Spin parity determination of unbound states in ^{26}Mg from neutron spectroscopy

C. Massimi[1], P. Koehler[2], S. Kopecky[3] and P. Schillebeeckx[3]

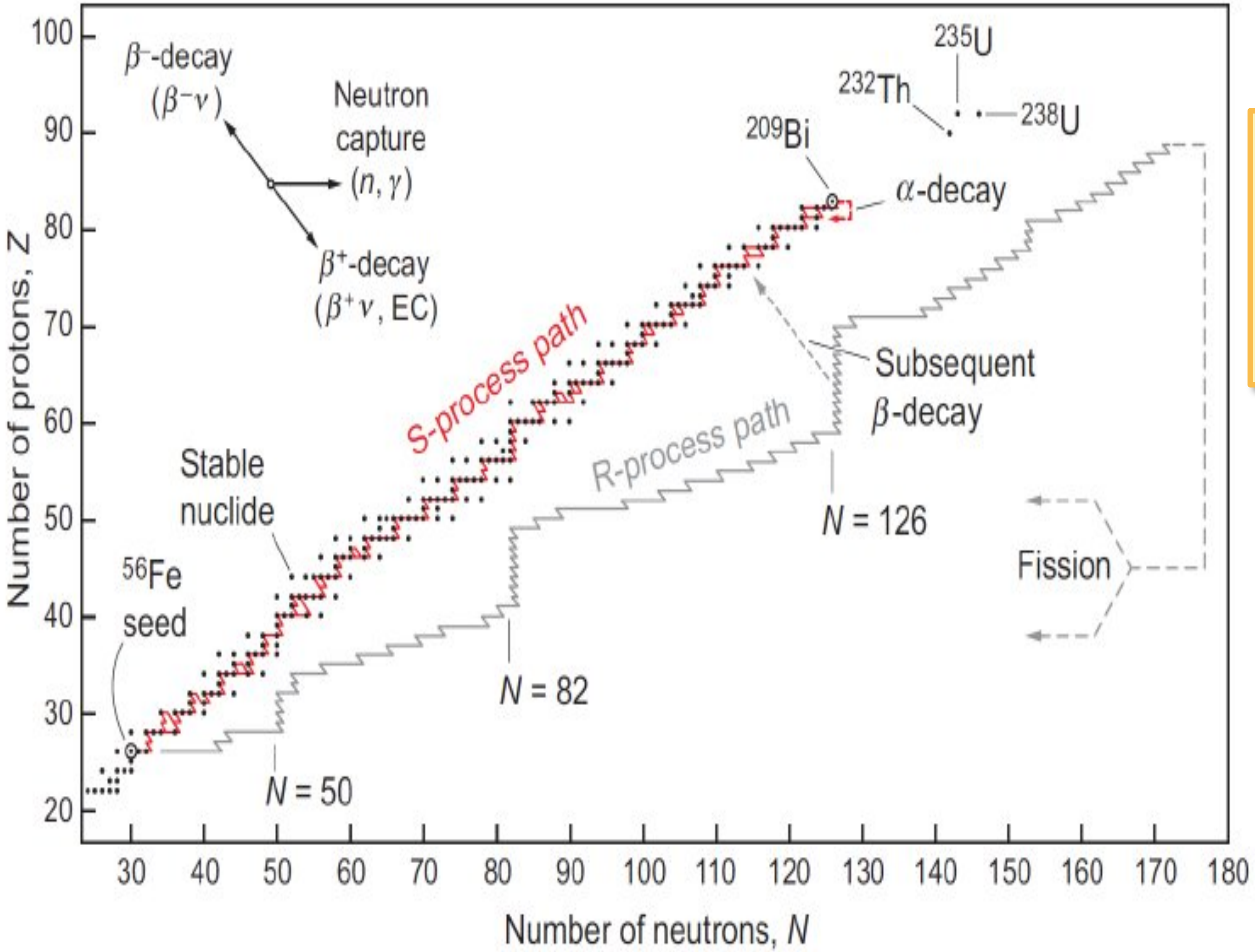
[1] University of Bologna and INFN, Italy
[2] Los Alamos Neutron Science Center, USA
[3] European Commission, JRC-IRMM, Belgium

The 2016 R-Matrix Workshop on Methods and Applications
Santa Fe - USA, 26 June – 1 July

outline

- Motivations
- Measurements:
  - ^{25}Mg(n,γ) @ n_TOF (CERN, Switzerland)
  - **^{25}Mg(n,tot) @ GELINA (EC-JRC, Belgium)**
- Results and impact on the neutron source reaction ^{22}Ne(α,n)
  - Spin and parity determination
  - Improved parameterization of ^{25}Mg(n,γ)

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

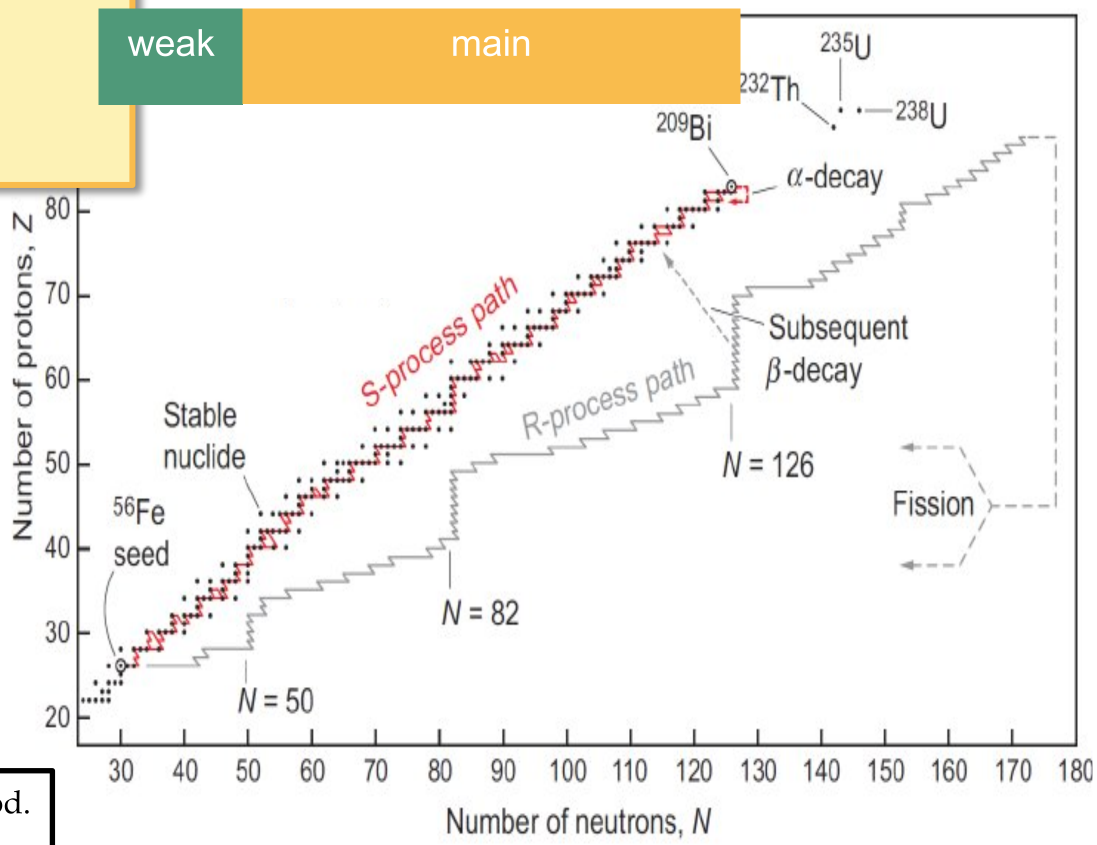
and 2 different components:

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:

neutron capture on Mg stable isotopes in competition with neutron capture on ^{56}Fe (the s-process seed for the production of heavy isotopes).

2. NEUTRON BUDGET:

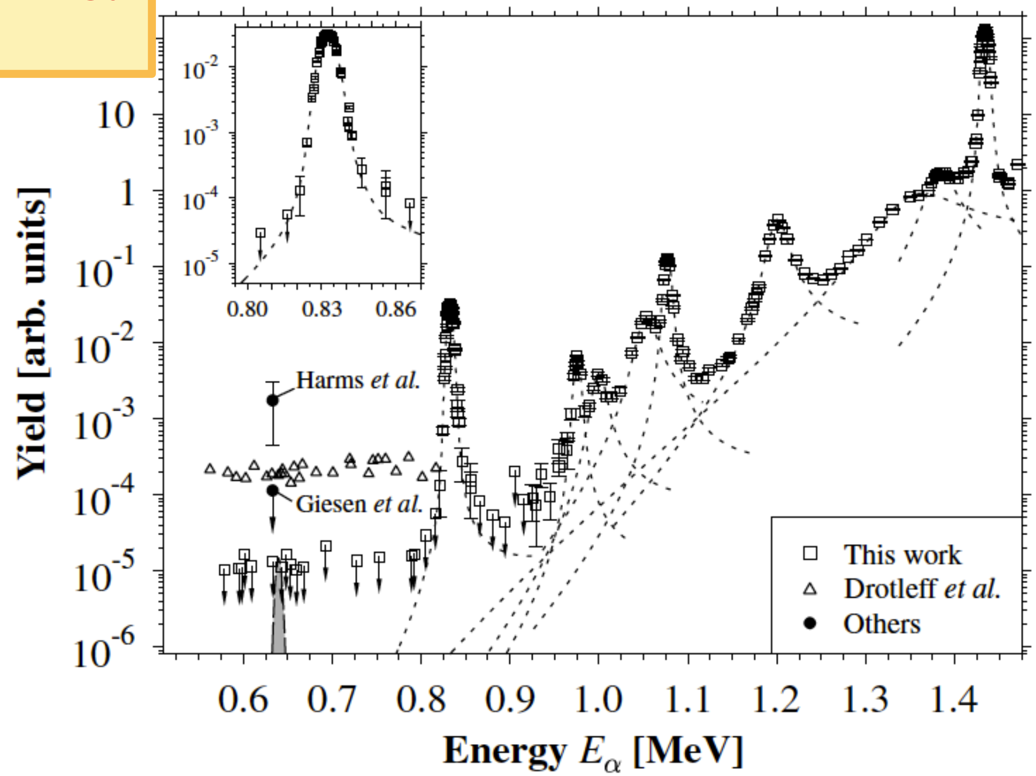
✓ **$^{22}Ne(\alpha,n)^{25}Mg$** is one of the most important **neutron source reaction in Red Giant stars.** Its **reaction rate** is very **uncertain** because of the **poorly known property of the states in ^{26}Mg**.

✓ **$^{22}Ne(\alpha,\gamma)^{26}Mg$** reaction contributes to the destruction of ^{22}Ne during the entire helium burning phase because of its positive Q-value

Motivation: J^{π}

Direct measurement $^{22}Ne(\alpha,n)^{25}Mg$ exceedingly difficult in the energy region of interest

M. Jaeger, *et al.*, Phys Rev. Lett. **87** (2001) 20



Motivation: J^{π}

Direct measurement $^{22}Ne(\alpha,n)^{25}Mg$ exceedingly difficult in the energy region of interest

Below E_{α} = 800 keV
experimental sensitivity:
$\sigma \sim 10^{-11}$ b

Need for indirect approaches:

- α-transfer reaction $^{22}Ne(^{6}Li,d)^{26}Mg$ and α-scattering $^{26}Mg(\alpha, \alpha')$
- photon reaction $^{26}Mg(\gamma, \gamma')$
- neutron spectroscopy n+^{25}Mg

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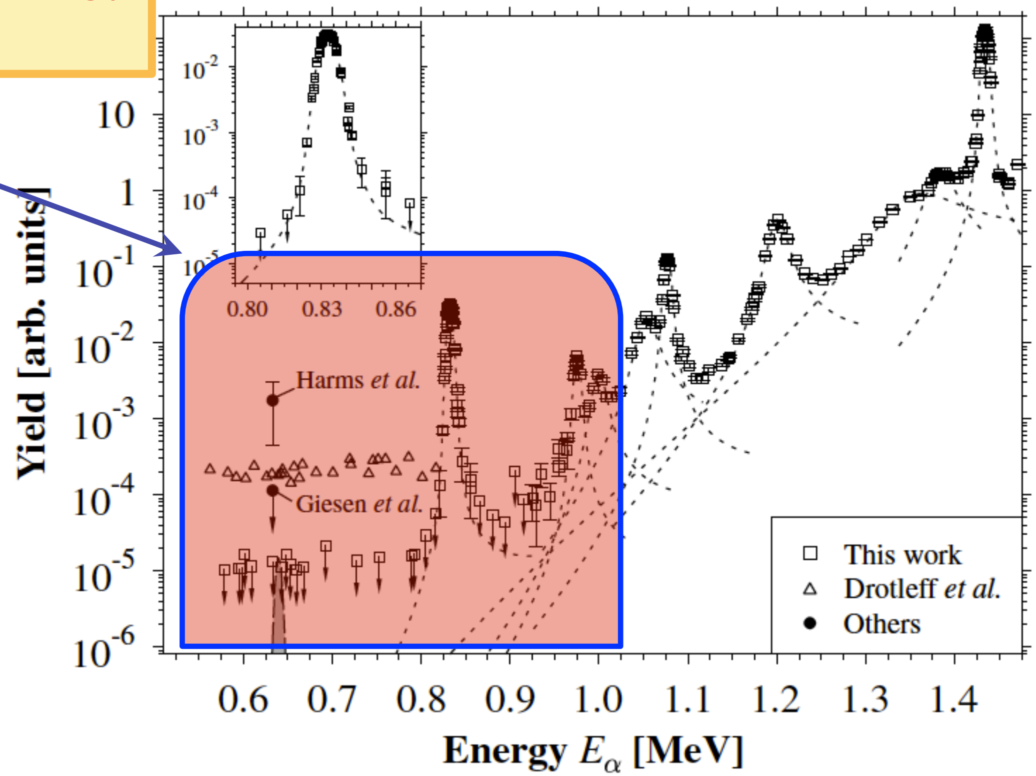

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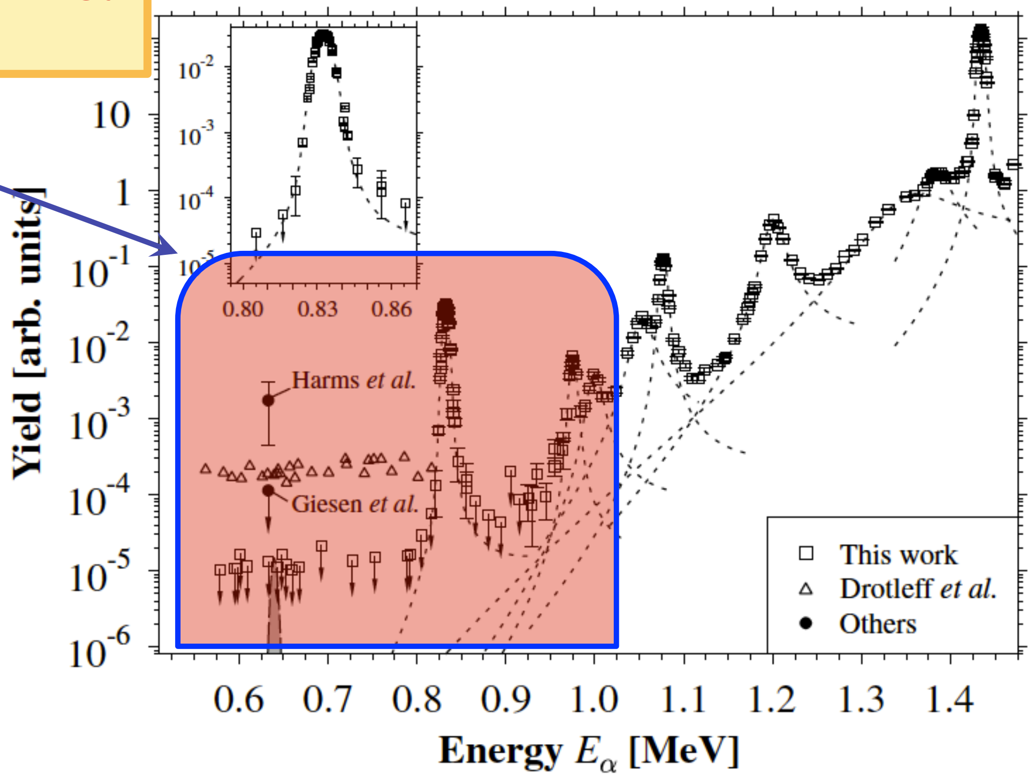


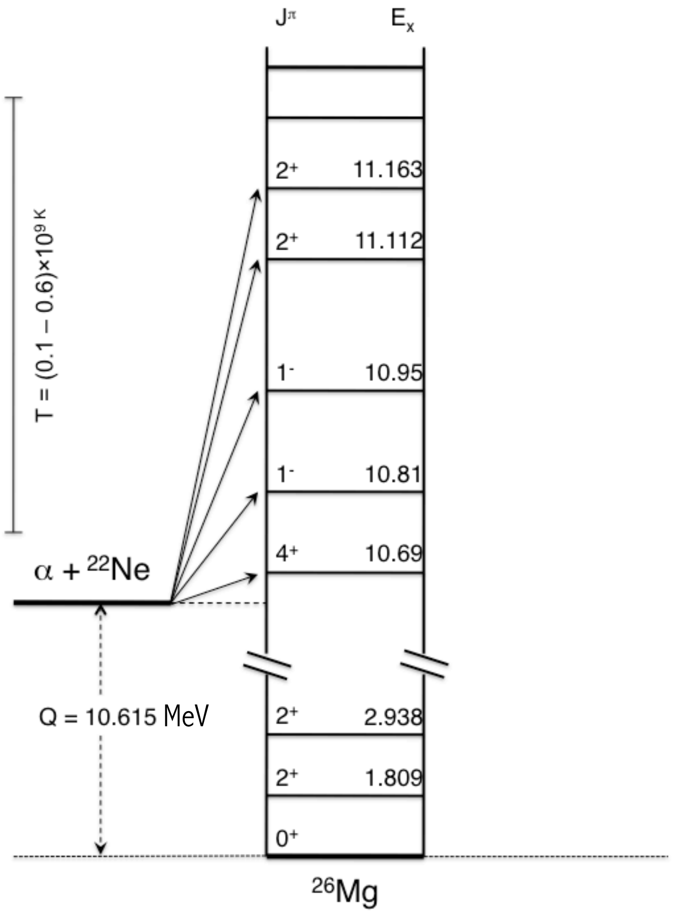
No data on $^{22}Ne(\alpha,\gamma)^{25}Mg$ below E_{α} = 1 MeV. The reaction rates are based on indirect measurements

Motivation: J^{π}

Constraints for the ^{22}**Ne(α,n)**^{25}**Mg** and the ^{22}**Ne(α,γ)**^{26}**Mg** reaction
from **neutron spectroscopy**

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

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



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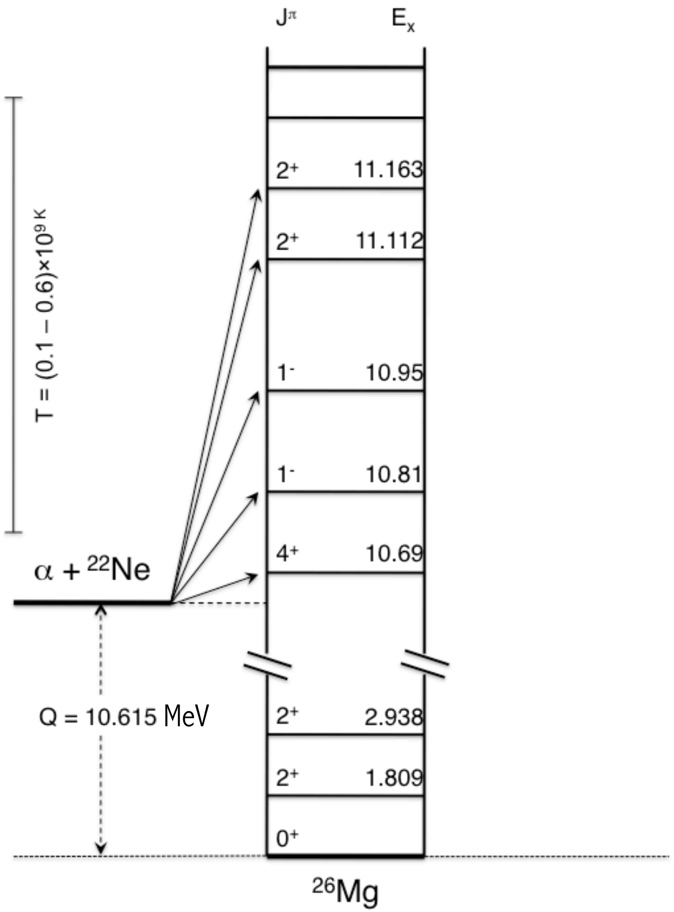
$$\vec{J} = \underbrace{\vec{I} + \vec{i}} + \vec{\ell}$$

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

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

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



Motivation: J^{π}

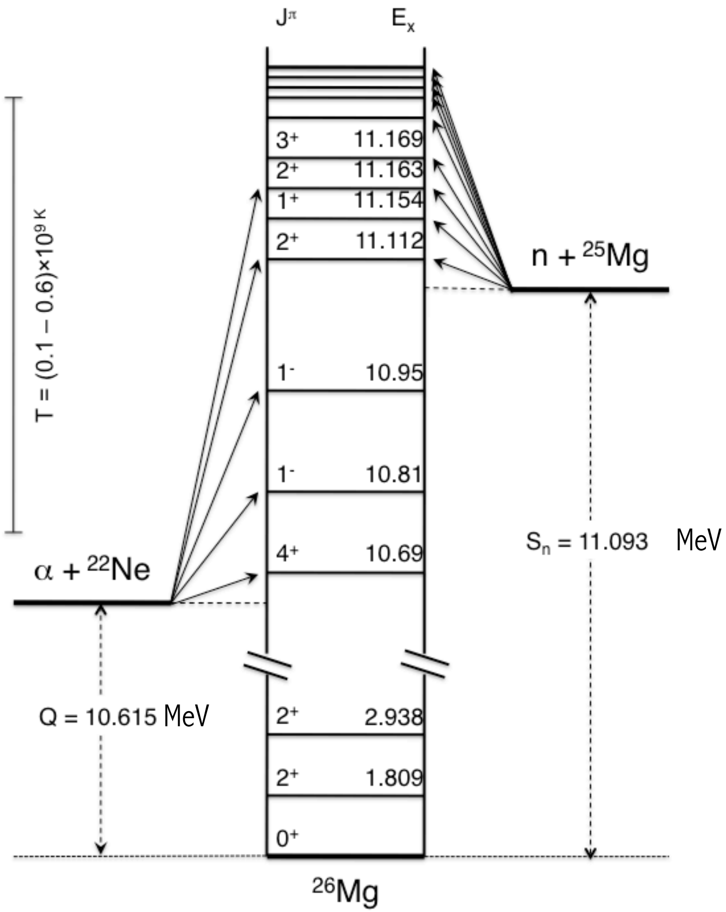
Constraints for the **$^{22}Ne(\alpha,n)^{25}Mg$** and the **$^{22}Ne(\alpha,\gamma)^{26}Mg$** reaction
from **neutron spectroscopy**

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: J^{π}

Study of ^{22}Ne(α,n)^{25}Mg and ^{22}Ne(α,γ)^{26}Mg by n+^{25}Mg

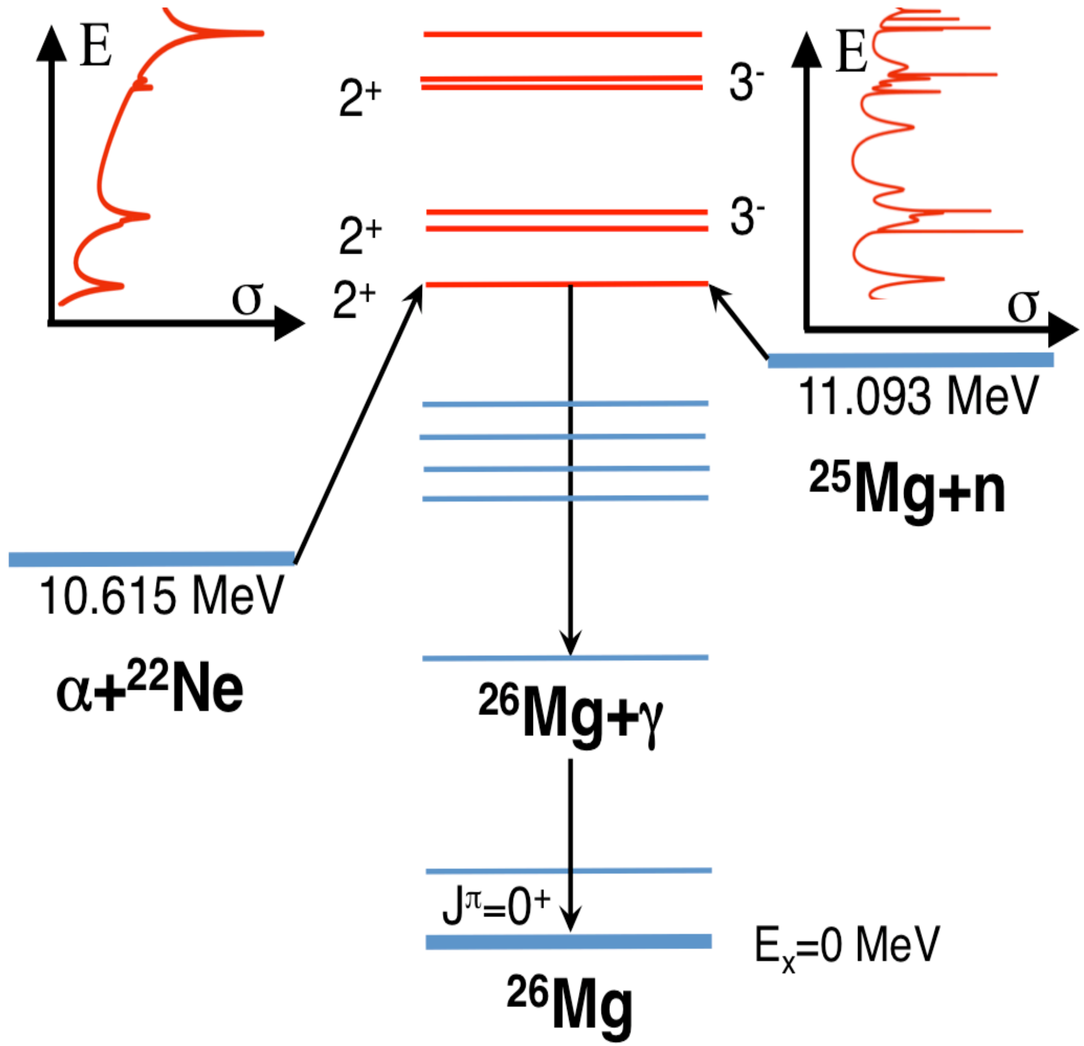
Neutron spectroscopy

Advantages:

- ✓ Access to low-energy states (energy region of interest E_n<300 keV)
- ✓ Good energy resolution (<< 0.1 keV) → Doublets observed

Drawbacks:

- x No information about Γ_α
- x Sensitivity Γ_γ~ 0.5 eV (capture)



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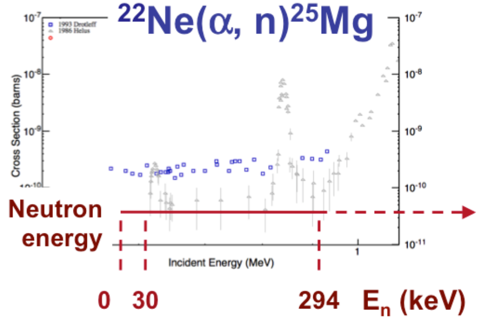
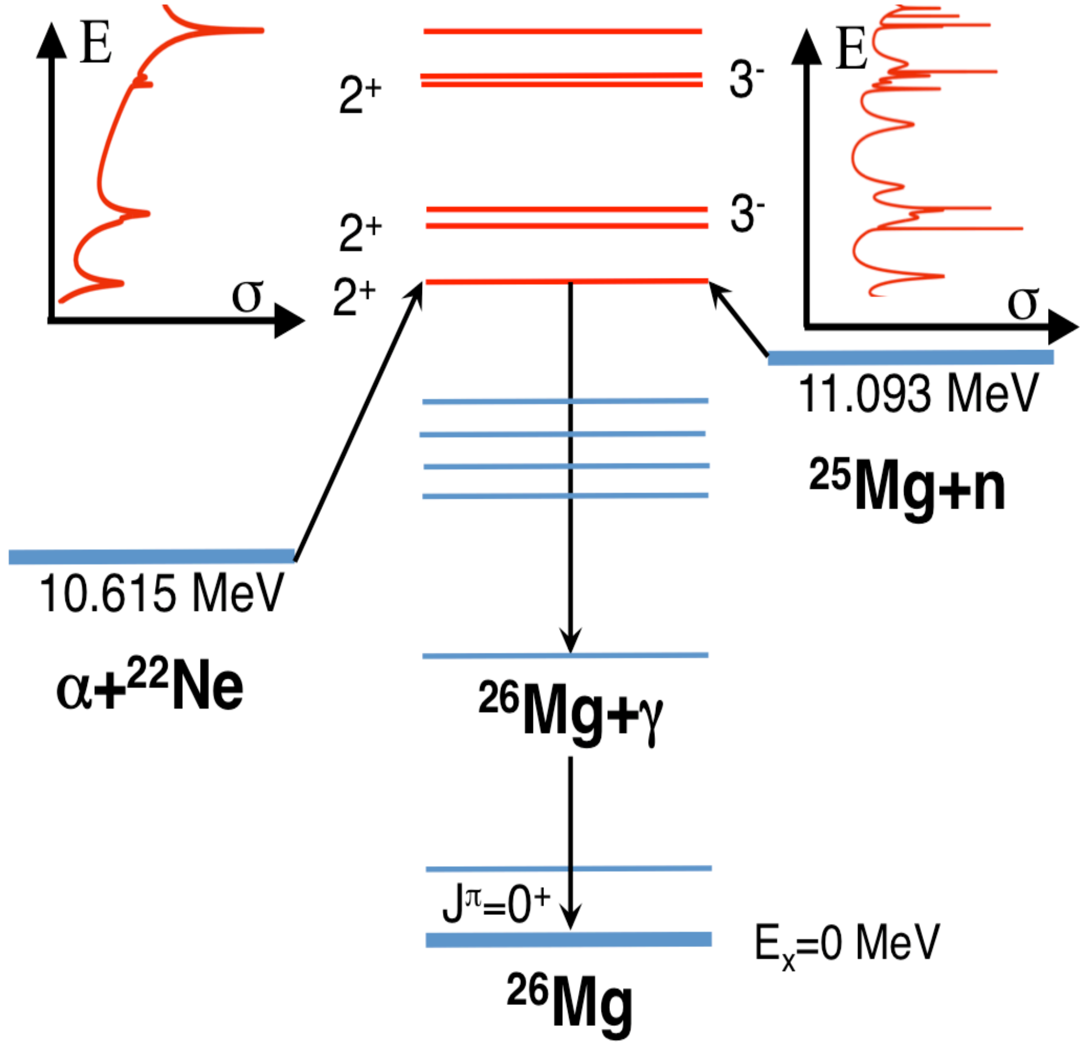
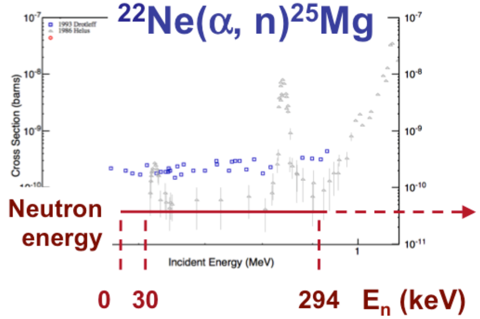


$^{25}Mg(n, \gamma)^{26}Mg$ resonances

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 ± 3]
[107.60 ± 0.02]	$[0]^b$	$[3^+]$	[0.3 ± 0.1]	[2 ± 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)



Motivation: J^{π}



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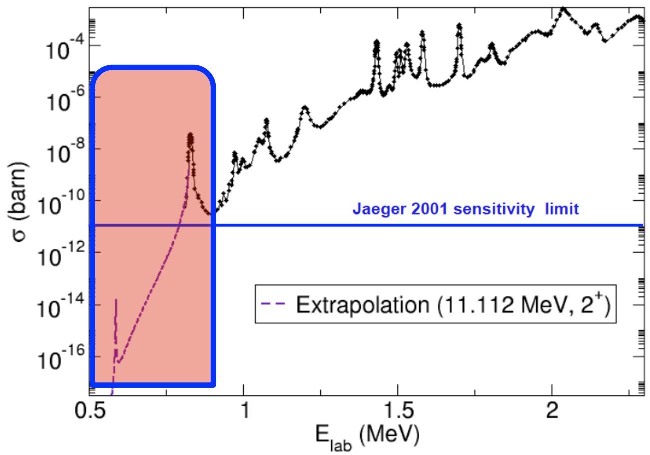
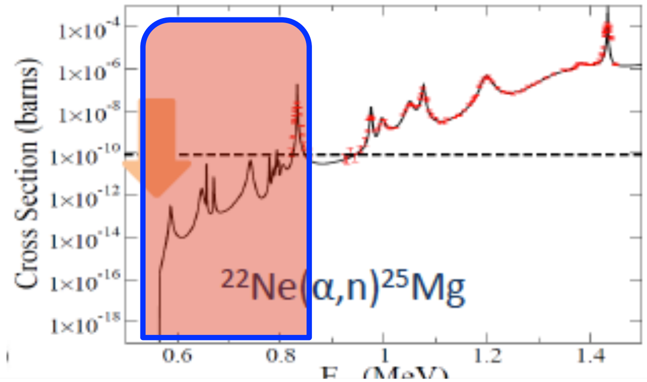
^{22}Ne(α,n) Reaction rate estimation



C. Ugalde, *et al.*, LUNA workshop 2011



M. Wiescher, *et al.*, SPES workshop 2015

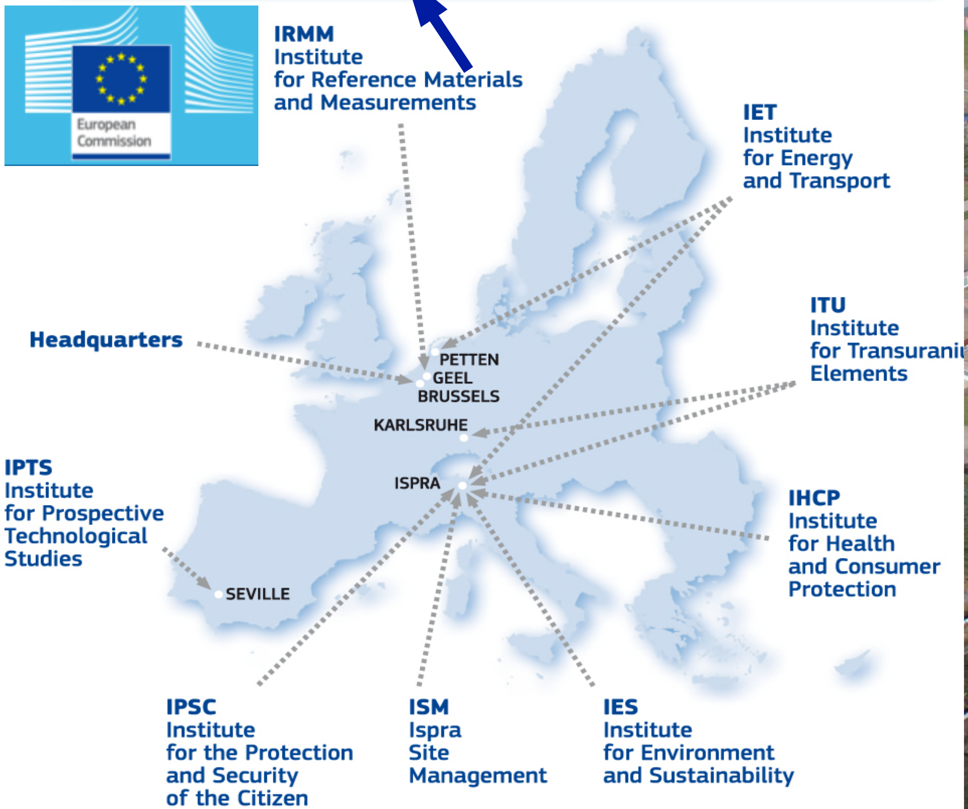
Monte Carlo methods: Longland, *et al.*, Phys. Rev. C **85** (2012)

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

Measurement

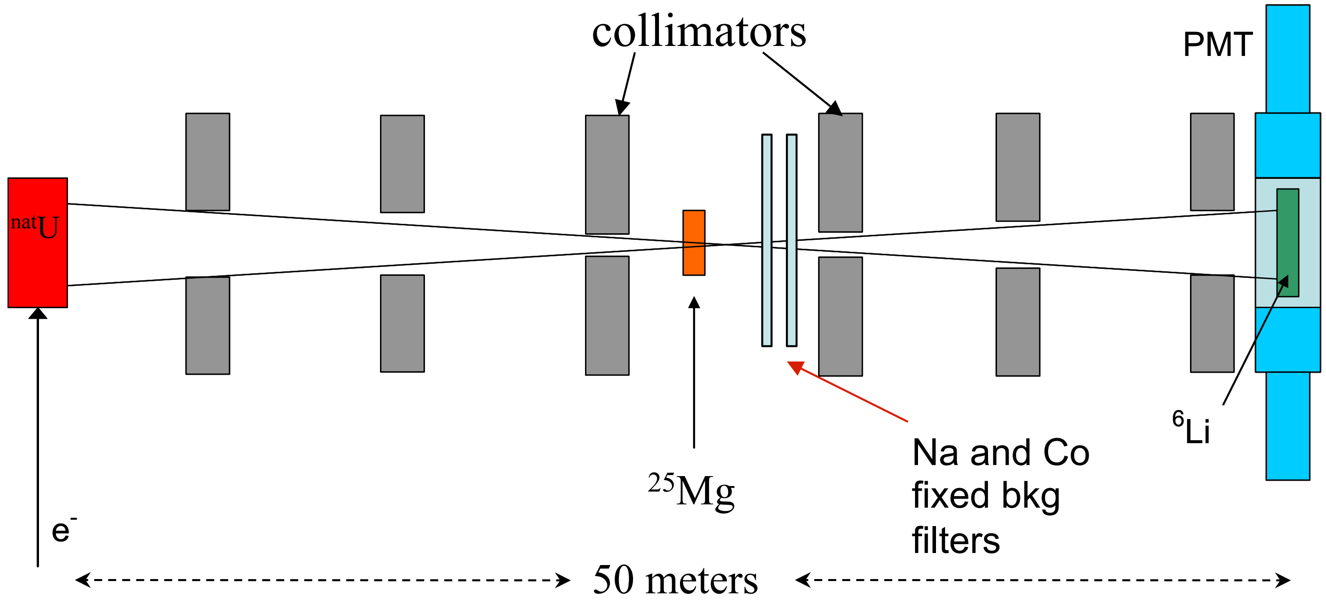
INFN Istituto Nazionale di Fisica Nucleare

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).



Measurement

Experimental set up



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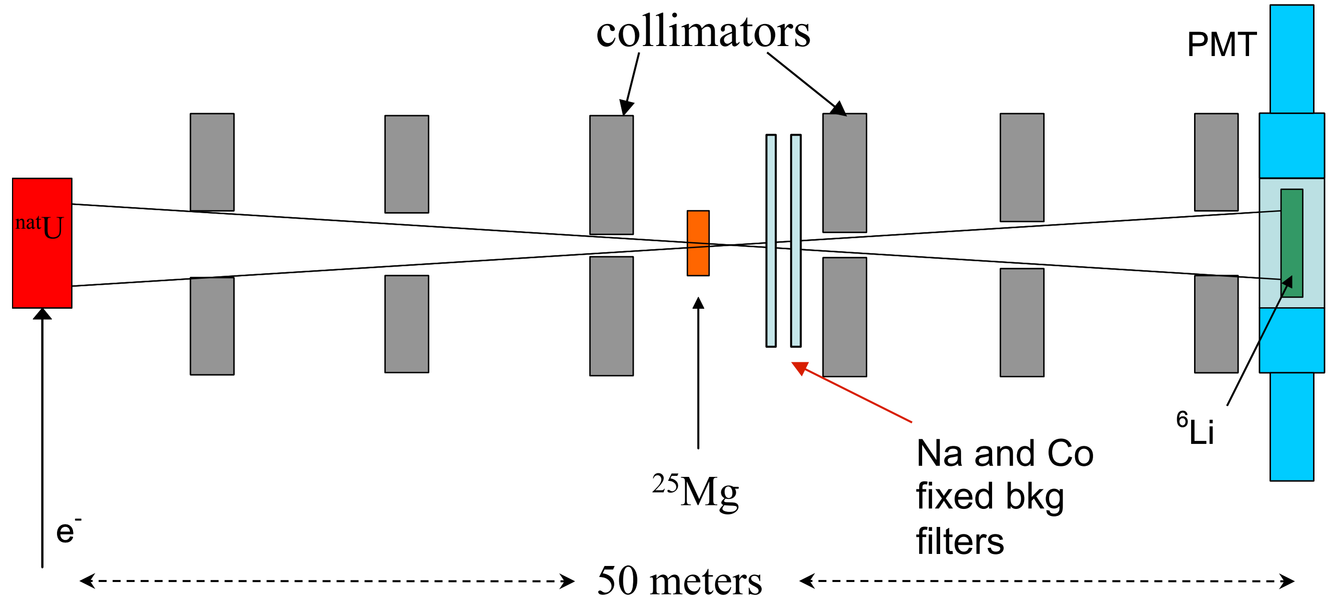

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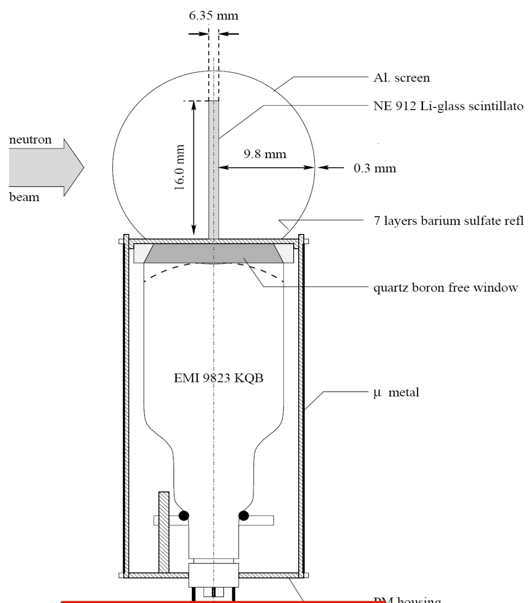
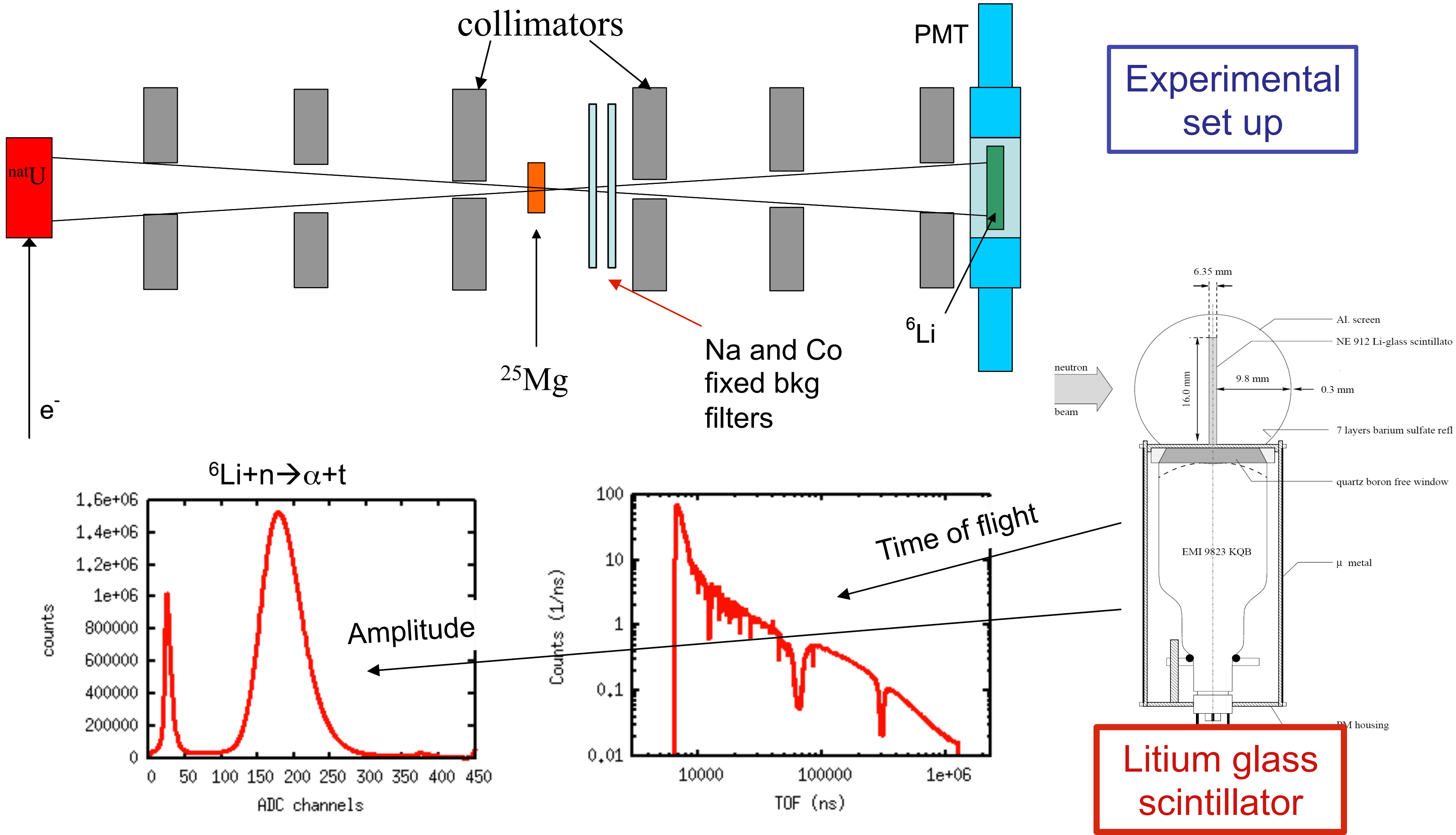


Litium glass scintillator

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

Measurement



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Istituto Nazionale di Fisica Nucleare

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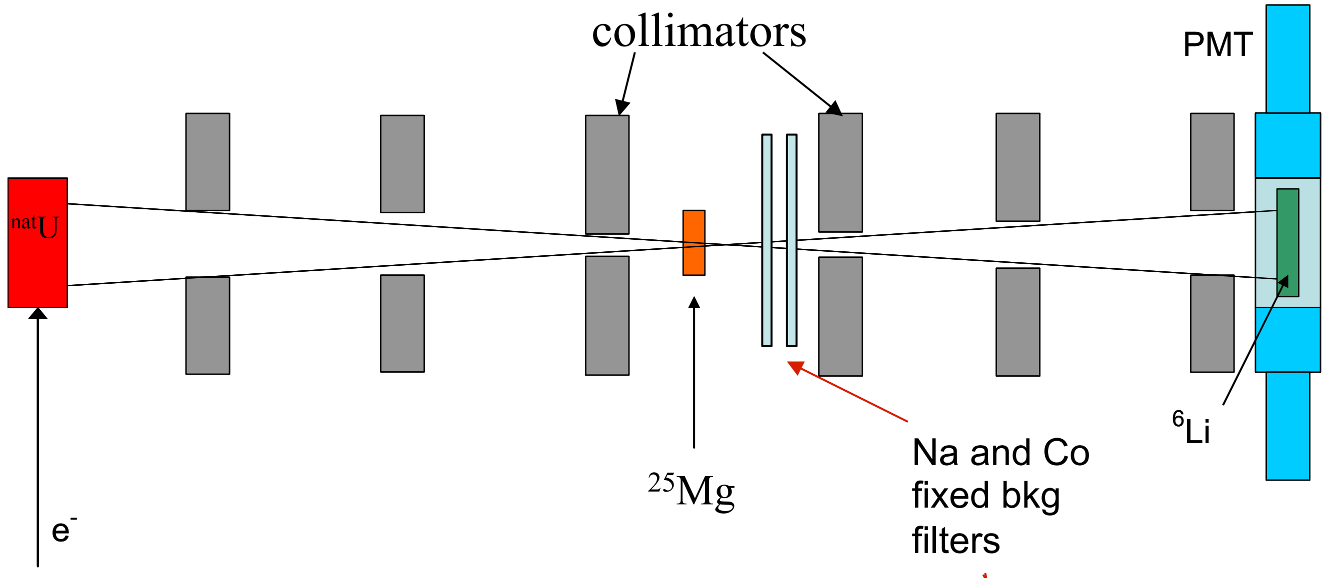

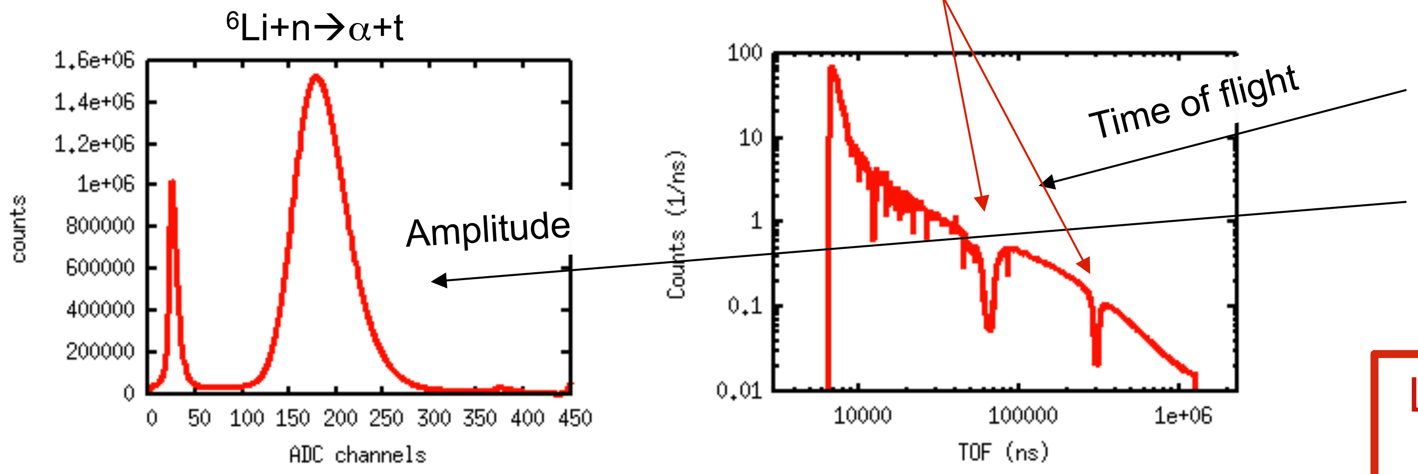

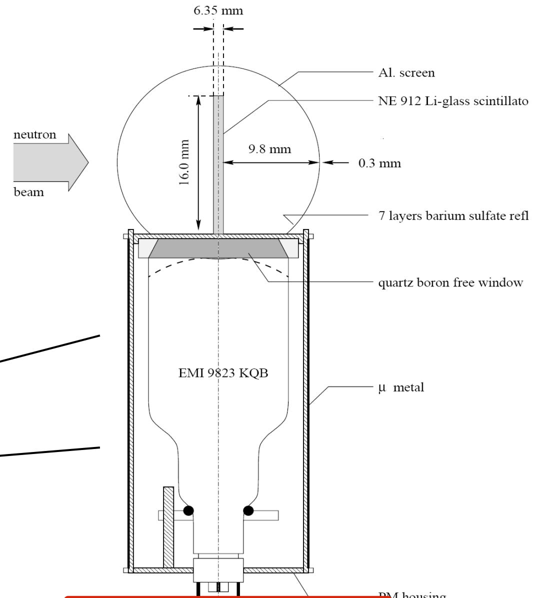

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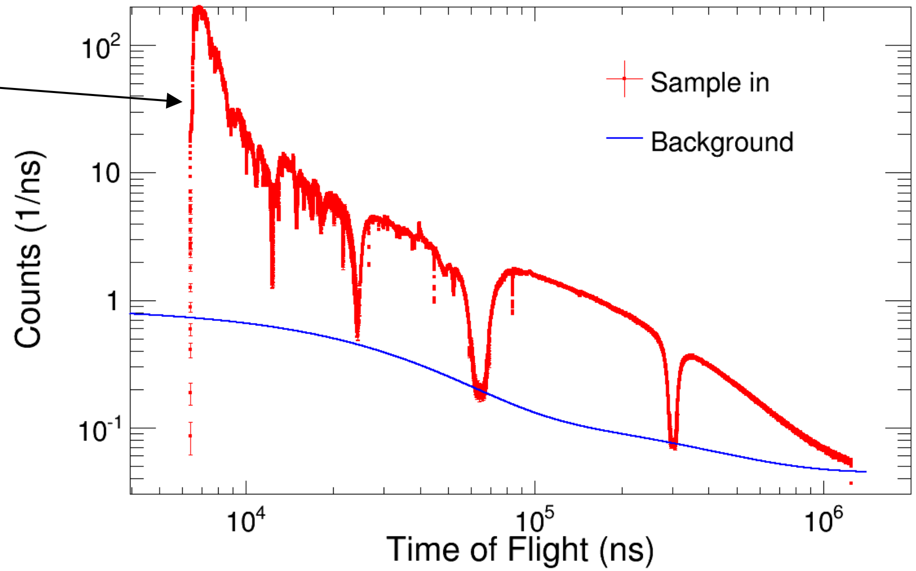
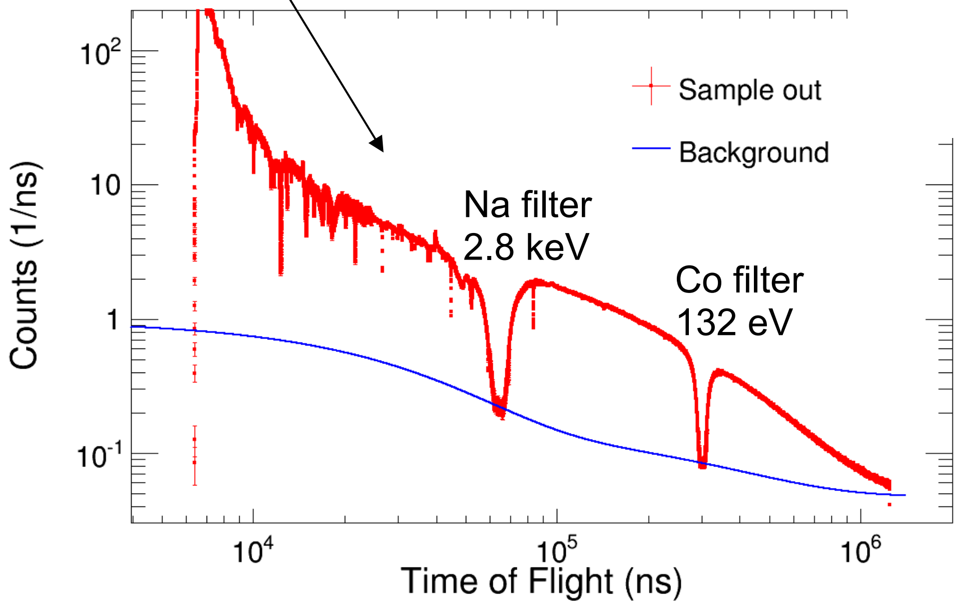
$$T = \frac{C_{in}}{C_{out}} \propto e^{-n\,\sigma_{tot}}$$





Background determined by **black resonance** technique:

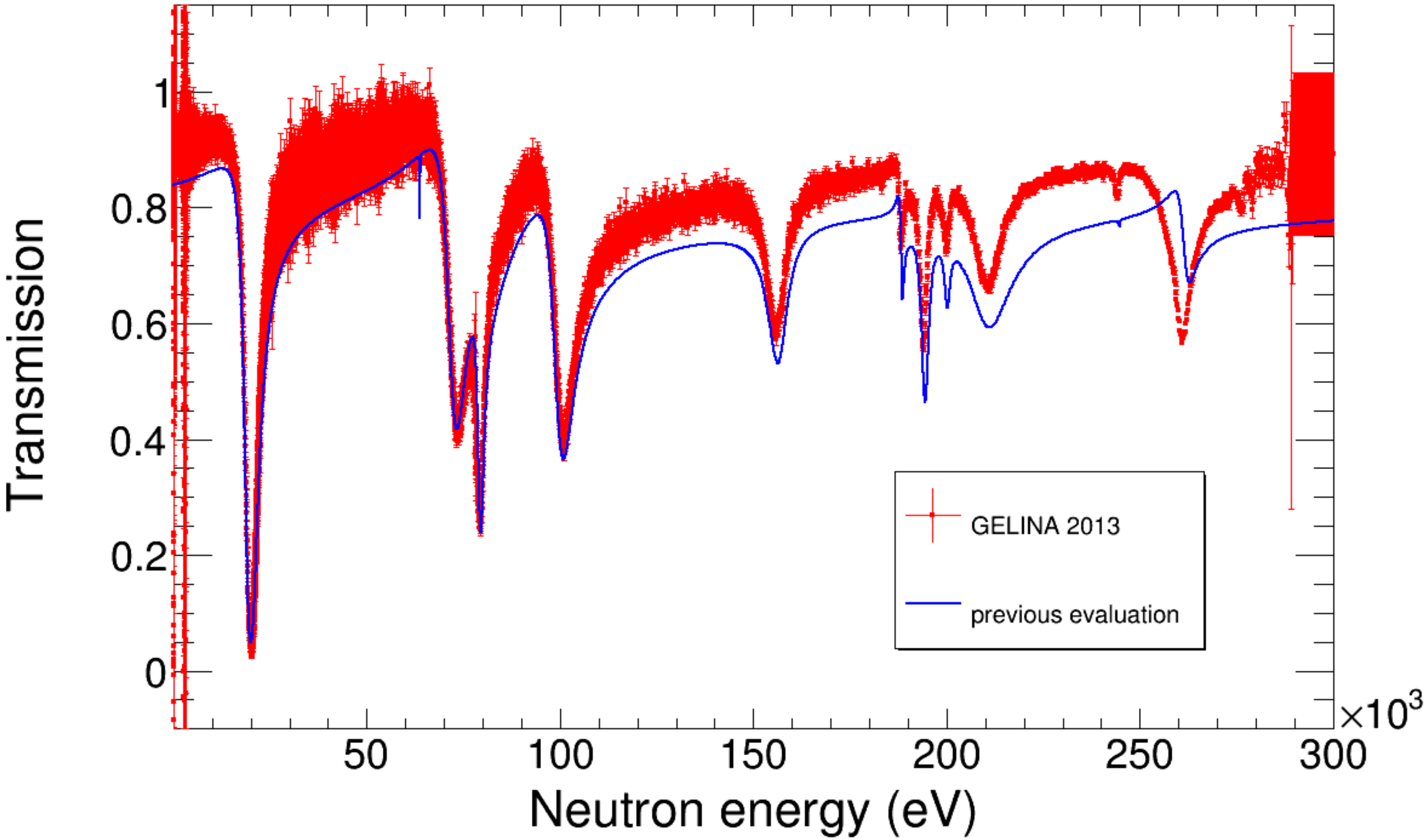
$$B(t) = b_0 + b_1 e^{-\lambda_1 t} + b_2 e^{-\lambda_2 t} + b_3 e^{-\lambda_3 (t+t_0)}$$

→ fixed background filters

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

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

Measurement



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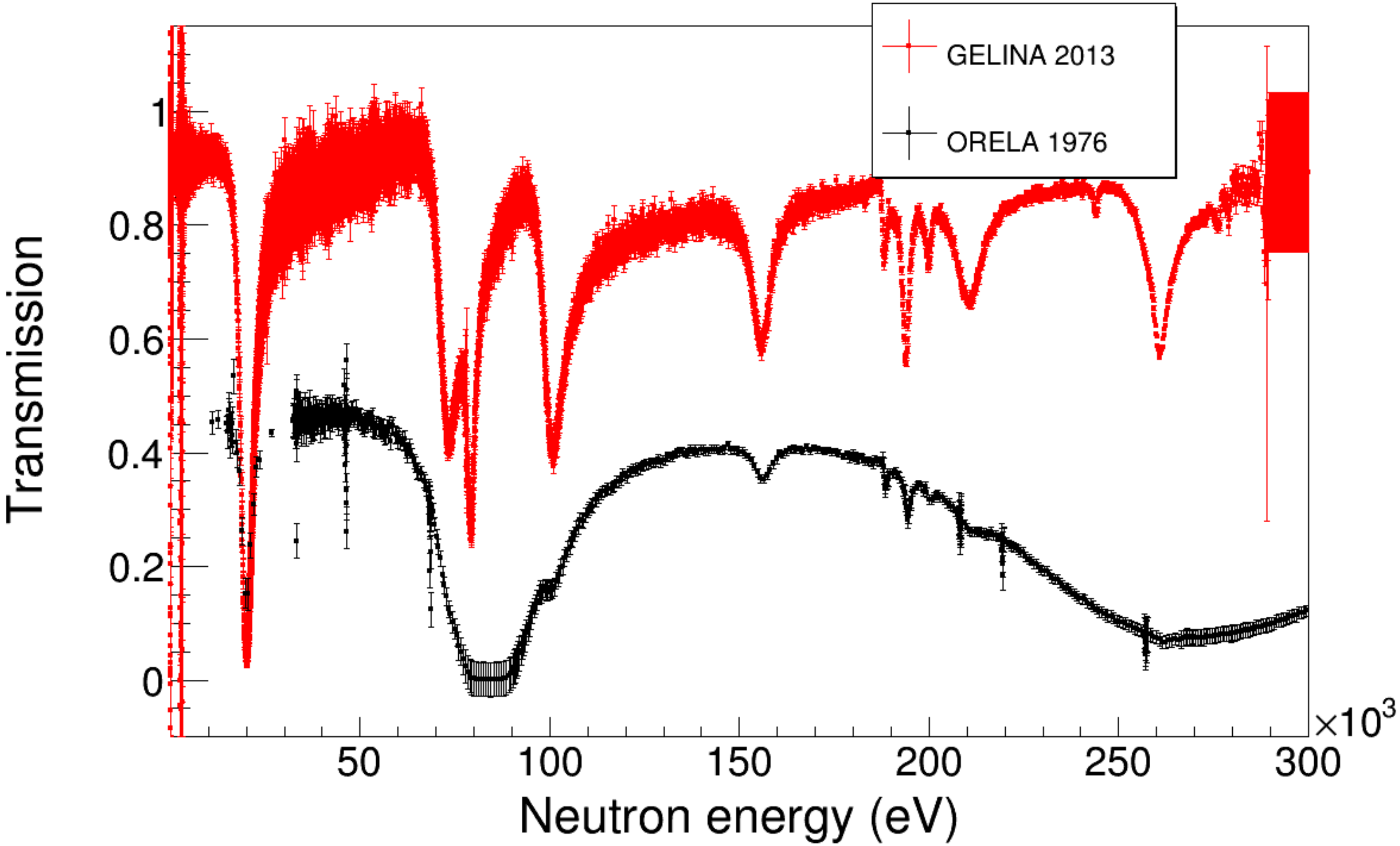
Istituto Nazionale di Fisica Nucleare



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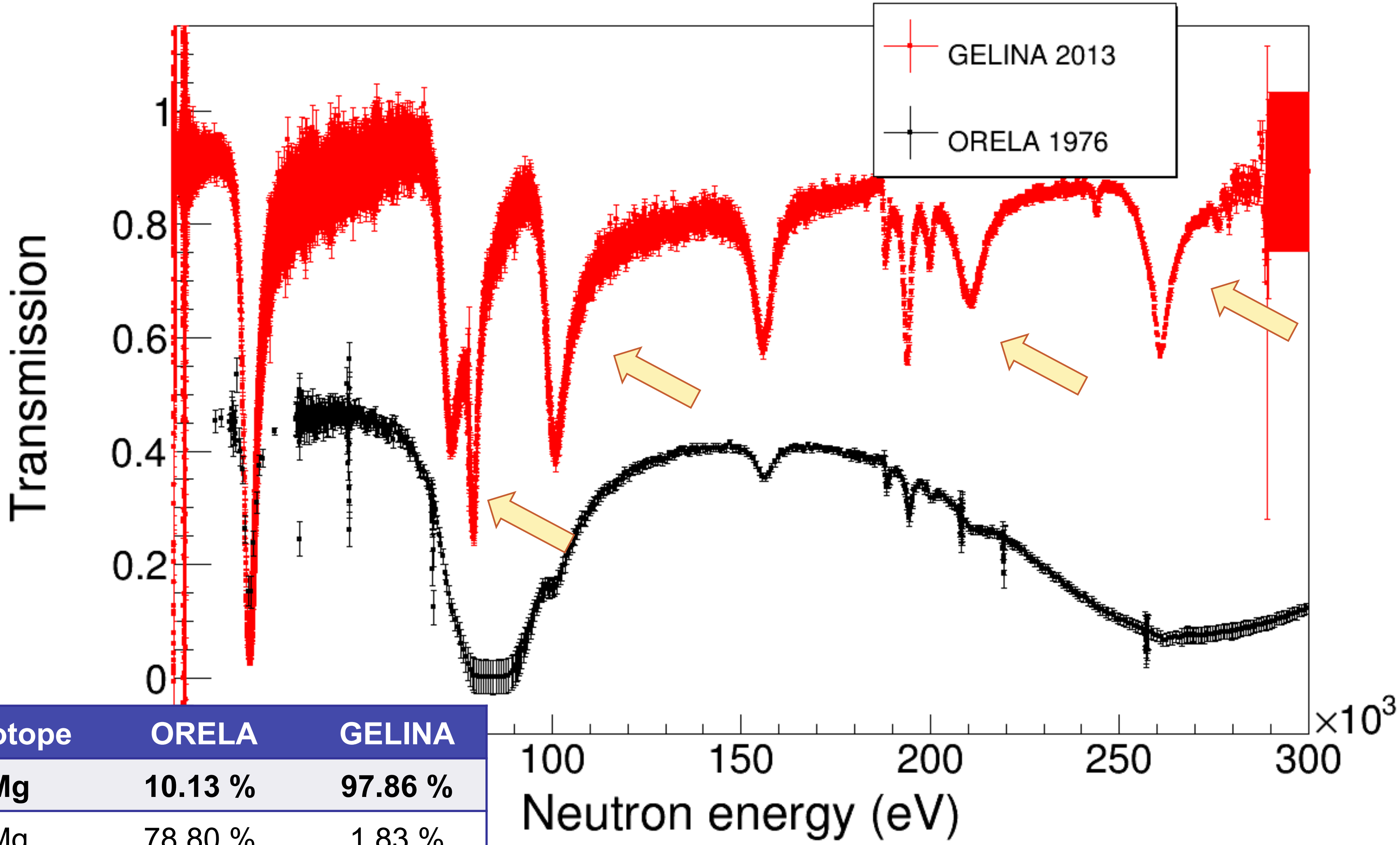


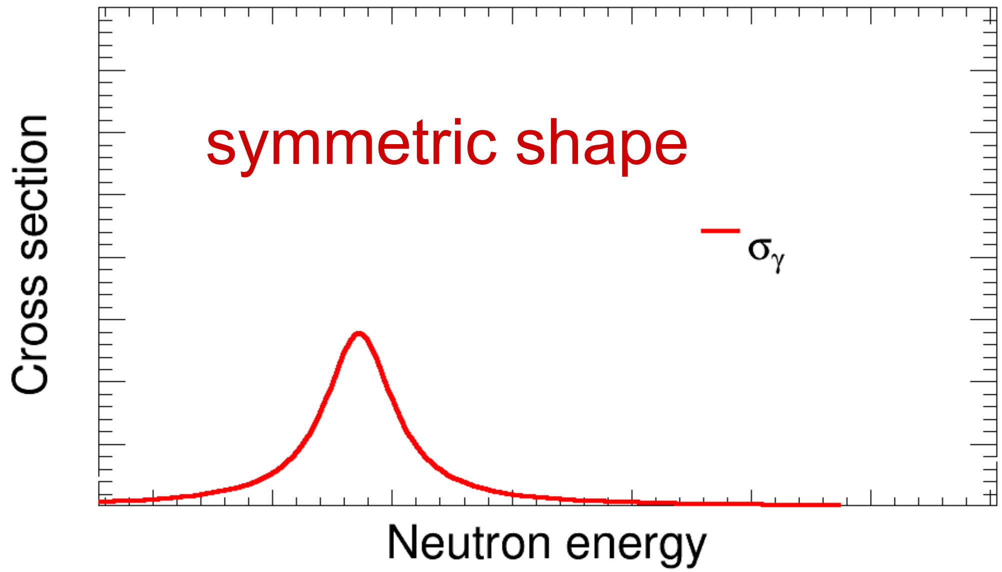
Isotope	ORELA	GELINA
^{25}Mg	**10.13 %**	**97.86 %**
^{24}Mg	78.80 %	1.83 %
^{26}Mg	11.17 %	0.31 %

Measurement

Analysis of Transmission data → $\sigma_{tot} = \sigma_\gamma + \sigma_{el}$

$\sigma_{el} >> \sigma_\gamma$

SLBW $$\sigma_\gamma(E_n) = g_n \frac{\pi}{k_n^2} \frac{\Gamma_n \Gamma_\gamma}{(E_n - E_o)^2 + (\Gamma/2)^2}$$



s-wave neutron resonance

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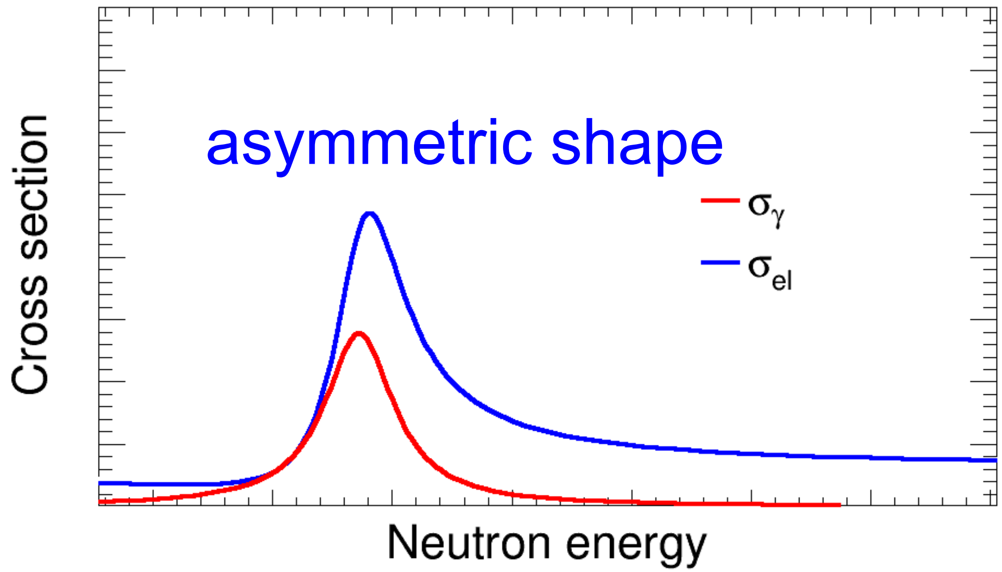

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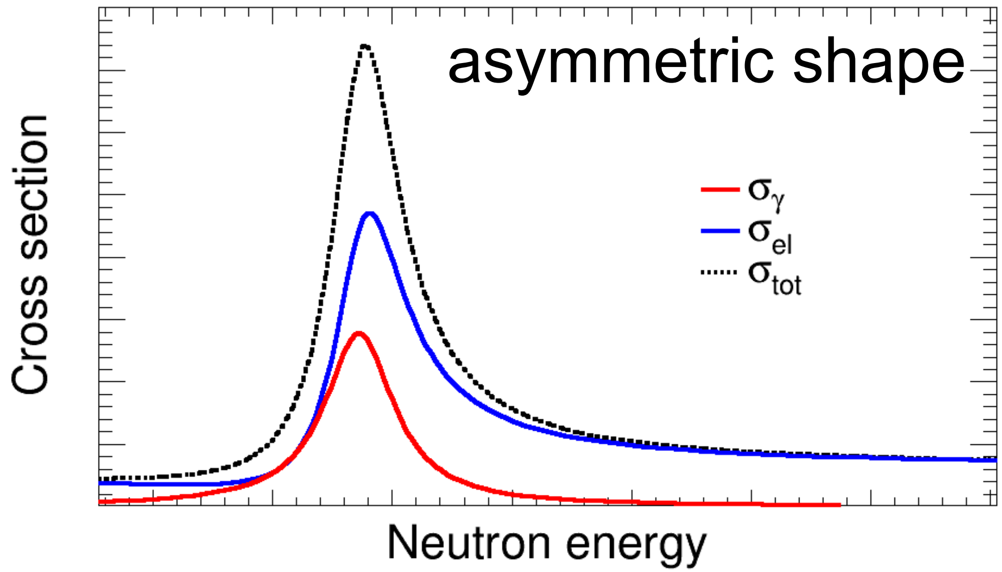

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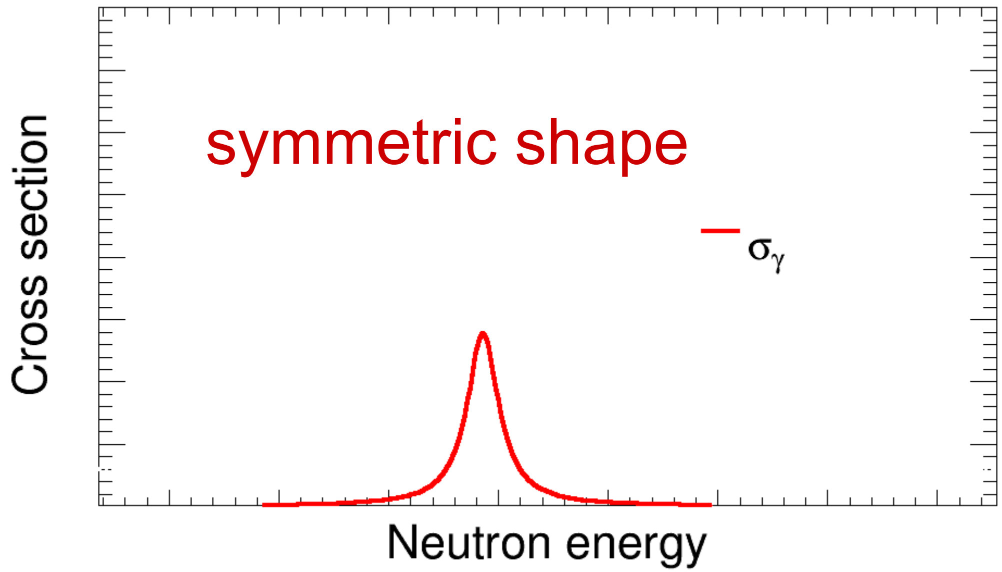

p-wave neutron resonance

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

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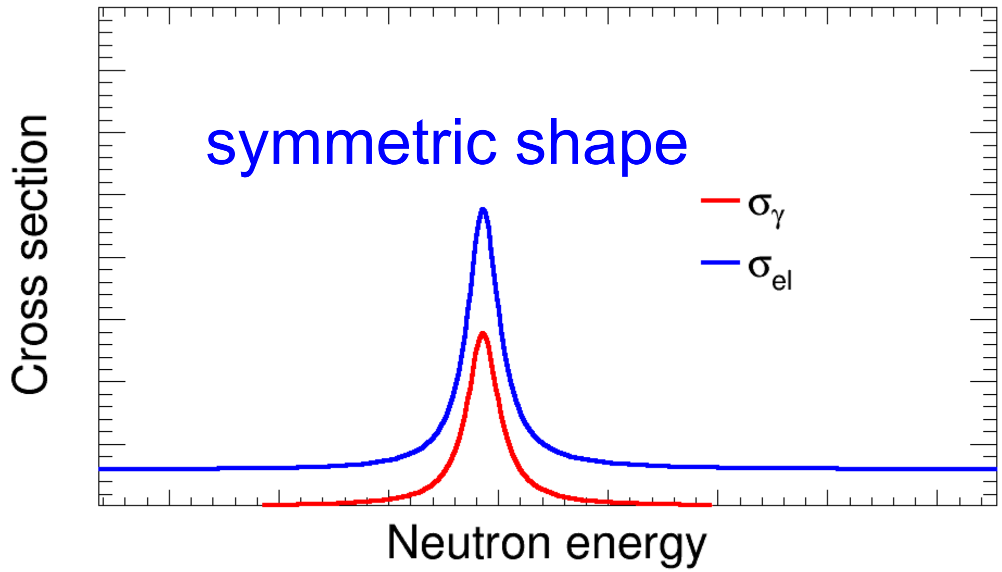

p-wave neutron resonance

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

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Istituto Nazionale di Fisica Nucleare

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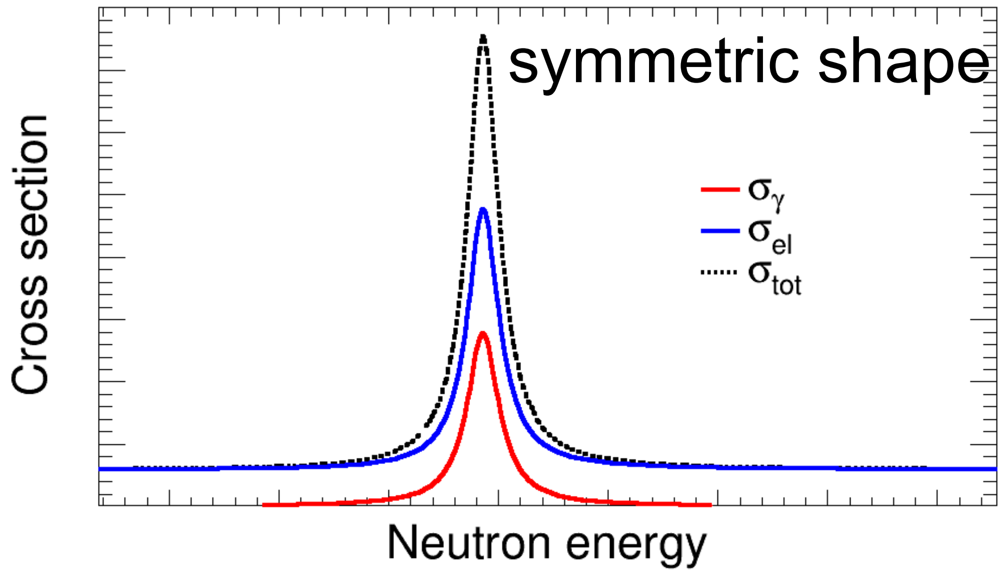
SLBW

$$\sigma_{tot}(E_n) = g_n \frac{\pi}{k_n^2} \frac{\Gamma_n \Gamma}{(E_n - E_o)^2 + (\Gamma/2)^2} + g_n \frac{4\pi}{k_n} \frac{\Gamma_n (E - E_o) a}{(E_n - E_o)^2 + (\Gamma/2)^2} + g_n 4\pi a^2$$



p-wave neutron resonance

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

Measurement

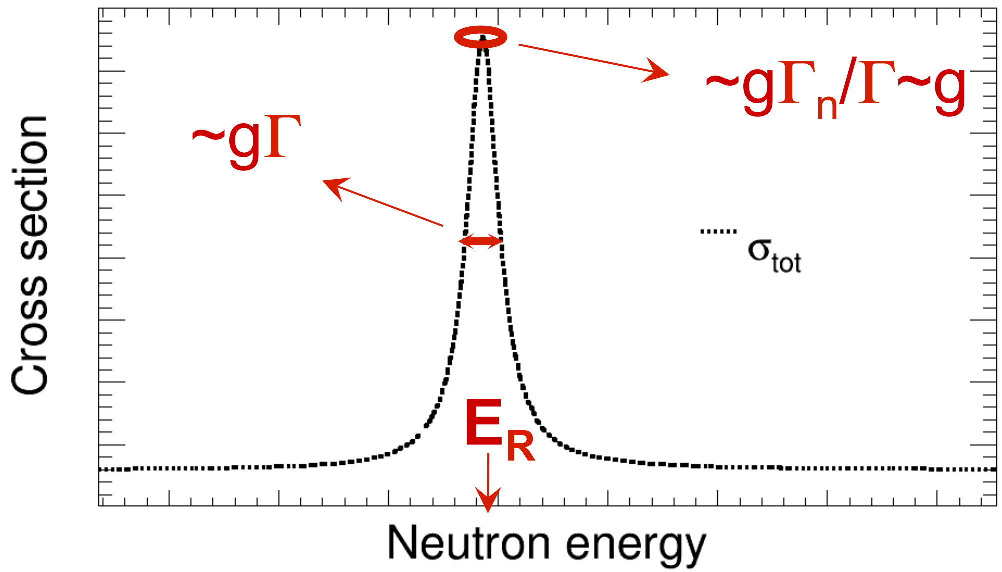
Istituto Nazionale di Fisica Nucleare

Analysis of Transmission data → $\sigma_{tot} = \sigma_\gamma + \sigma_{el}$

$\sigma_{el} >> \sigma_\gamma$

SLBW

$$\sigma_{tot}(E_n) = g_n \frac{\pi}{k_n^2} \frac{\Gamma_n \Gamma}{(E_n - E_o)^2 + (\Gamma/2)^2} + g_n \frac{4\pi}{k_n} \frac{\Gamma_n (E - E_o) a}{(E_n - E_o)^2 + (\Gamma/2)^2} + g_n 4\pi a^2$$



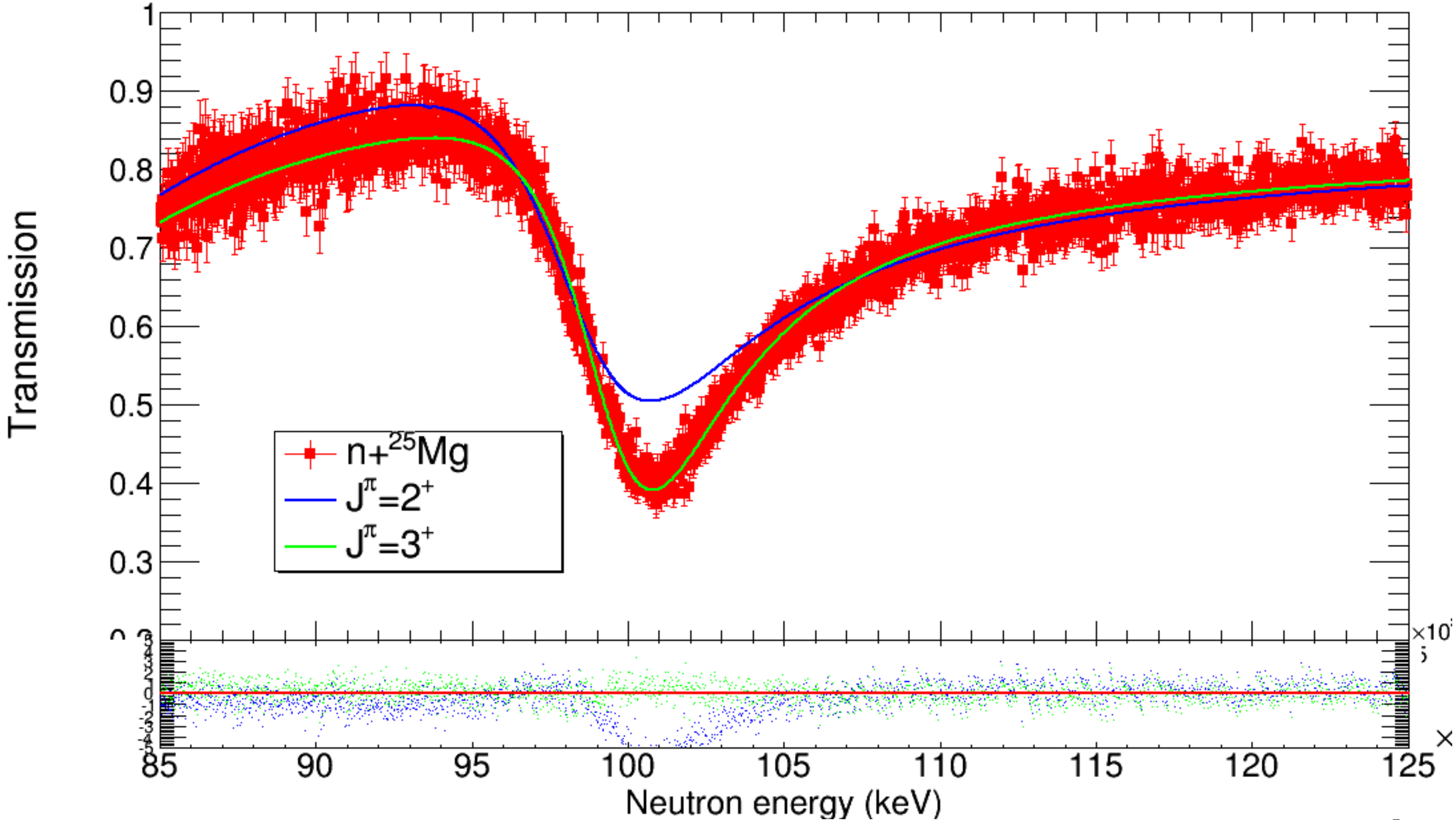
Resonance shape analysis of transmission data:

- ✓ **Resonance energy**
- ✓ **Parity**
- ✓ **$g = (2J+1)/[(2I+1)(2i+1)]$**
- ✓ Γ_n

E_R, Γ_n, J^π

Measurement

Example of sensitivity to J^π

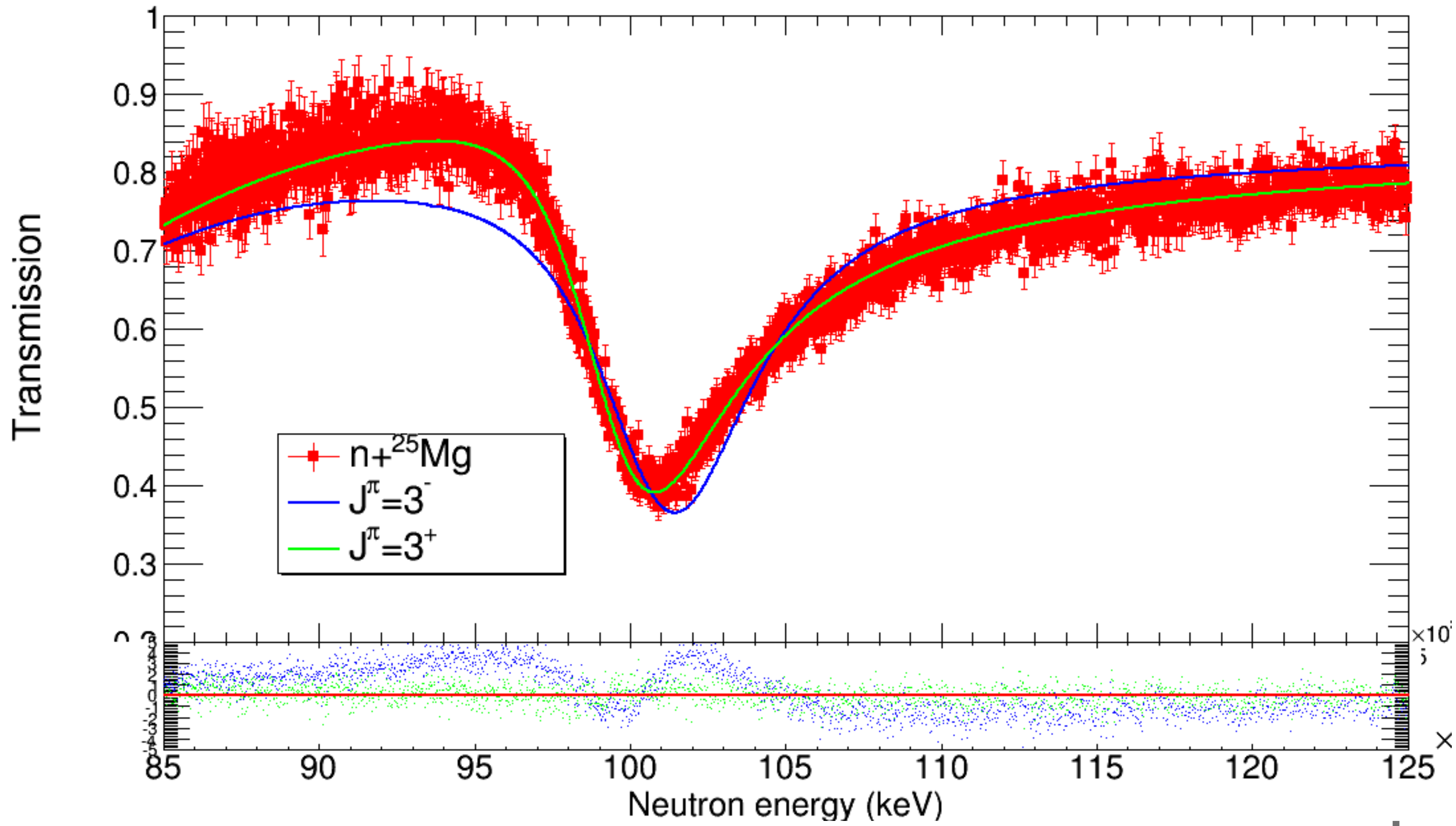


$^{25}Mg(n, tot)$ @ GELINA

Measurement

Istituto Nazionale di Fisica Nucleare

Example of sensitivity to J^{π}



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

Measurement

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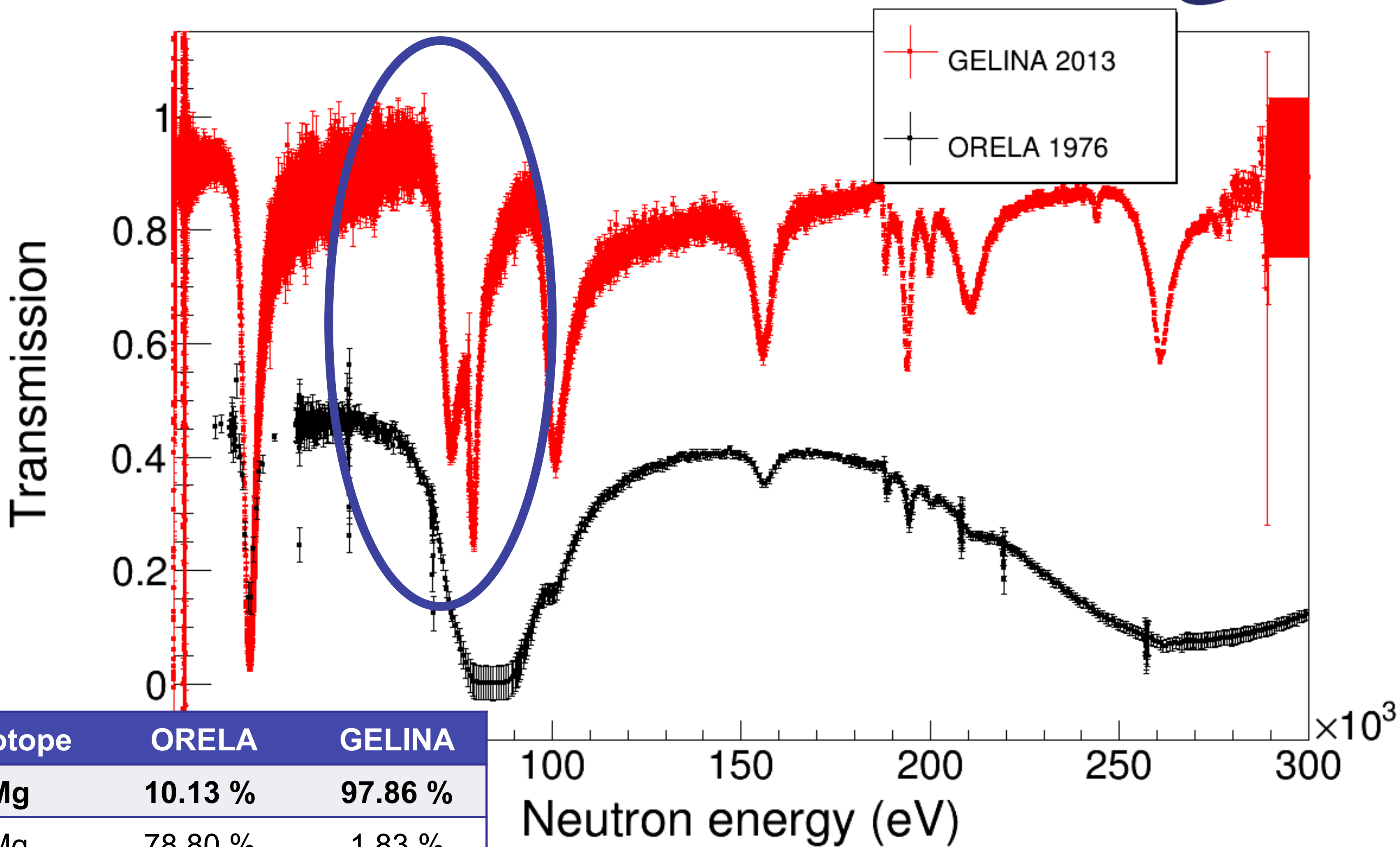
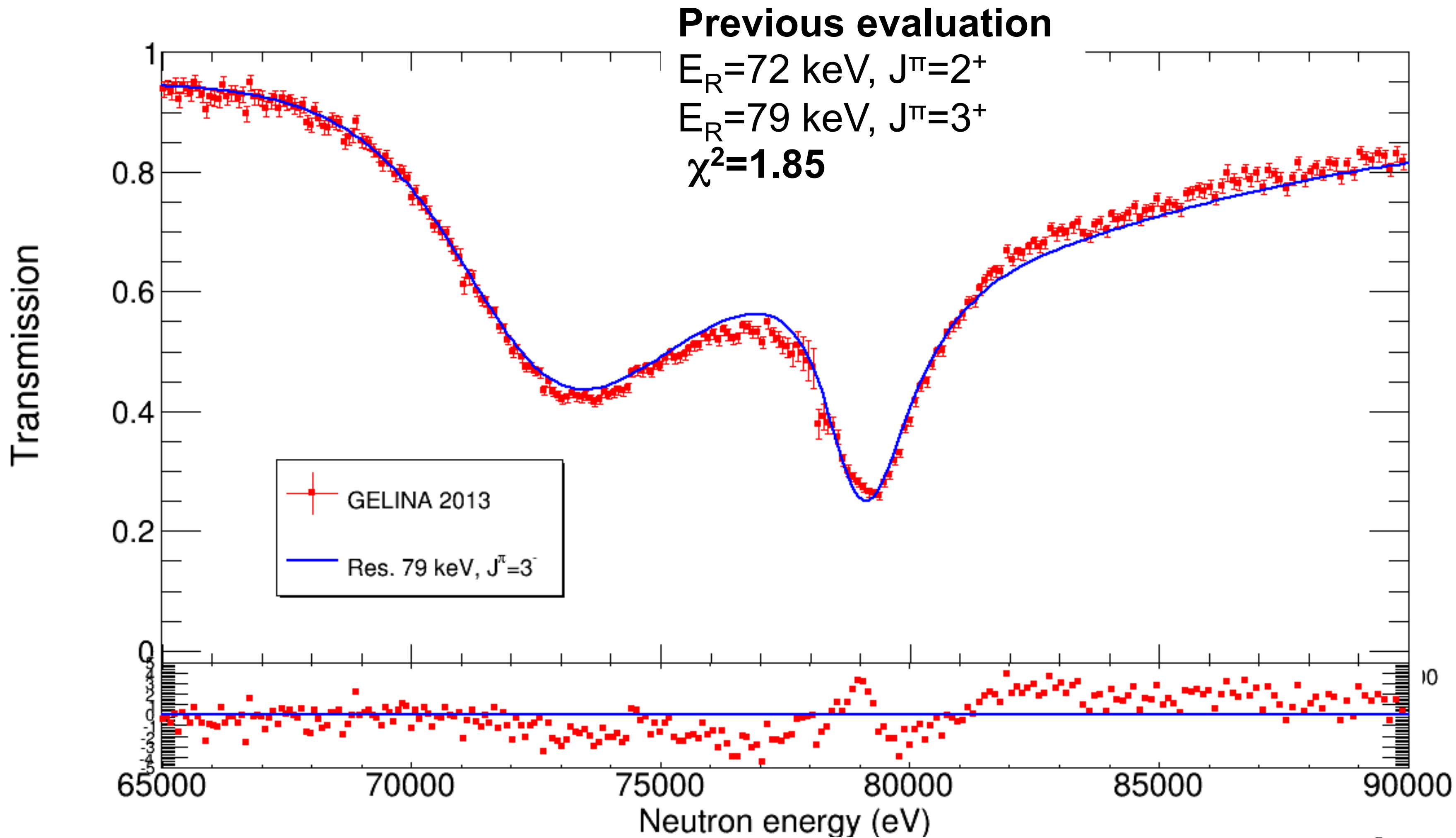


Isotope	ORELA	GELINA
^{25}Mg	**10.13 %**	**97.86 %**
^{24}Mg	78.80 %	1.83 %
^{26}Mg	11.17 %	0.31 %

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

Measurement



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

Measurement

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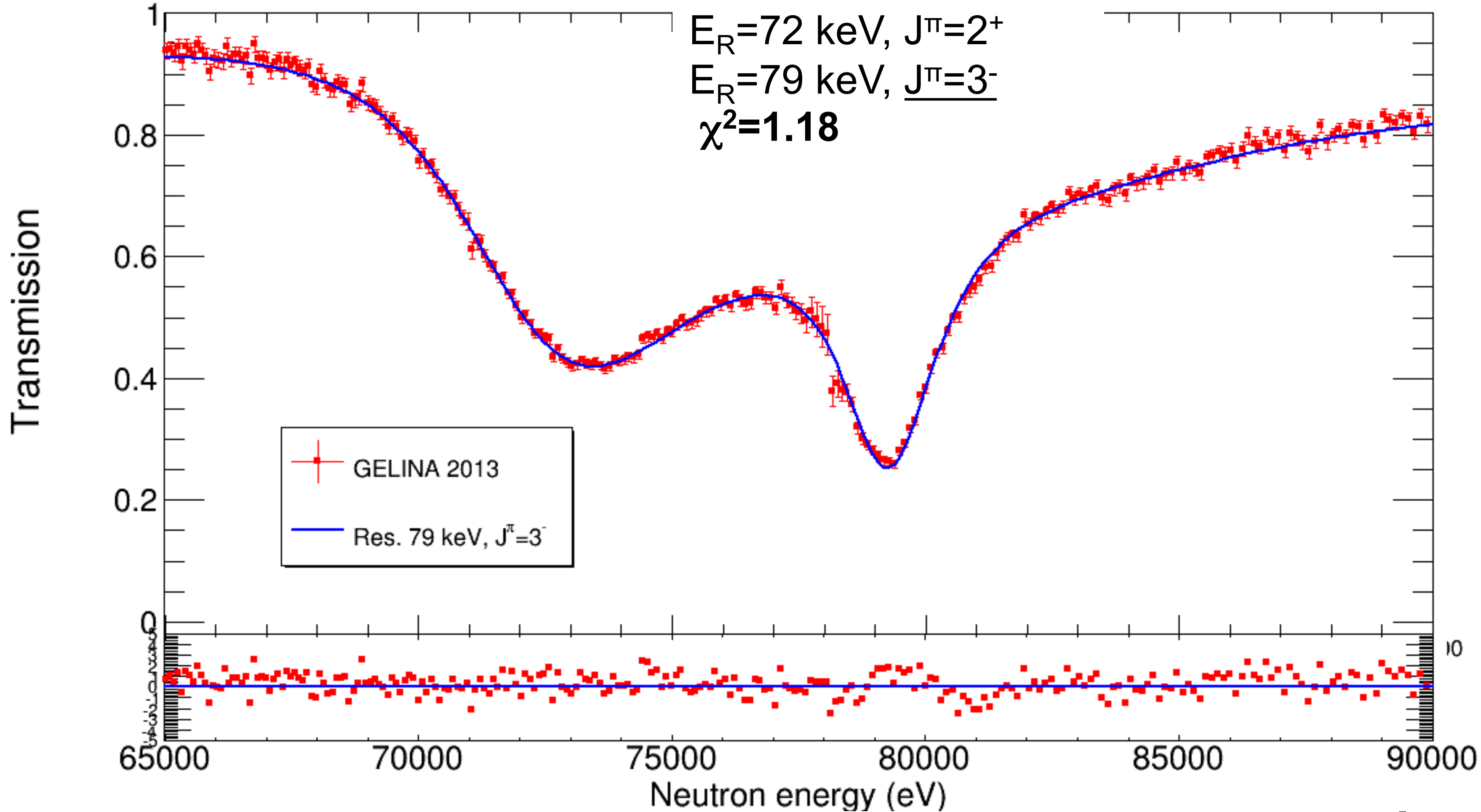
This work

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

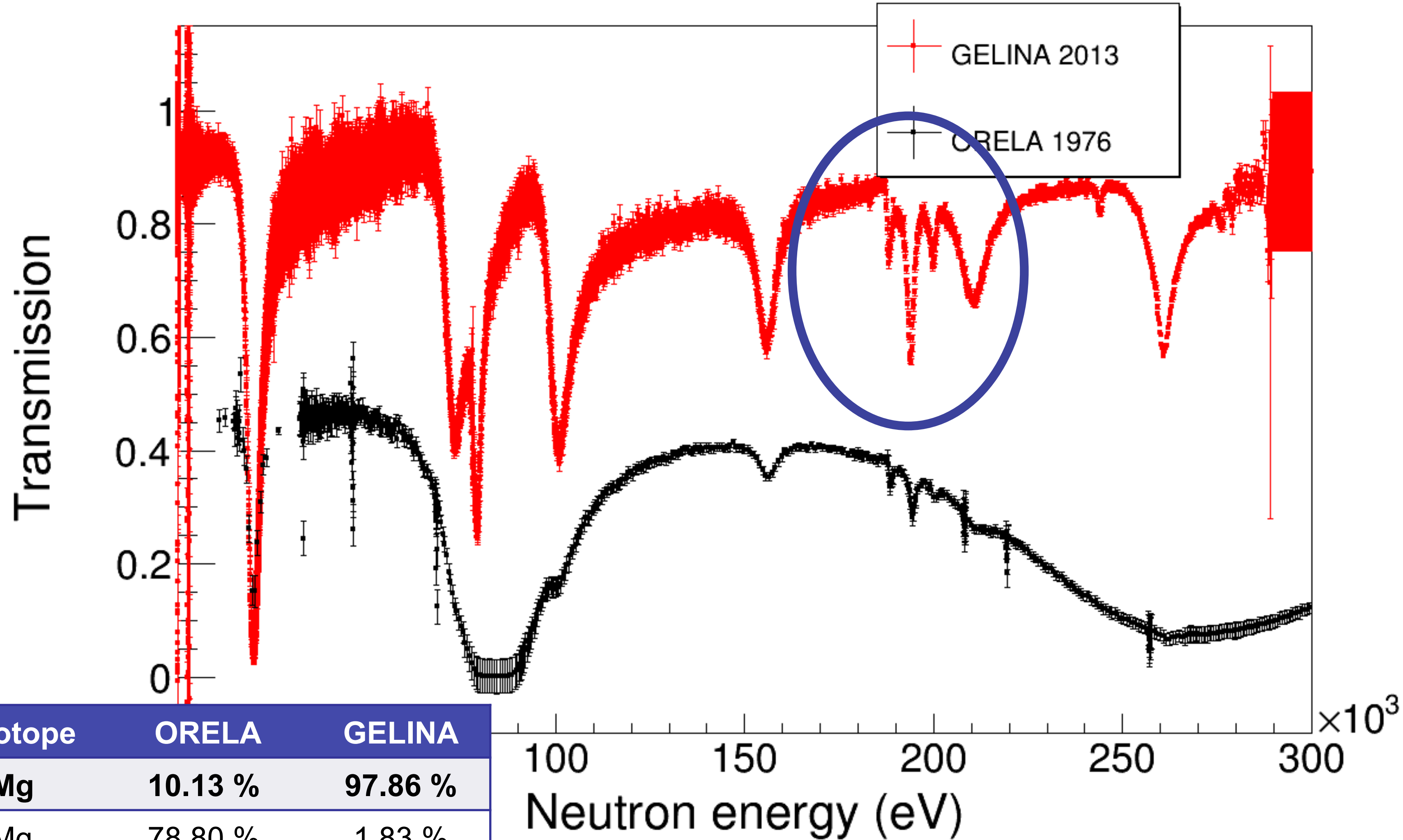
E_R=79 keV, $J^\pi=3^-$

χ^2=1.18



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

Measurement



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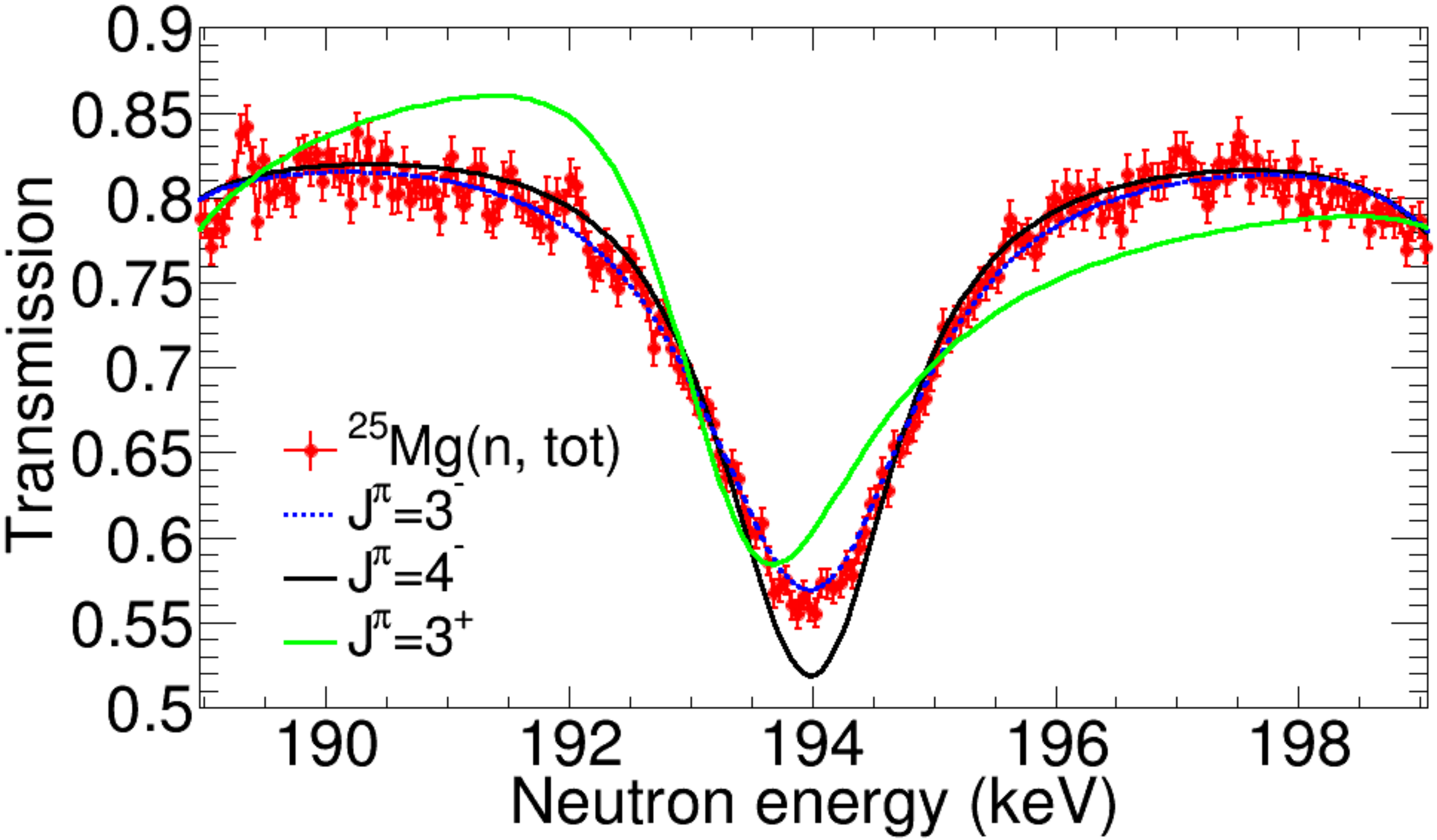
$^{25}Mg(n, tot)$ @ GELINA

Measurement



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

Results

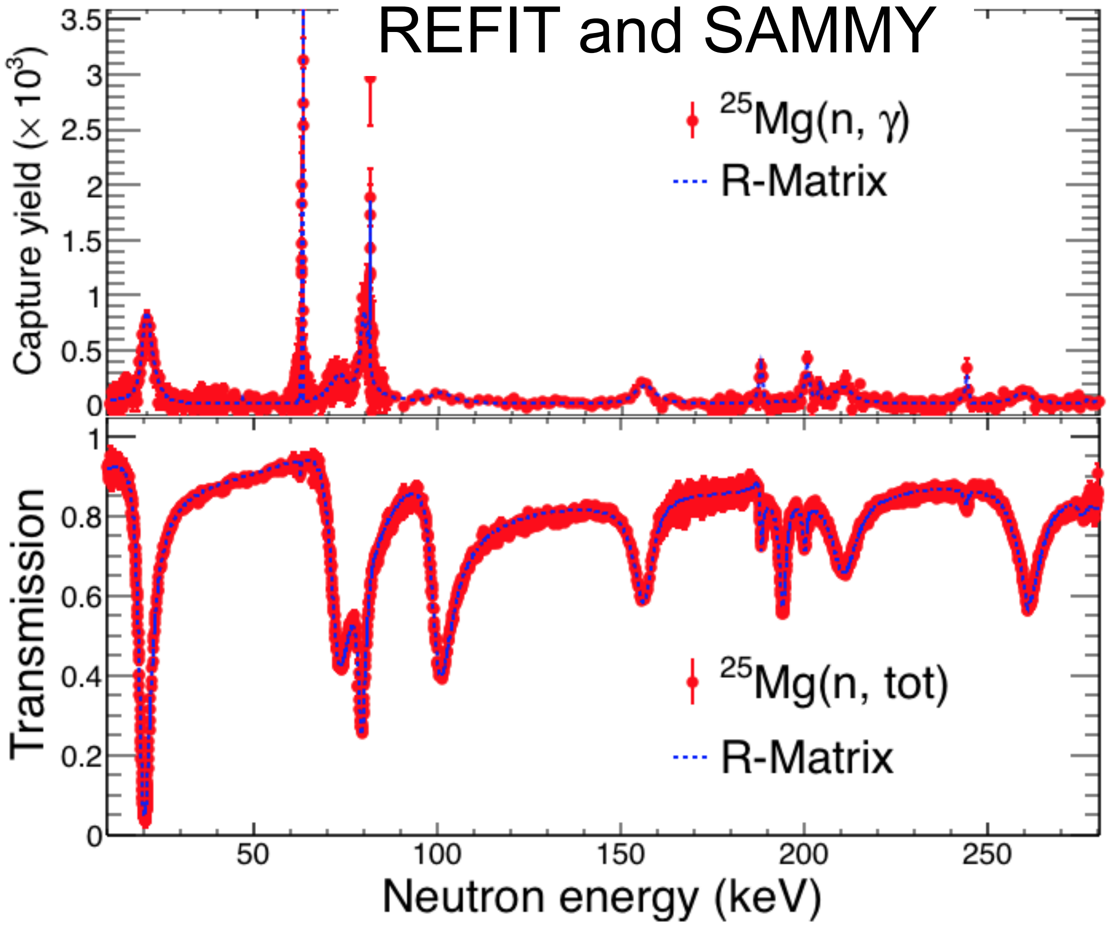
^{25}Mg(n,γ) improved parameterization

PRELIMINARY

Table 1: n+^{25}Mg resonance parameters and corresponding excitation e[illegible]gies of the ^{26}Mg compound nucleus.

E_n (keV)	E_x (keV)	E_α^{Lab} (keV)	J^π ($\hbar$)	Γ_γ (eV)	Γ_n (eV)
19.92(1)	11112	589	2^+	1.37(6)	[illegible]
62.73(1)	11154		1^+	[illegible]	[illegible]7(2)
72.82(1)	11163	649	2^+	[illegible]	5310(50)
79.23(1)	11169	656	$3^{-(a)}$	[illegible]	1940(20)
81.11(1)	11171			[illegible]	1 – 30
100.33(2)	11190		[illegible]	[illegible]	5230(30)
155.83(2)	11243		[illegible]	4.7(5)	5950(50)
187.95(2)	11274	[illegible]	[illegible]	2.2(2)	410(10)
194.01(2)	11280	[illegible]	$3^{-(a)}$	0.3(1)	1810(20)
199.84(2)	[illegible]		2^-	4.8(4)	1030(30)
203.88(4)	[illegible]			0.9(3)	3 – 20
[illegible]	[illegible]		2^-	6.6(6)	7370(60)
[illegible]	[illegible]	843	$2^{+(b)}$	2.2(3)	171(6)
[illegible]	11344			1.0(2)	300 – 3900
[illegible]	11344		> 3	3.0(3)	6000 – 9000

$^{(a)}$ Parity change with respect to previous evaluations.
$^{(b)}$ Spin/parity assignment from ^{22}Ne(α, n) cross section.



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

Results

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

Table 1: n+^{25}Mg resonance parameters and corresponding excitation e[illegible]gies of the ^{26}Mg compound nucleus.

E_n (keV)	E_x (keV)	E_α^{Lab} (keV)	J^π ($\hbar$)	Γ_γ (eV)	Γ_n (eV)
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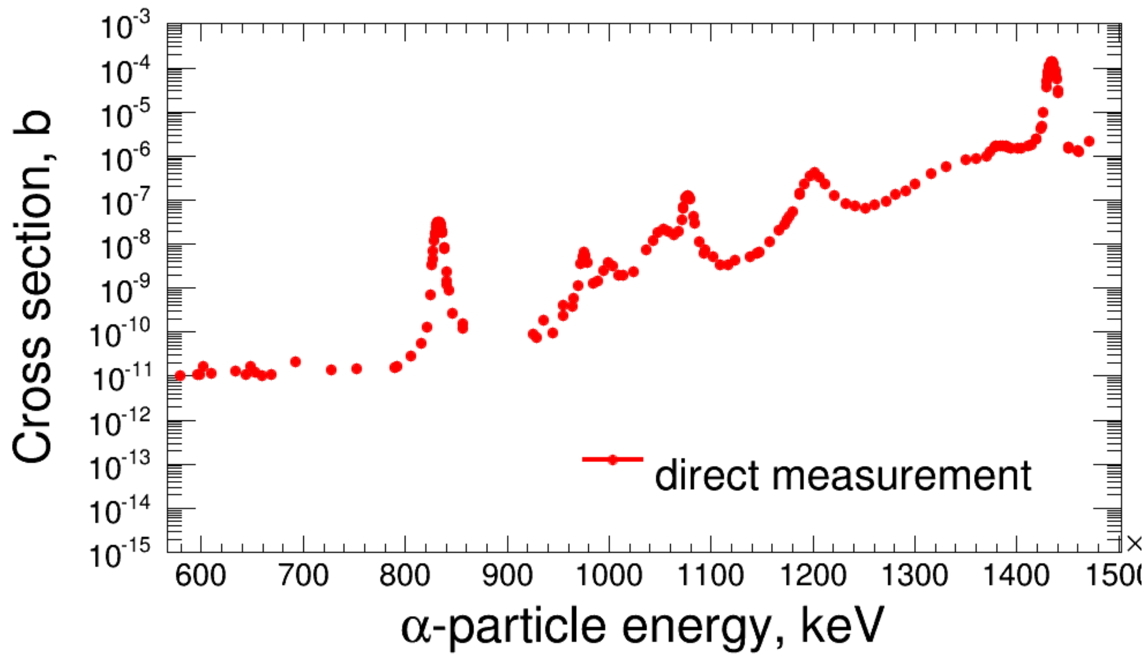
[illegible] Parity change with respect to previous evaluations.
$^{(b)}$ Spin/parity assignment from ^{22}Ne(α, n) cross section.

PRELIMINARY

5 resonances with natural J^π below E_α = 800 keV

$^{22}Ne(\alpha,n)^{25}Mg$ reaction cross section(s)



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

Results

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

Table 1: $n+^{25}Mg$ resonance parameters and corresponding excitation e[illegible]gies of the ^{26}Mg compound nucleus.

PRELIMINARY

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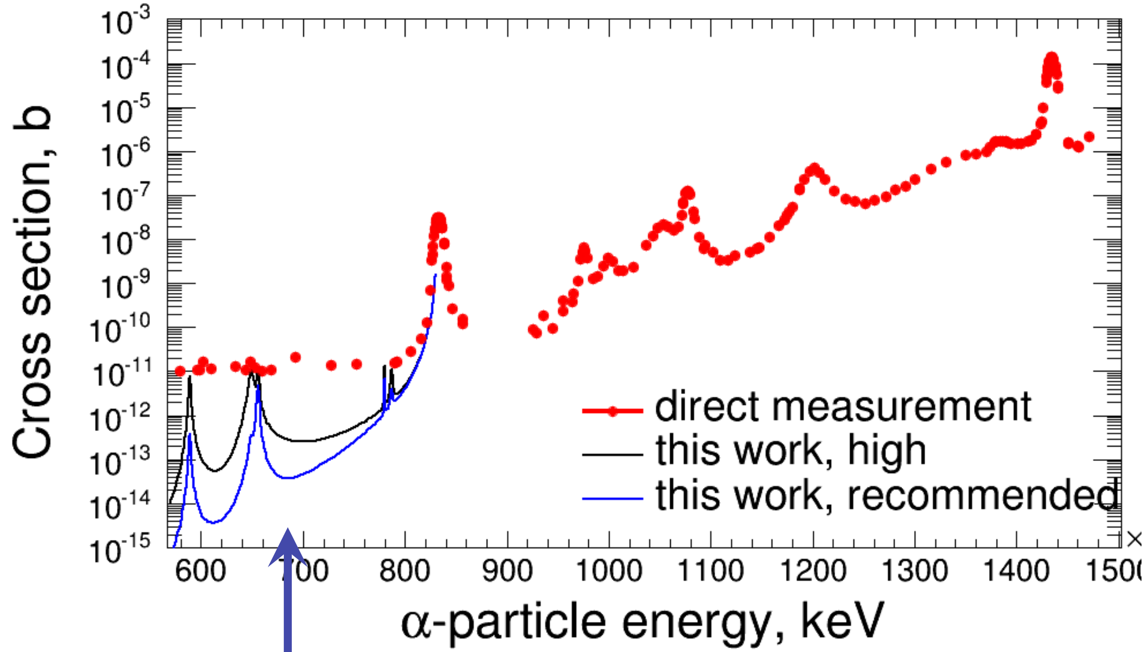

Results

$^{25}Mg(n,\gamma)$ improved parameterization → Γ_n, Γ_γ

Resonance strength $^{22}Ne(\alpha,n)^{25}Mg$:
$\omega_n = g\Gamma_\alpha\Gamma_n/(\Gamma_\alpha+\Gamma_\gamma+\Gamma_n)$

Resonance strength $^{22}Ne(\alpha,\gamma)^{25}Mg$:
$\omega_\gamma = g\Gamma_\alpha\Gamma_\gamma/(\Gamma_\alpha+\Gamma_\gamma+\Gamma_n)$

$$\frac{\omega_n}{\omega_\gamma} = \frac{\Gamma_n}{\Gamma_\gamma}$$

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

Results

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^{25}Mg(n,γ) improved parameterization → Γ_n, Γ_γ

Resonance strength ^{22}Ne(α,n)^{25}Mg:
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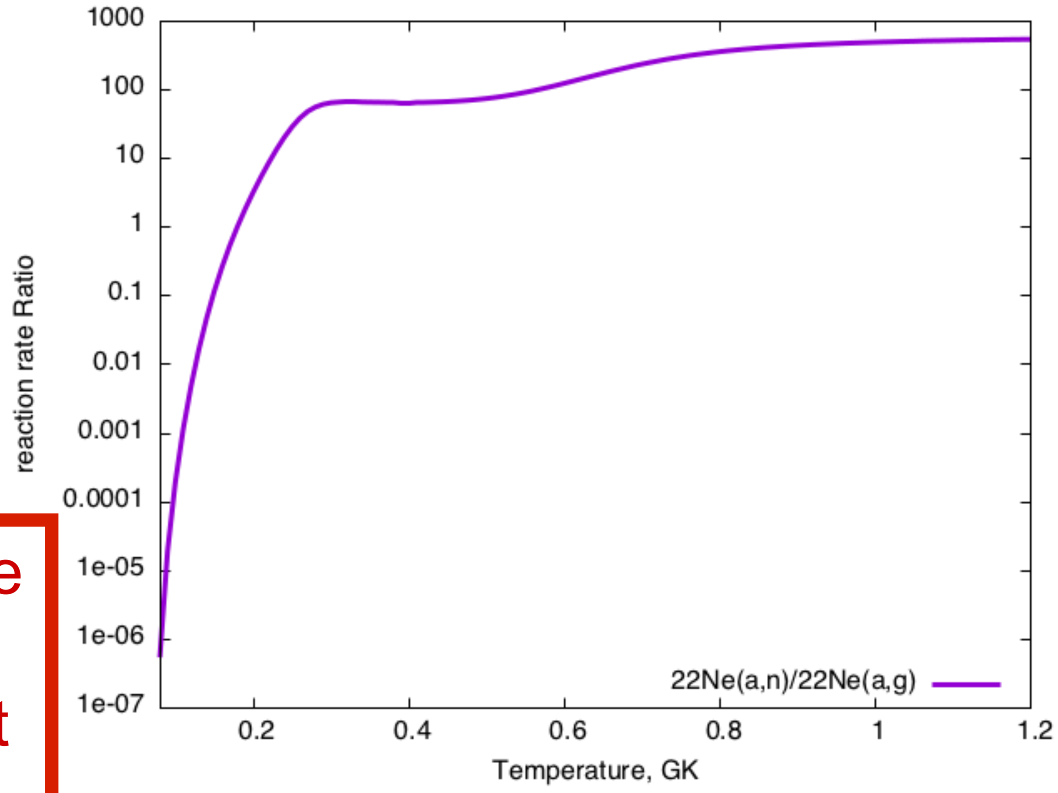
$\omega_\gamma = g\Gamma_\alpha\Gamma_\gamma/(\Gamma_\alpha+\Gamma_\gamma+\Gamma_n)$

$$\frac{\omega_n}{\omega_\gamma} = \frac{\Gamma_n}{\Gamma_\gamma}$$

Reaction rate **RATIO** independent of Γ_α

^{22}Ne(α,n)^{25}Mg / ^{22}Ne(α, γ)^{25}Mg



Conclusions

- ^{22}Ne(α,n) and (α,γ) represent a long-standing problem in nuclear astrophysics
- The ^{25}Mg(n, tot) measurement was performed at the GELINA facility in 2013 for the study of excited states in ^{26}Mg
- Final analysis - simultaneous resonance shape analysis of capture and transmission:
  - accurate ^{25}Mg(n,γ) cross section ≈ confirms previous n_TOF data;
  - J^{π} information on ^{26}Mg levels → evidence for more natural states than previously thought →**HIGHER ^{22}Ne(α, n) reaction rate;**
  - **Study of the competing ^{22}Ne(α, γ) reaction → Lower reaction rate**

Istituto Nazionale di Fisica Nucleare

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

Cristian Massimi
Dipartimento di Fisica e Astronomia
massimi@bo.infn.it

www.unibo.it

Direct Vs Indirect