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NUCLEAR REACTION RATES FOR THE S-PROCESS Workshop

Università degli Studi della Campania Luigi Vanvitelli

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Neutron spectroscopy of ^{26}Mg states: Constraining the stellar neutron source ^{22}Ne(α,n)^{25}Mg

Cristian Massimi

Department of Physics and Astronomy

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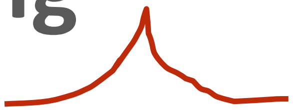
Neutron spectroscopy of ^{26}Mg states: Constraining the stellar neutron source ^{22}Ne(α,n)^{25}Mg



and ^{22}Ne(α,γ)^{26}Mg
… and ^{25}Mg(n,γ)

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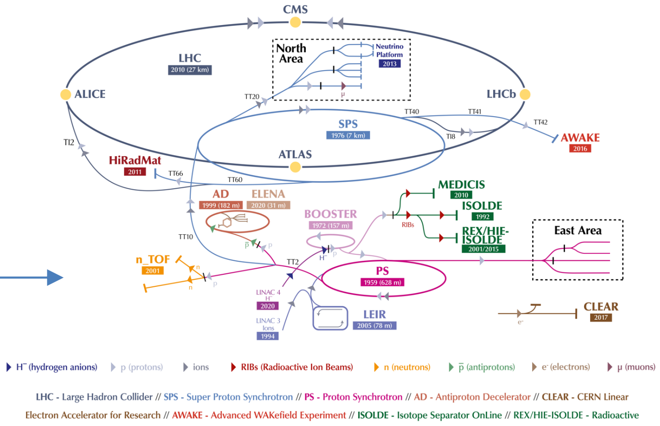
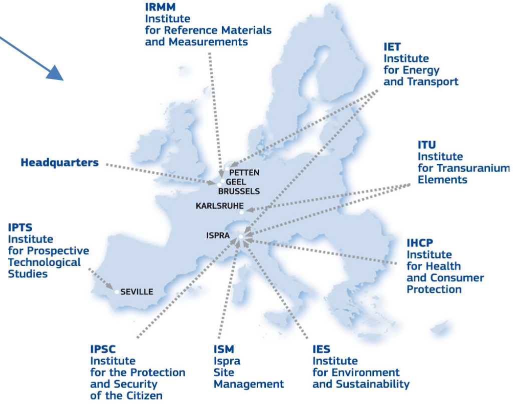
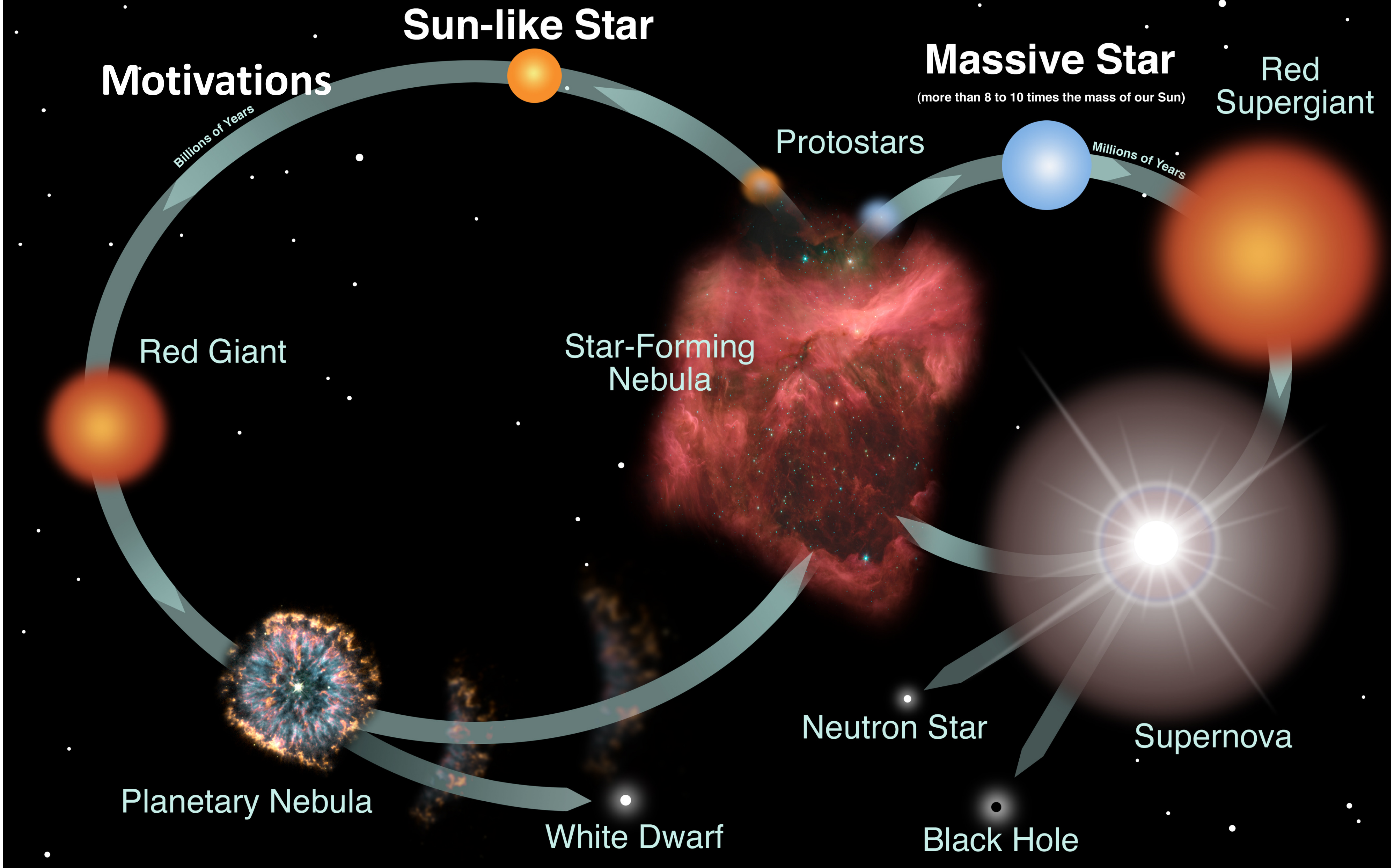
Outline

- ➢ Motivations
- ➢ TOF measurements
  - ○ ^{25}Mg(n,γ) @ n_TOF
  - ○ ^{25}Mg(n,tot) @ GELINA
- ➢ Results
- ➢ Outlook



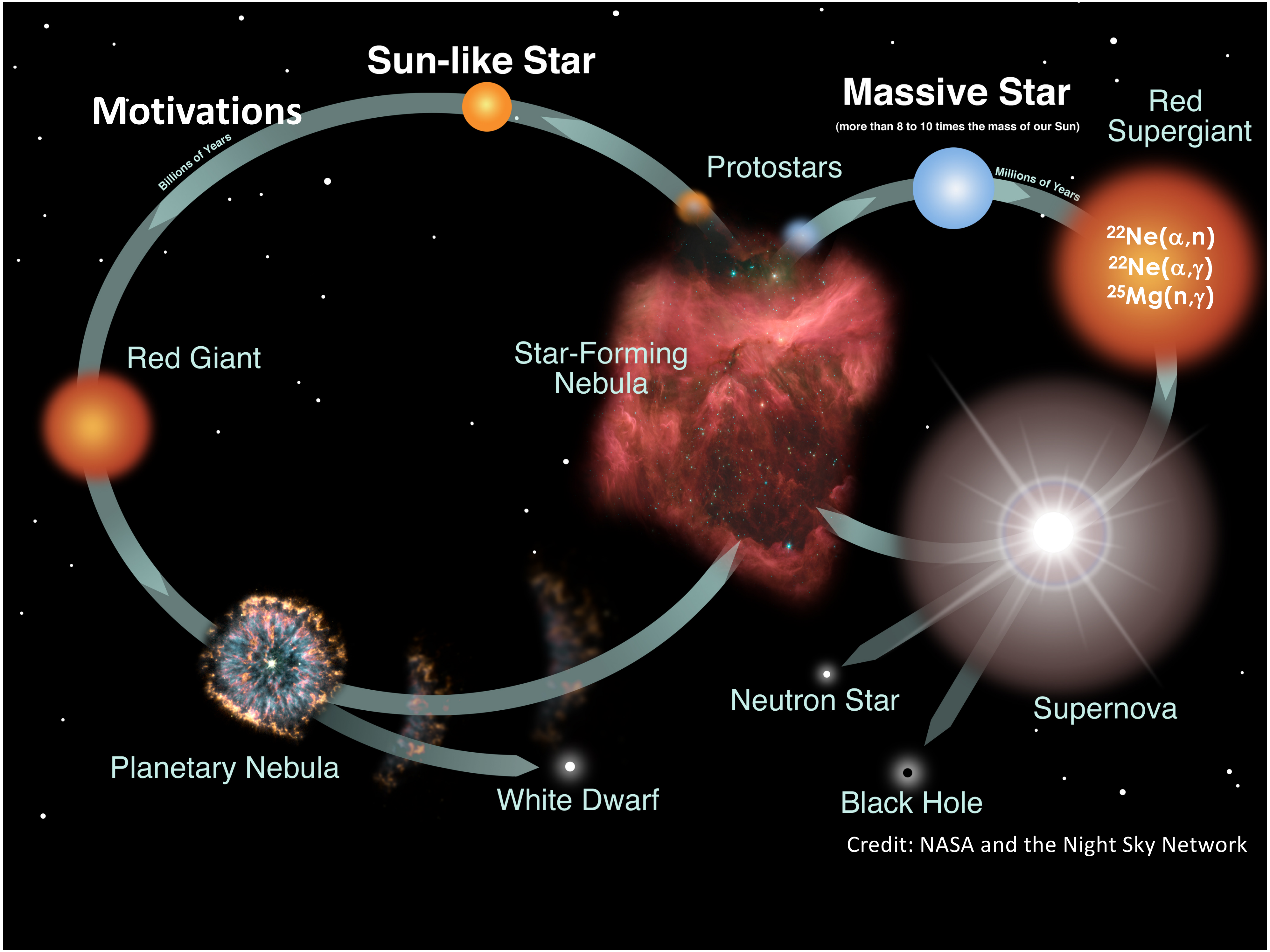


Motivations



Credit: NASA and the Night Sky Network

Motivations



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

$^{22}Ne(\alpha,\gamma)$

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

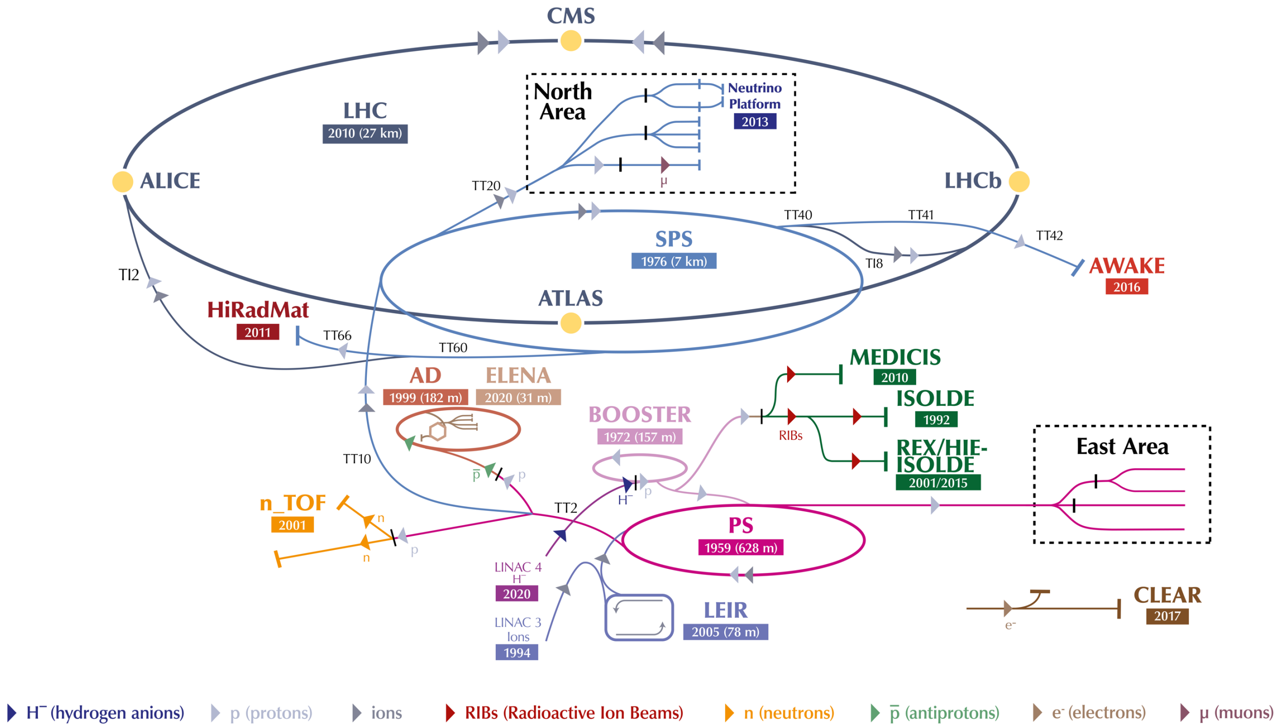
Credit: NASA and the Night Sky Network

Motivations

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

- CONSTRAINTS for ^{22}Ne(α,n)^{25}Mg and ^{22}Ne(α,γ)^{26}Mg:
  - ^{22}Ne(α,n)^{25}Mg 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 energy, **J$^{\pi}$** and **energy** of **^{26}Mg** states can be deduced, in addition to Γ_γ and **Γ_n.**

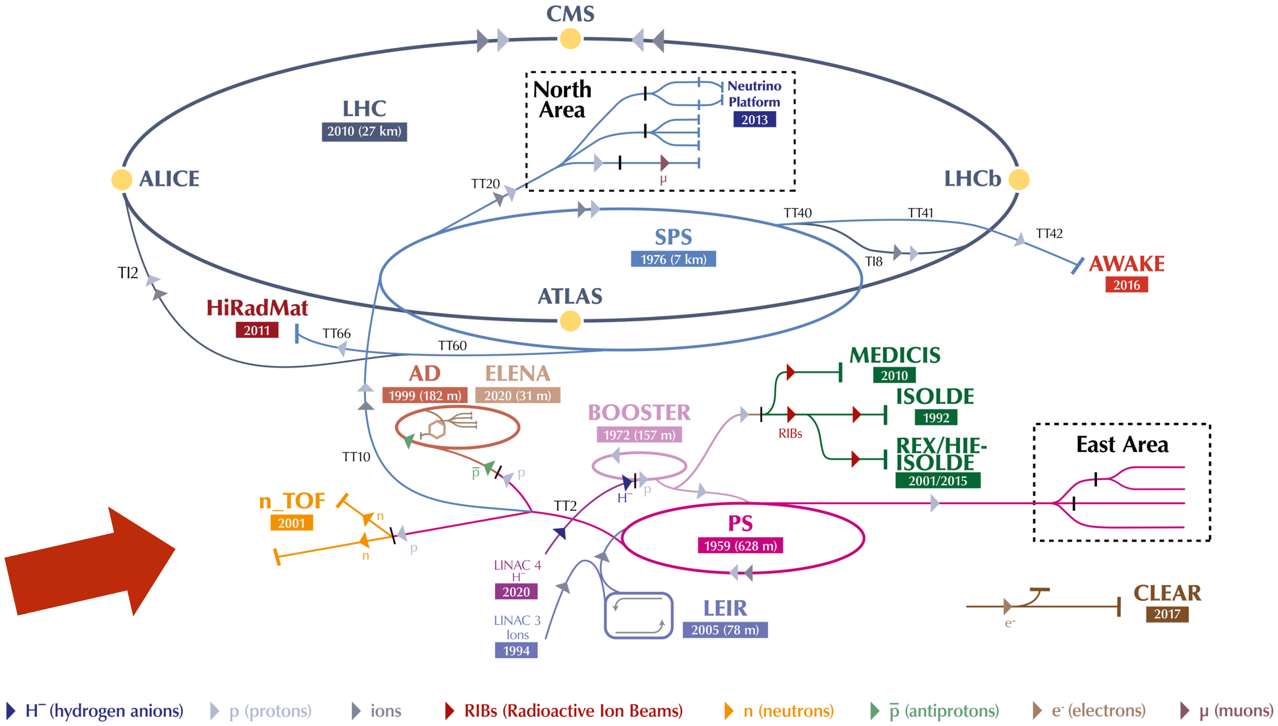
Measurement of $^{25}\text{Mg}(n,\gamma)$ @ n_TOF - CERN



LHC - Large Hadron Collider // SPS - Super Proton Synchrotron // PS - Proton Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linear Electron Accelerator for Research // AWAKE - Advanced WAKefield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE-ISOLDE - Radioactive

Measurement of ^{25}Mg(n,γ) @ n_TOF - CERN

C. Rubbia et al., A high resolution spallation driven facility at the CERN-PS to measure neutron cross sections in the interval from 1 eV to 250 MeV CERN/LHC/98 02(EET) 1998



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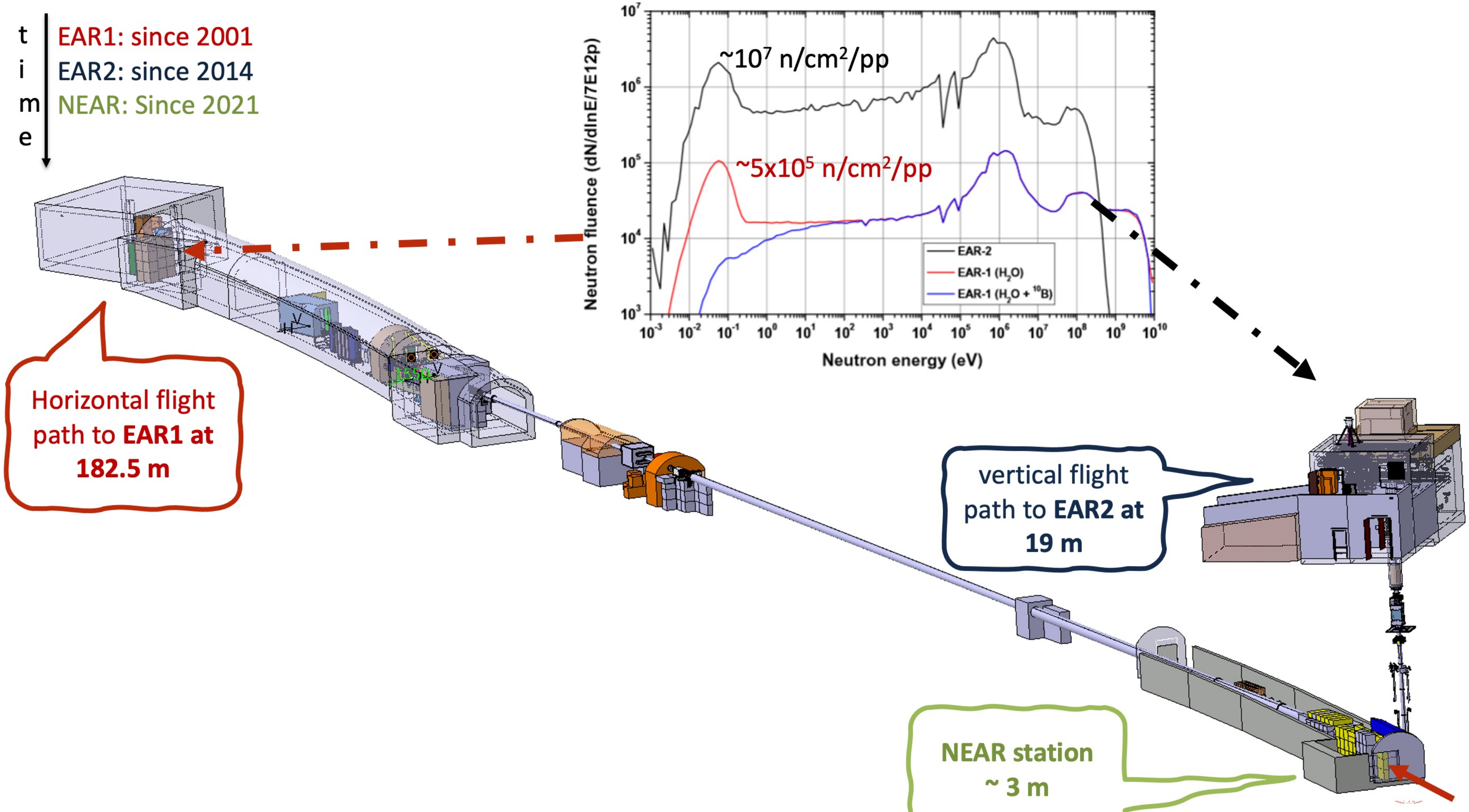
Measurement of ^{25}Mg(n,γ) @ n_TOF - CERN

t
i
m
e

EAR1: since 2001
EAR2: since 2014
NEAR: Since 2021



~10^7 n/cm^2/pp

~5×10^5 n/cm^2/pp

Horizontal flight path to **EAR1 at 182.5 m**

vertical flight path to **EAR2 at 19 m**

NEAR station ~ 3 m

20 Gev/c protons from the PS

Measurement of ^{25}Mg(n,γ) @ n_TOF - CERN

t
i
m
e

EAR1: since 2001
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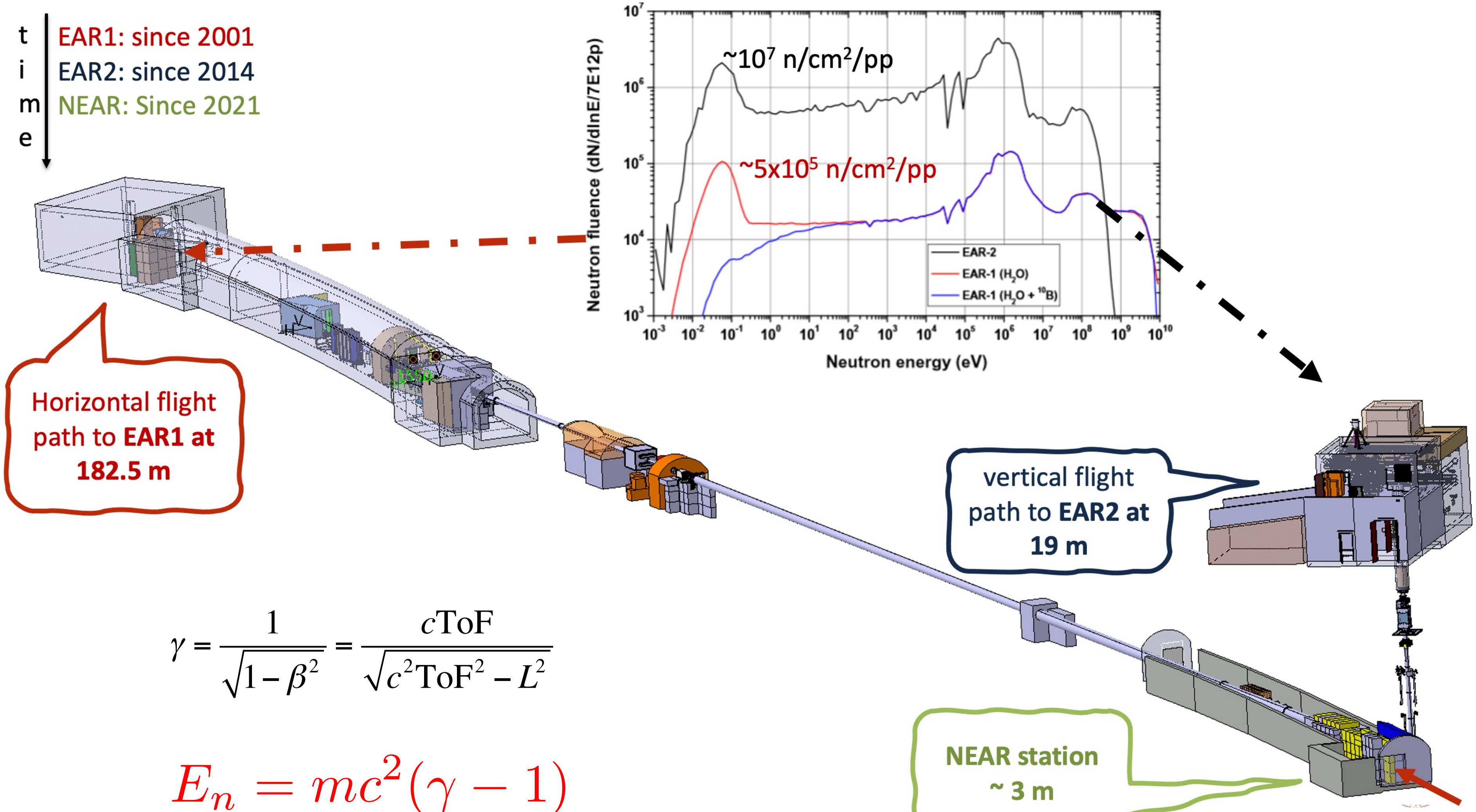


Horizontal flight path to **EAR1 at 182.5 m**

vertical flight path to **EAR2 at 19 m**

NEAR station ~ 3 m

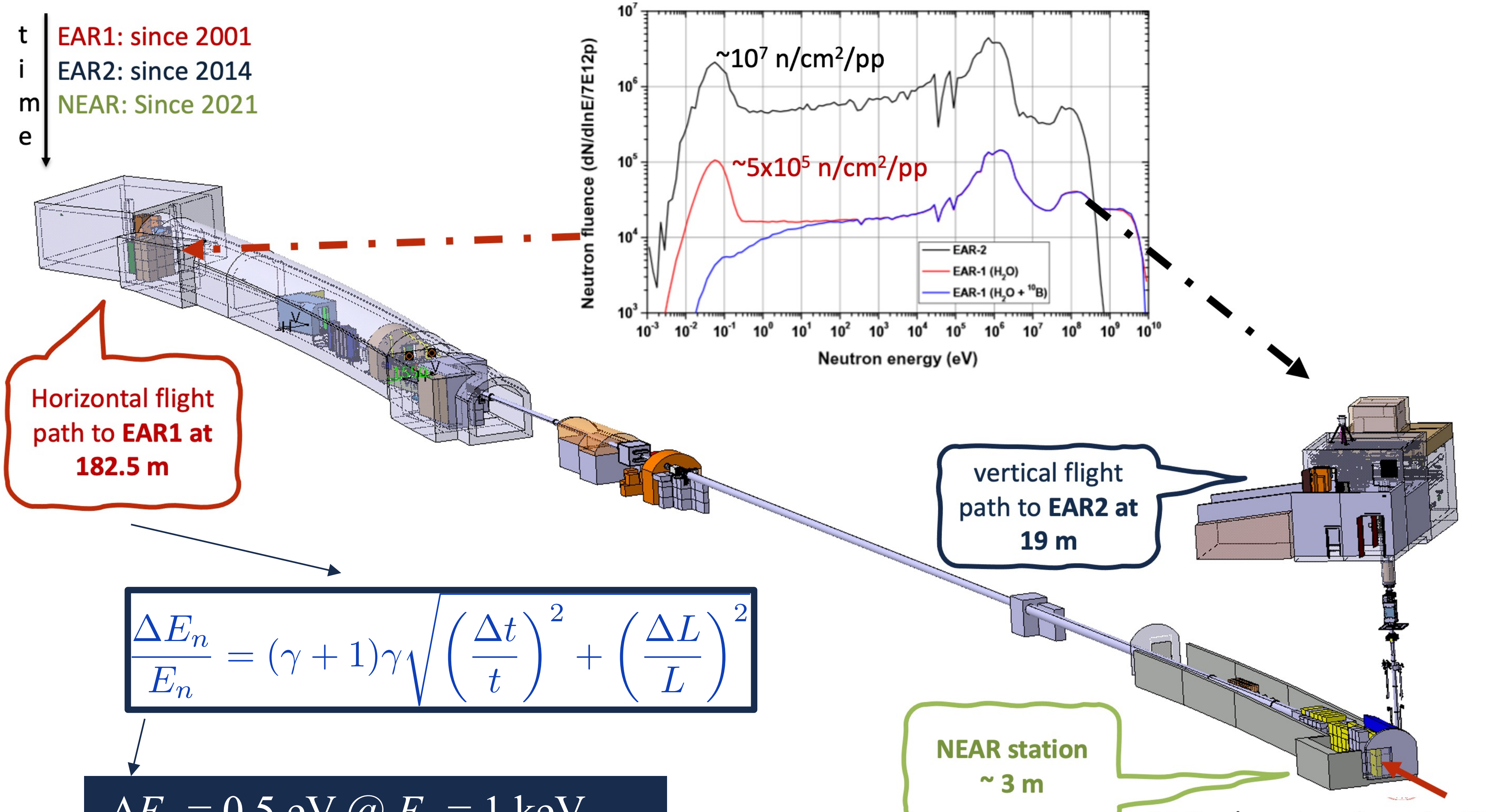
20 Gev/c protons from the PS

$$\gamma = \frac{1}{\sqrt{1-\beta^2}} = \frac{c\mathrm{ToF}}{\sqrt{c^2\mathrm{ToF}^2 - L^2}}$$

$$E_n = mc^2(\gamma - 1)$$

Measurement of ^{25}Mg(n,γ) @ n_TOF - CERN

time
- EAR1: since 2001
- EAR2: since 2014
- NEAR: Since 2021



Horizontal flight path to **EAR1 at 182.5 m**

vertical flight path to **EAR2 at 19 m**

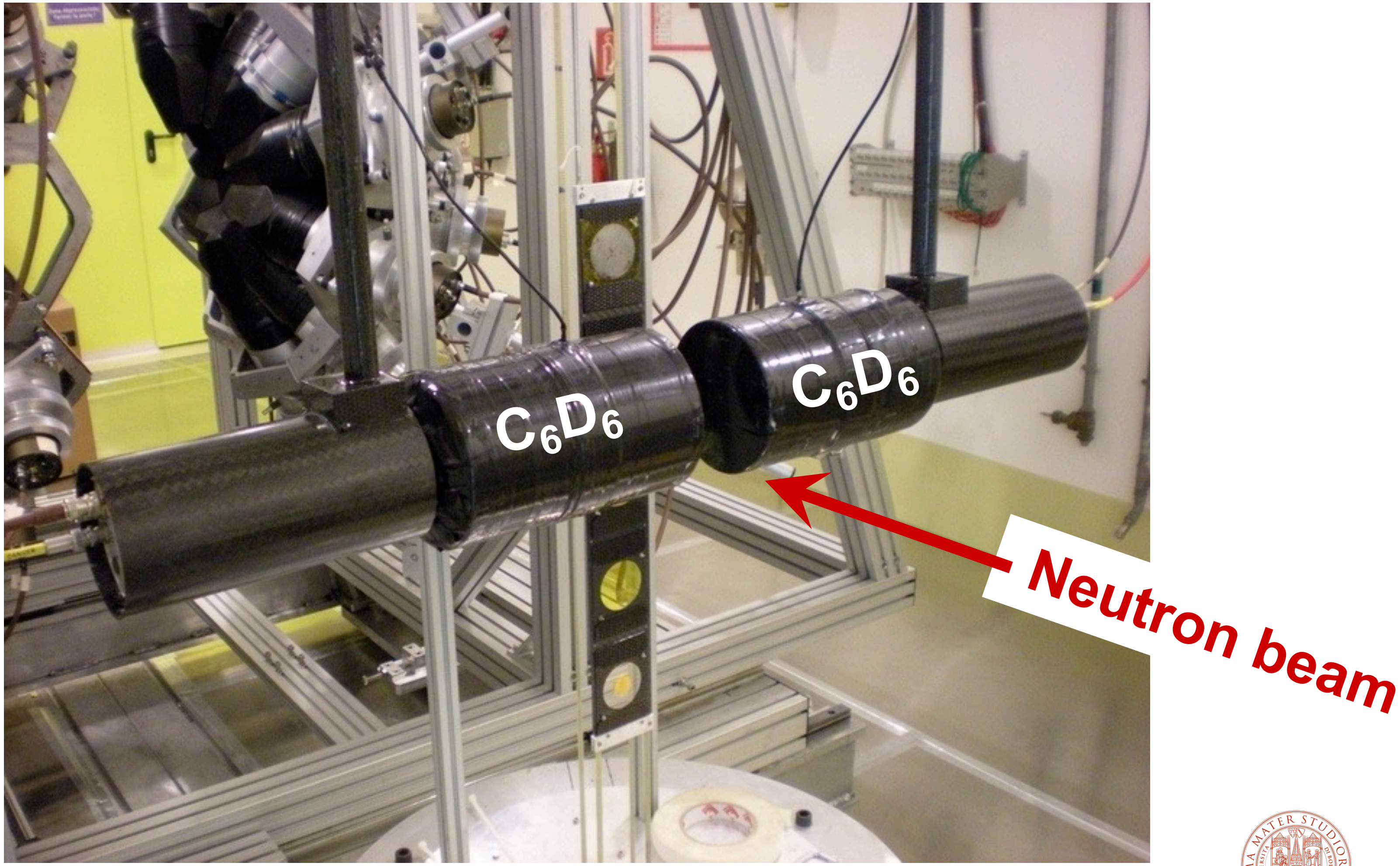
NEAR station ~ 3 m

20 Gev/c protons from the PS

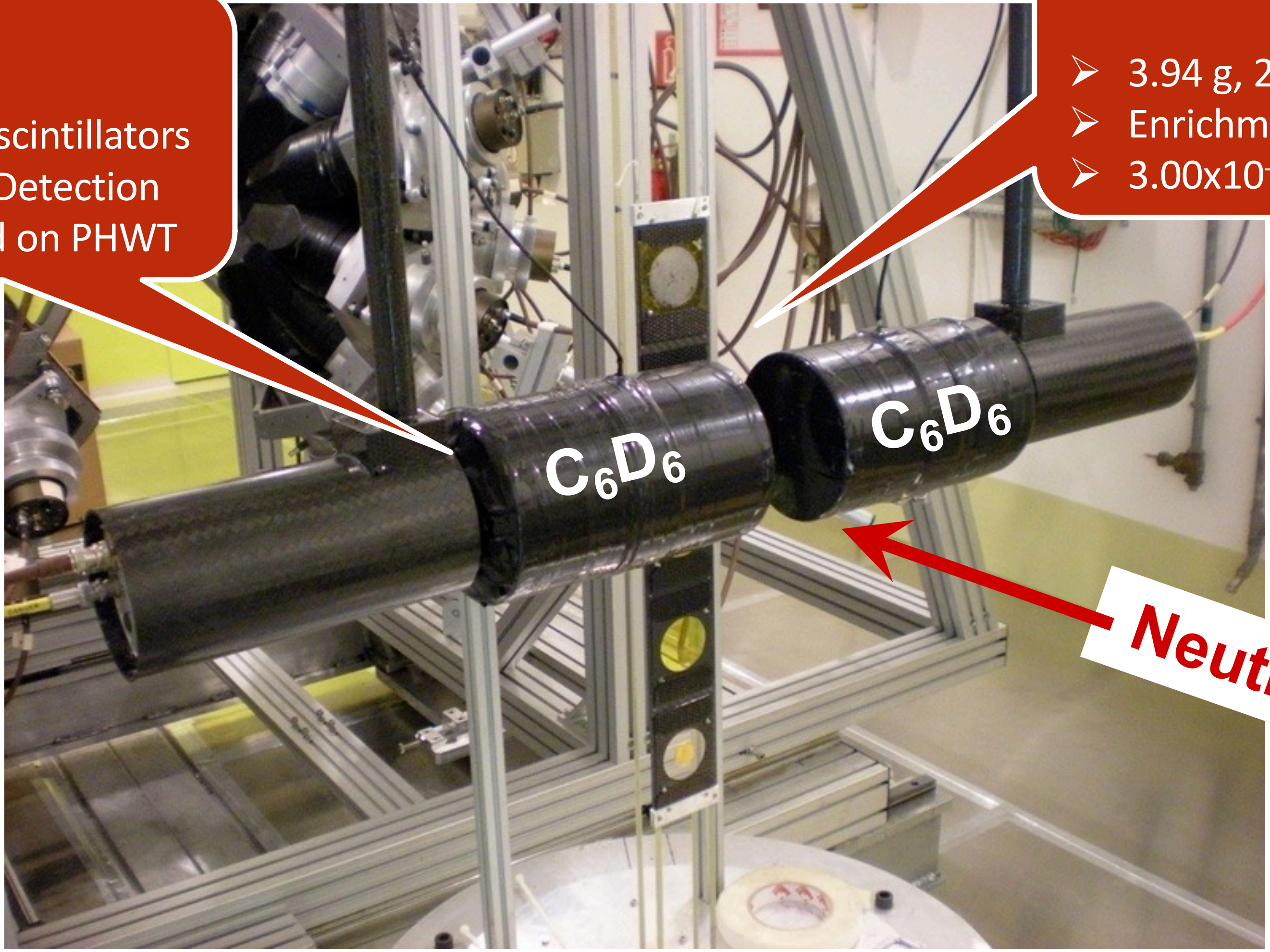
$$\frac{\Delta E_n}{E_n} = (\gamma+1)\gamma\sqrt{\left(\frac{\Delta t}{t}\right)^2 + \left(\frac{\Delta L}{L}\right)^2}$$

$$\Delta E_n = 0.5\ \text{eV} \ @\ E_n = 1\ \text{keV}$$
$$\Delta E_n = 900\ \text{eV} \ @\ E_n = 300\ \text{keV}$$

Measurement of ^{25}Mg(n,γ) @ n_TOF - CERN



Measurement of ^{25}Mg(n,γ) @ n_TOF - CERN



Capture setup:

- 2 C_6D_6 liquid scintillators
- Total Energy Detection System based on PHWT

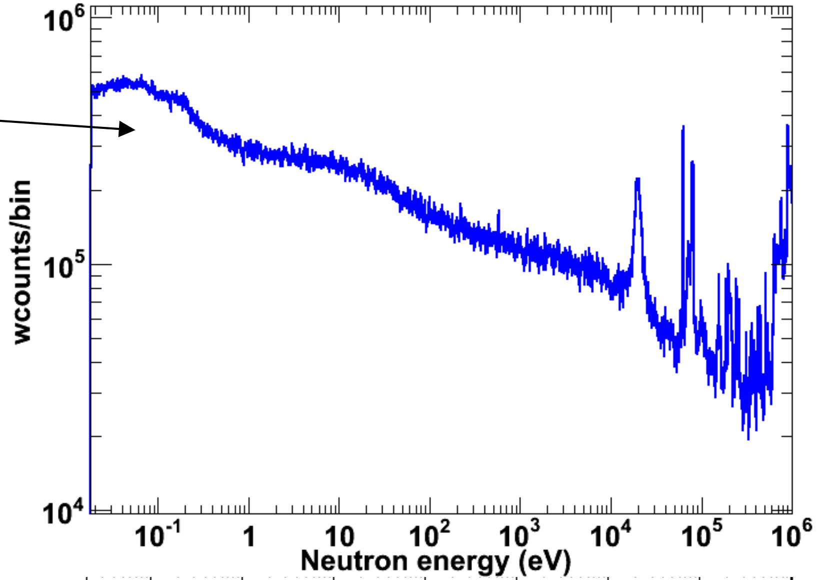
Mg sample:

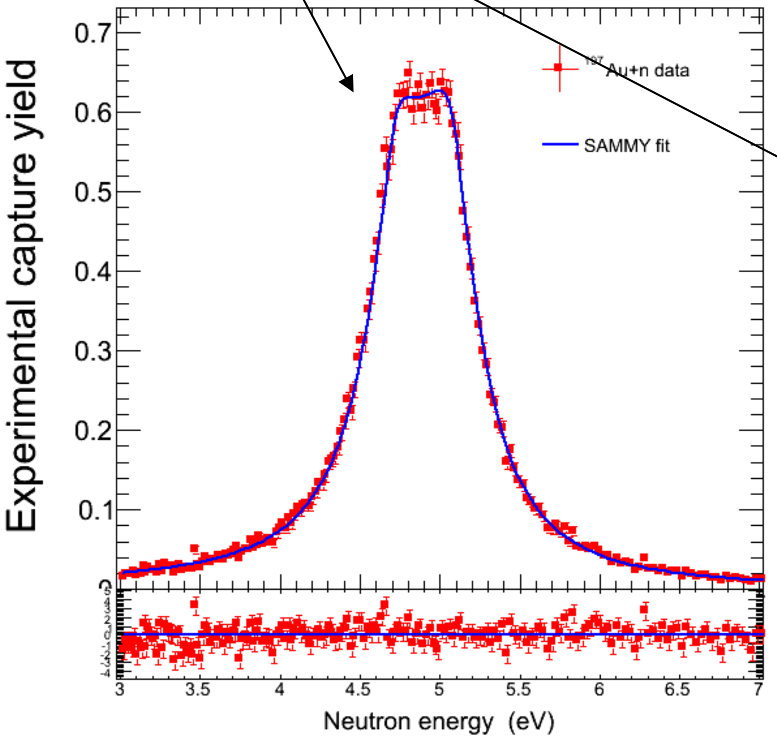
- 3.94 g, 2 cm diameter
- Enrichment 97.86 %
- 3.00x10^{-2} at/b

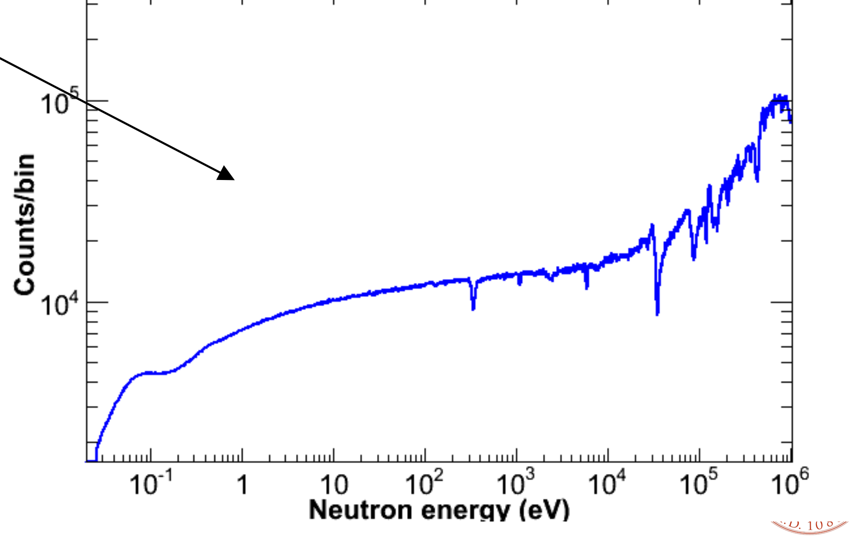
Measurement of ^{25}Mg(n,γ) @ n_TOF - CERN

Experimental capture yield

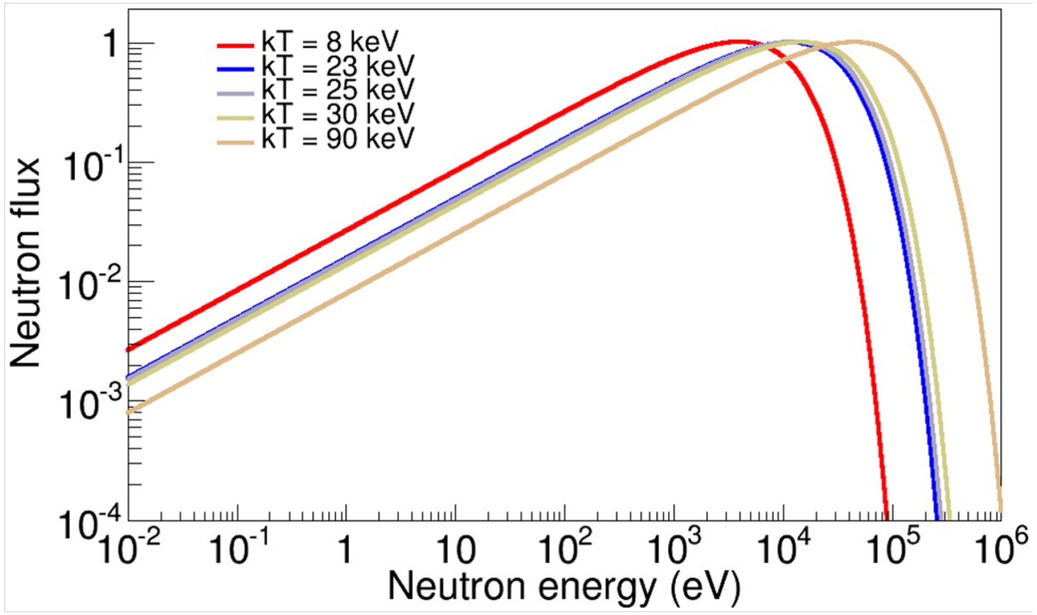
$$Y(E_n) = N\frac{C_w(E_n)}{\varphi_n(E_n)} \propto (1-e^{-n\sigma_{tot}})\frac{\sigma_\gamma}{\sigma_{tot}}$$







Measurement of ^{25}Mg(n,γ) @ n_TOF - CERN



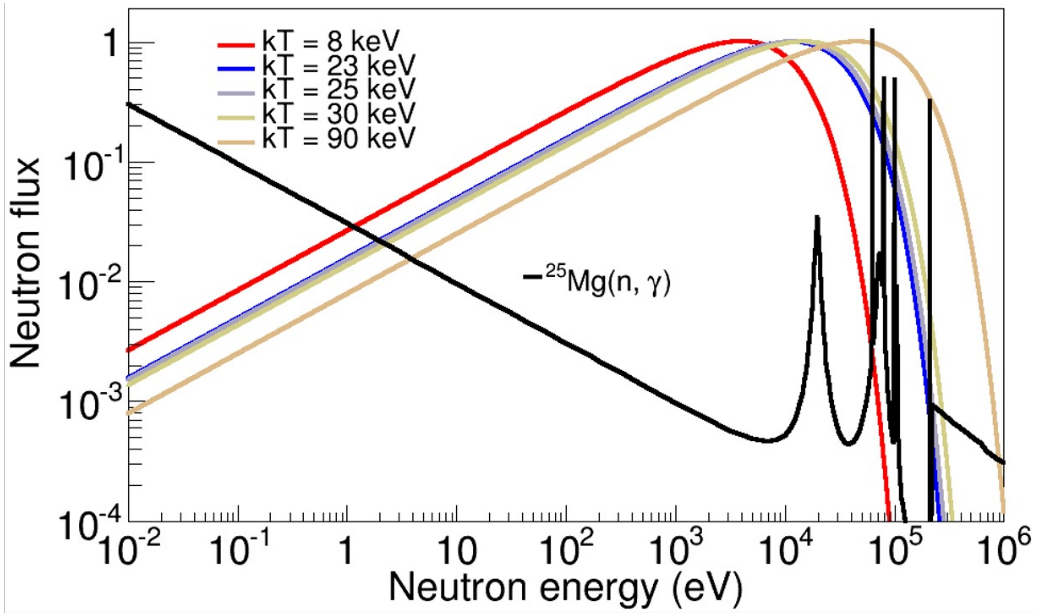
Reaction rate ($cm^{-3}s^{-1}$):

$$r = N_A N_n \langle \sigma \cdot v \rangle$$

$$MACS \equiv \frac{\langle \sigma \cdot v \rangle}{v_T} = \frac{2}{\sqrt{\pi}(kT)^2} \int_0^\infty \sigma(E) E e^{-E/(kT)} dE$$

C Massimi *et al.*, Phys. Rev. C **85**, 044615 (2012)
C Massimi *et al.*, Phys. Lett. B **768**, 1 (2017)

Measurement of ^{25}Mg(n,γ) @ n_TOF - CERN



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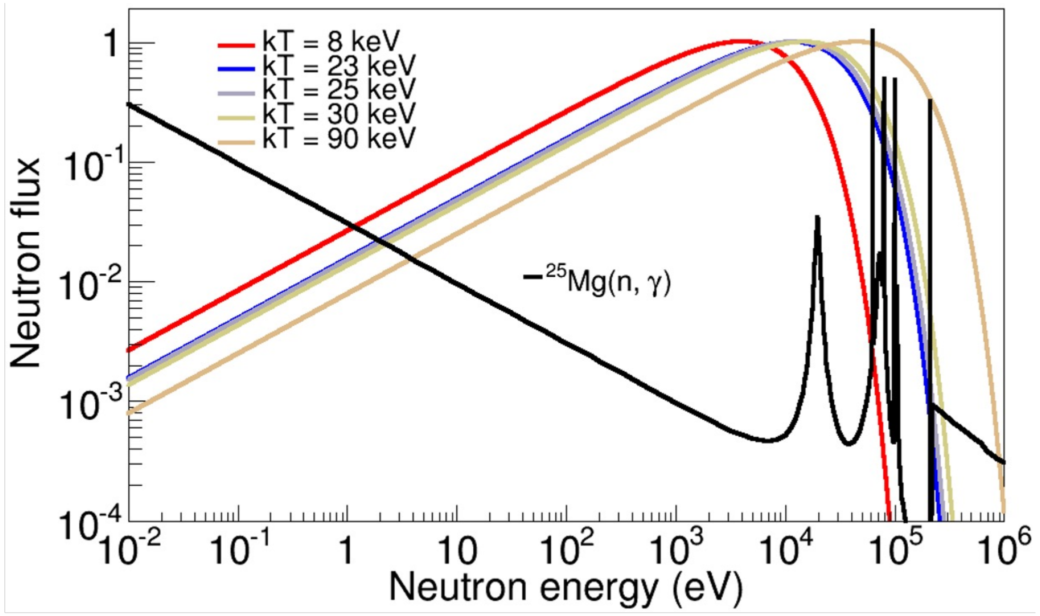

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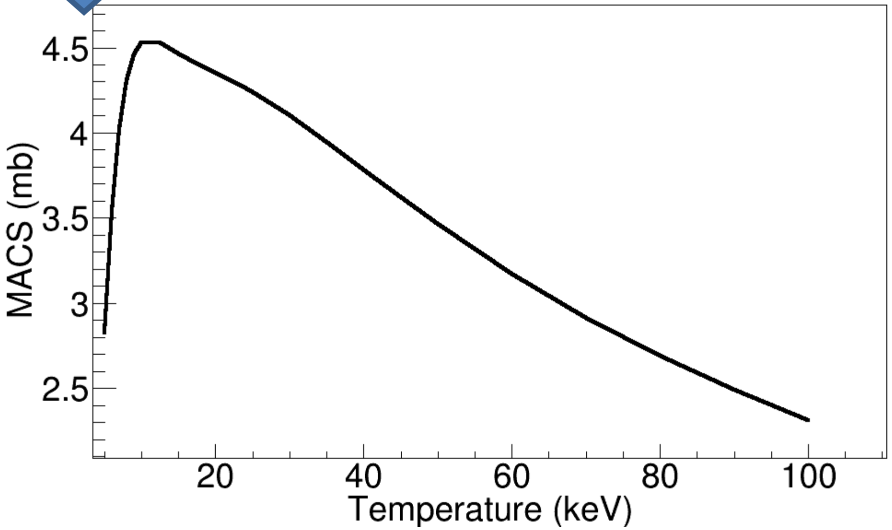

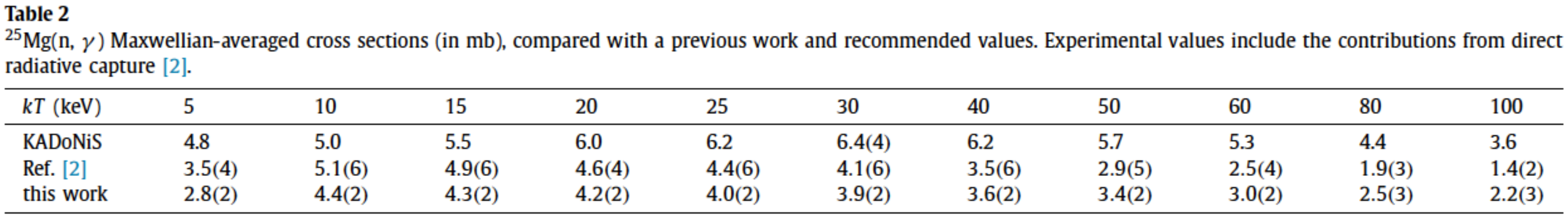

Table 2
^{25}Mg(n, γ) Maxwellian-averaged cross sections (in mb), compared with a previous work and recommended values. Experimental values include the contributions from direct radiative capture [2].

kT (keV)	5	10	15	20	25	30	40	50	60	80	100
KADoNiS	4.8	5.0	5.5	6.0	6.2	6.4(4)	6.2	5.7	5.3	4.4	3.6
Ref. [2]	3.5(4)	5.1(6)	4.9(6)	4.6(4)	4.4(6)	4.1(6)	3.5(6)	2.9(5)	2.5(4)	1.9(3)	1.4(2)
this work	2.8(2)	4.4(2)	4.3(2)	4.2(2)	4.0(2)	3.9(2)	3.6(2)	3.4(2)	3.0(2)	2.5(3)	2.2(3)

C Massimi *et al.*, Phys. Rev. C **85**, 044615 (2012)
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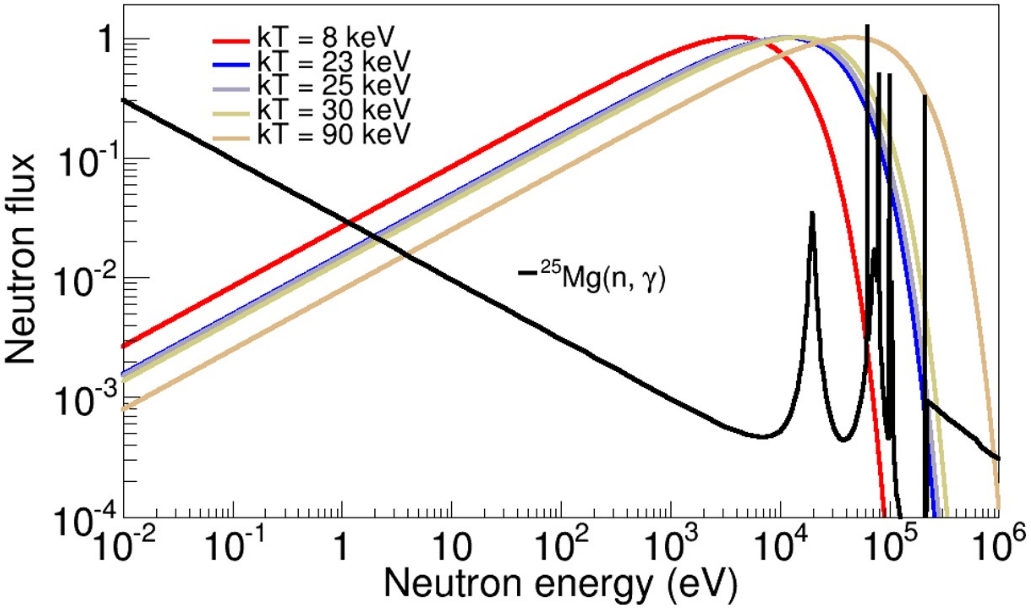
Measurement of ^{25}Mg(n,γ) @ n_TOF - CERN



Reaction rate (cm^{-3}s^{-1}):

$$r = N_A N_n \langle \sigma \cdot v \rangle$$

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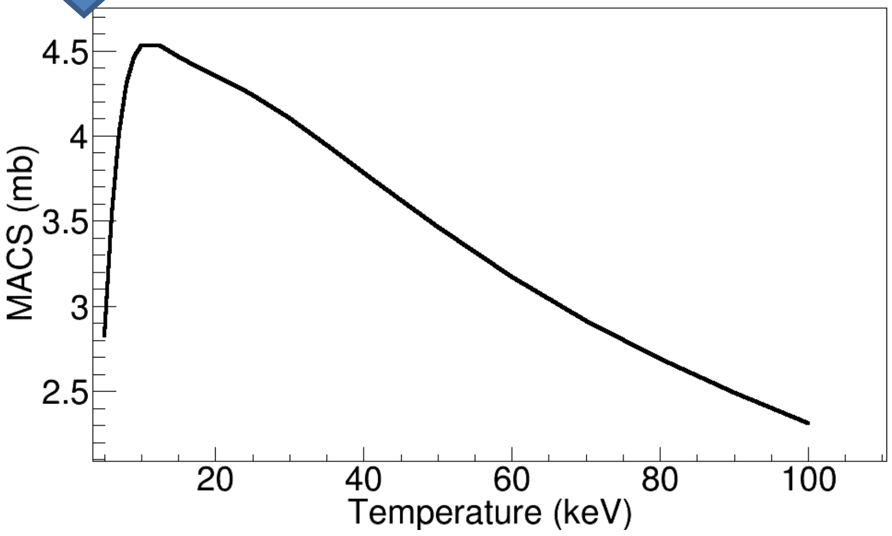
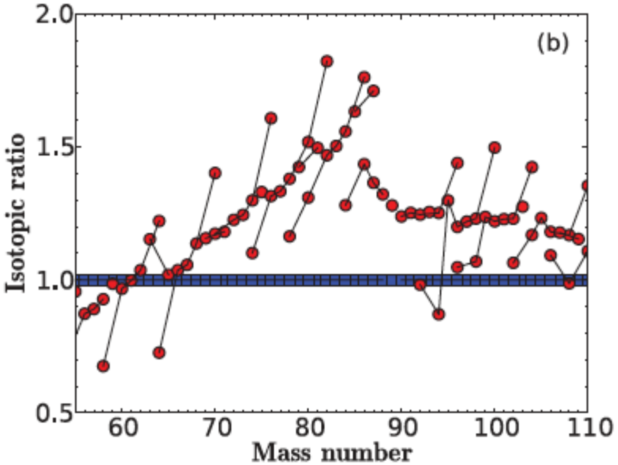
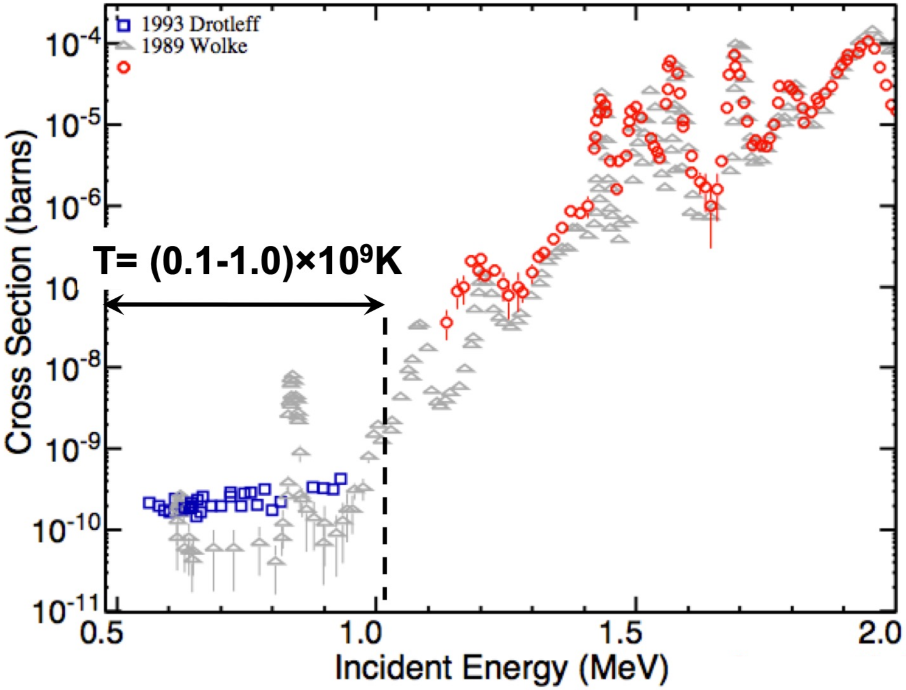




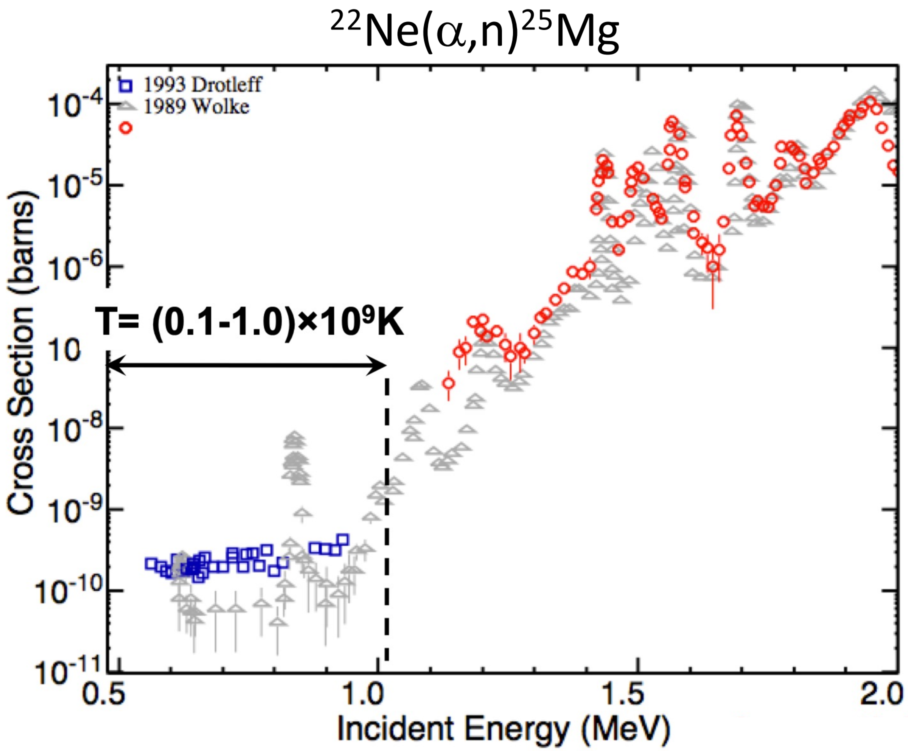
Poisoning effect in Massive Stars (by M. Pignatari)

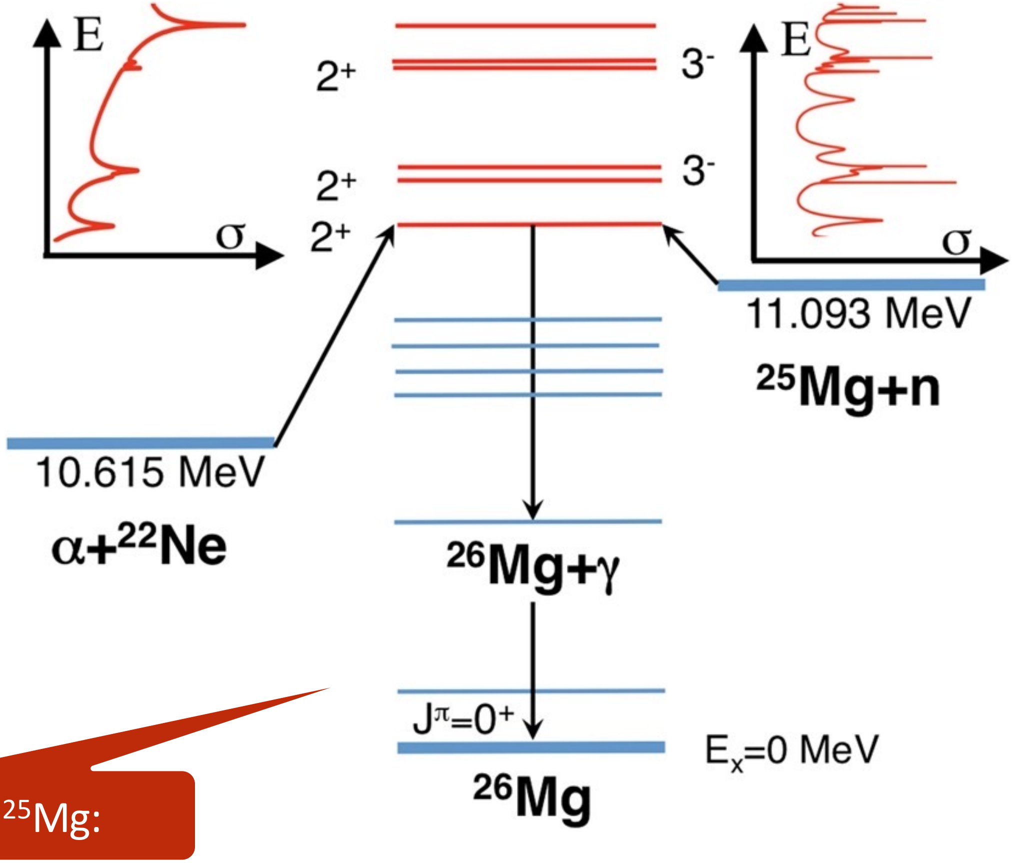
Measurement of $^{25}Mg(n,\gamma) \leftarrow\rightarrow$ $^{22}Ne(\alpha,n)^{25}Mg$

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



Measurement of ^{25}Mg(n,γ) ←→ ^{22}Ne(α,n)^{25}Mg



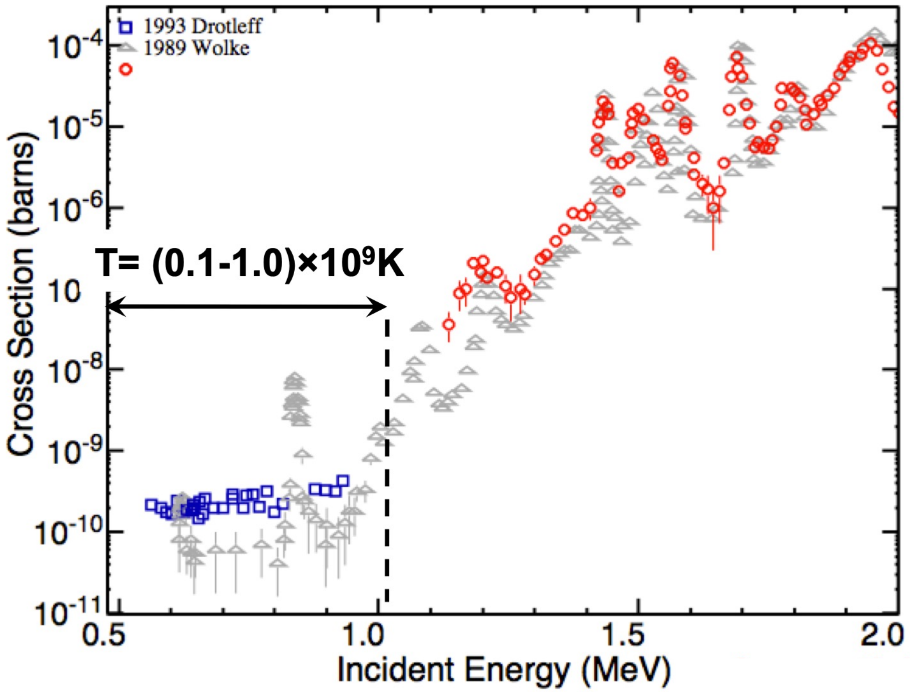


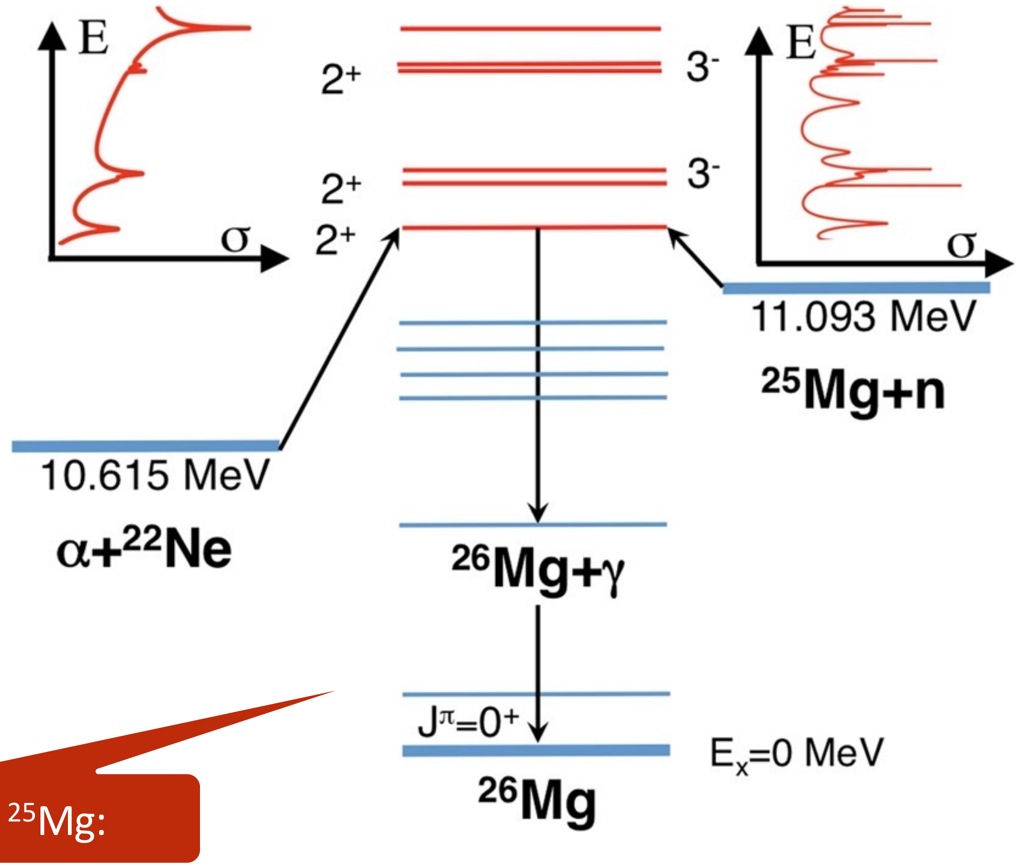
^{26}Mg levels via n + ^{25}Mg:

Measurement of ^{25}Mg(n,γ) ←→ ^{22}Ne(α,n)^{25}Mg

^{25}Mg(n,γ) is not conclusive enough, need for other reaction channels

^{22}Ne(α,n)^{25}Mg





^{26}Mg levels via n + ^{25}Mg:

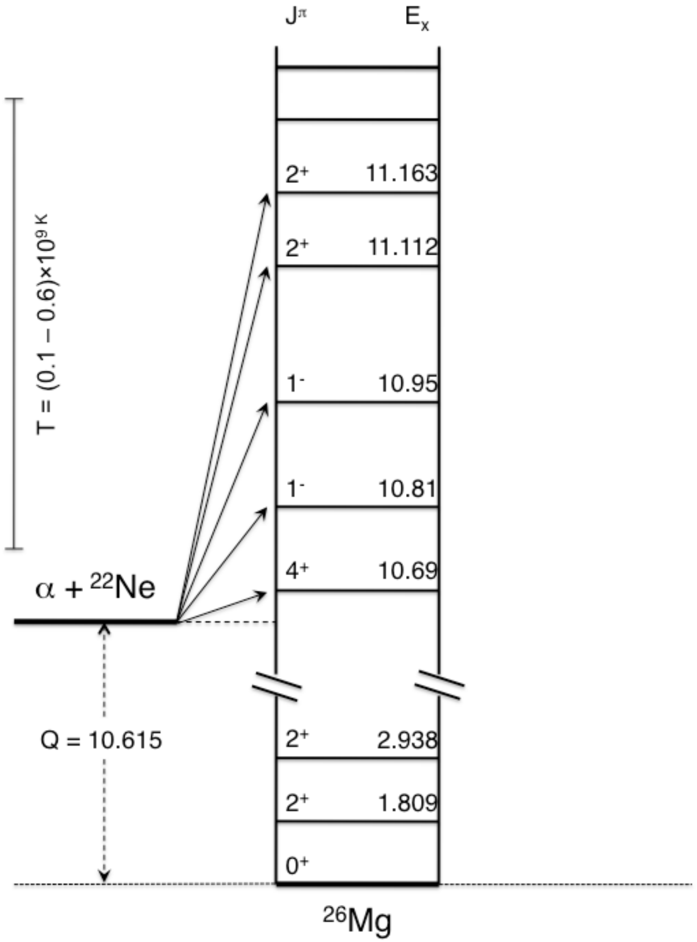
Measurement of $^{25}Mg(n,\gamma)$ ←→ $^{22}Ne(\alpha,n)^{25}Mg$

$\alpha + {}^{22}Ne$

α	$J^\pi = 0^+$
^{22}Ne	$J^\pi = 0^+$

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

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



Measurement of ^{25}Mg(n,γ) ←→ ^{22}Ne(α,n)^{25}Mg

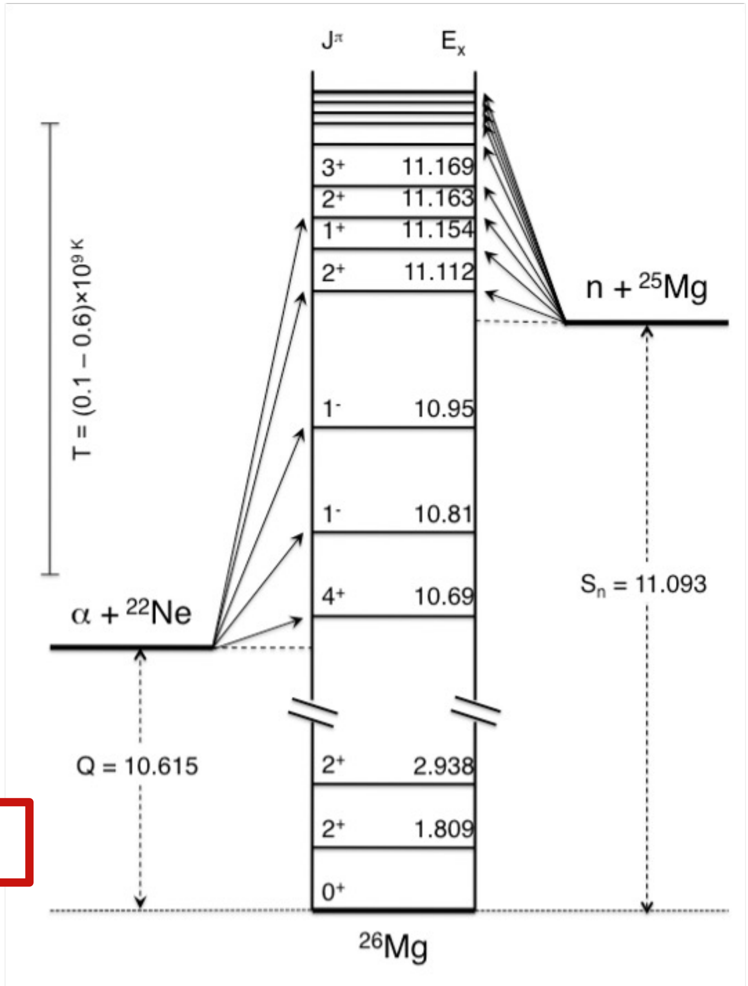
^{25}Mg(n,γ) is not conclusive enough, **need for other reaction channels**

α + ^{22}Ne

α	$J^\pi = 0^+$
^{22}Ne	$J^\pi = 0^+$

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

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



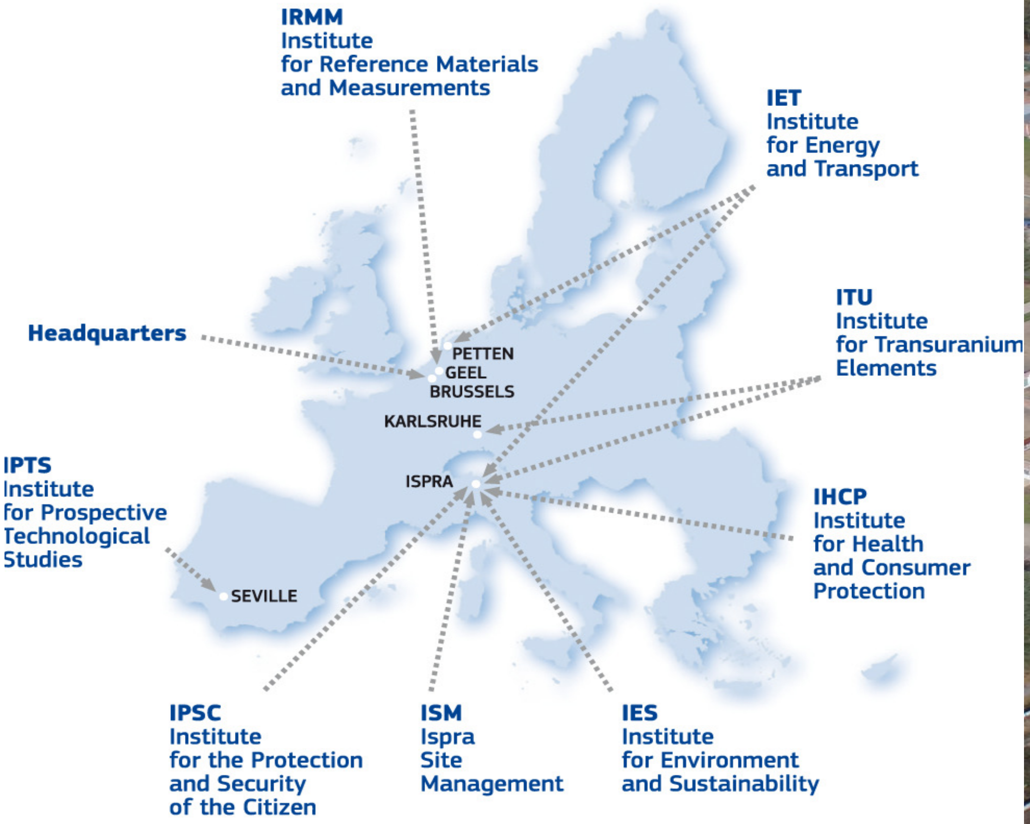
n + ^{25}Mg

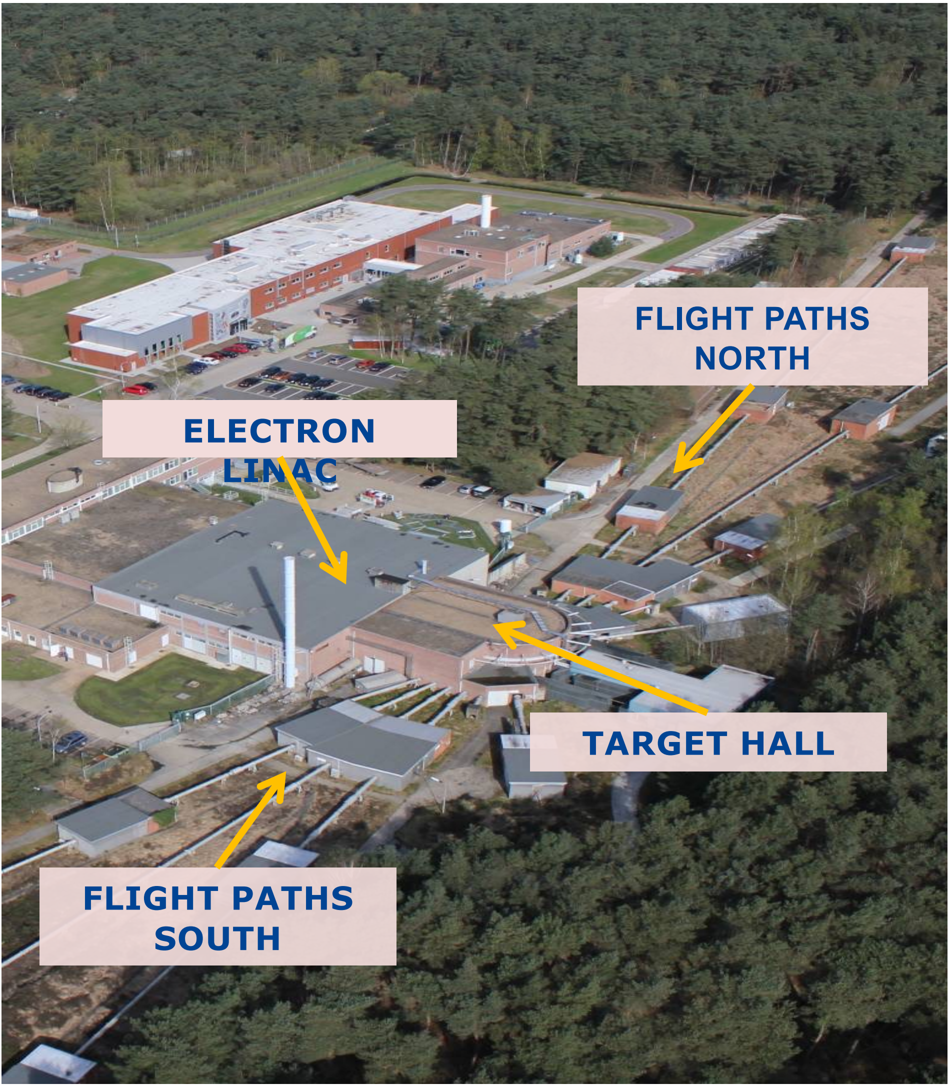
n	$J^\pi = 1/2^+$
^{25}Mg	$J^\pi = 5/2^+$

All **states in ^{26}Mg** can participate in the **^{25}Mg(n,γ)^{26}Mg** reaction:

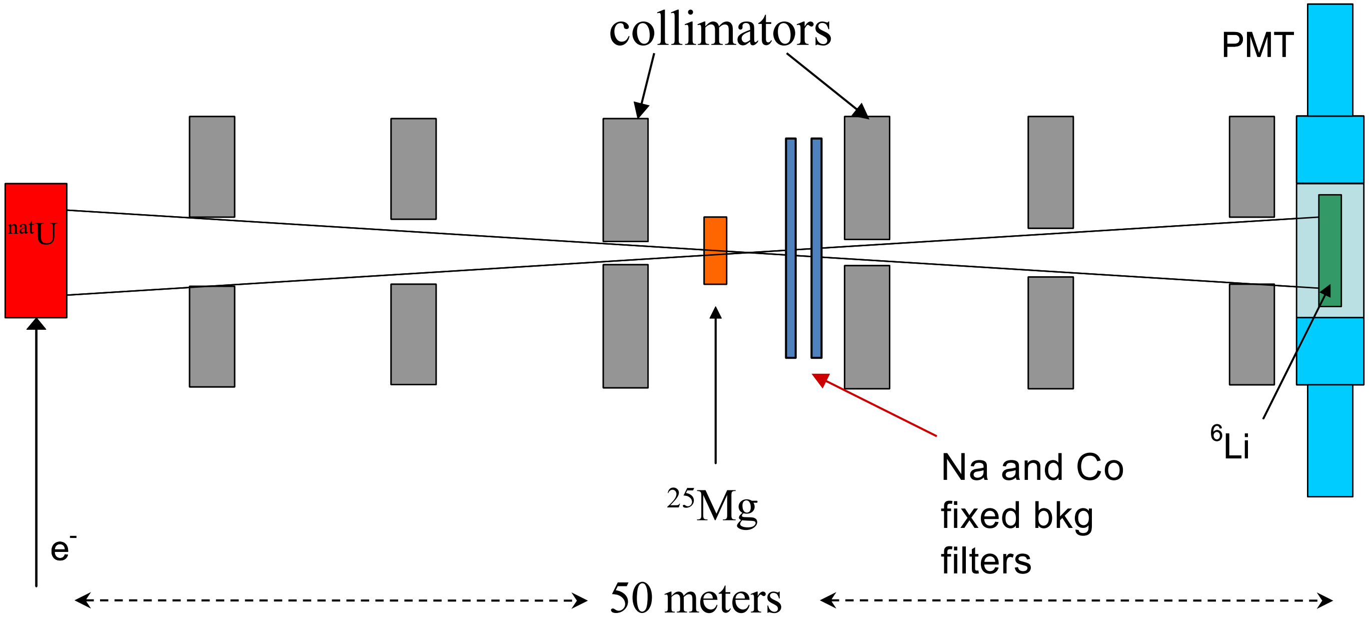
J^π = **0^+**, 0^-, 1^+, **1^-**, **2^+**, 2^-, …

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

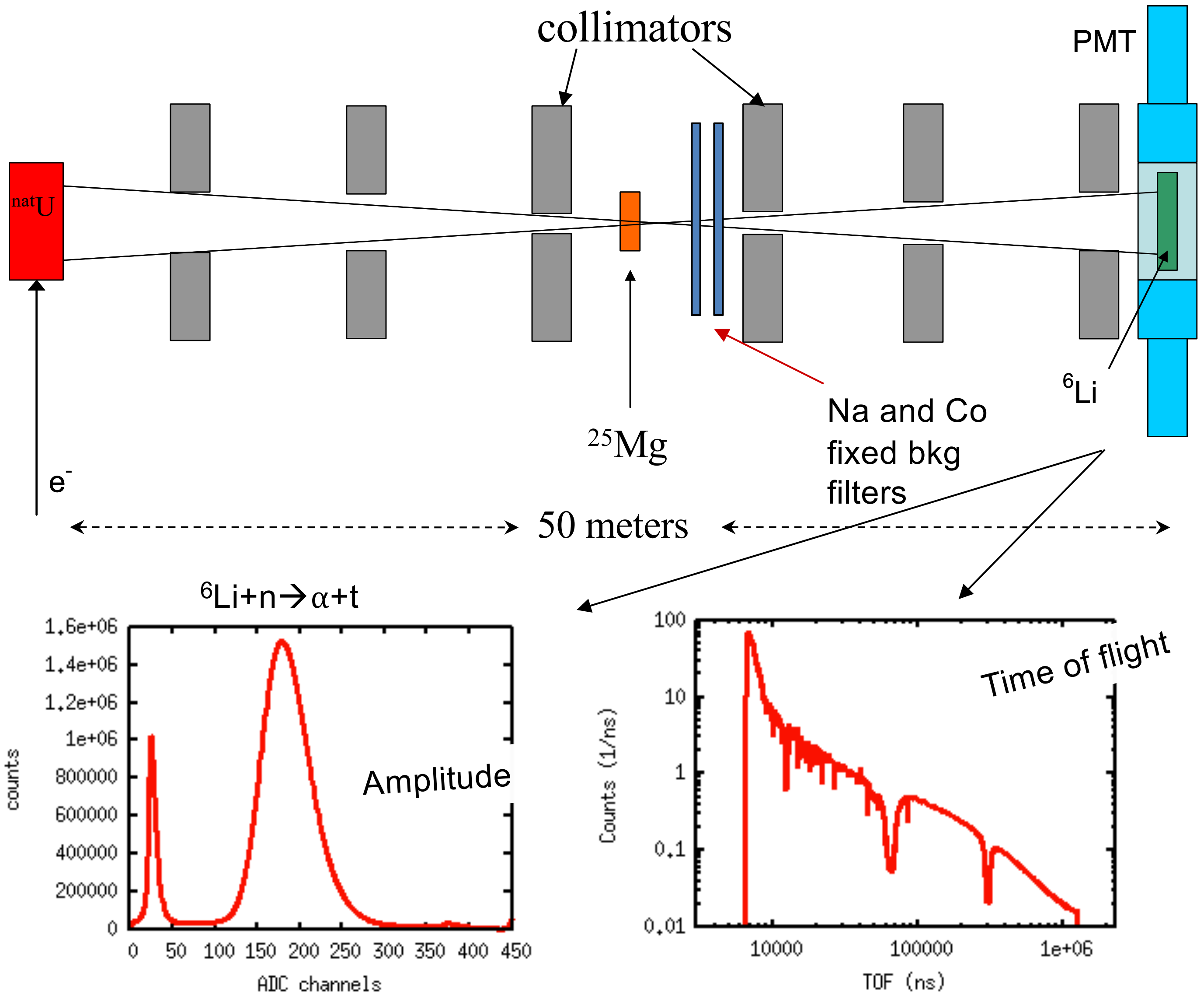




Measurement of ^{25}Mg(n,tot) @ GELINA



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

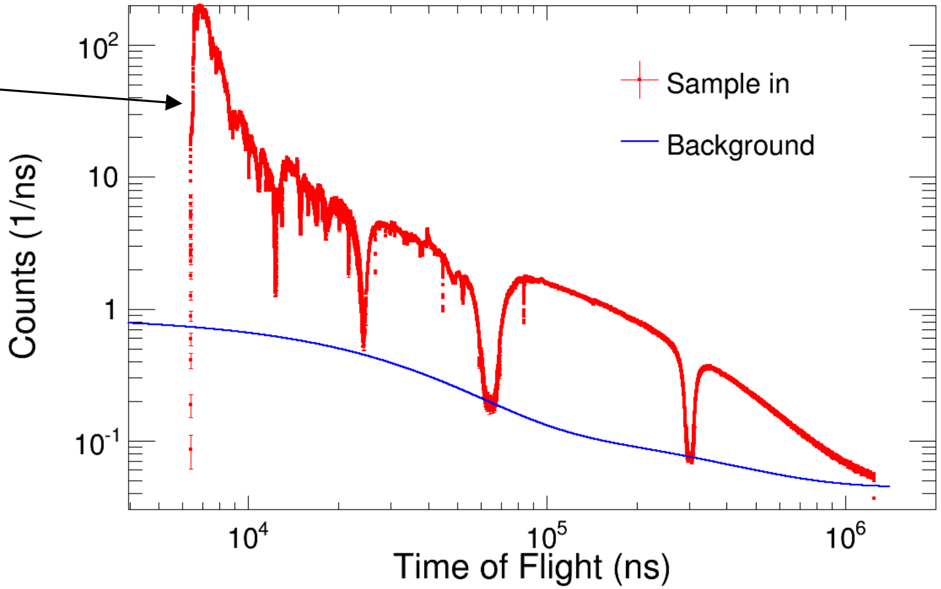


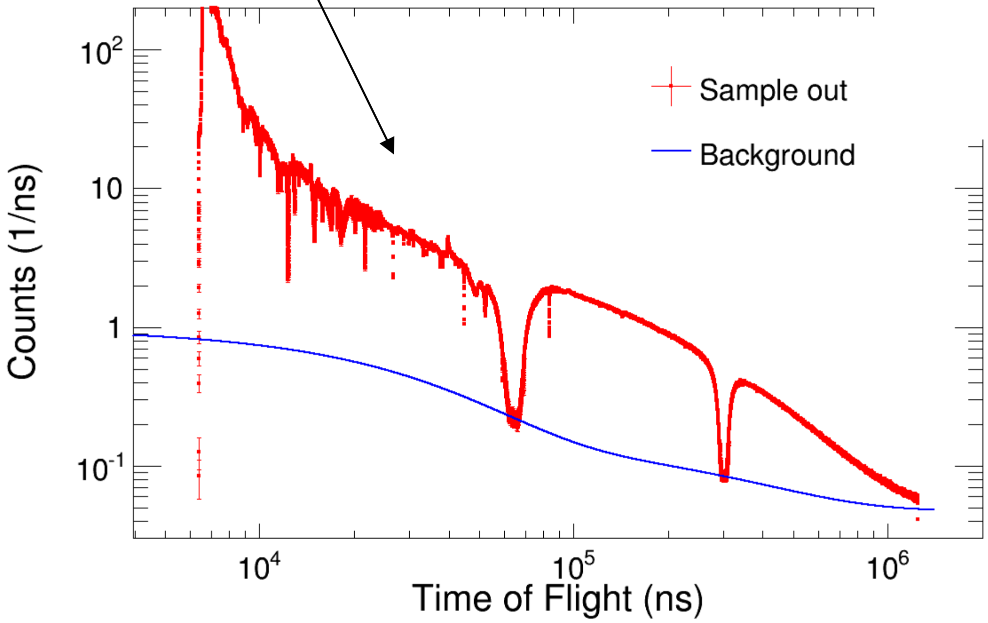
Transmission setup:

- ➢ 2 ^{6}Li-glass scintillators

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

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





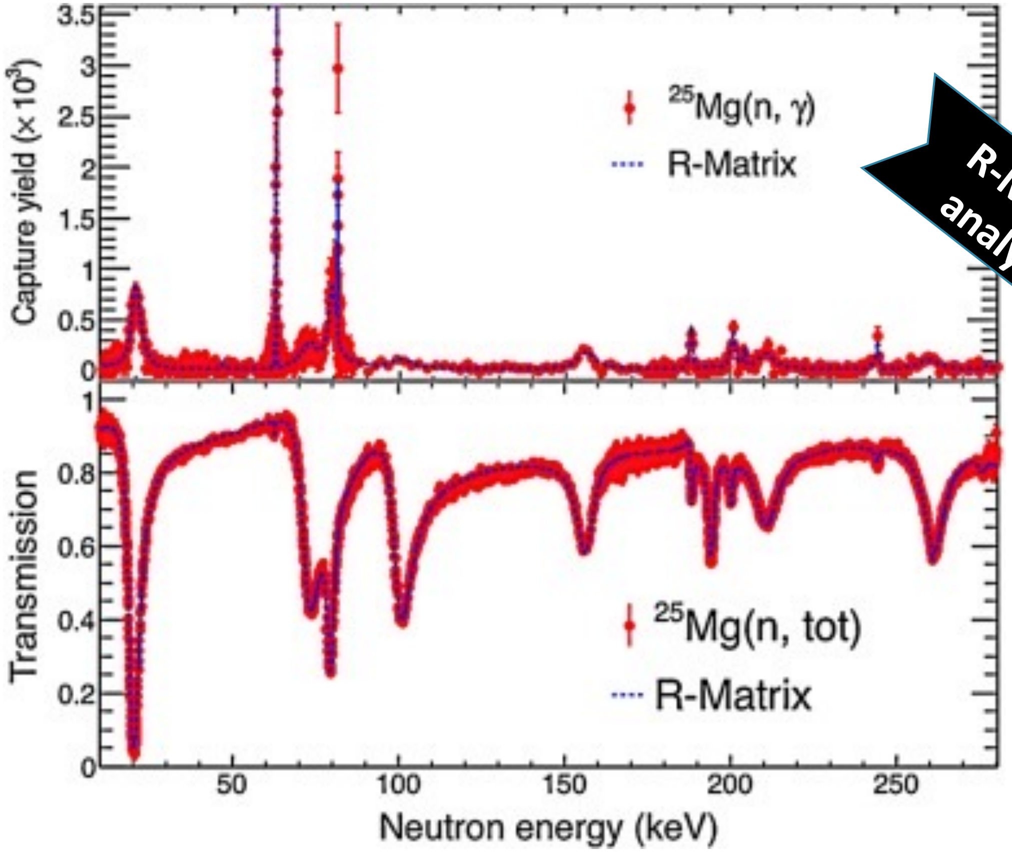
Background determined by **black resonance** technique:

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

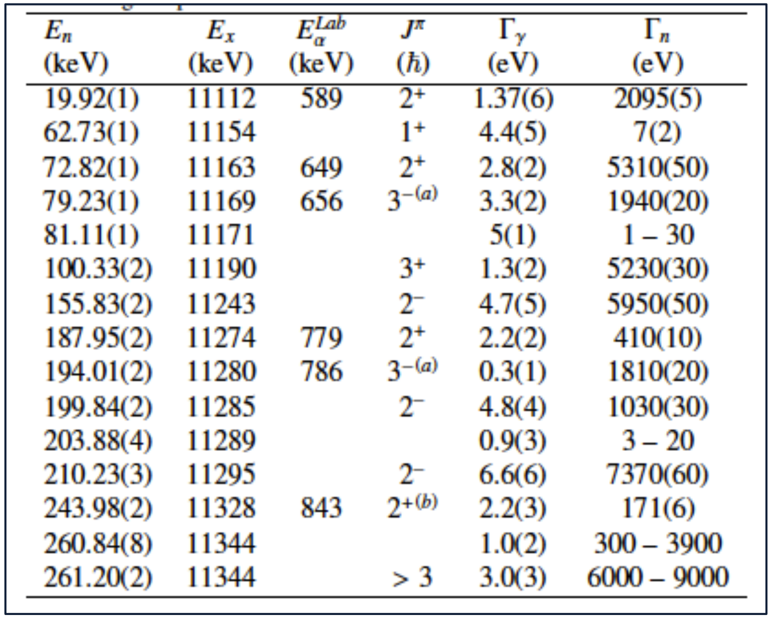
P. Schillebeeckx, *et al.*, Nucl. Data Sheets **113** (2012) 3054

C Massimi *et al.*, Phys. Rev. C **85**, 044615 (2012)
C Massimi *et al.*, Phys. Lett. B **768**, 1 (2017)

^{25}Mg(n,tot) and ^{25}Mg(n,γ) R-Matrix analysis



R-Matrix analysis



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)	2095(5)
62.73(1)	11154		1^+	4.4(5)	7(2)
72.82(1)	11163	649	2^+	2.8(2)	5310(50)
79.23(1)	11169	656	$3^{-(a)}$	3.3(2)	1940(20)
81.11(1)	11171			5(1)	1 – 30
100.33(2)	11190		3^+	1.3(2)	5230(30)
155.83(2)	11243		2^-	4.7(5)	5950(50)
187.95(2)	11274	779	2^+	2.2(2)	410(10)
194.01(2)	11280	786	$3^{-(a)}$	0.3(1)	1810(20)
199.84(2)	11285		2^-	4.8(4)	1030(30)
203.88(4)	11289			0.9(3)	3 – 20
210.23(3)	11295		2^-	6.6(6)	7370(60)
243.98(2)	11328	843	$2^{+(b)}$	2.2(3)	171(6)
260.84(8)	11344			1.0(2)	300 – 3900
261.20(2)	11344		> 3	3.0(3)	6000 – 9000

Energy, J^π, Γ_γ, Γ_n

C Massimi *et al.*, Phys. Rev. C **85**, 044615 (2012)
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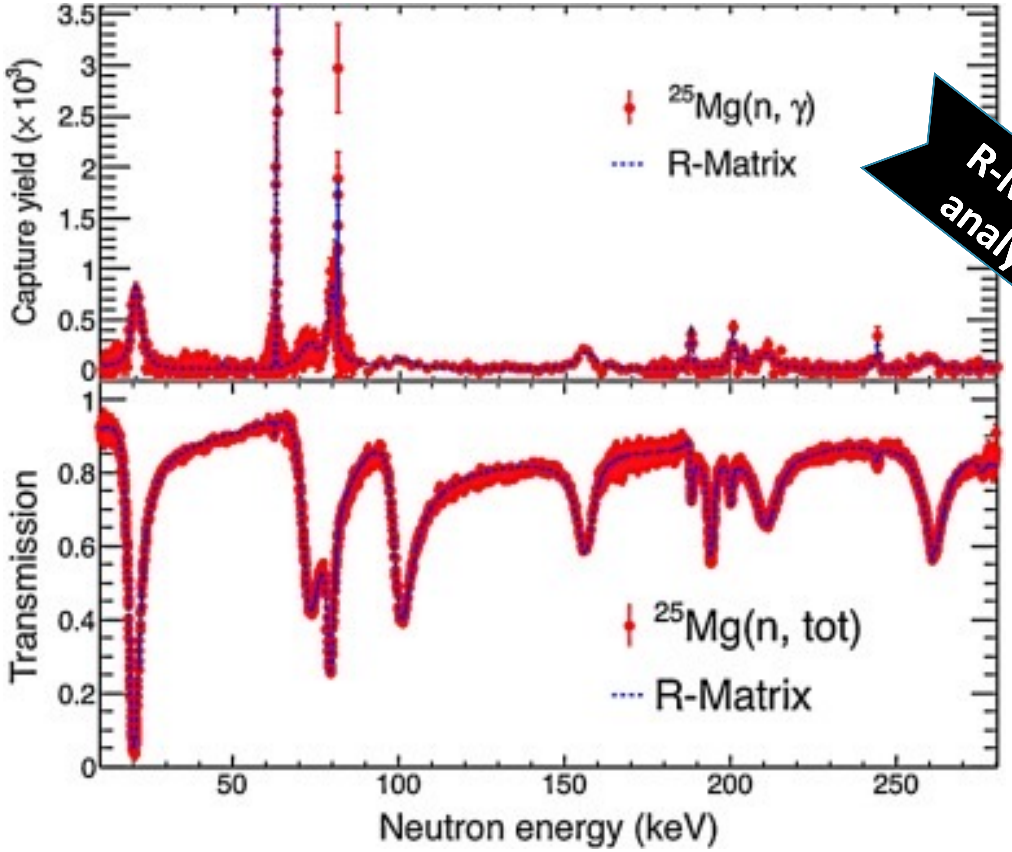
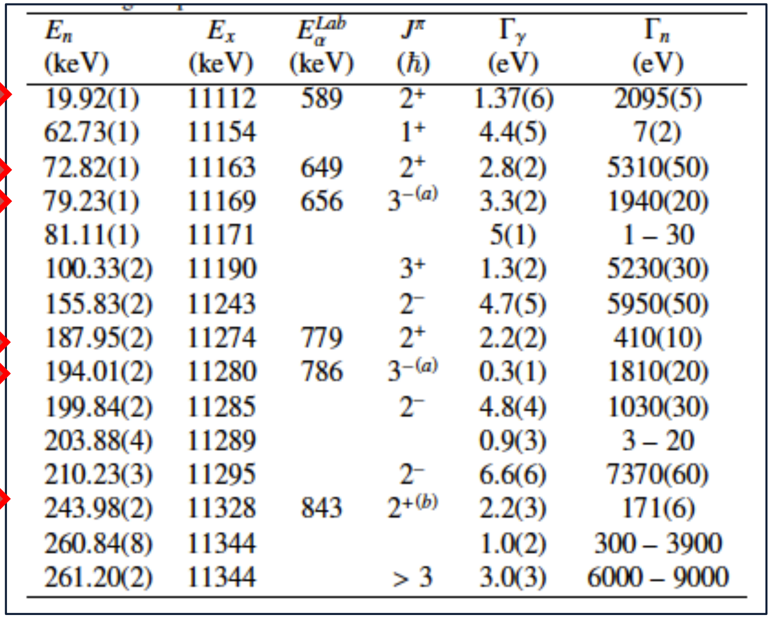
^{25}Mg(n,tot) and ^{25}Mg(n,γ) R-Matrix analysis



R-Matrix analysis



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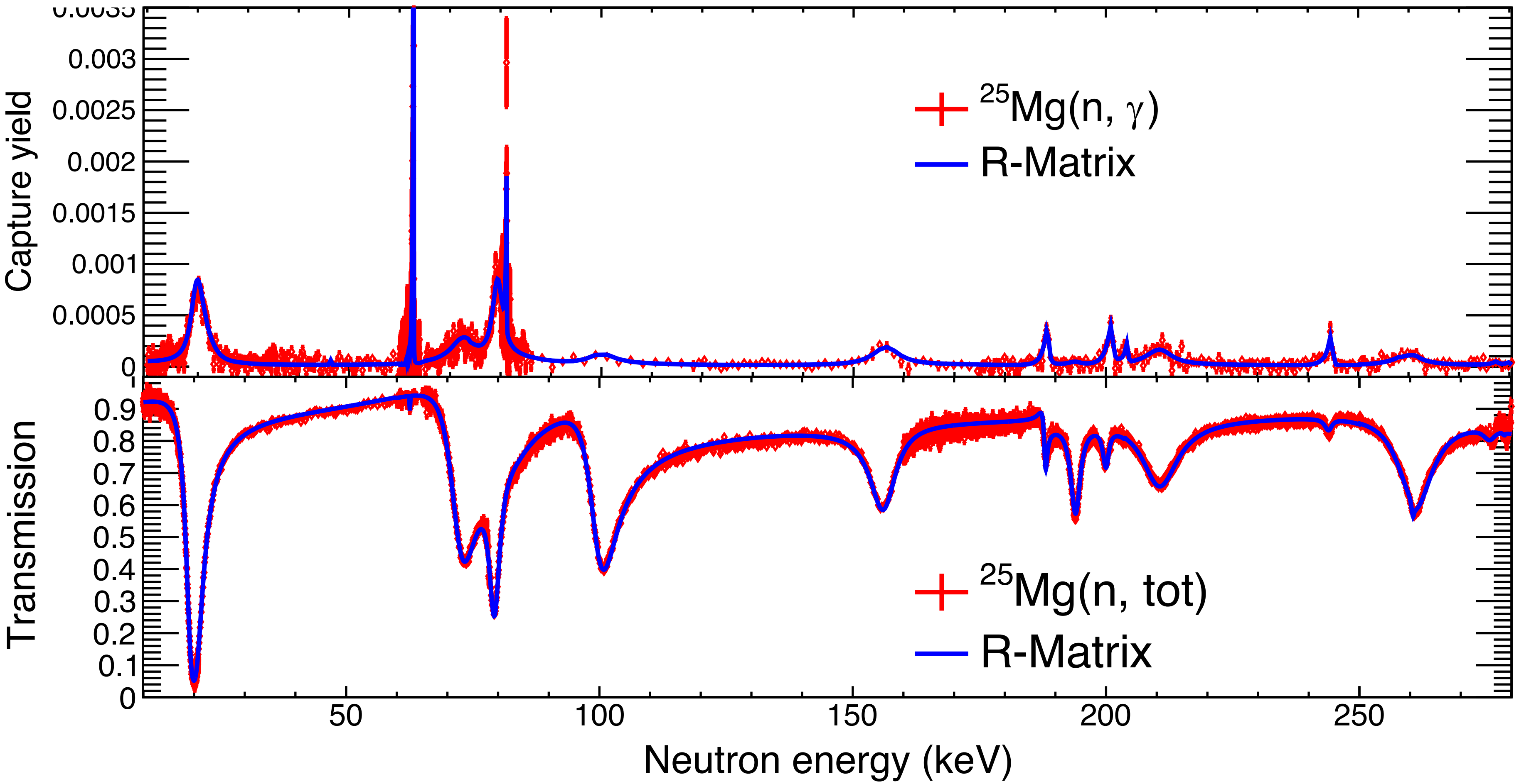
19.92(1)	11112	589	2^+	1.37(6)	2095(5)
62.73(1)	11154		1^+	4.4(5)	7(2)
72.82(1)	11163	649	2^+	2.8(2)	5310(50)
79.23(1)	11169	656	$3^{-(a)}$	3.3(2)	1940(20)
81.11(1)	11171			5(1)	1 – 30
100.33(2)	11190		3^+	1.3(2)	5230(30)
155.83(2)	11243		2^-	4.7(5)	5950(50)
187.95(2)	11274	779	2^+	2.2(2)	410(10)
194.01(2)	11280	786	$3^{-(a)}$	0.3(1)	1810(20)
199.84(2)	11285		2^-	4.8(4)	1030(30)
203.88(4)	11289			0.9(3)	3 – 20
210.23(3)	11295		2^-	6.6(6)	7370(60)
243.98(2)	11328	843	$2^{+(b)}$	2.2(3)	171(6)
260.84(8)	11344			1.0(2)	300 – 3900
261.20(2)	11344		> 3	3.0(3)	6000 – 9000

Energy, J^π, Γ_γ, Γ_n

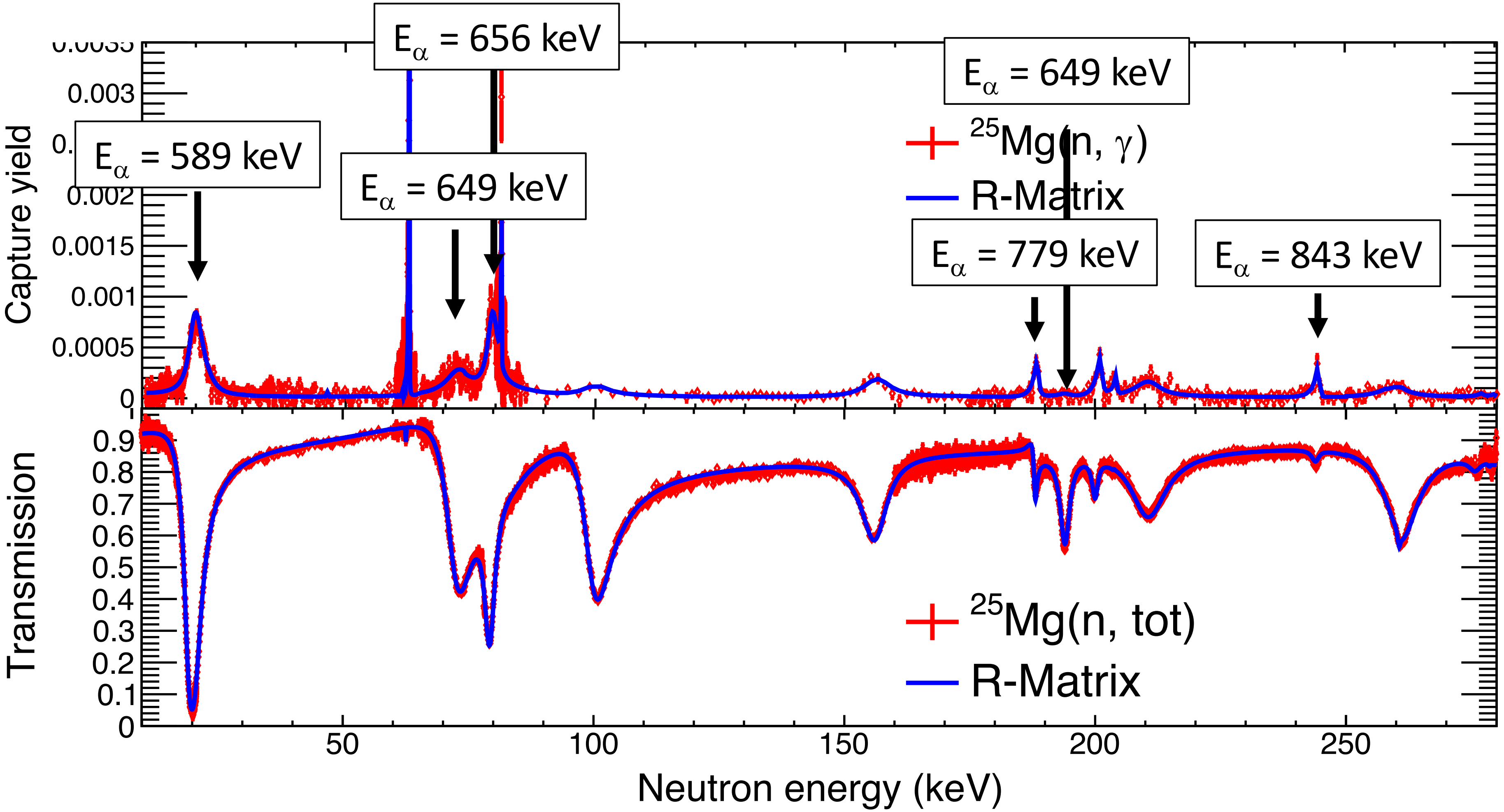
C Massimi *et al.*, Phys. Rev. C **85**, 044615 (2012)
C Massimi *et al.*, Phys. Lett. B **768**, 1 (2017)

^{25}Mg(n,tot) and ^{25}Mg(n,γ) R-Matrix analysis



C Massimi *et al.*, Phys. Rev. C **85**, 044615 (2012)
C Massimi *et al.*, Phys. Lett. B **768**, 1 (2017)

^{25}Mg(n,tot) and ^{25}Mg(n,γ) R-Matrix analysis



C Massimi *et al.*, Phys. Rev. C **85**, 044615 (2012)
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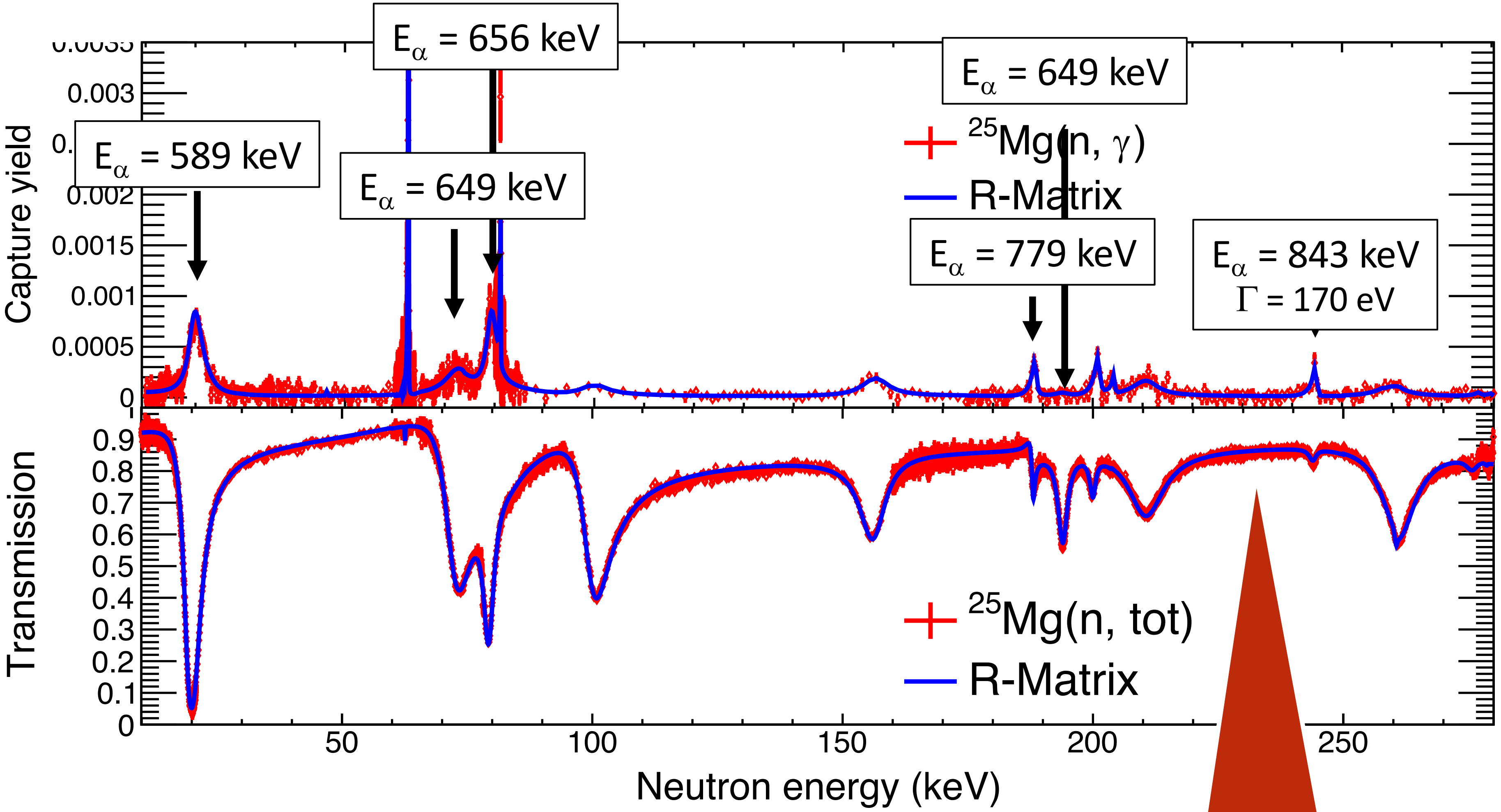
^{25}Mg(n,tot) and ^{25}Mg(n,γ) R-Matrix analysis



E_α = 830±2 keV ???
Γ = 250±170 eV

C Massimi *et al.*, Phys. Rev. C **85**, 044615 (2012)
C Massimi *et al.*, Phys. Lett. B **768**, 1 (2017)

^{25}Mg(n,tot) and ^{25}Mg(n,γ) R-Matrix analysis

Resonance strength ^{22}Ne(α,n)^{25}Mg:

$$\omega_\alpha = g\,\Gamma_\alpha \Gamma_n / (\Gamma_\alpha + \Gamma_\gamma + \Gamma_n)$$

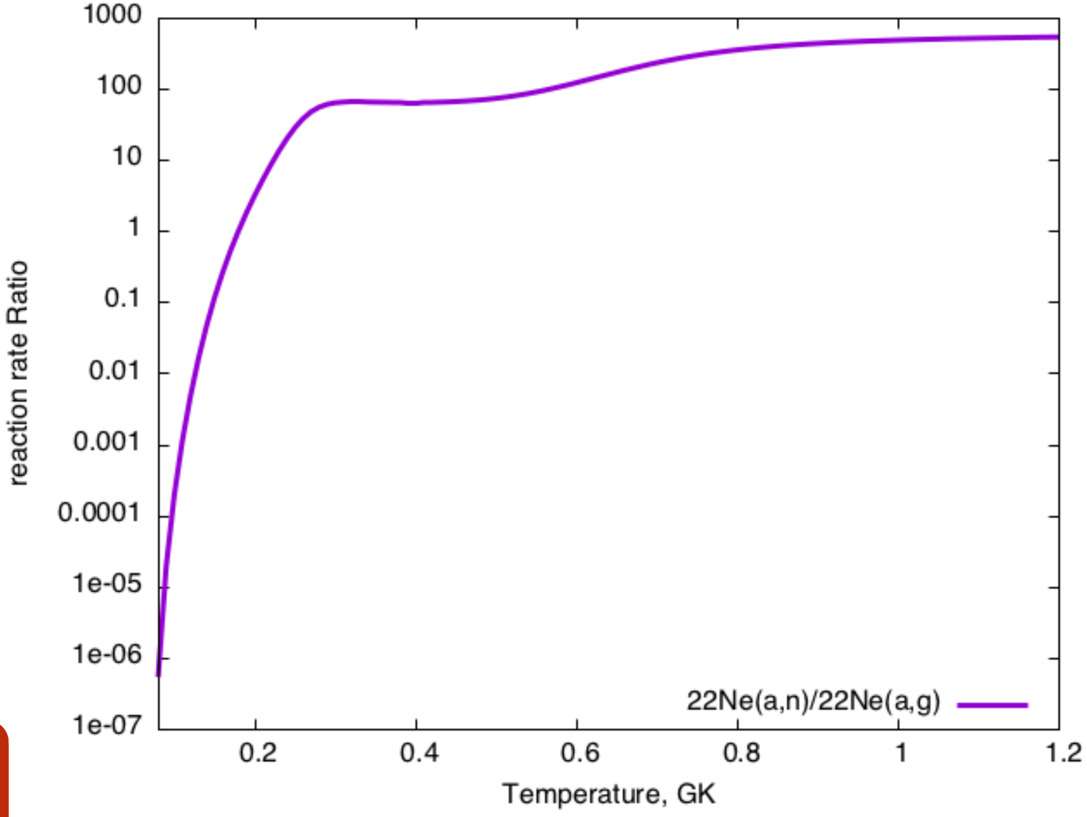
Resonance strength ^{22}Ne(α,γ)^{25}Mg:

$$\omega_\gamma = g\,\Gamma_\alpha \Gamma_\gamma / (\Gamma_\alpha + \Gamma_\gamma + \Gamma_n)$$

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

Resonance strength ratio → Reaction rate ratio independent of Γ_α

^{22}Ne(α,n) / ^{22}Ne(α,γ)



Conclusions

- ^{22}Ne(α,n) and (α,γ) represent a long-standing “problem” in nuclear astrophysics
- Measurements of ^{25}Mg(n,tot) and ^{25}Mg(n,γ) were performed at the GELINA facility and the n_TOF facility, respectively, to study excited states in ^{26}Mg

- Simultaneous resonance shape (R-Matrix) analysis of capture and transmission resulted in:
  - accurate ^{25}Mg(n,γ) cross section;
  - **energy** and **J$^{\pi}$** determination of ^{26}Mg levels: evidence for natural states;
  - constraints for the competing ^{22}Ne(α,γ) reaction;
  - doubts on the **E_{α} = 830 keV** resonance.

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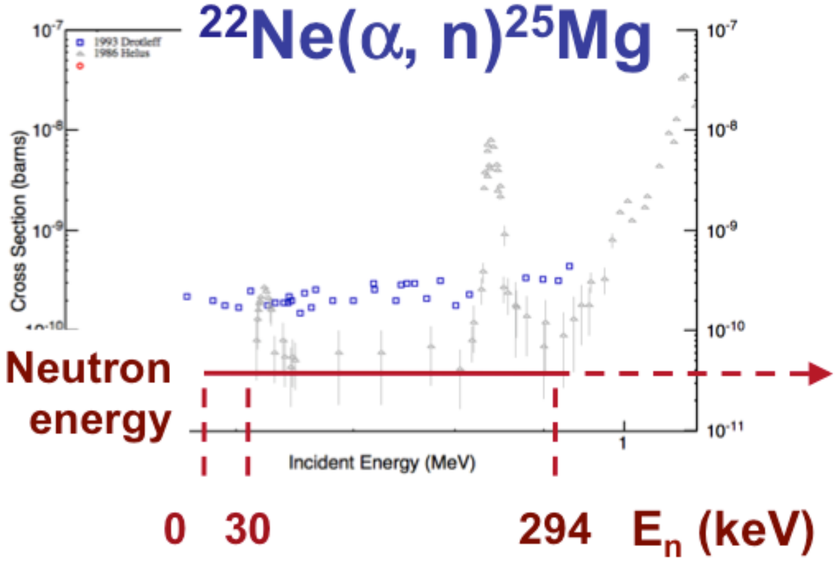
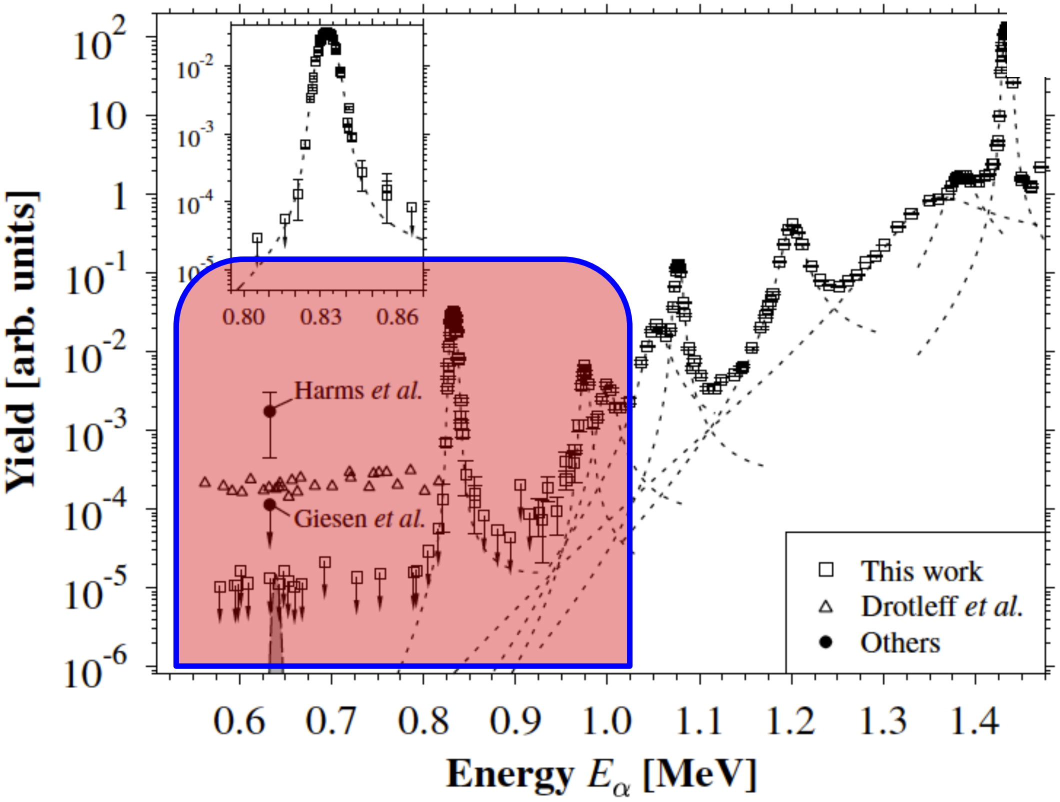
Extra slides

Extra slides

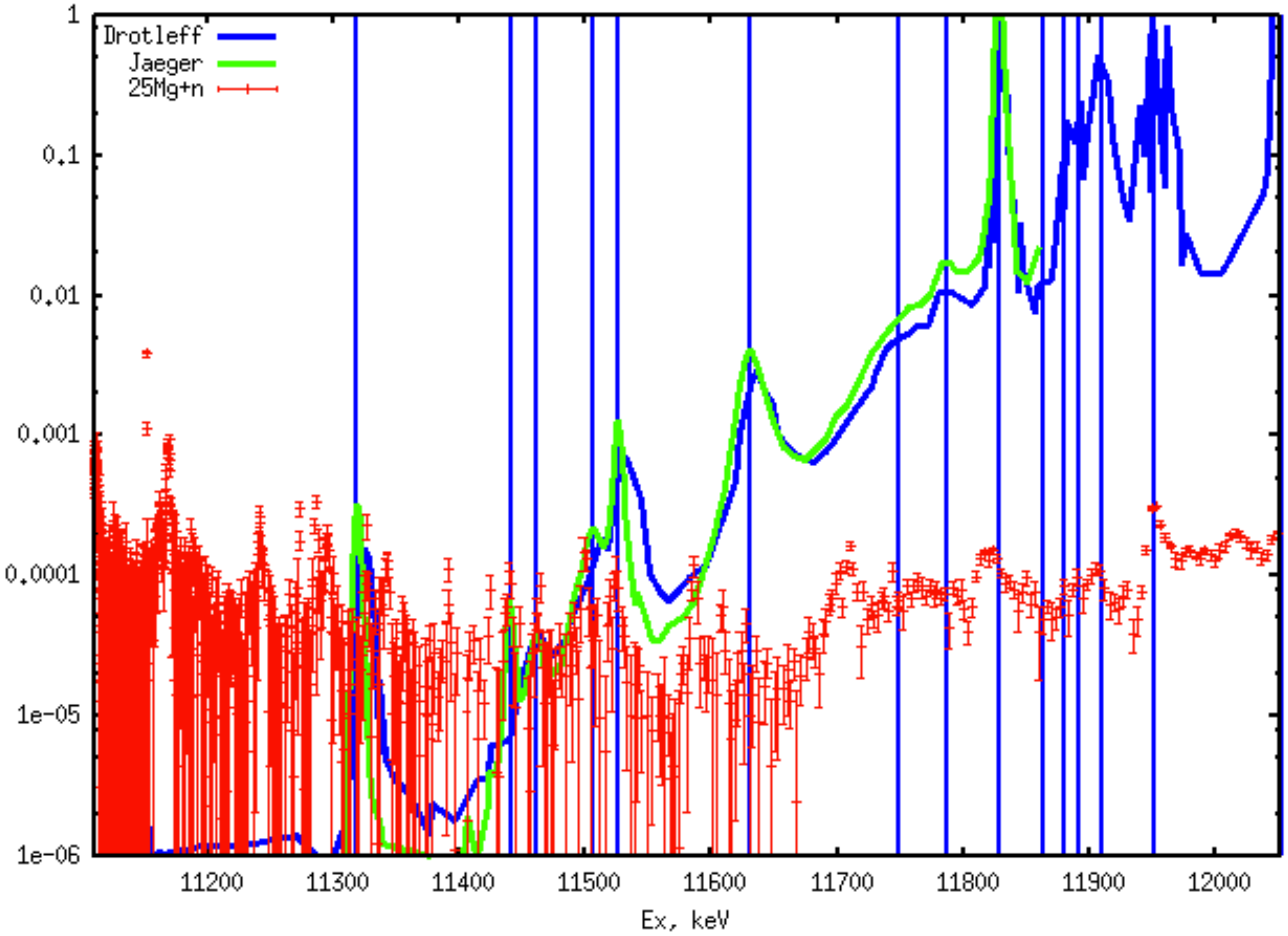


$^{22}\mathrm{Ne}(\alpha, n)^{25}\mathrm{Mg}$

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



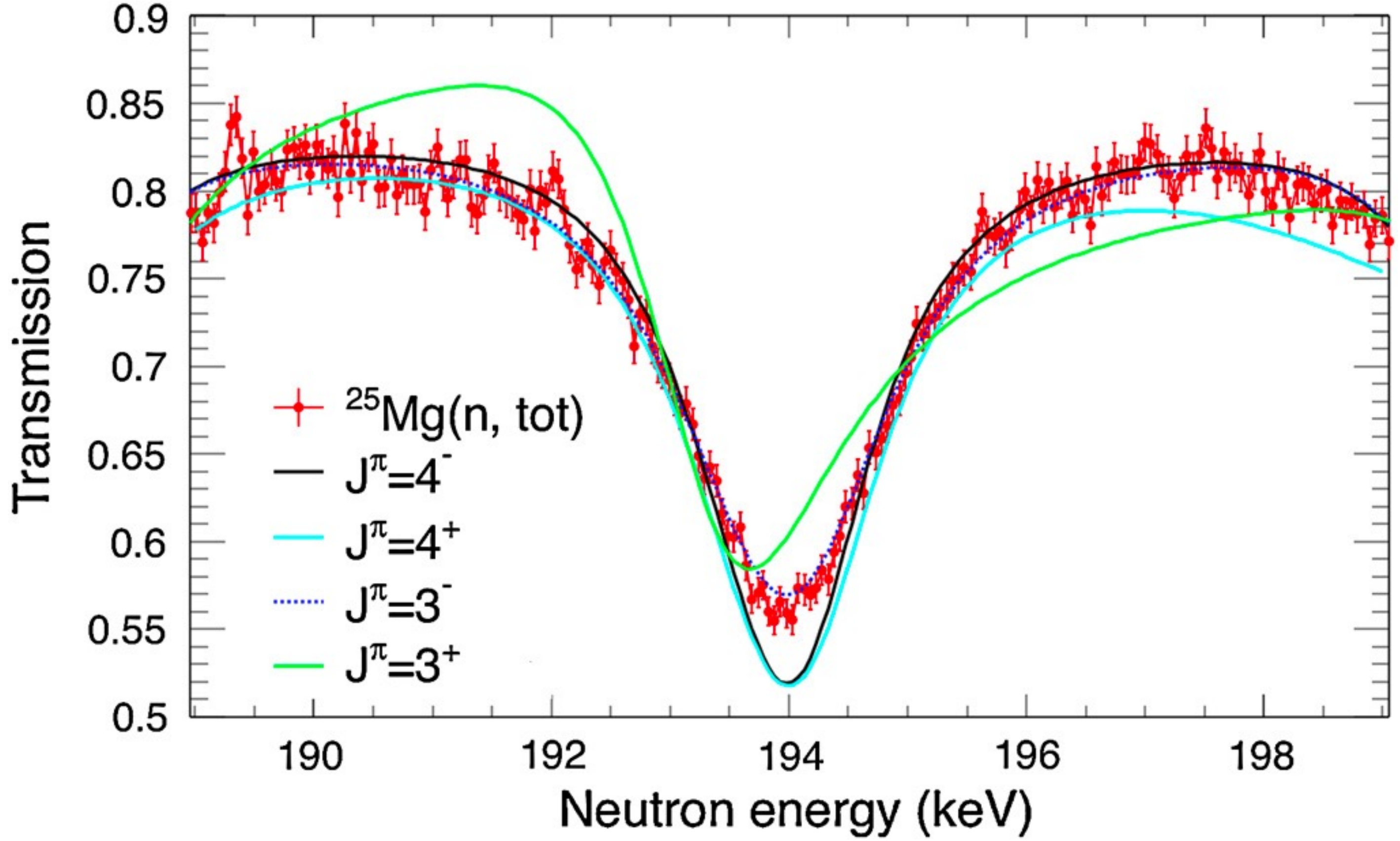
Extra slides



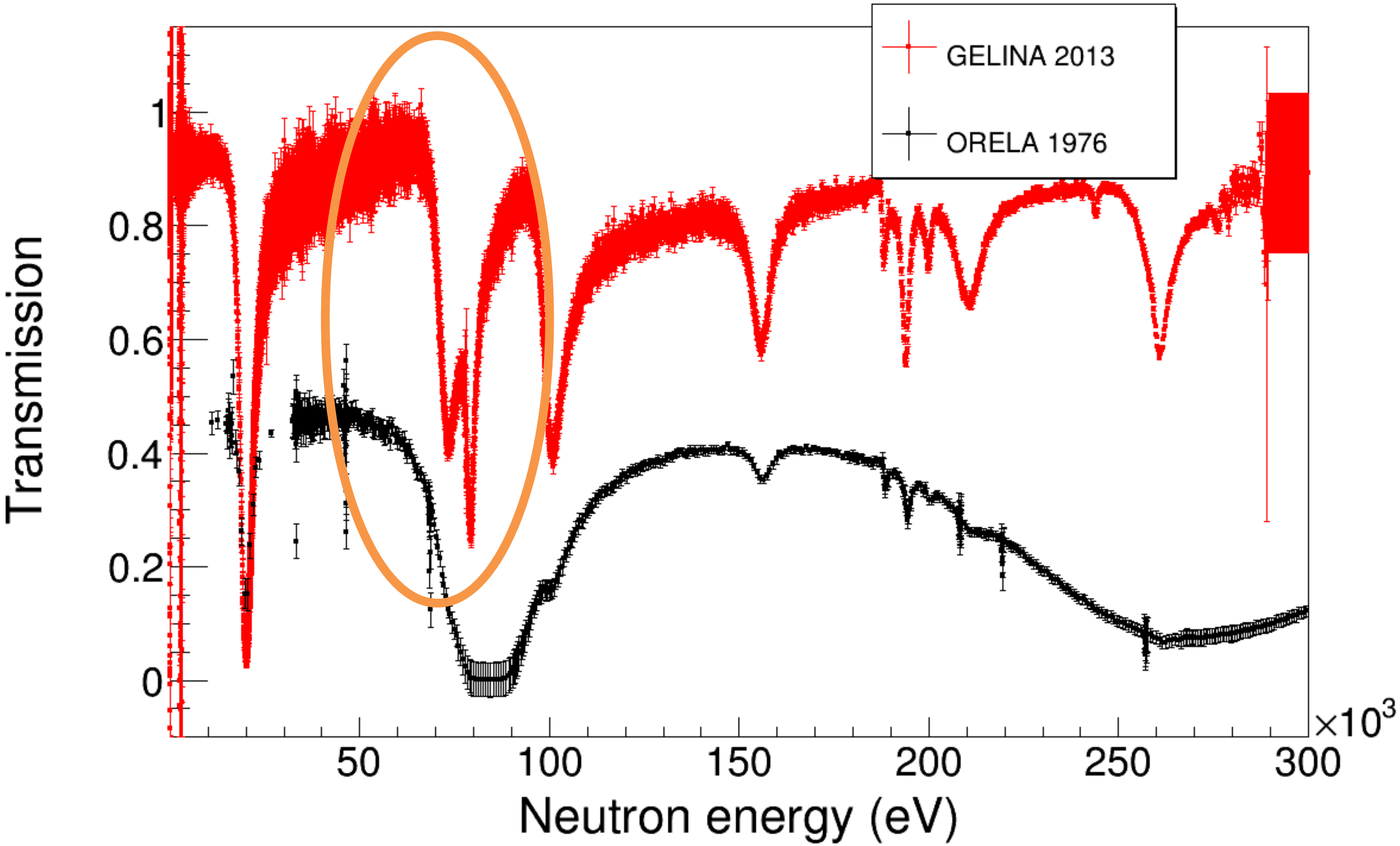
C Massimi *et al.*, Phys. Rev. C **85**, 044615 (2012)
C Massimi *et al.*, Phys. Lett. B **768**, 1 (2017)

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

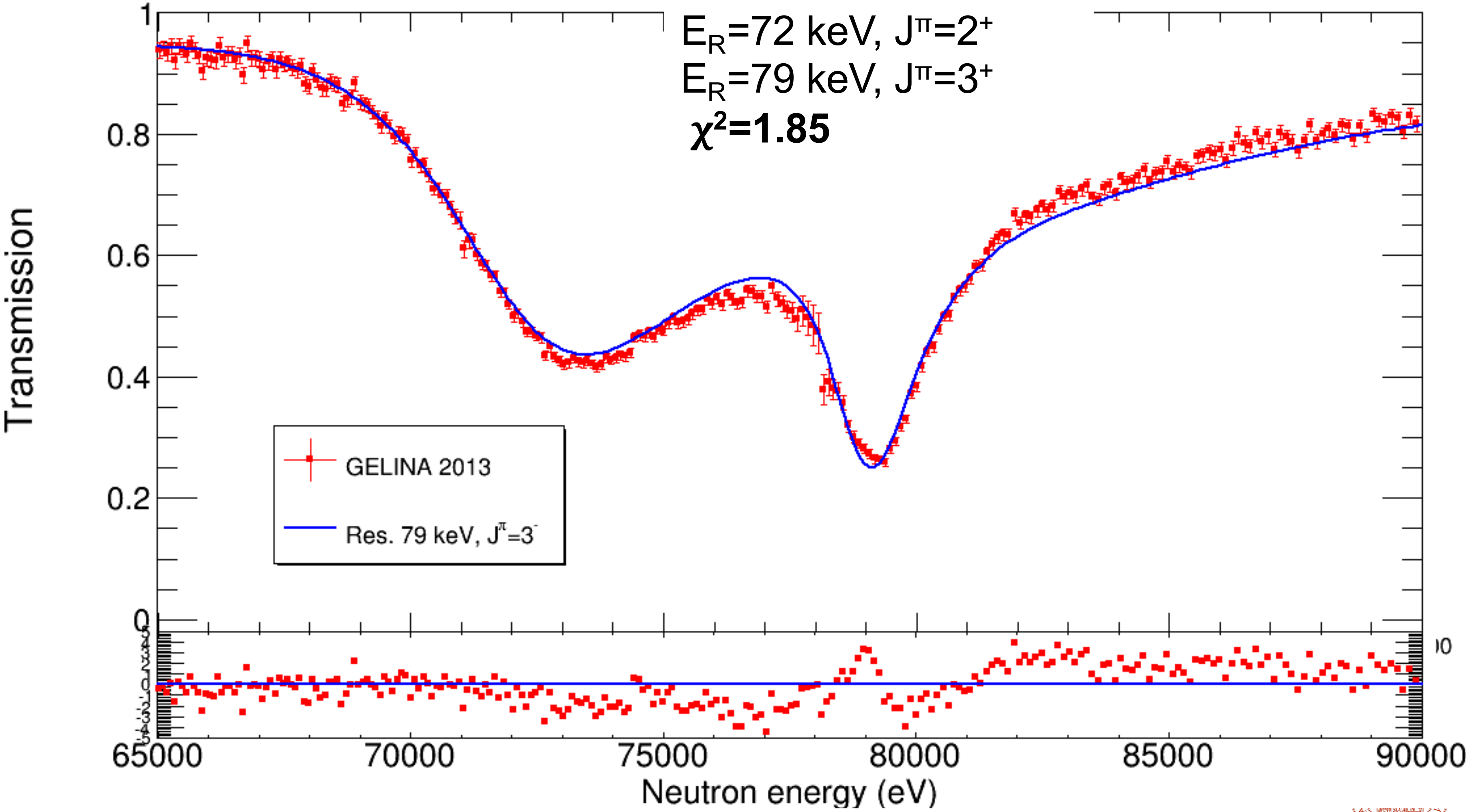
Example of the sensitivity to Spin and Parity J^{π}



Extra slides



Extra slides



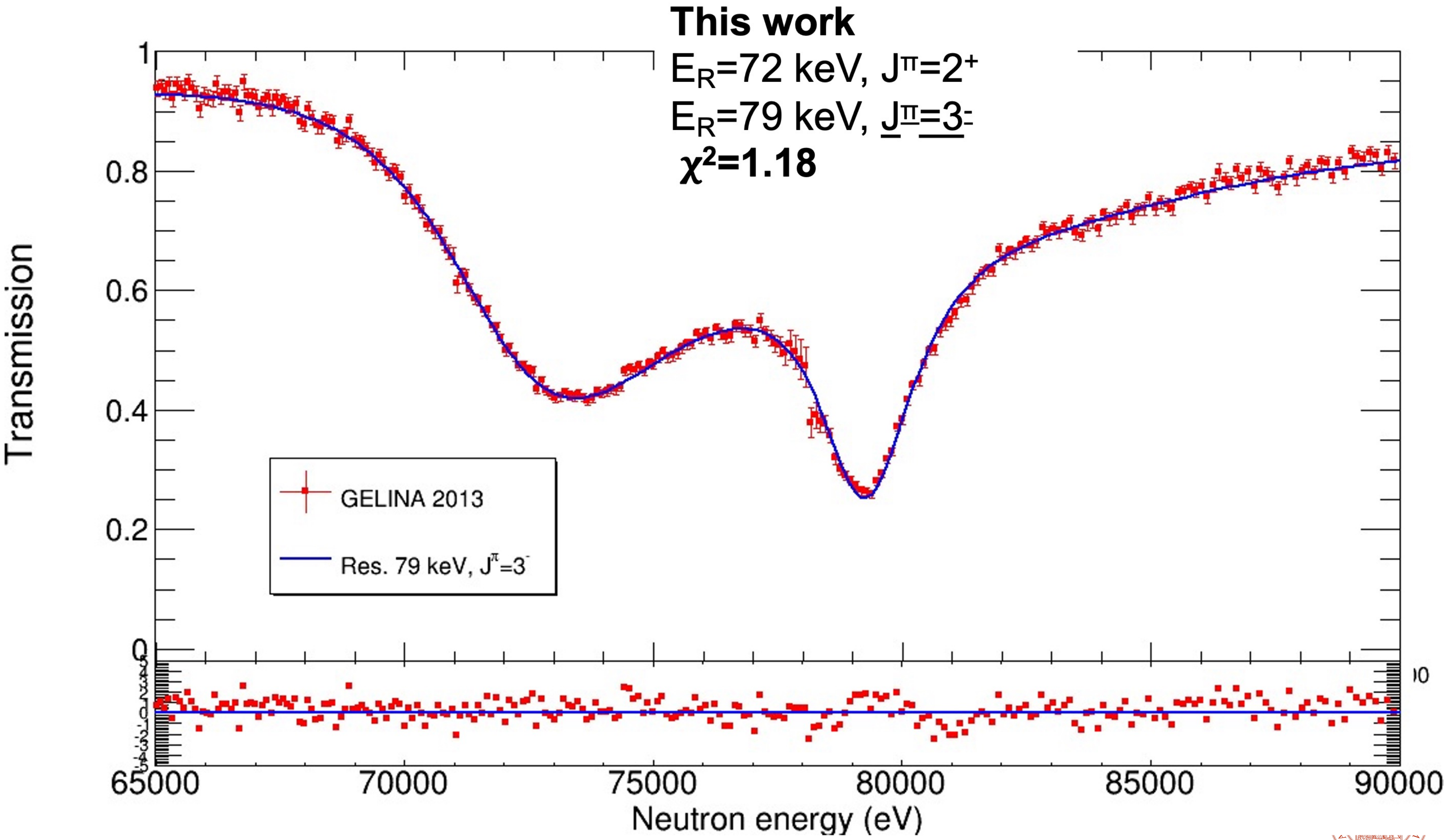
Previous evaluation

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

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

χ^2=1.85

Extra slides



This work

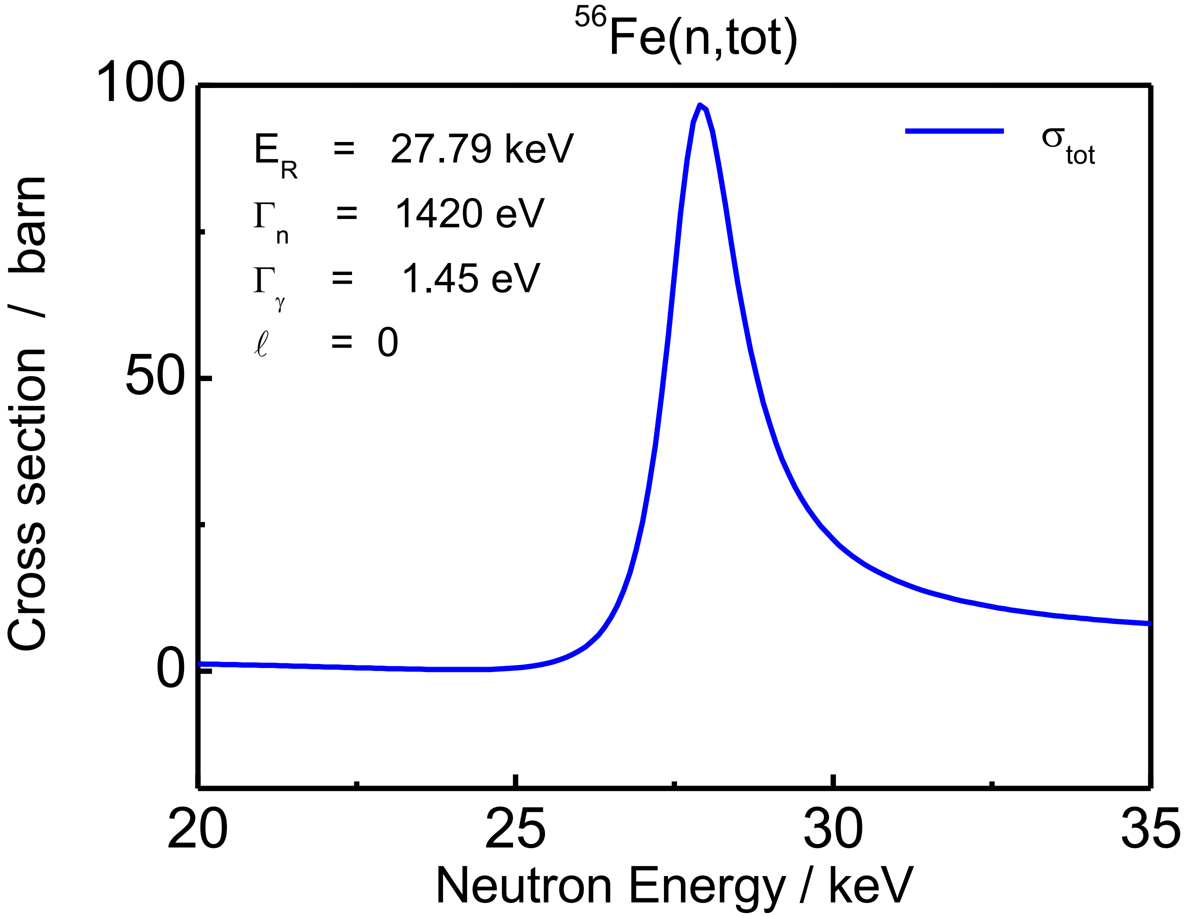
E_R=72 keV, $J^{\pi}=2^{+}$

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

χ^2=1.18

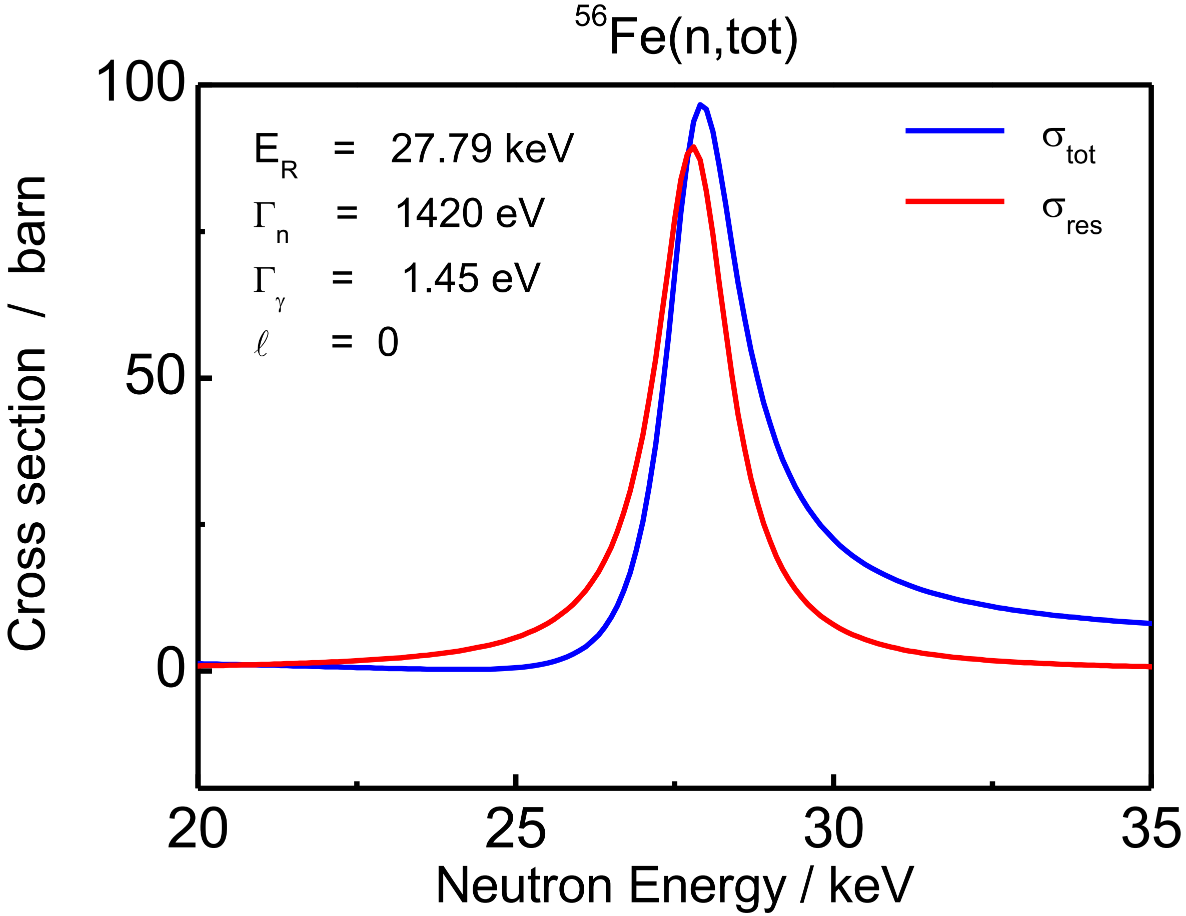
Extra slides: total cross section

$$\sigma_{tot}(E_n) = g\frac{\pi}{k_n^2}\frac{\Gamma_n\Gamma}{(E_n-E_R)^2+(\Gamma/2)^2} + g\frac{4\pi}{k_n}\frac{\Gamma_n(E_n-E_R)R'}{(E_n-E_R)^2+(\Gamma/2)^2} + 4\pi R'^2$$



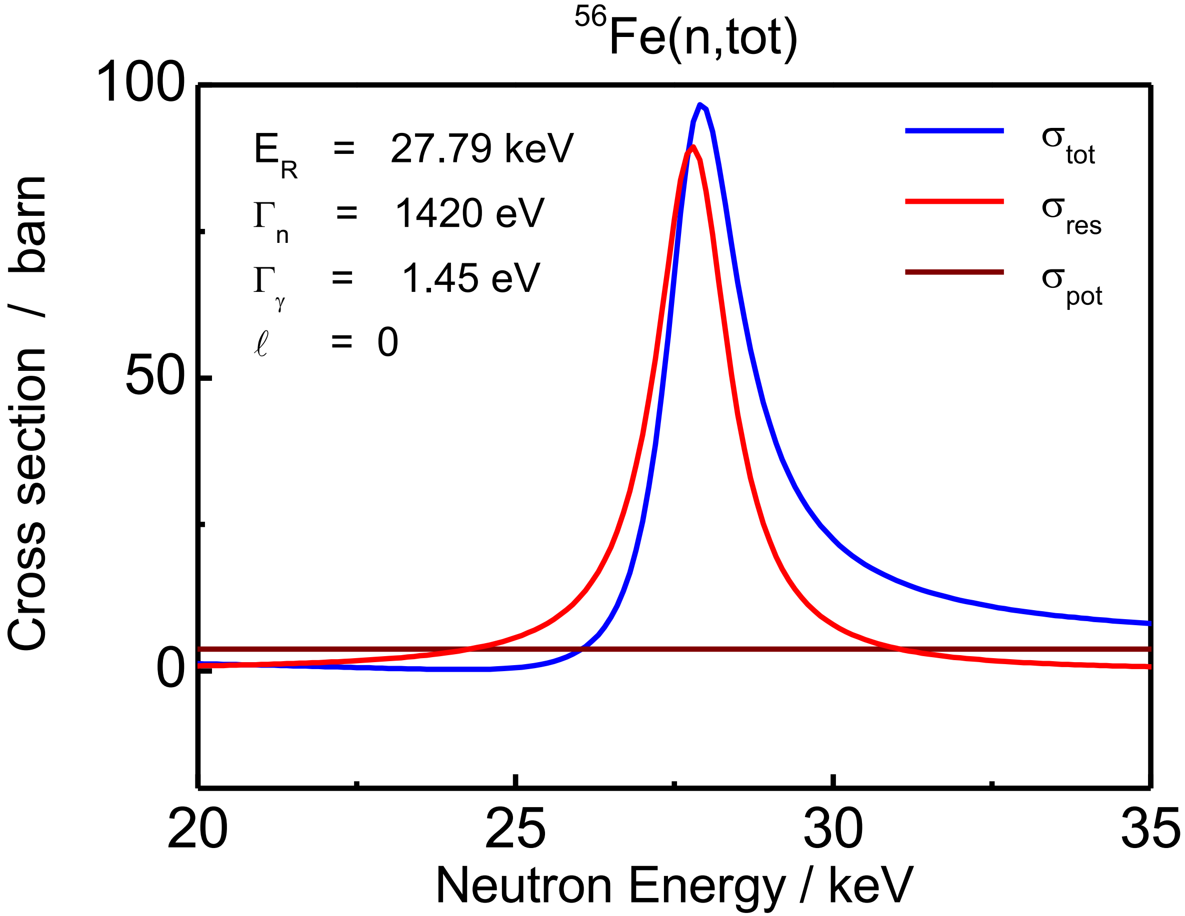
Extra slides: total cross section

$$\sigma_{tot}(E_n) = \boxed{g\,\frac{\pi}{k_n^2}\,\frac{\Gamma_n\Gamma}{(E_n-E_R)^2+(\Gamma/2)^2}} + g\,\frac{4\pi}{k_n}\,\frac{\Gamma_n(E_n-E_R)R'}{(E_n-E_R)^2+(\Gamma/2)^2} + 4\pi R'^2$$



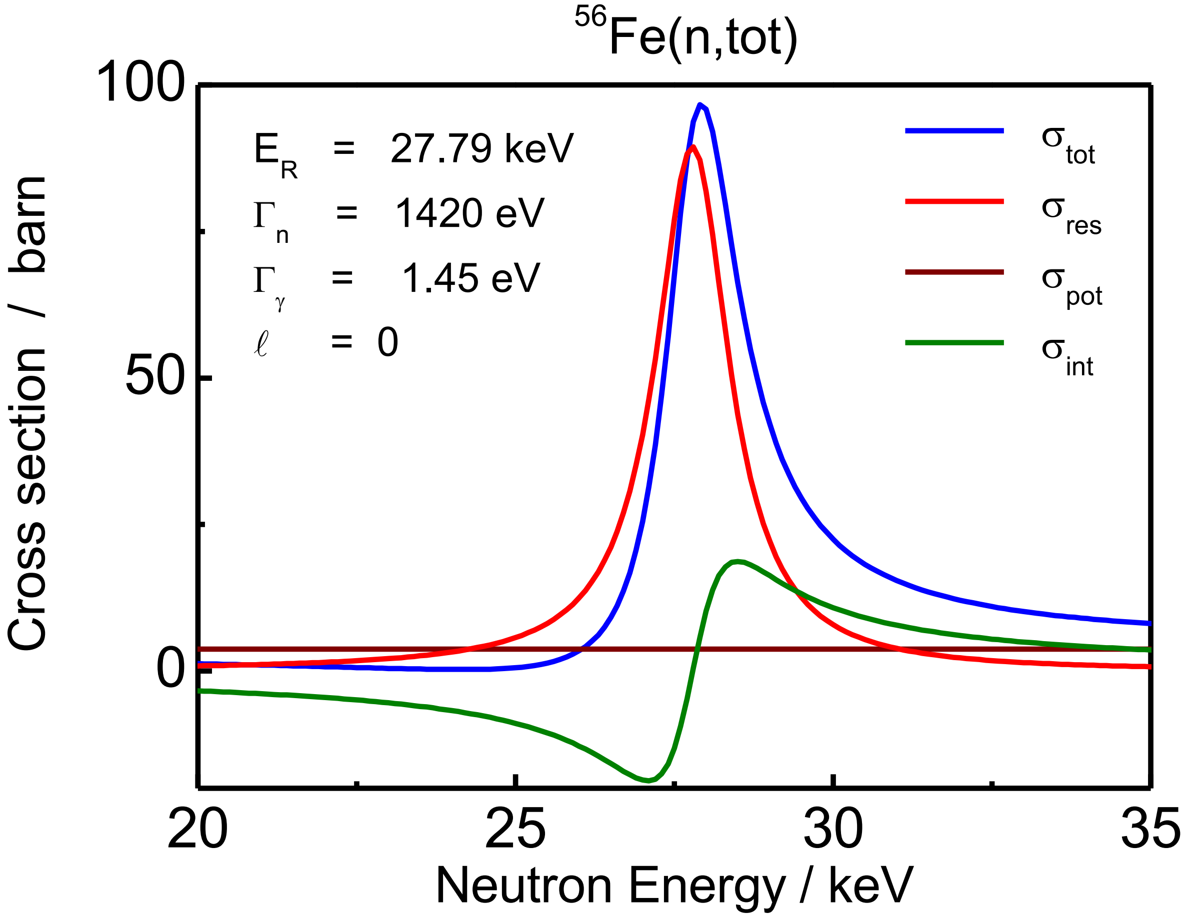
Extra slides: total cross section

$$\sigma_{tot}(E_n) = \boxed{g\,\frac{\pi}{k_n^2}\,\frac{\Gamma_n\Gamma}{(E_n-E_R)^2+(\Gamma/2)^2}} + g\,\frac{4\pi}{k_n}\,\frac{\Gamma_n(E_n-E_R)R'}{(E_n-E_R)^2+(\Gamma/2)^2} + \boxed{4\pi R'^2}$$



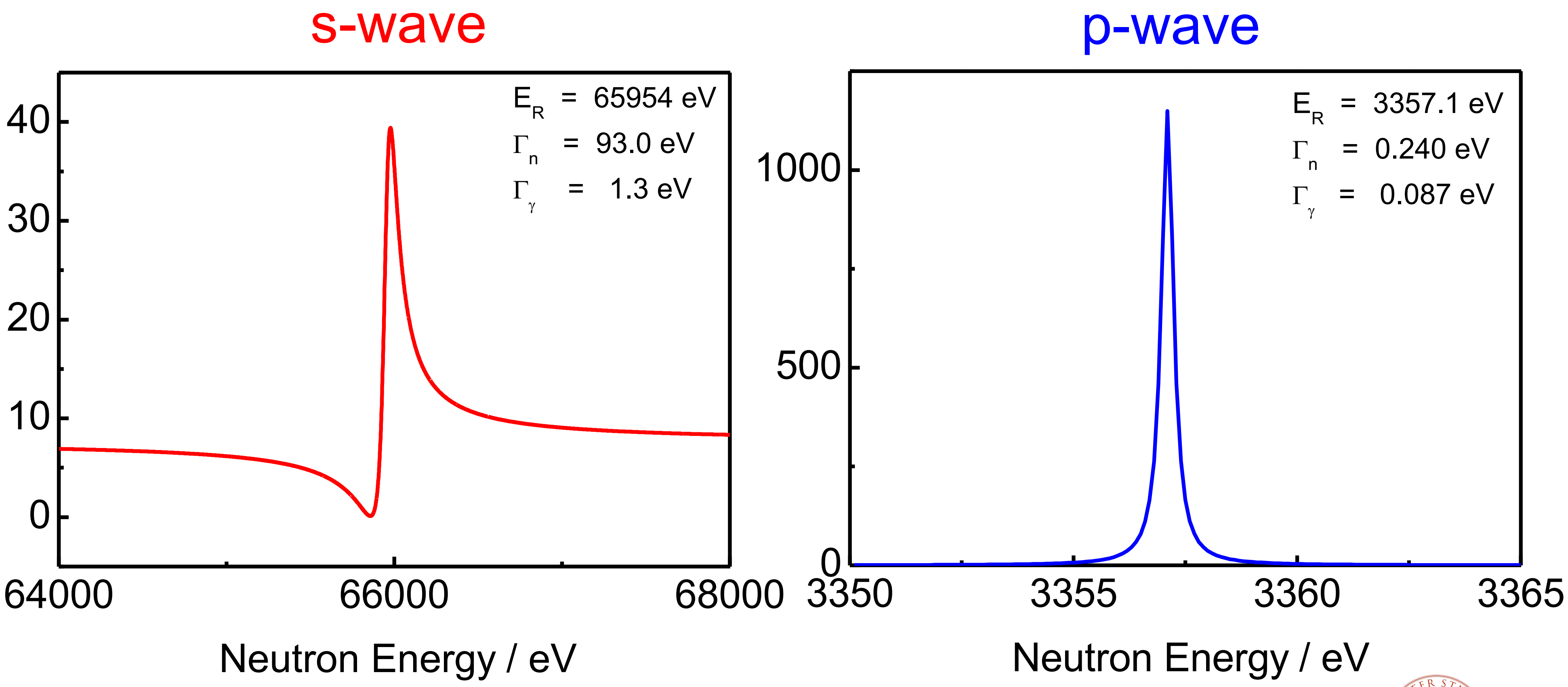
Extra slides: total cross section

$$\sigma_{tot}(E_n) = \boxed{g\,\frac{\pi}{k_n^2}\,\frac{\Gamma_n\Gamma}{(E_n-E_R)^2+(\Gamma/2)^2}} + \boxed{g\,\frac{4\pi}{k_n}\,\frac{\Gamma_n(E_n-E_R)R'}{(E_n-E_R)^2+(\Gamma/2)^2}} + \boxed{4\pi R'^2}$$



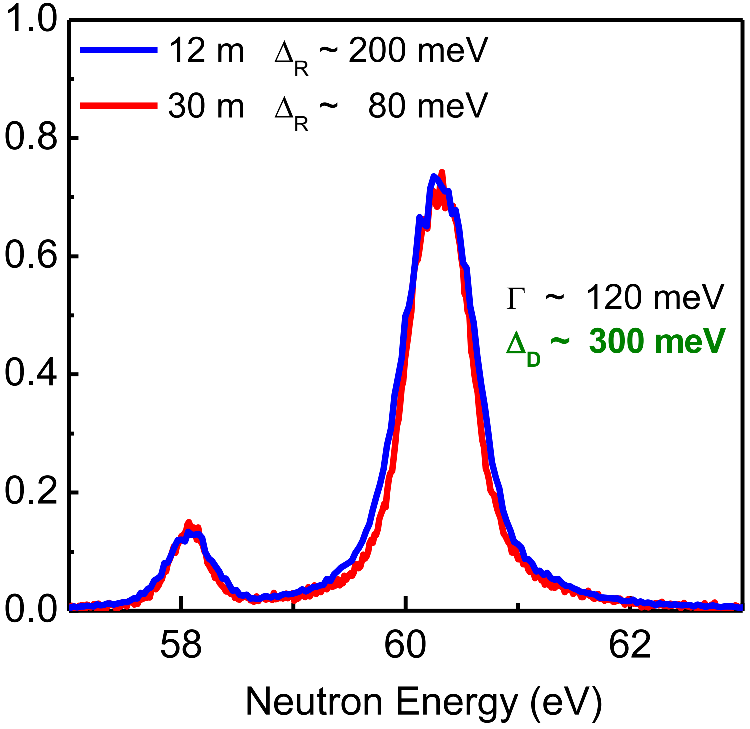
Extra slides: total cross section

$$\sigma_{tot}(E_n) = g\frac{\pi}{k_n^2}\frac{\Gamma_n\Gamma}{(E_n - E_R)^2 + (\Gamma/2)^2} + g\frac{4\pi}{k_n}\frac{\Gamma_n(E_n - E_R)R'}{(E_n - E_R)^2 + (\Gamma/2)^2} + 4\pi R'^2$$

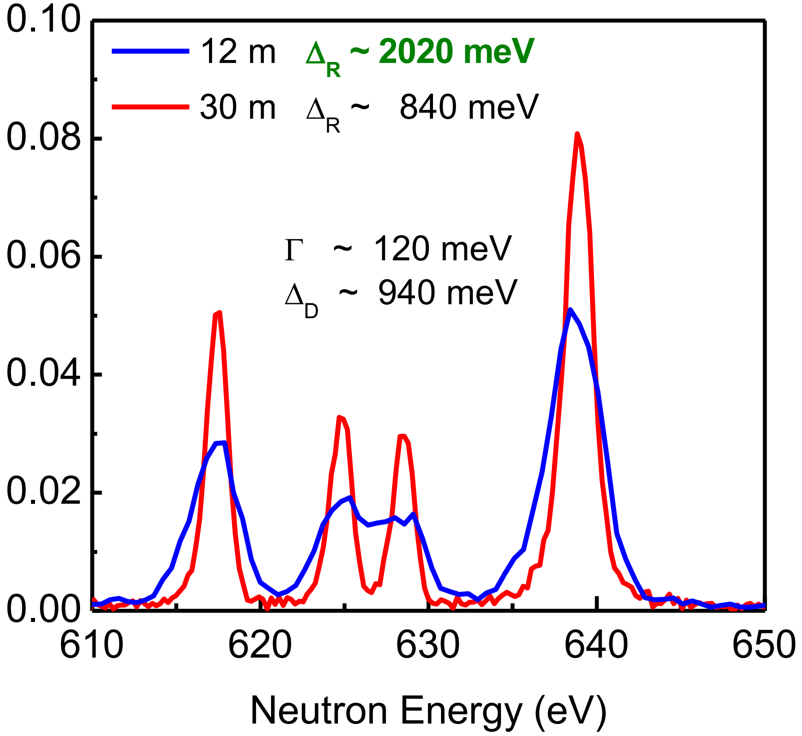


Extra slides: experimental complication in TOF measurements

Doppler dominates



Experimental broadening dominates



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