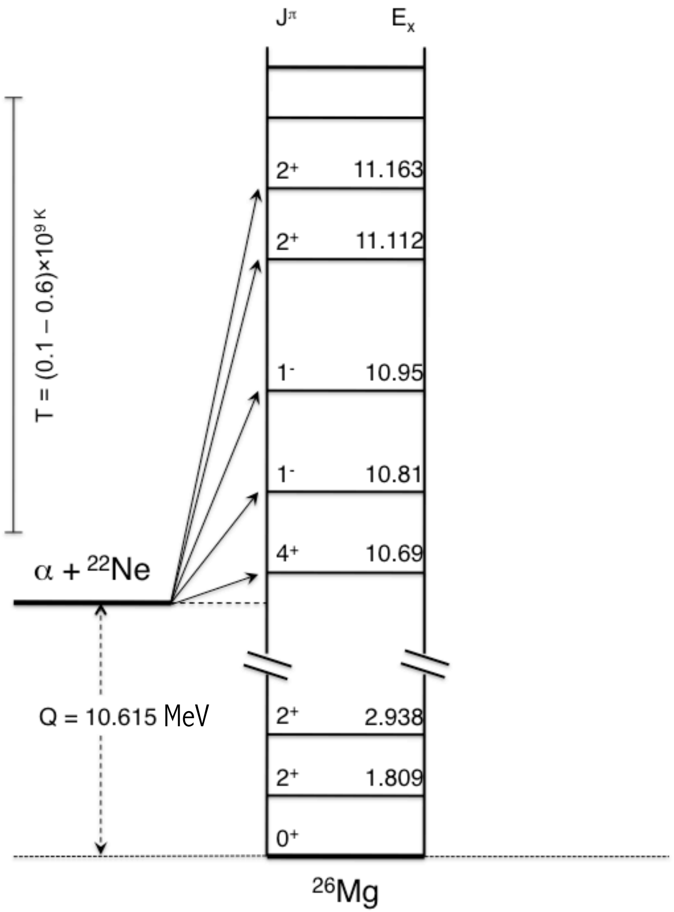
Only **natural-parity states in ^{26}Mg** can participate in the $^{22}Ne(\alpha ,n)^{25}Mg$ reaction

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

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

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

$J^\pi = 0^+, 1^-, 2^+, 3^-, 4^+ \dots$



^{25}Mg(n, tot)
^{25}Mg(n, γ)

Motivation 2

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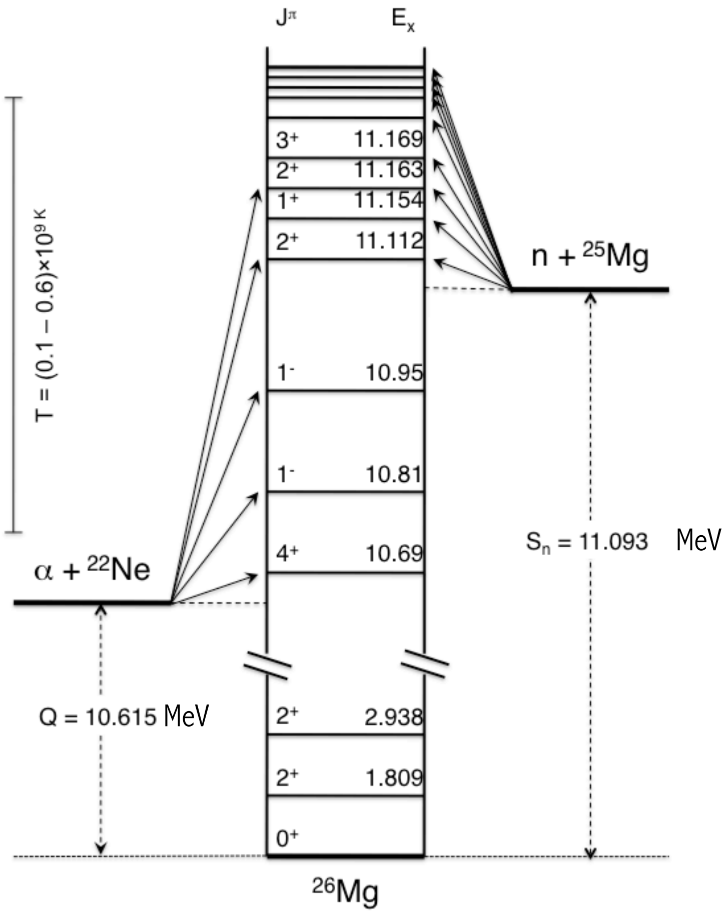
Constraints for the ^{22}Ne(α, n)^{25}Mg reaction

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

nTOF

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

Motivation 2

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$^{25}Mg(n, \gamma)^{26}Mg$ 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 ± 0.009]	[1]	$[2^-]$	[0.2 ± 0.1]	[4 ±
[107.60 ± 0.02]	$[0]^b$	$[3^+]$	[0.3 ± 0.1]	[2 ±
156.34 ± 0.02	(1)	(2^-)	6.1 ± 0.4	5520
188.347 ± 0.009	0	$(2)^+$	1.7 ± 0.2	590 ±
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
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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
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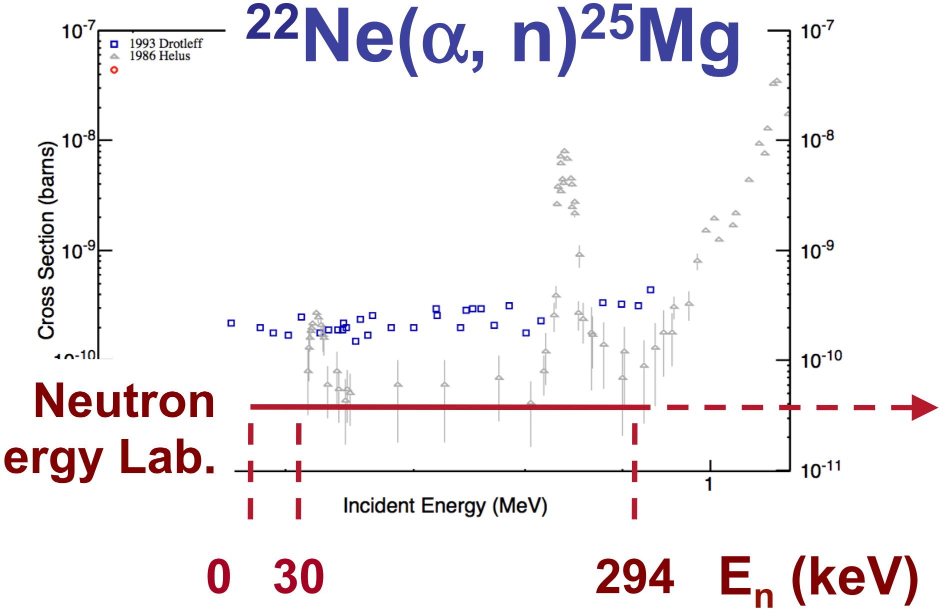

Constraints for the $^{22}Ne(\alpha, n)^{25}Mg$ reaction

Observed ~ 30 resonances in the energy region of interest

nTOF

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

New Measurement

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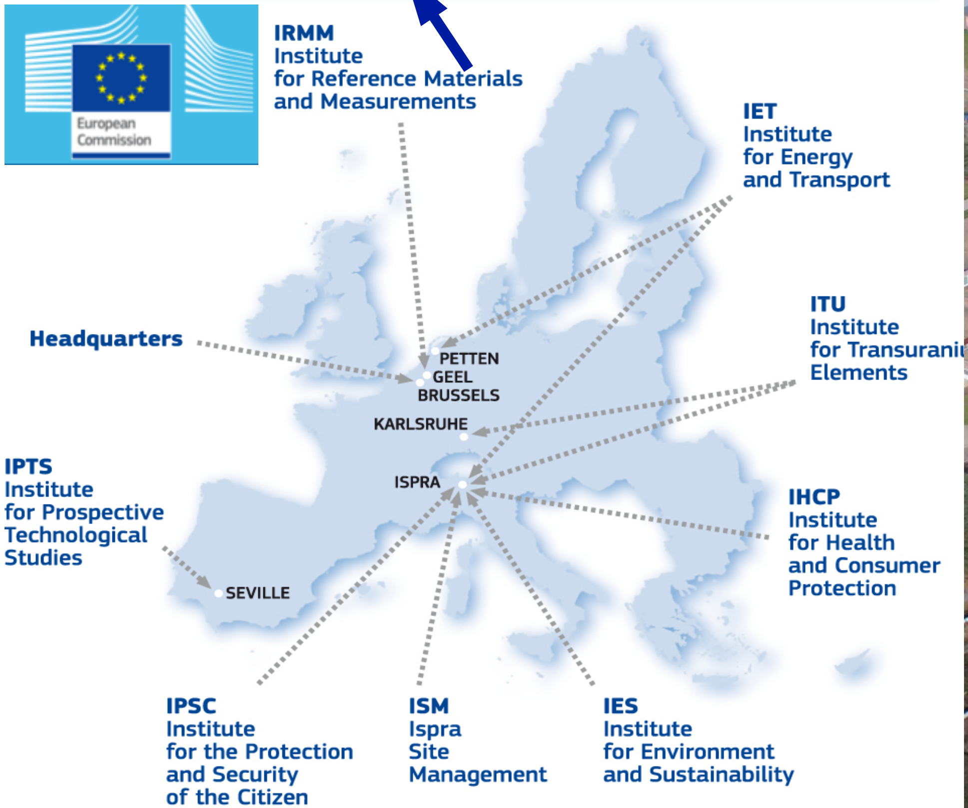
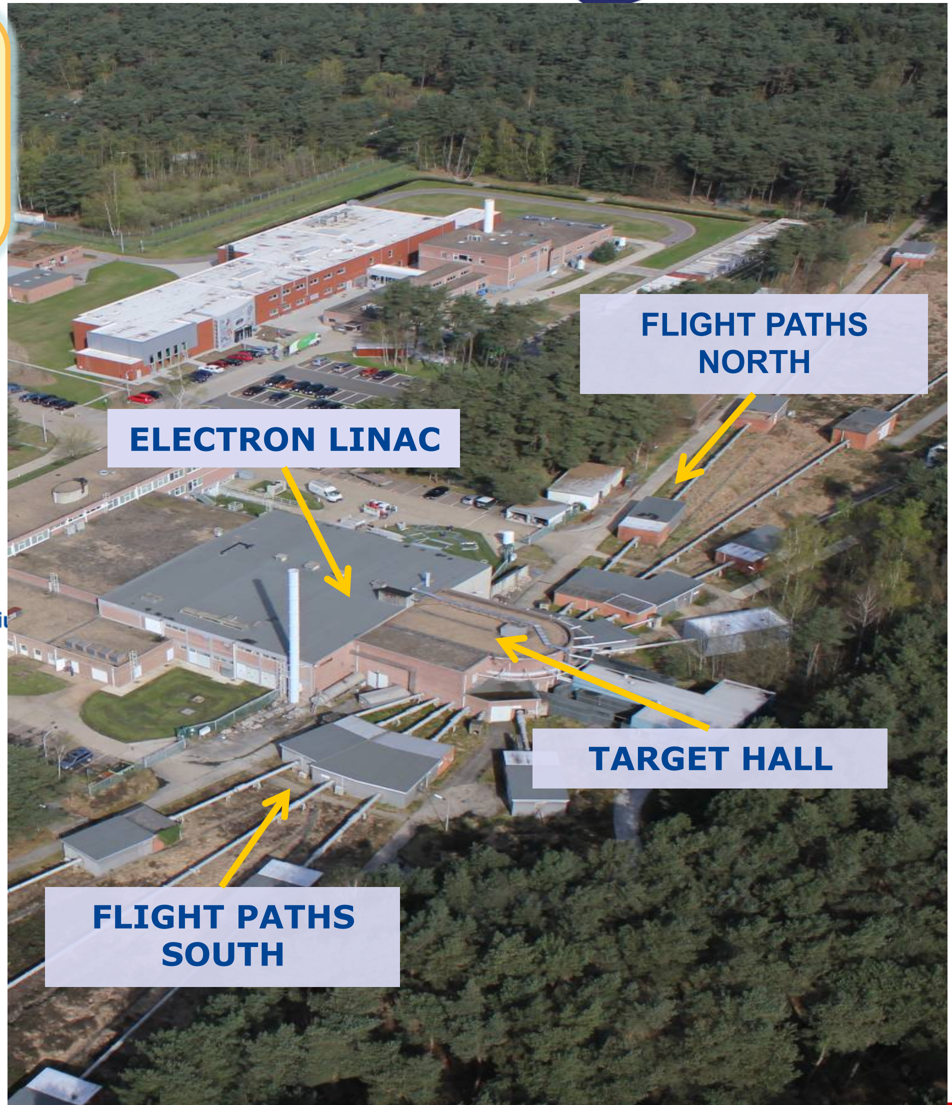
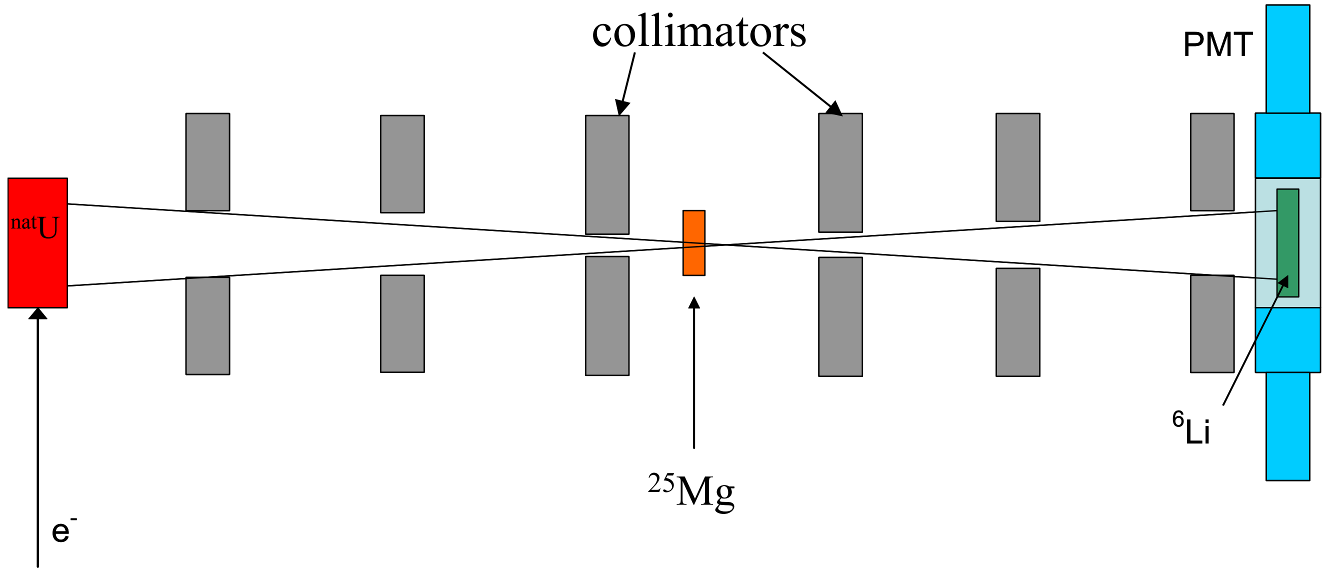
GELINA is a photonuclear **neutron source** based on **140 MeV e$^-$** impinging on a **U target**. 10 Experimental areas at different flight paths (10 m - 400 m).



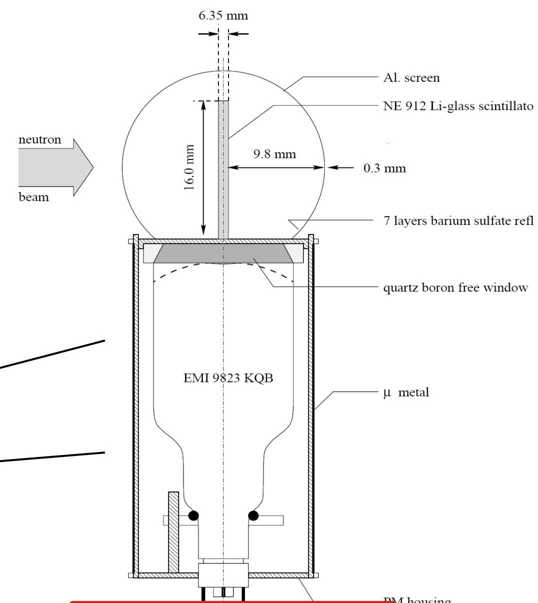


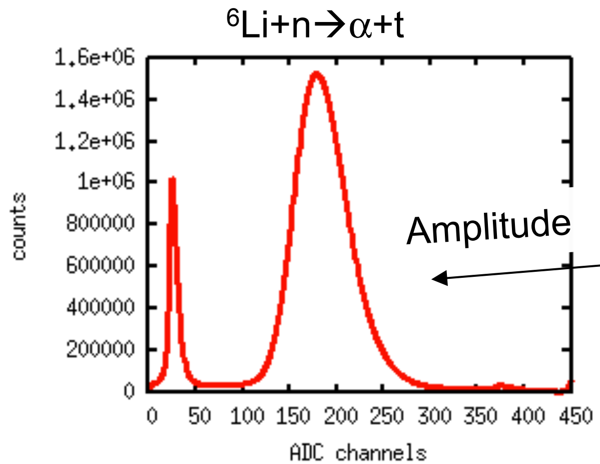
^{25}Mg(n, tot) @ GELINA

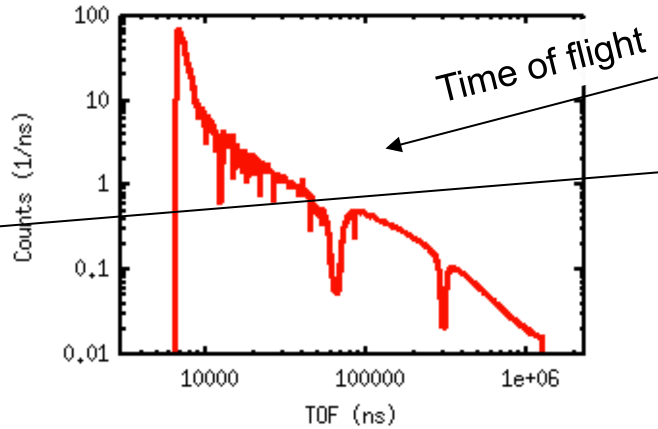
New Measurement



Experimental set up



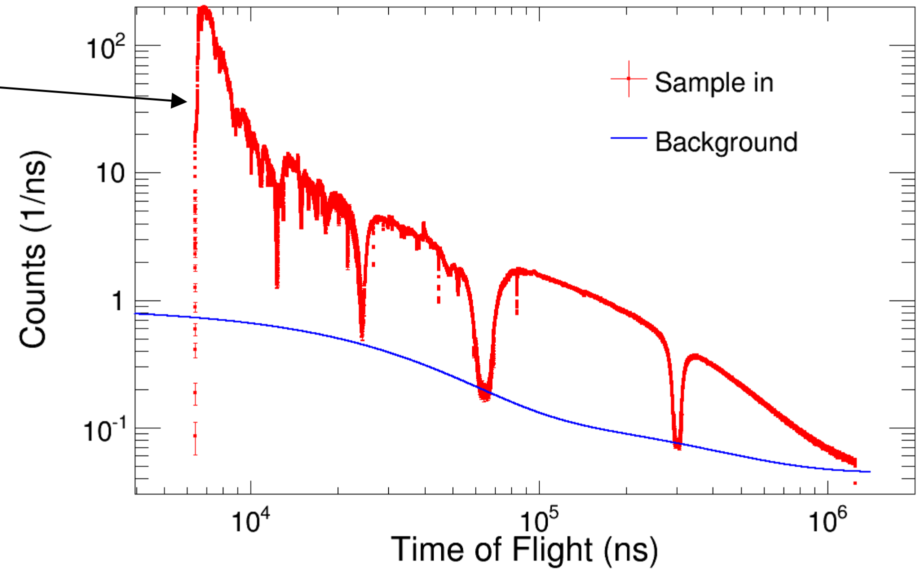


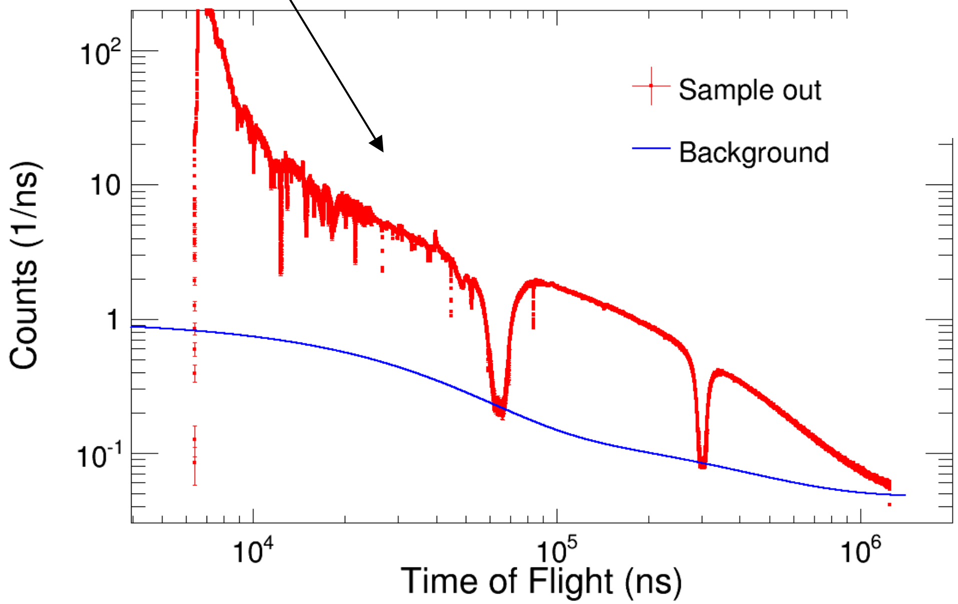


Litium glass scintillator

New Measurement

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



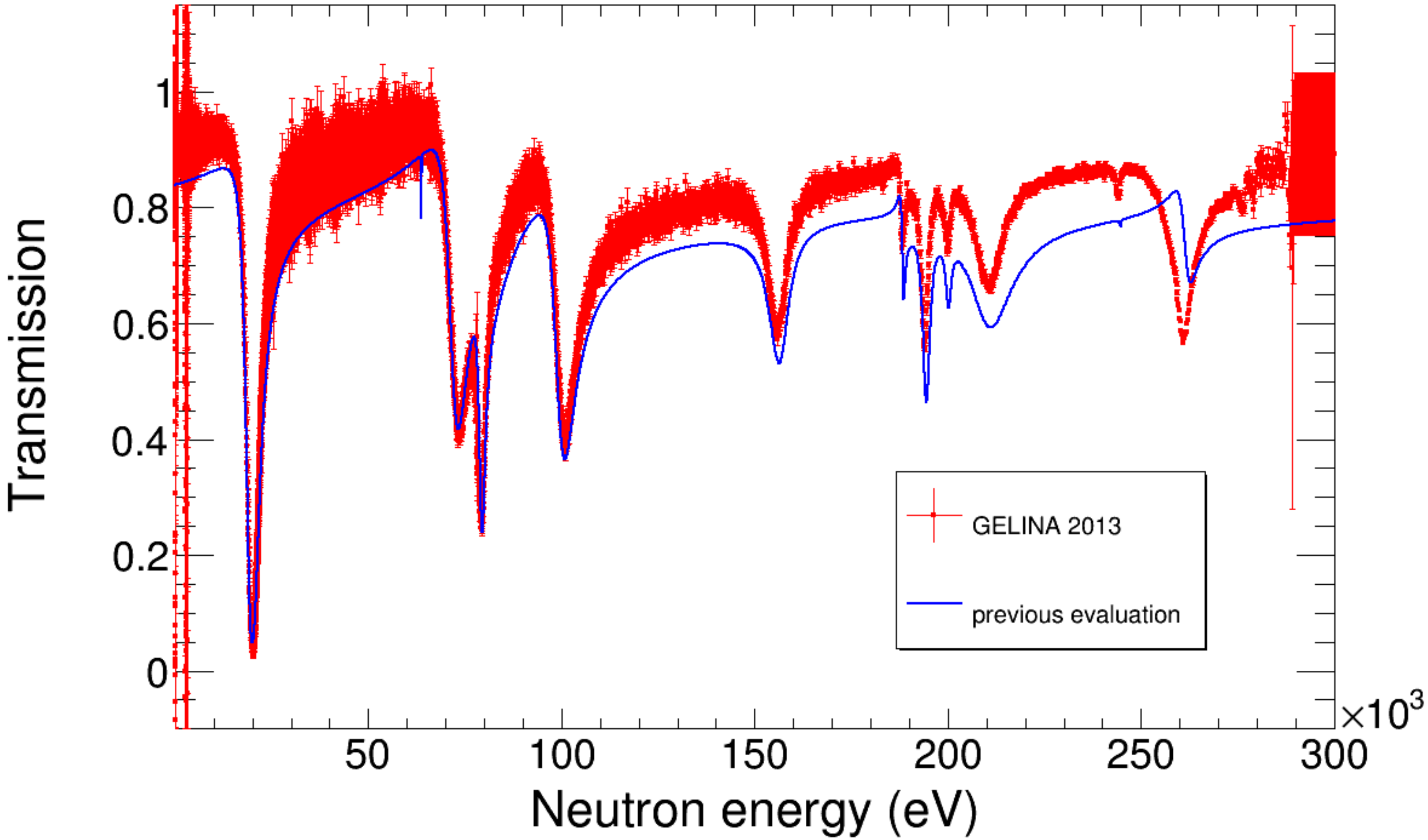


Background determined by **black resonance** technique:

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

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

New Measurement



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

New Measurement

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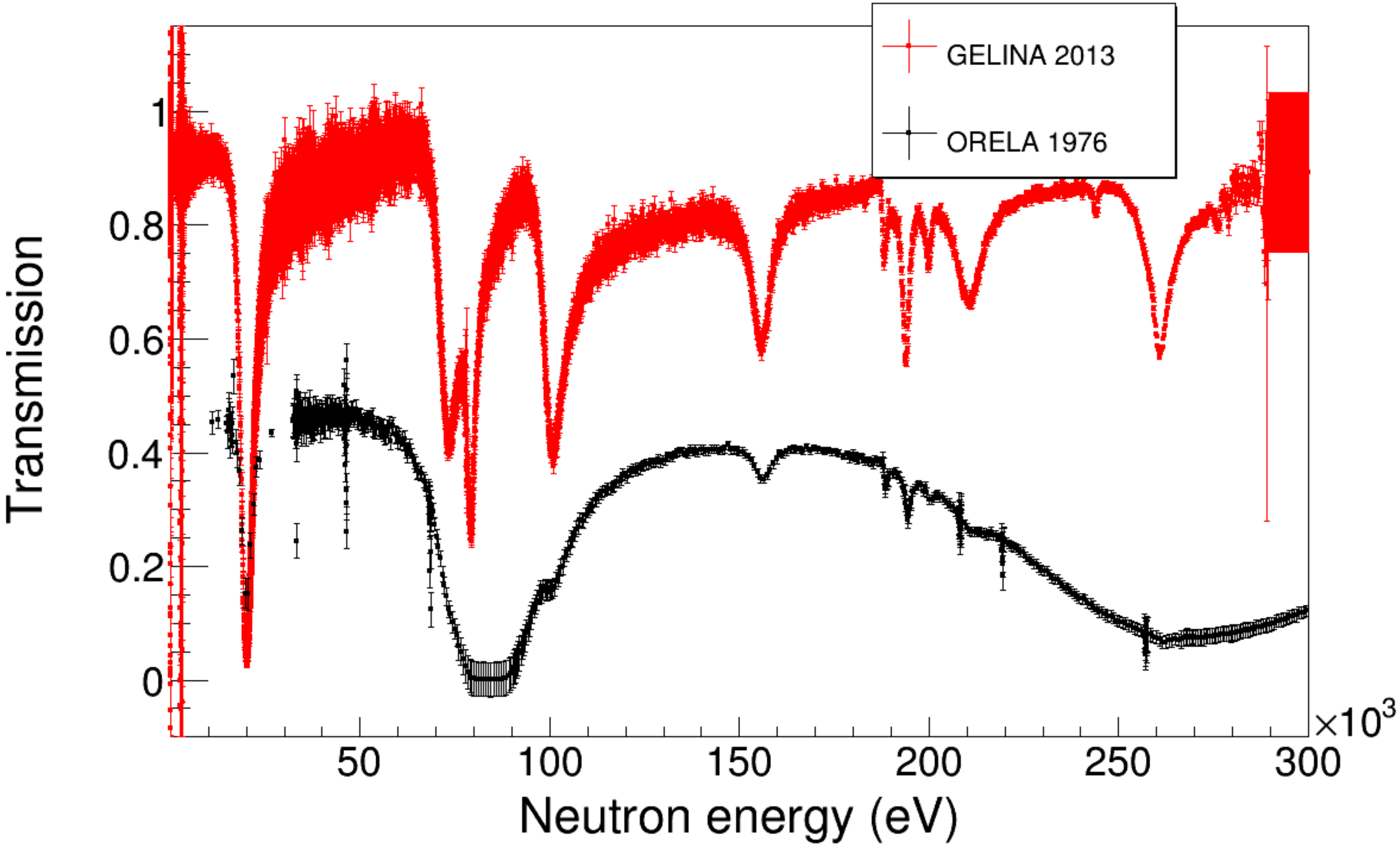
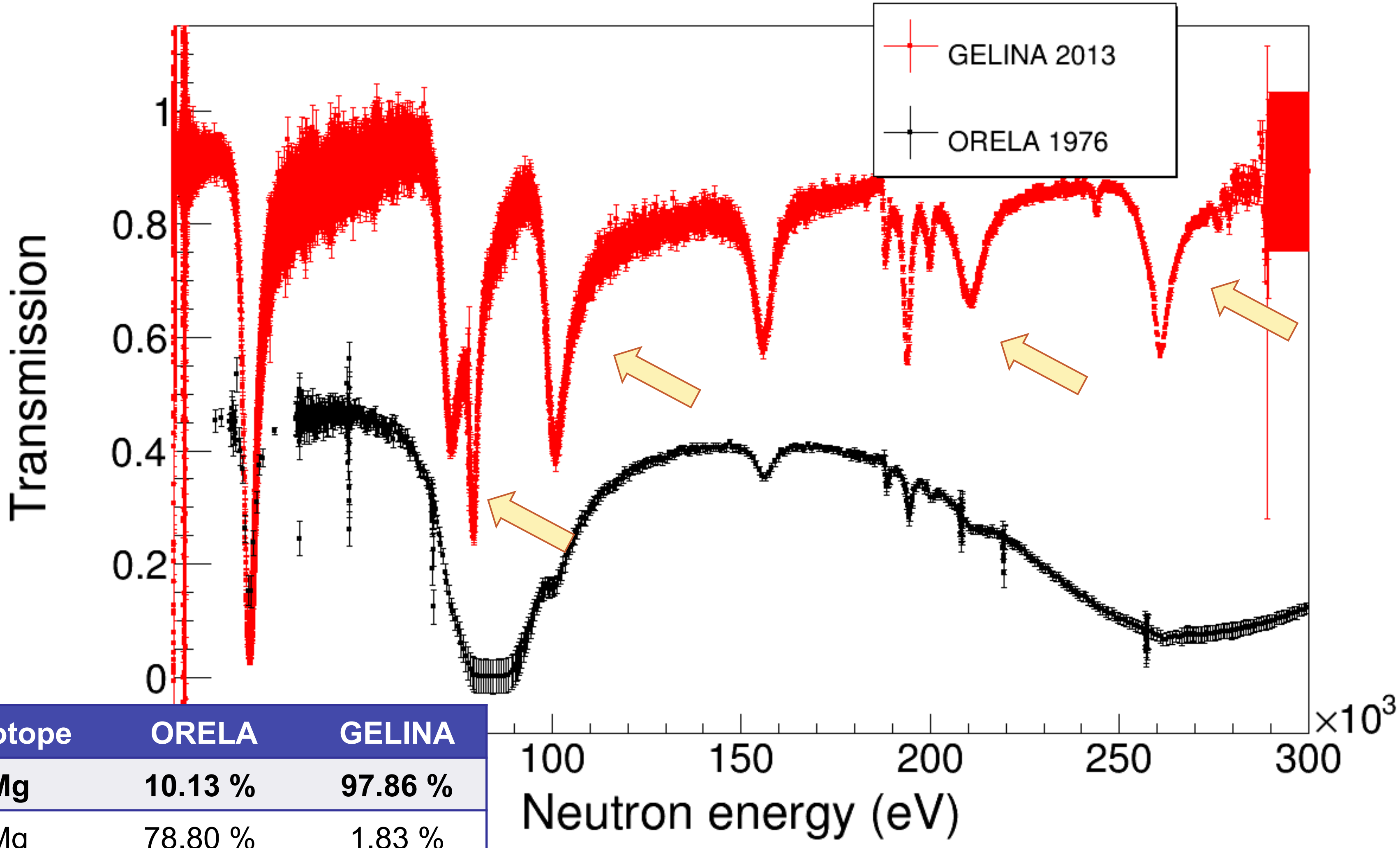


New Measurement



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

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

New Measurement

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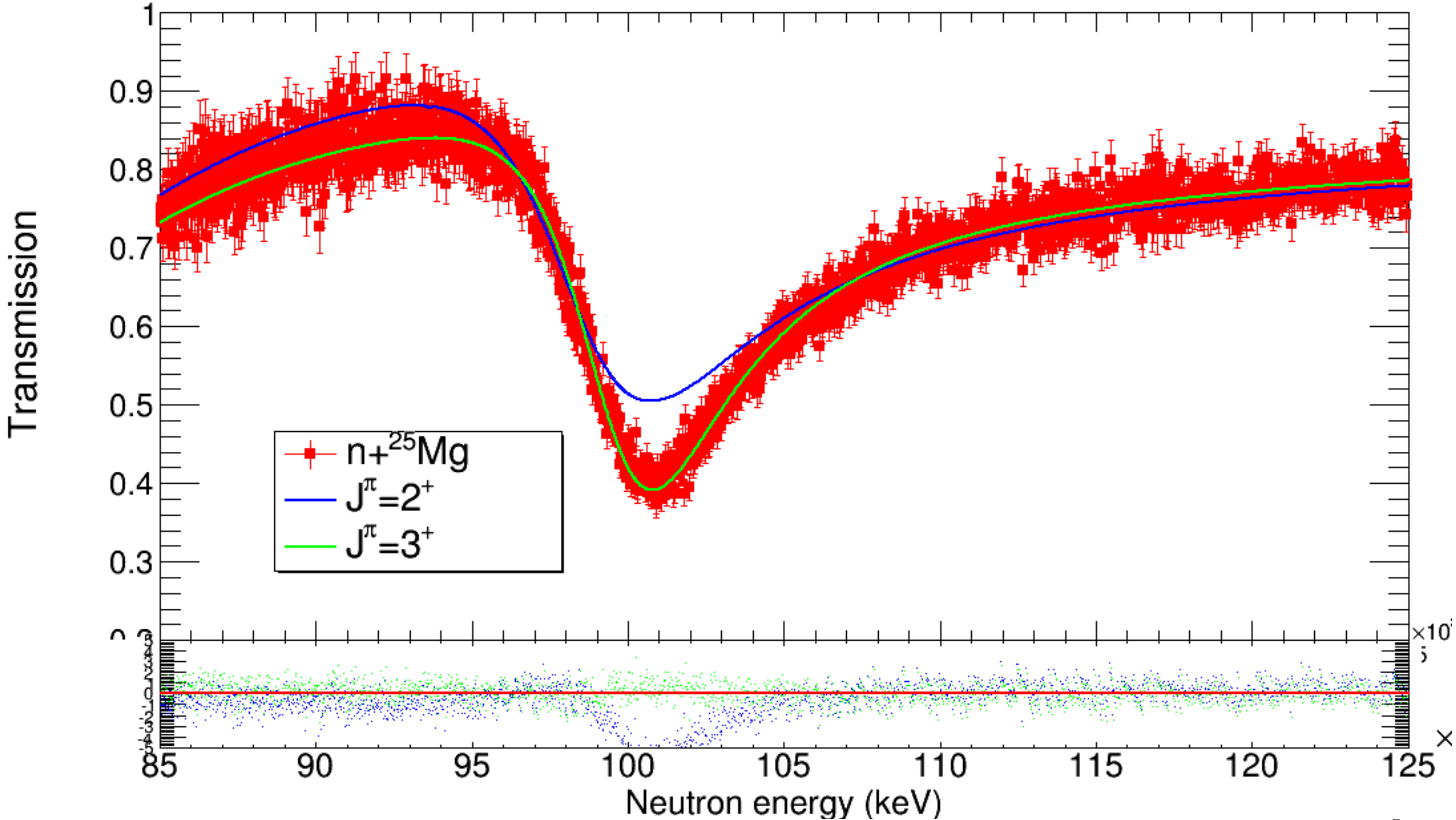
Example of sensitivity to J$^{\pi}$



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

New Measurement

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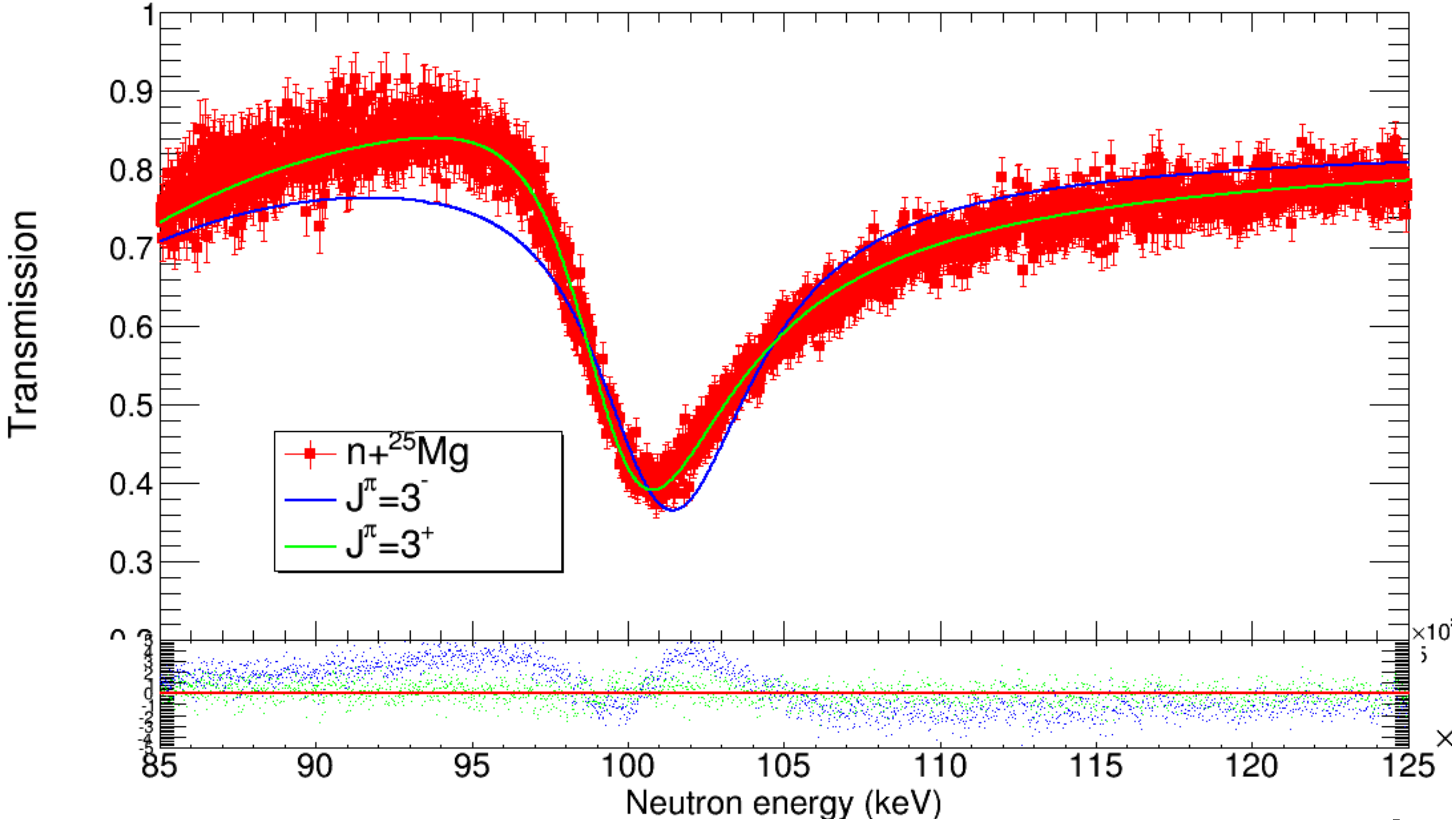
Example of sensitivity to J^{π}



New Measurement

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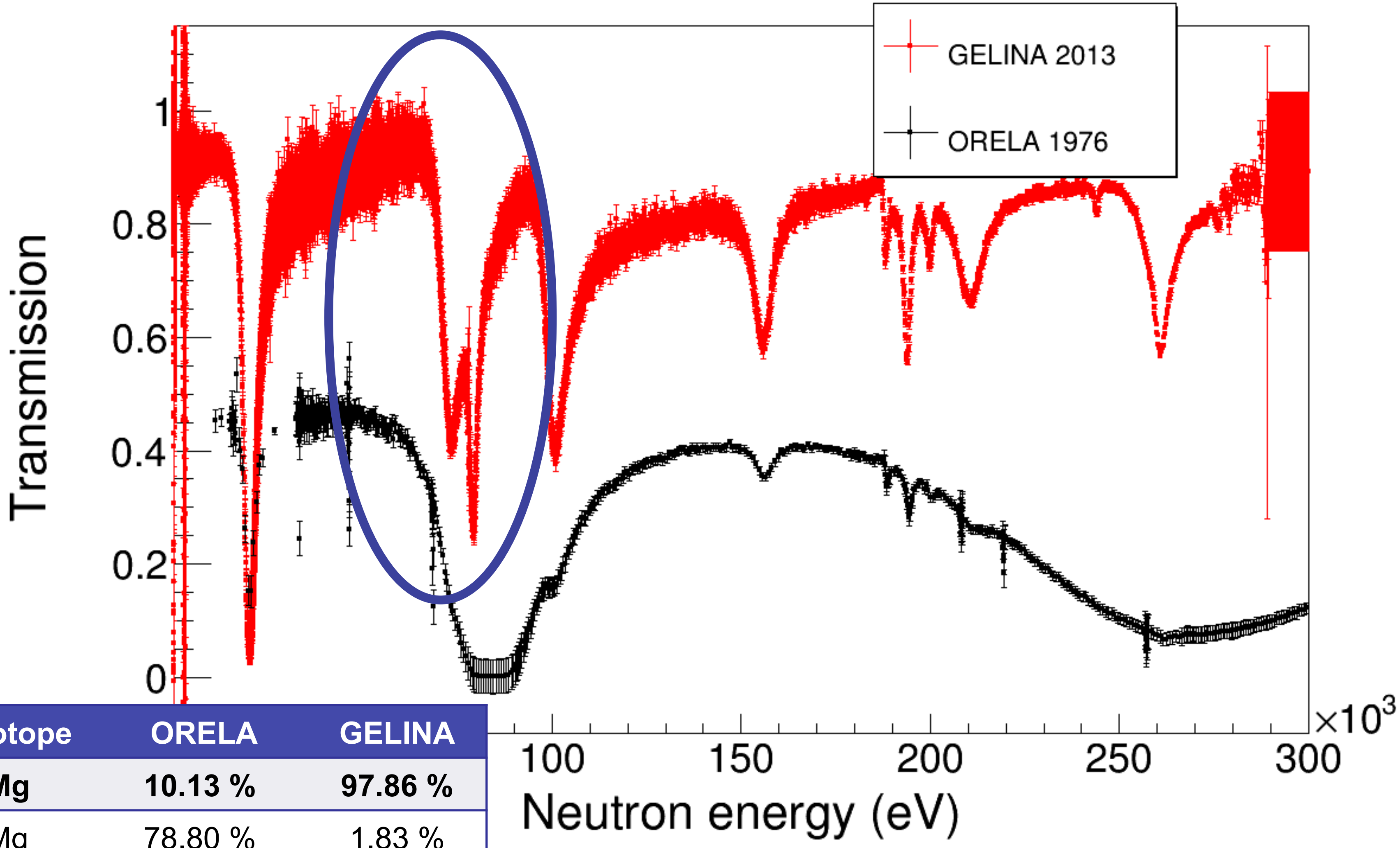

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$^{25}Mg(n, tot)$ @ GELINA

New Measurement

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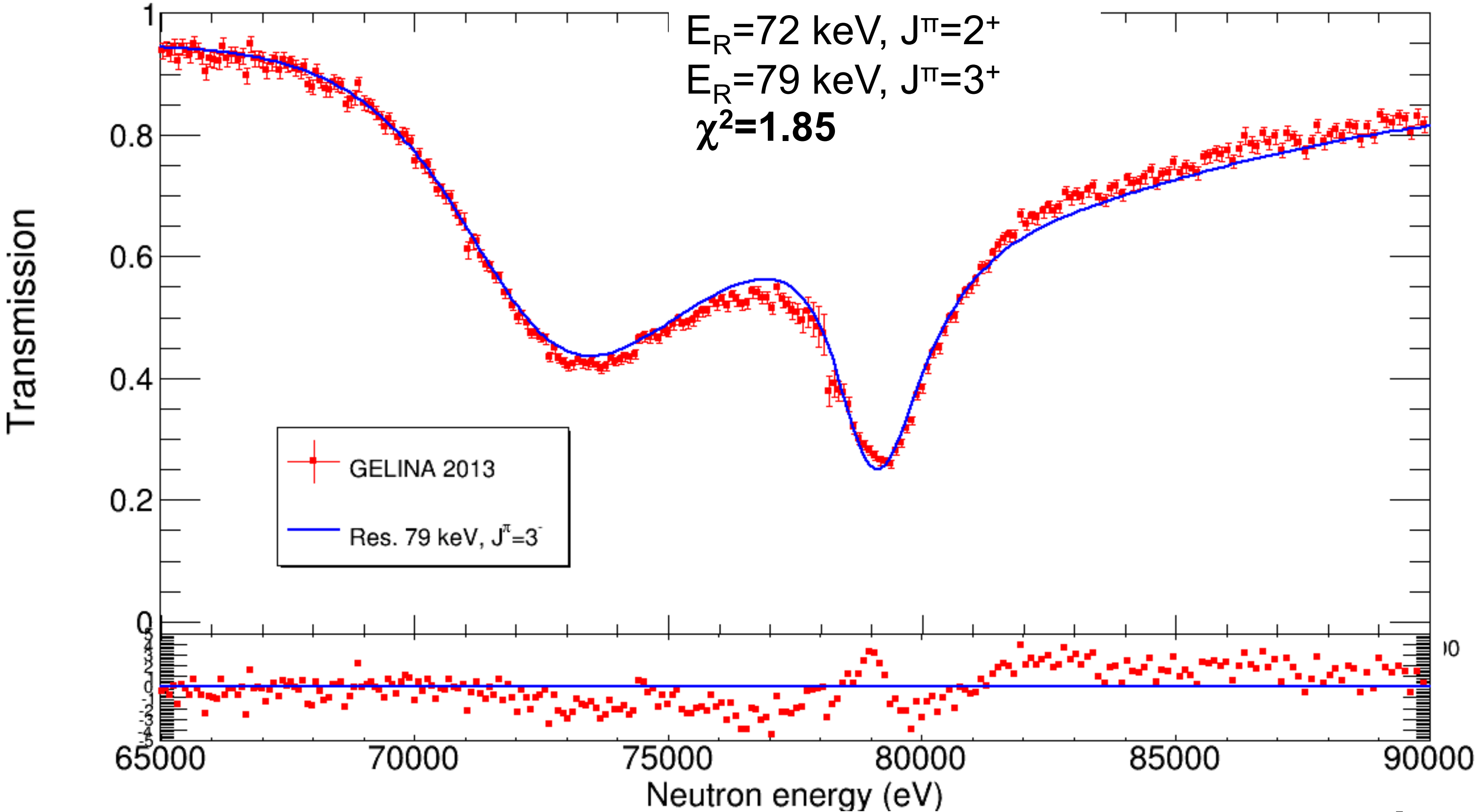
Previous evaluation

E_R=72 keV, $J^{\pi}=2^+$

E_R=79 keV, $J^{\pi}=3^+$

χ^2=1.85



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

New Measurement

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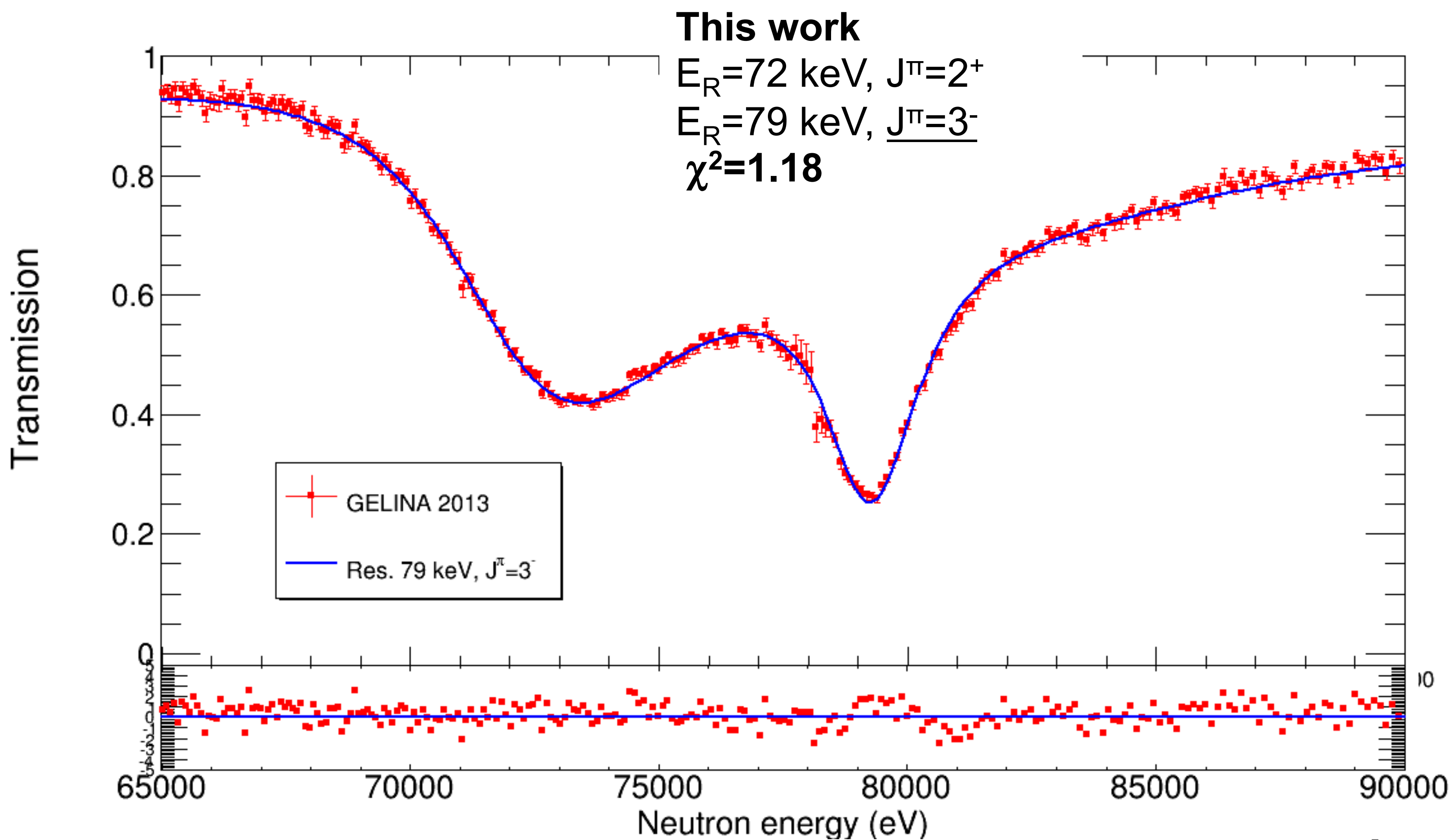

^{25}Mg(n, γ) @ n_TOF

New Measurement

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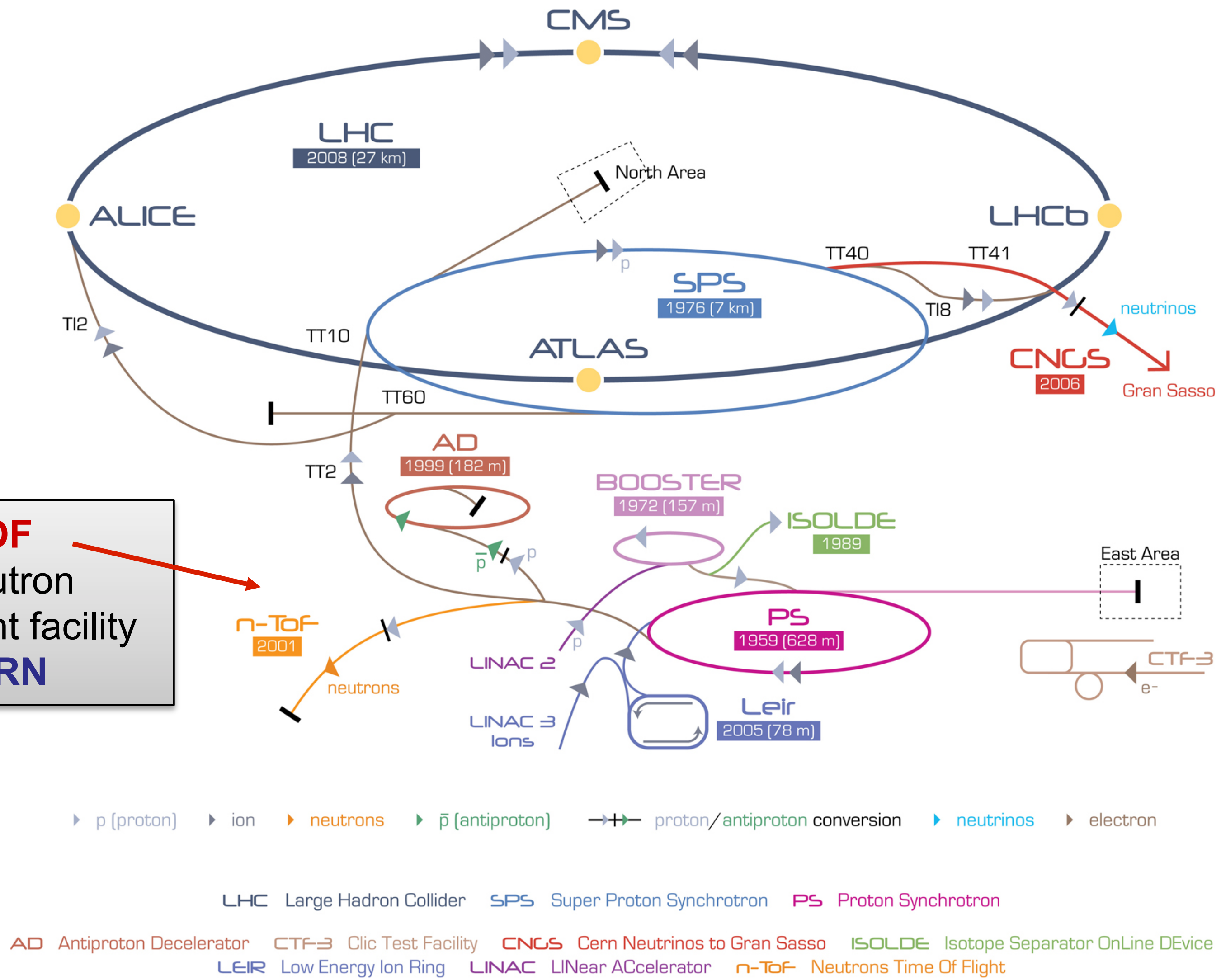
CERN



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

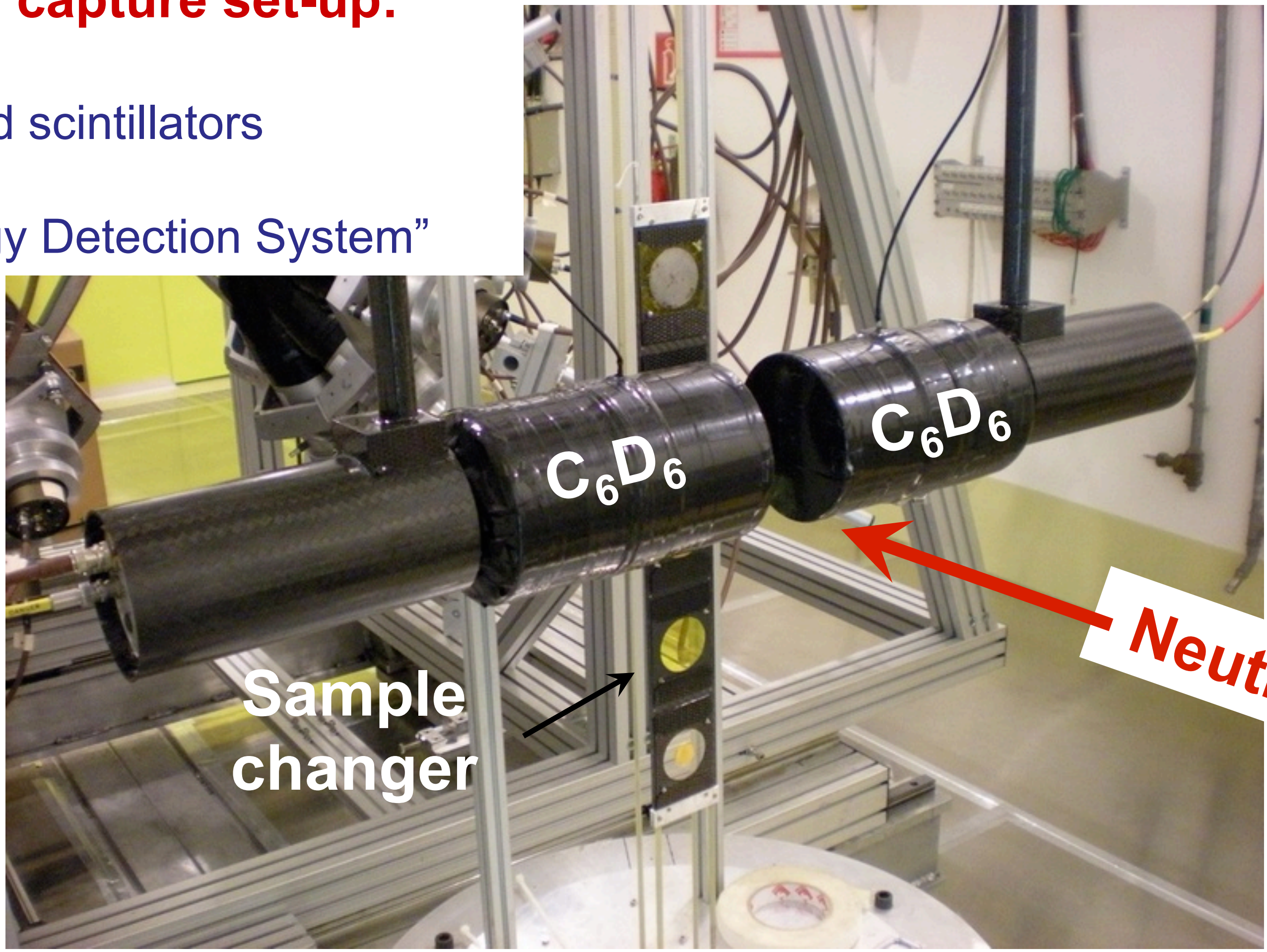
nTOF

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

New Measurement

Typical capture set-up:

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



^{25}Mg(n, γ) @ n_TOF

Data Analysis

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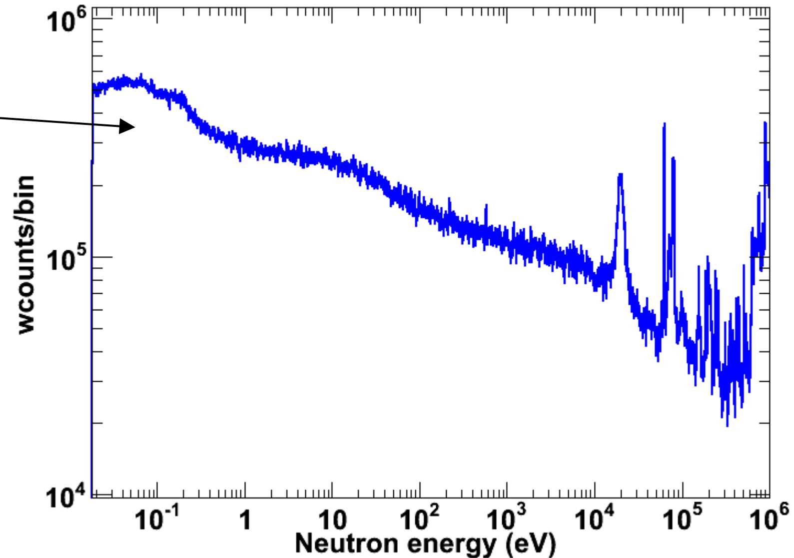
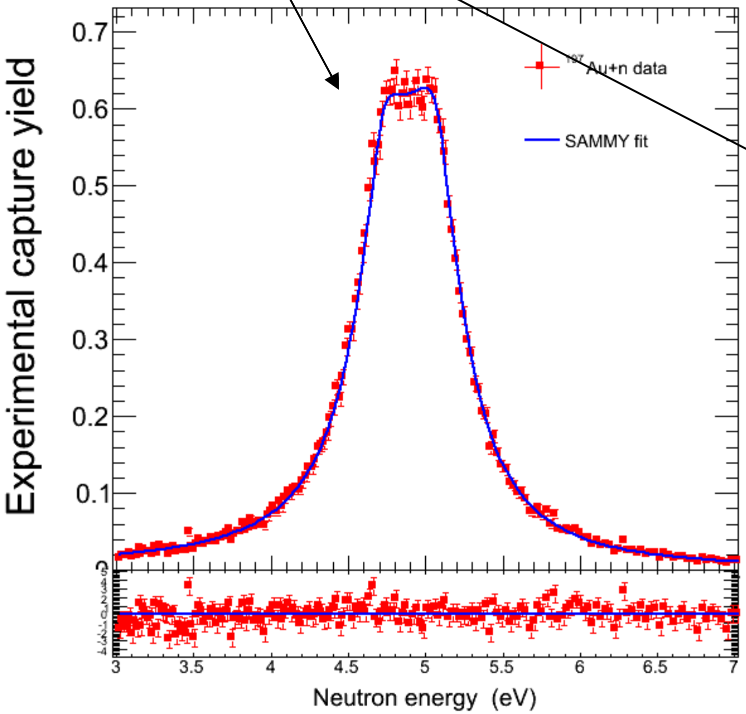
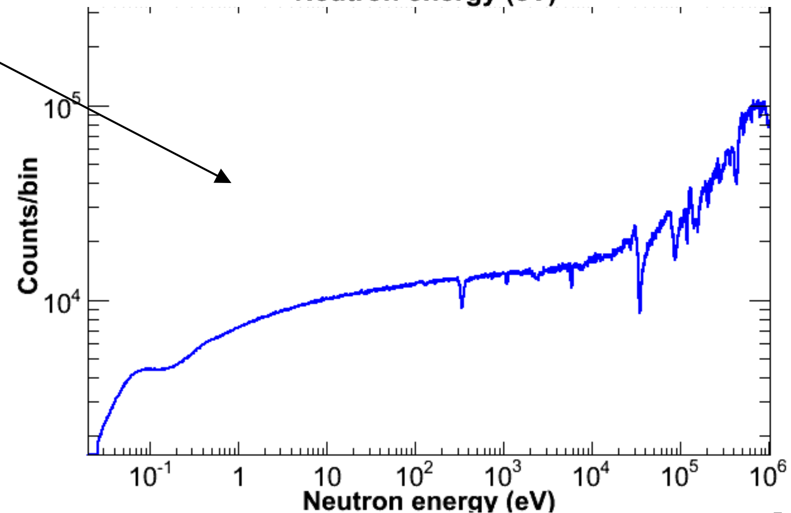
Experimental capture yield

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

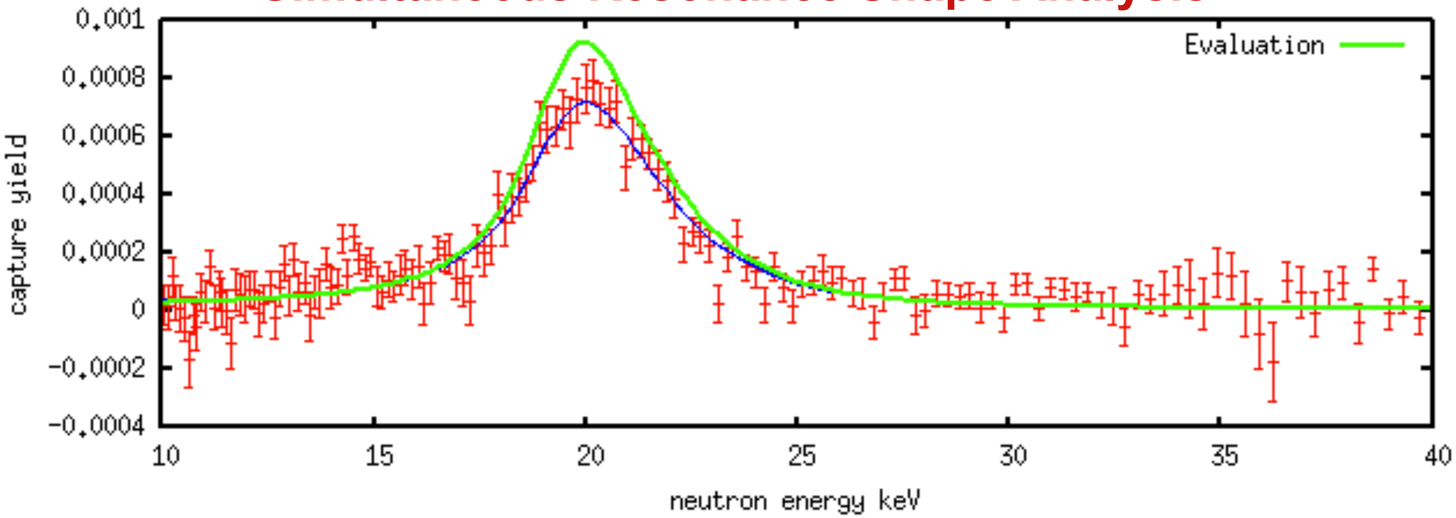




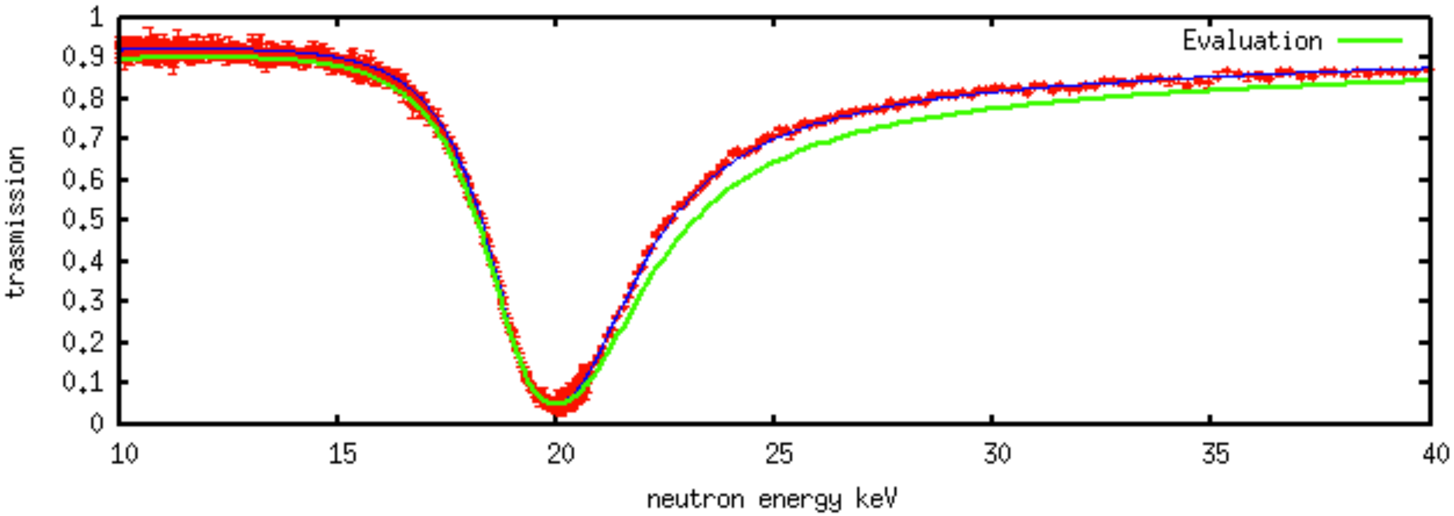


Data Analysis

Simultaneous Resonance Shape Analysis



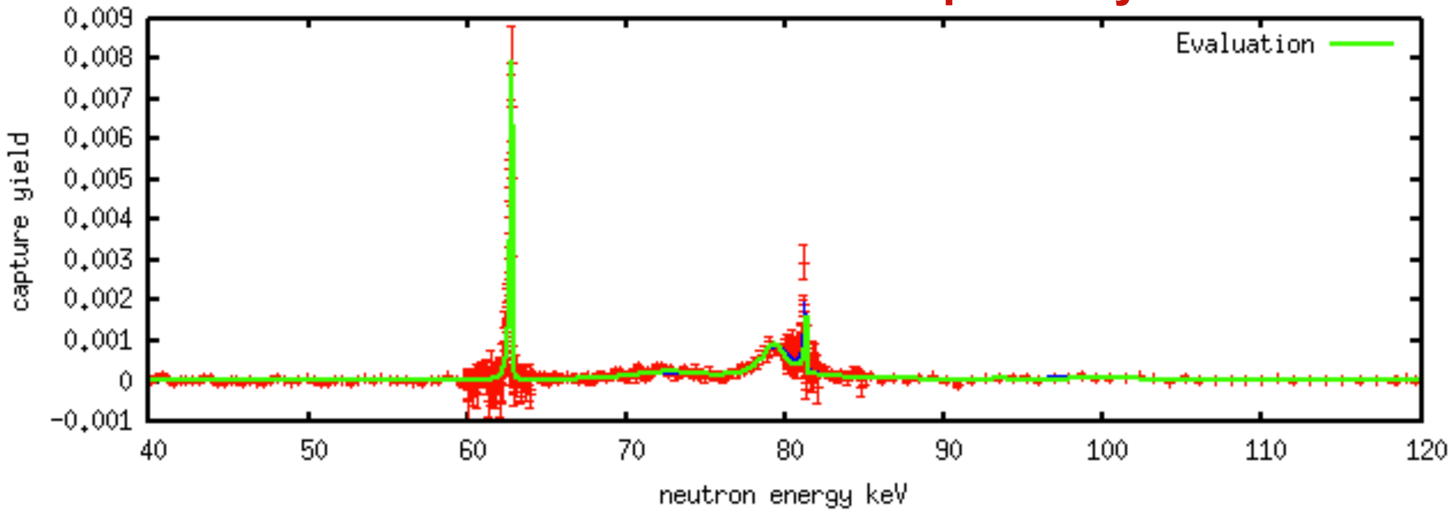
^{25}Mg(n, γ) @ n_TOF



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

Data Analysis

Simultaneous Resonance Shape Analysis



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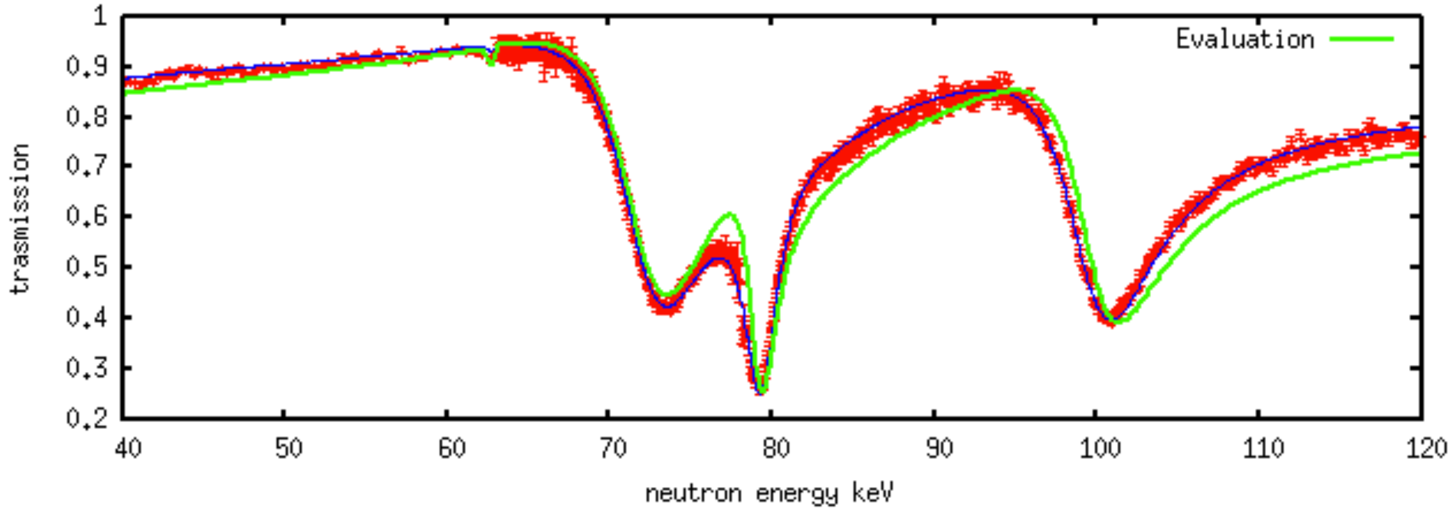

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Data Analysis

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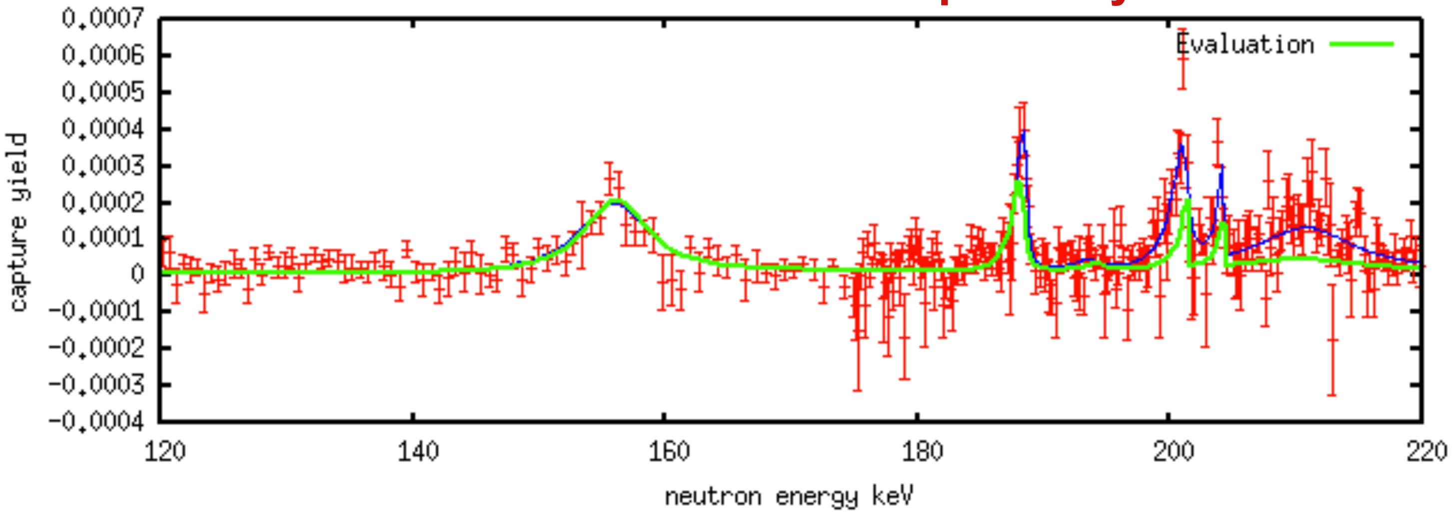

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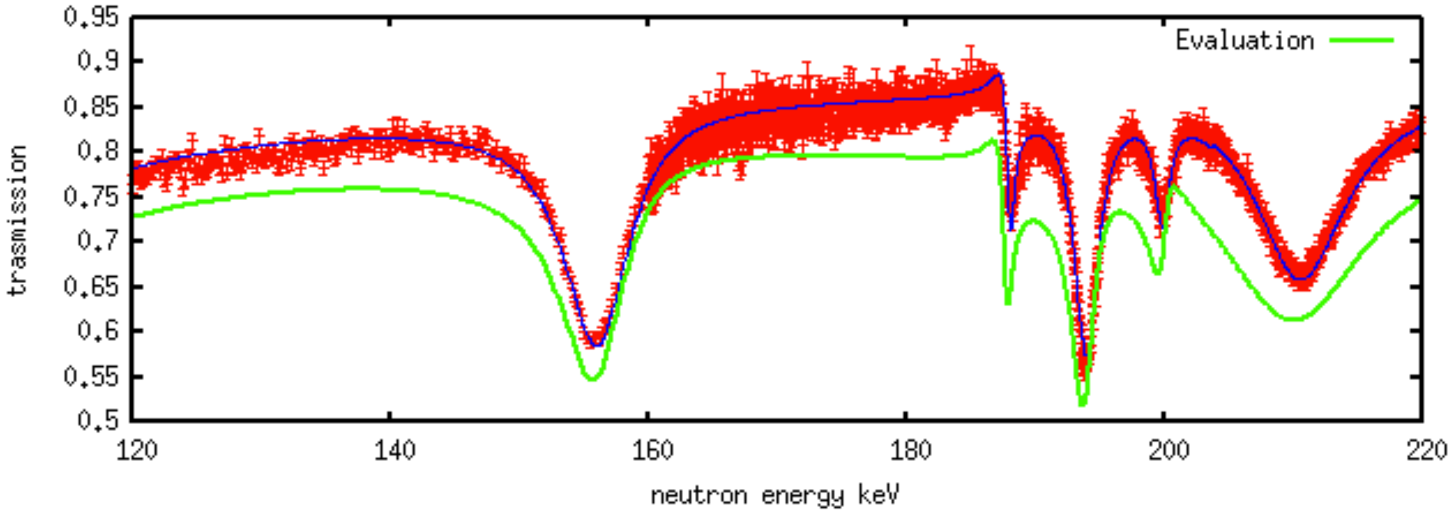

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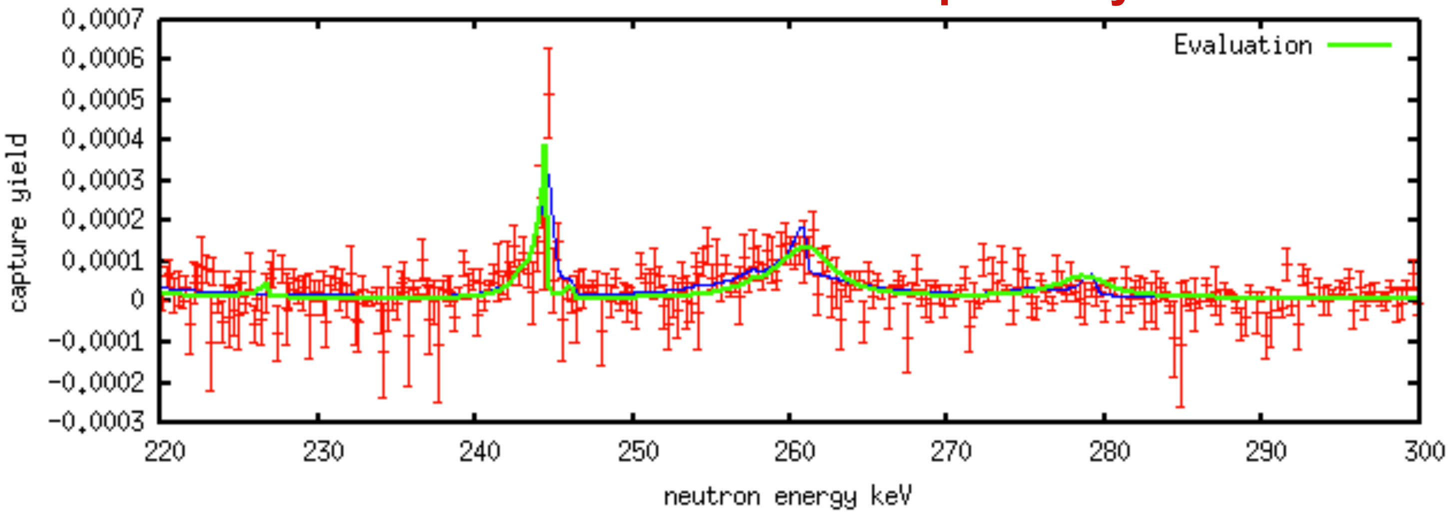
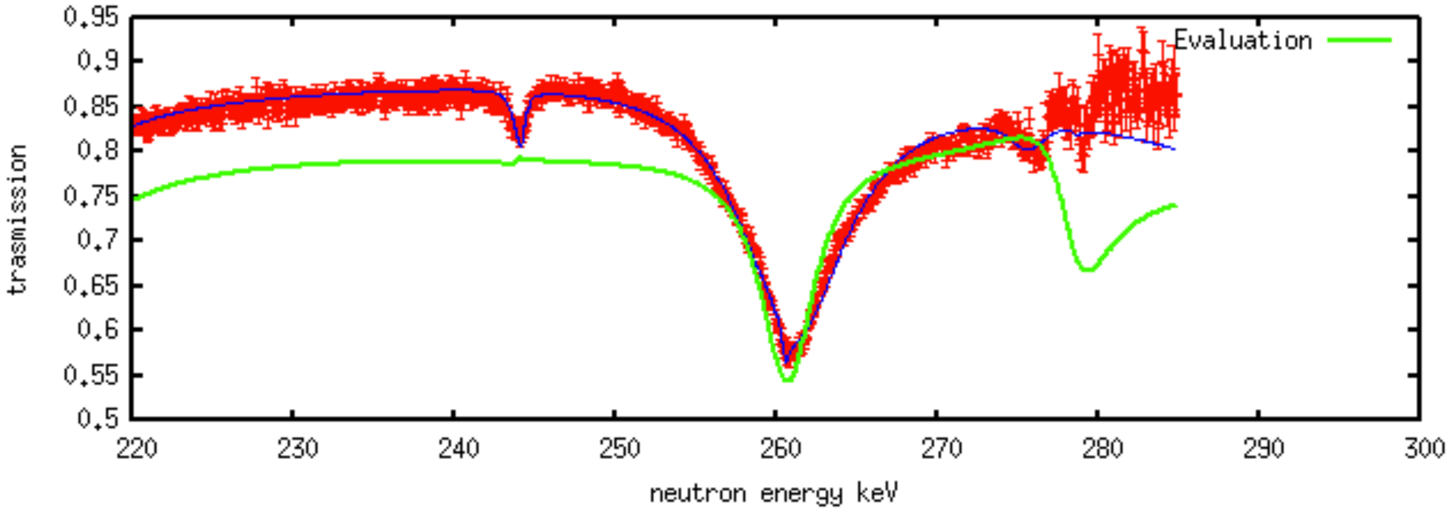


$^{25}Mg(n, \gamma)$ @ n_TOF



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

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

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
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$[101.997 \pm 0.009]$	[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
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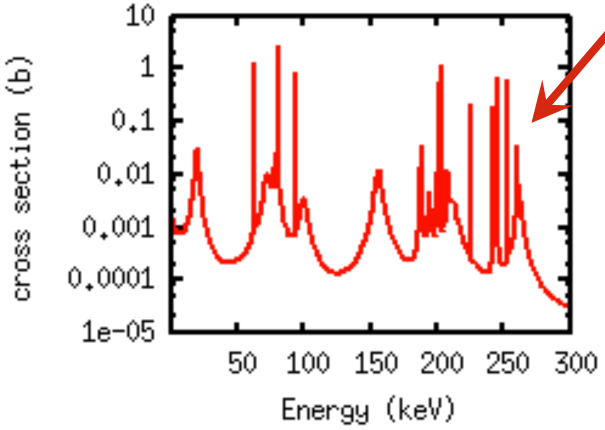
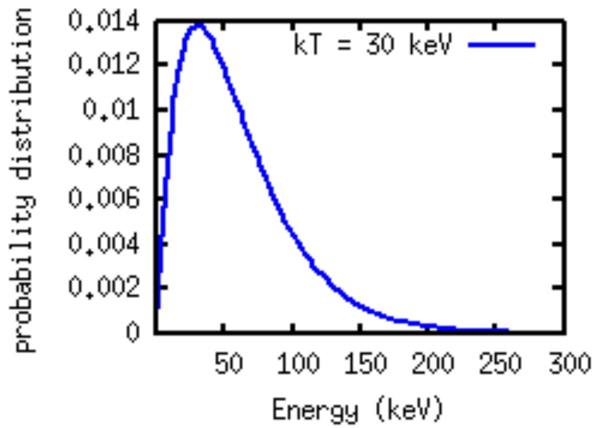


Convoluted with **neutron** stellar **flux**



MACS and reaction rate

n_TOF

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

Results

Stellar site	Temperature keV	MACS (Massimi 2003)	MACS (KADoNiS)	MACS Massimi 2012
He - AGB	8	**4.9±0.6 mb**	4.9 mb	**4.3 mb**
He - AGB	23	**3.2±0.2 mb**	6.1 mb	**4.3 mb**
30	30	**4.1±0.6 mb**	6.4±0.4 mb	**4.1 mb**
He – Massive	25	**3.4±0.2 mb**	6.2 mb	**4.2 mb**
C - Massive	90	**2.6±0.3 mb**	4.0 mb	**2.5 mb**

Old Sample, oxide powder

Capture

New Sample, metal disc

Capture + transmission

Conclusion

- ^{25}Mg(n, γ) reaction cross-section was measured at n_TOF in 2003 and repeated 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:
  - accurate ^{25}Mg(n,γ) cross section don not completely confirms previous n_TOF data;
  - J$^{\pi}$ information on ^{26}Mg → evidence for more natural states than previously thought →**HIGHER ^{22}Ne(α, n) reaction rate;**
  - Constraints for the **^{22}Ne(α, γ)**

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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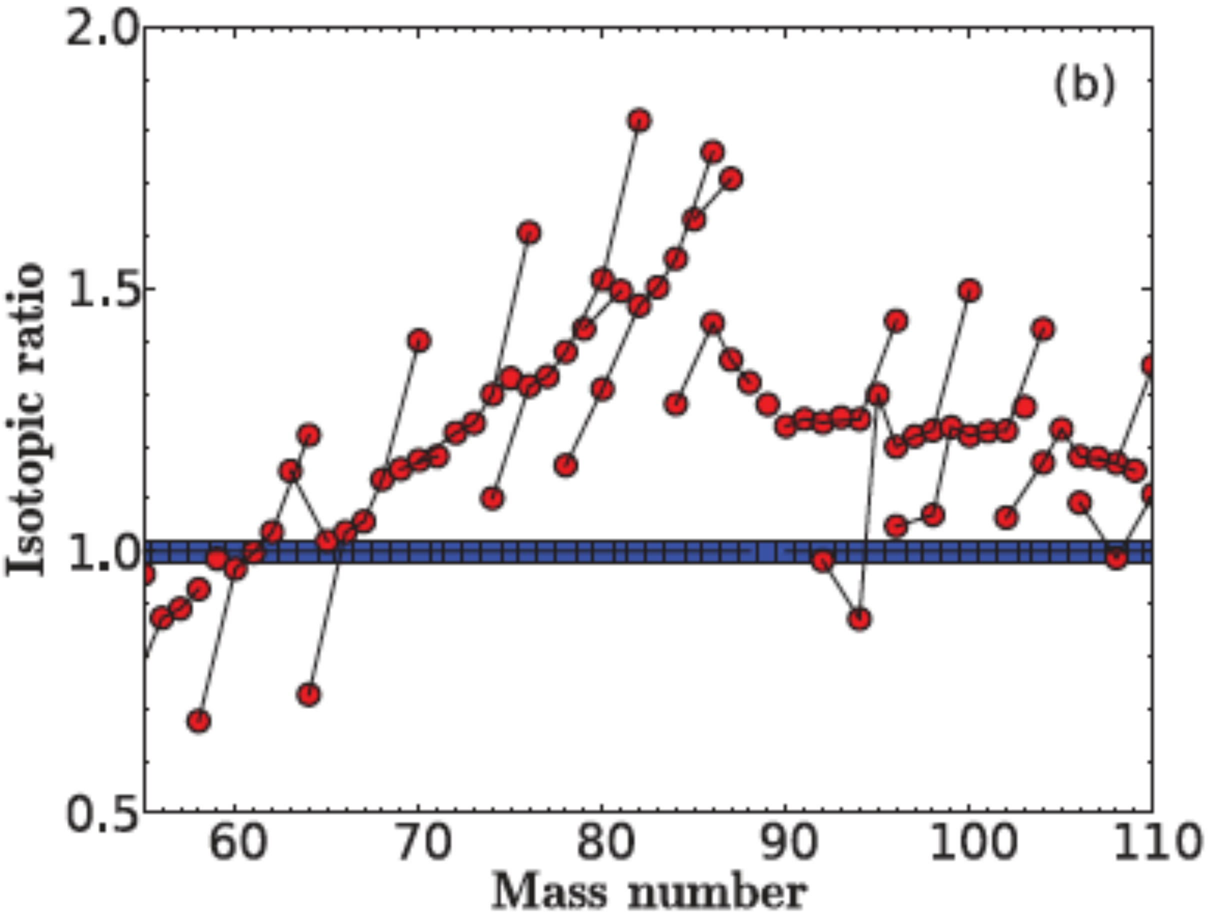

Reduced poisoning effect in Massive Stars

SPIN & PARITY

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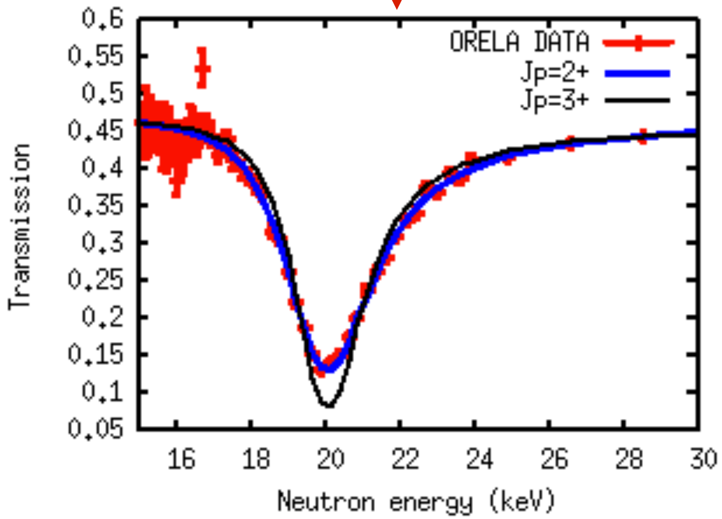
$^{25}Mg(n,g)^{26}Mg$

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)

SPIN & PARITY

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



$^{25}Mg(n,g)^{26}Mg$

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
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)

EXAMPLE Of SPIN ASSIGNMENT

Principles

Transmission : σ(n,tot)

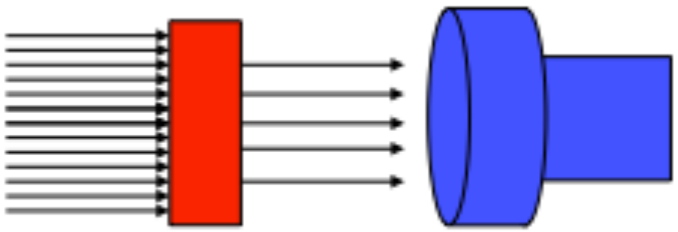
$$T \cong e^{-n\sigma_{tot}}$$

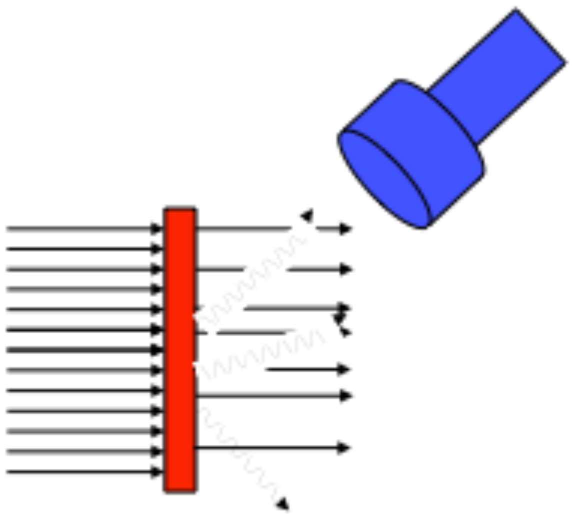
T : transmission
Fraction of the neutron beam traversing the sample without any interaction

Reaction yield : σ(n,r)

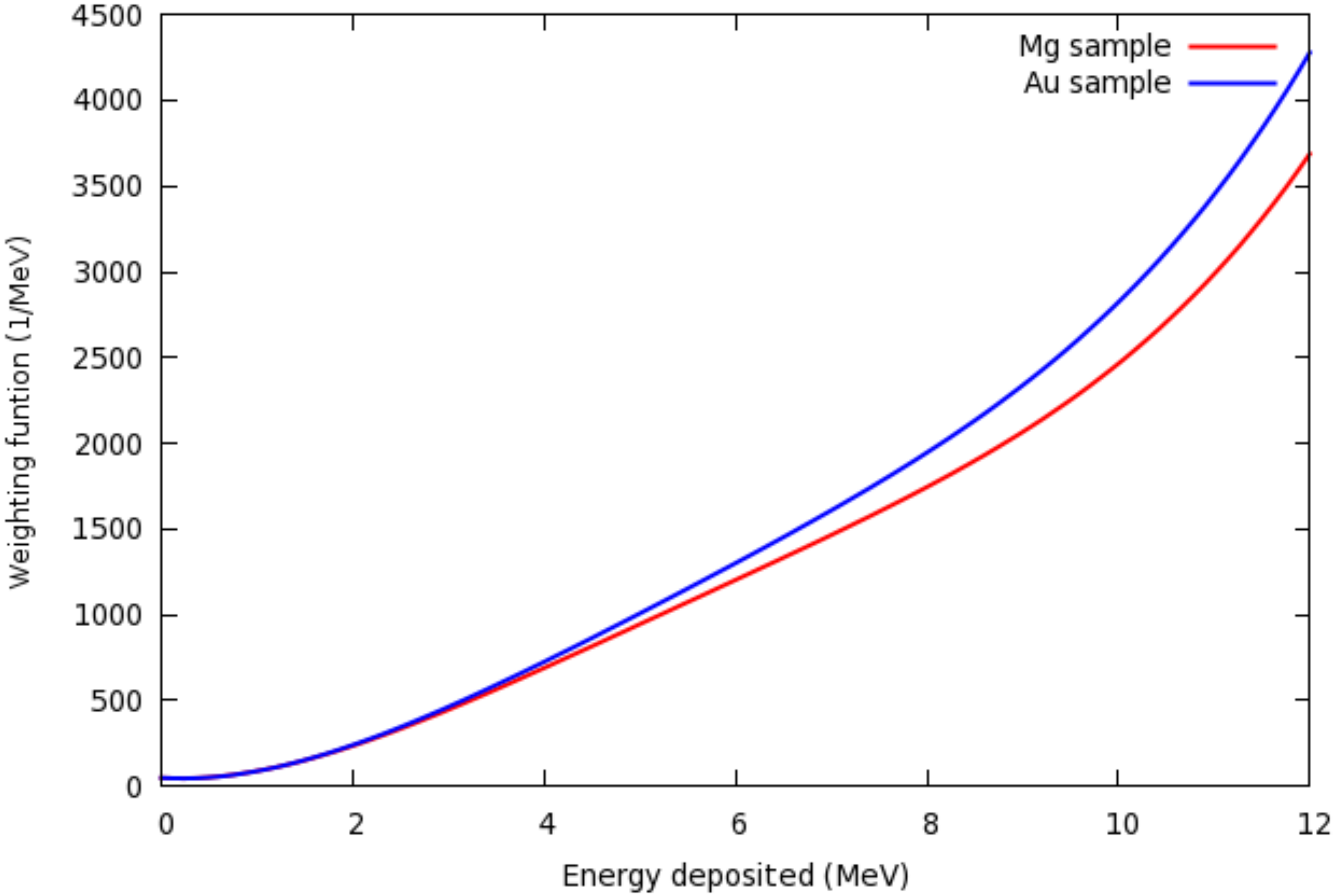
$$Y_r \approx (1-e^{-n\sigma_{tot}})\frac{\sigma_r}{\sigma_{tot}}$$

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





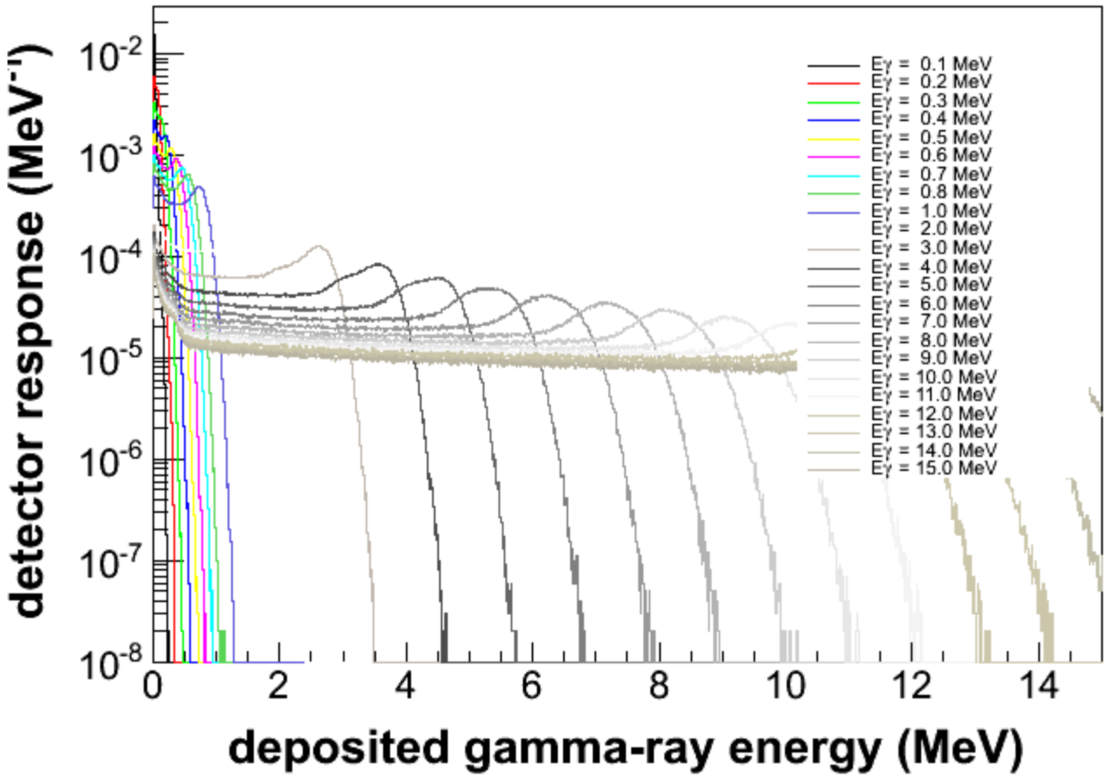
Weighting functions

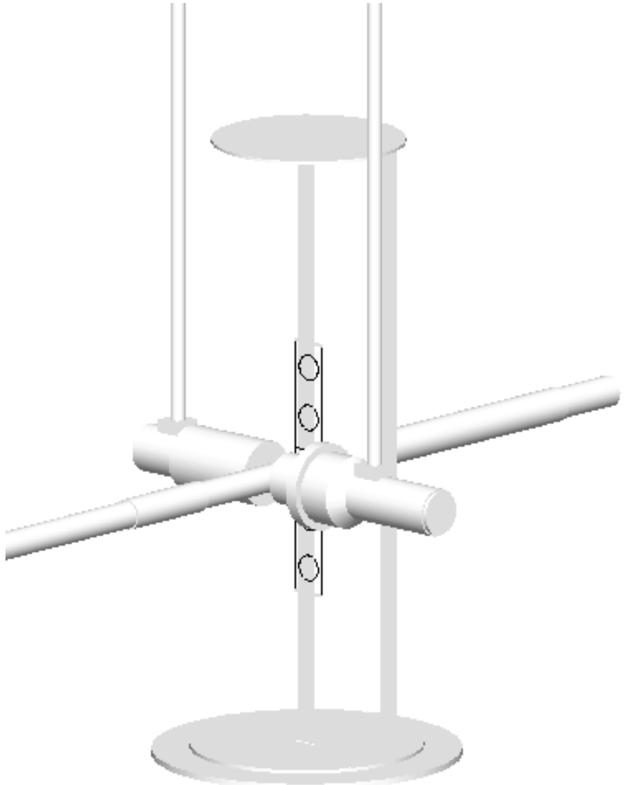


Monte Carlo Simulation

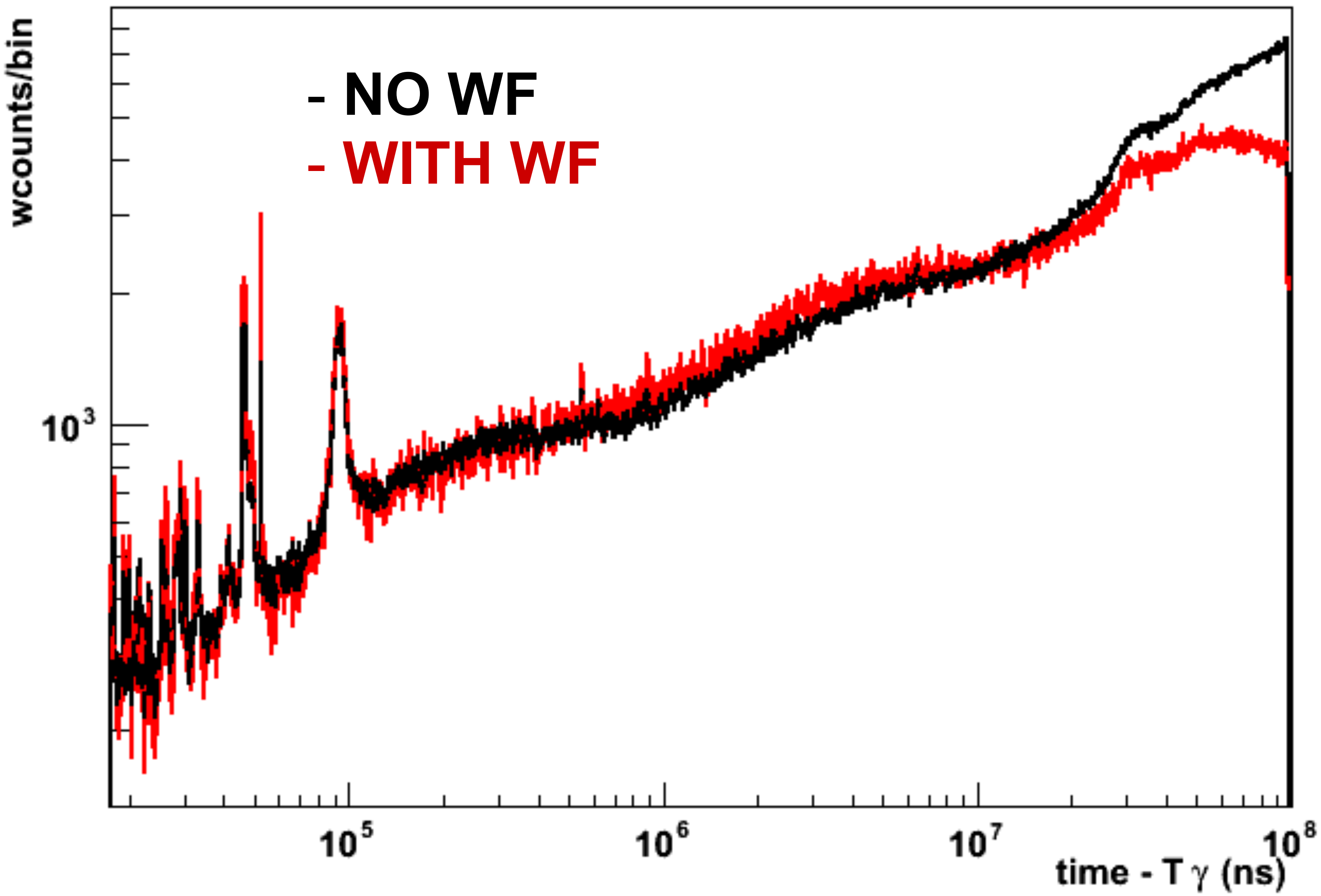
Pulse Height Weighting Function

Detailed Monte Carlo simulation





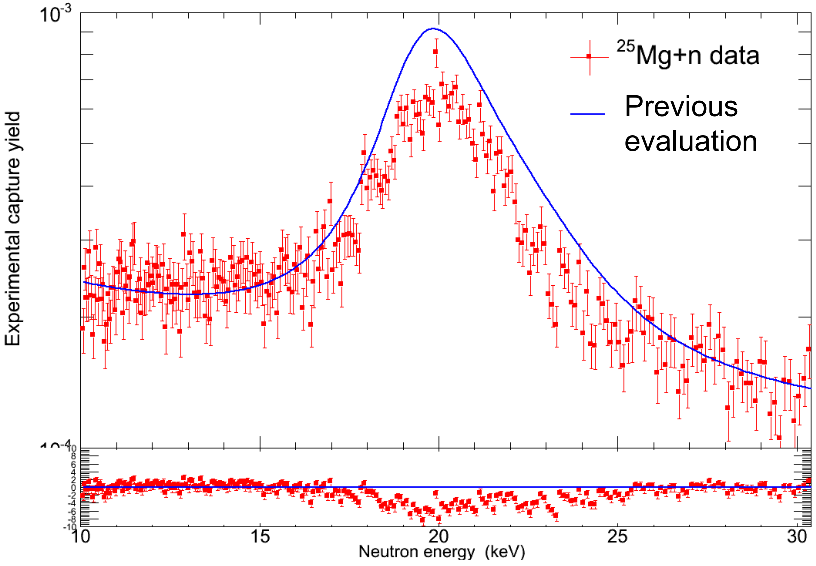
Weighting Function



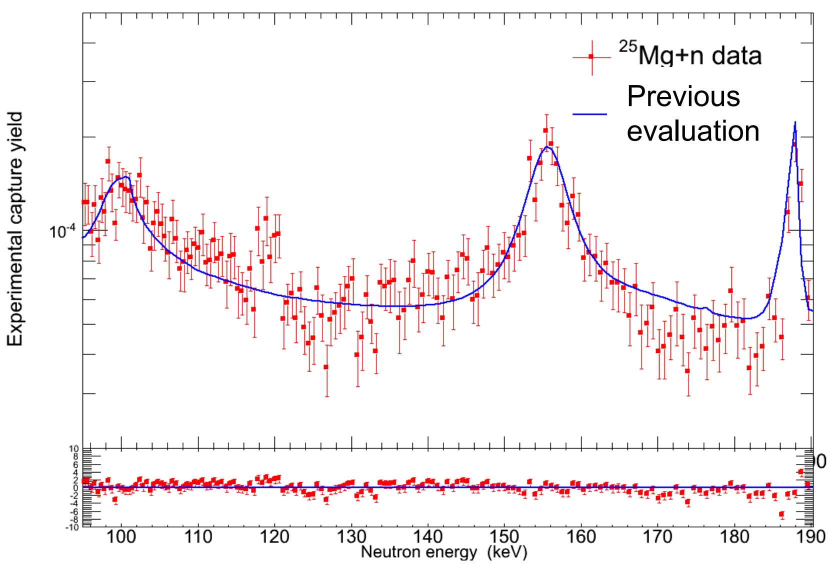
Preliminary Results

2012 data

First s-wave resonance at ~ 20 keV



Other resonances at ~ 150 keV



Energies relevant to s process

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

New Measurement

INFN Istituto Nazionale di Fisica Nucleare

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

Quality of the sample