Neutron cross sections in stellar nucleosynthesis: study of the key isotope ^{25}Mg

Federica Mingrone

SIF - XCIX Congresso Nazionale,
Trieste – 26 Settembre 2013

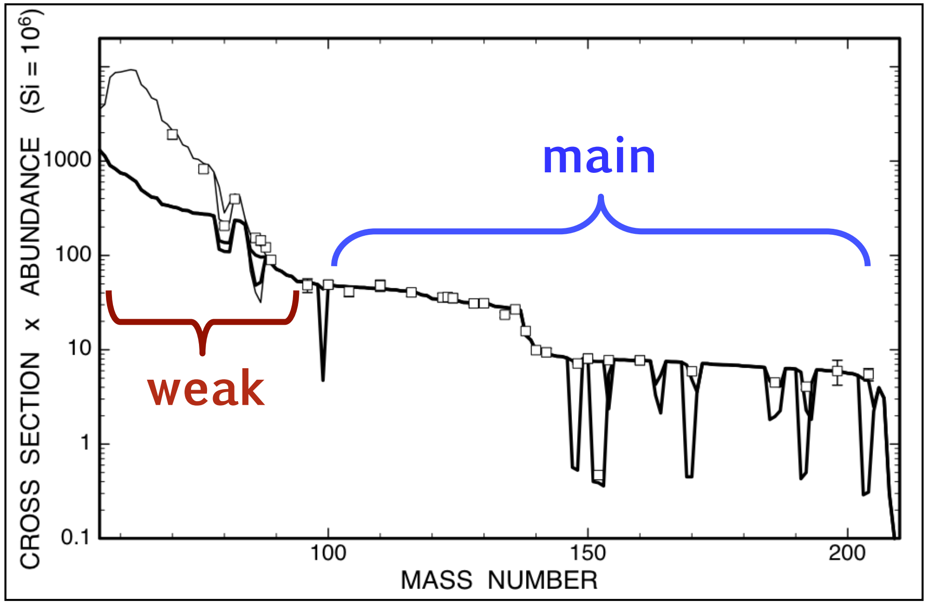
Stellar nucleosynthesis

Elements in stars are mainly produced via

- Nuclear fusion reactions
- Neutron capture reactions

→ **r-process** (Supernovae Type-II)

→ **s-process** (Red giants and AGB stars)

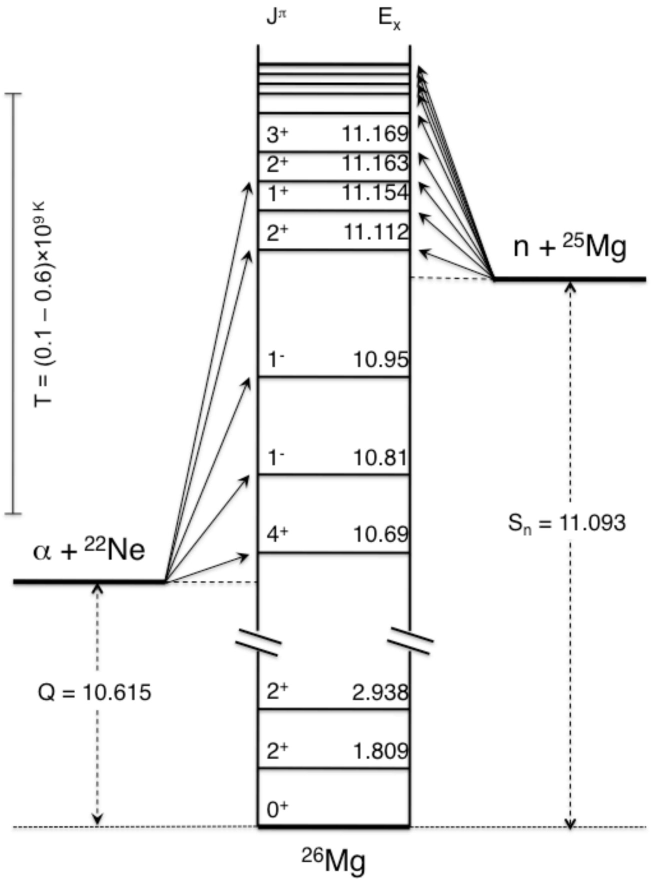


A<90 weak s-process $M \geq 8 M_\odot$

A>90 main s-process $1 \leq M/M_\odot \leq 3$

^{25}Mg in the s-process – I

^{22}Ne(α,n)^{25}Mg is the most important **neutron source for s-process**



Weak component

^{22}Ne(α,n)^{25}Mg is the main **neutron source** in massive stars ($M > 8\ M_{sun}$)

kT=25 keV and kT=90 keV

Main component

^{22}Ne(α,n)^{25}Mg is a **neutron source** in **AGB stars** ($1M_{sun} < M < 3M_{sun}$)

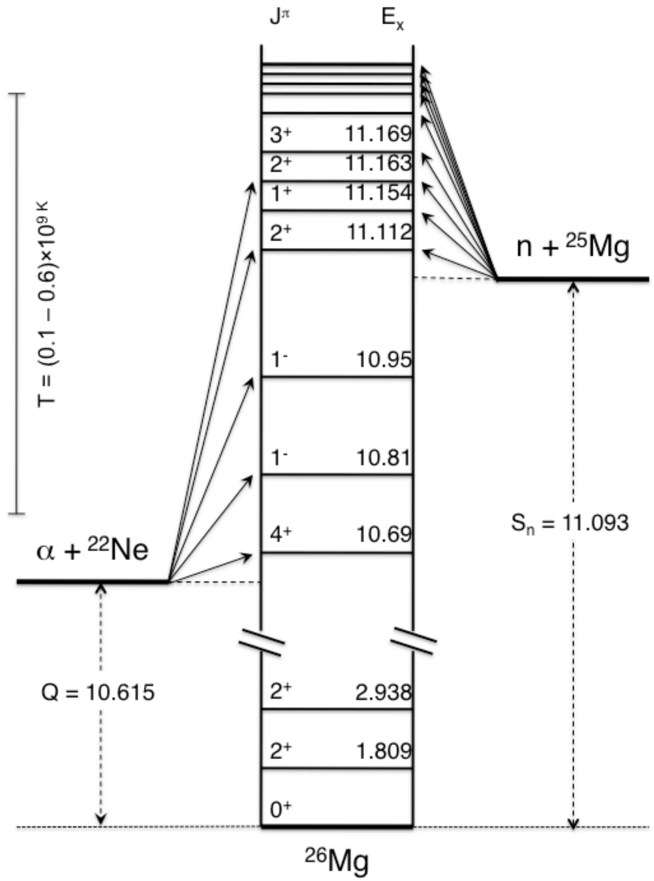
kT=8 keV and kT=25 keV

^{25}Mg in the s-process – I

^{22}Ne(α,n)^{25}Mg is the most important **neutron source for s-process**

Its reaction rate is **very uncertain** because of the poorly known property of the states in ^{26}Mg. Information can come from neutron measurements in terms of the knowledge of **J$^{\pi}$** for the ^{26}Mg states.

Element	Spin/parity
^{22}Ne	0^+
^{4}He	0^+
^{25}Mg	$5/2^+$
n	$1/2^+$

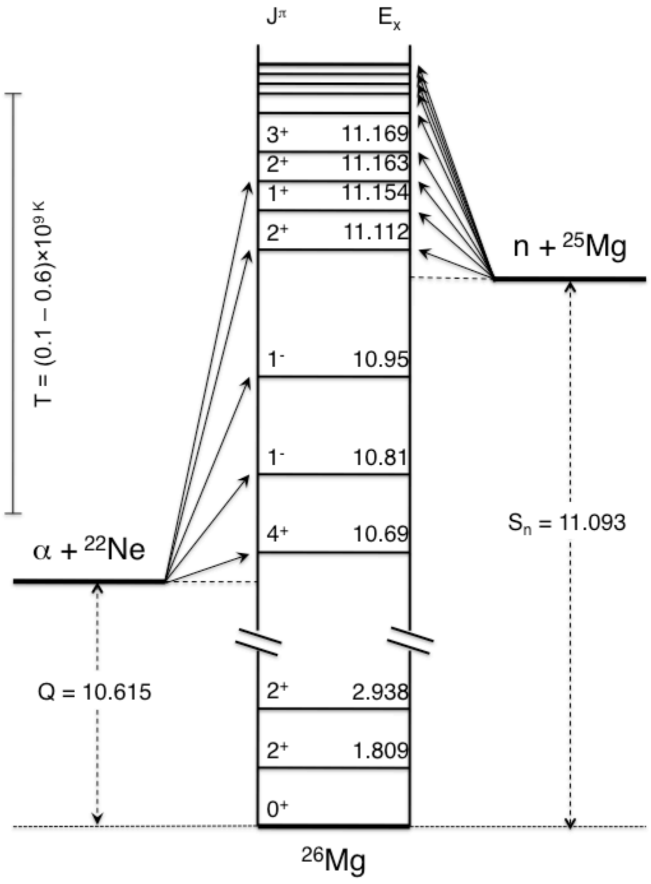


^{25}Mg in the s-process – I

^{22}Ne(α,n)^{25}Mg is the most important **neutron source for s-process**

Its reaction rate is **very uncertain** because of the poorly known property of the states in ^{26}Mg. Information can come from neutron measurements in terms of the knowledge of **J$^{\pi}$** for the ^{26}Mg states.

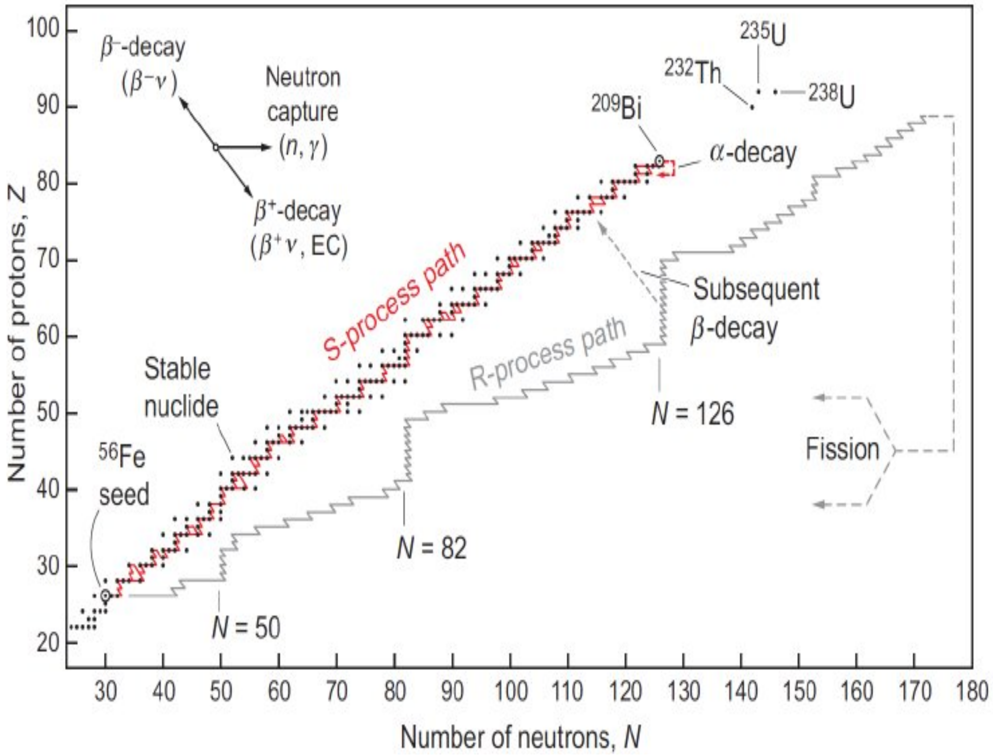
From neutron time of flight measurements:
→ J$^{\pi}$ for the ^{26}Mg states from ^{25}Mg(n,γ) measurement



^{25}Mg in the s-process – II

^{25}**Mg** is one of the most important **neutron poisons**

Neutron capture on Mg stable isotopes affects the process of neutron capture on ^{56}Fe, the basic s-process seed for the production of heavy isotopes.



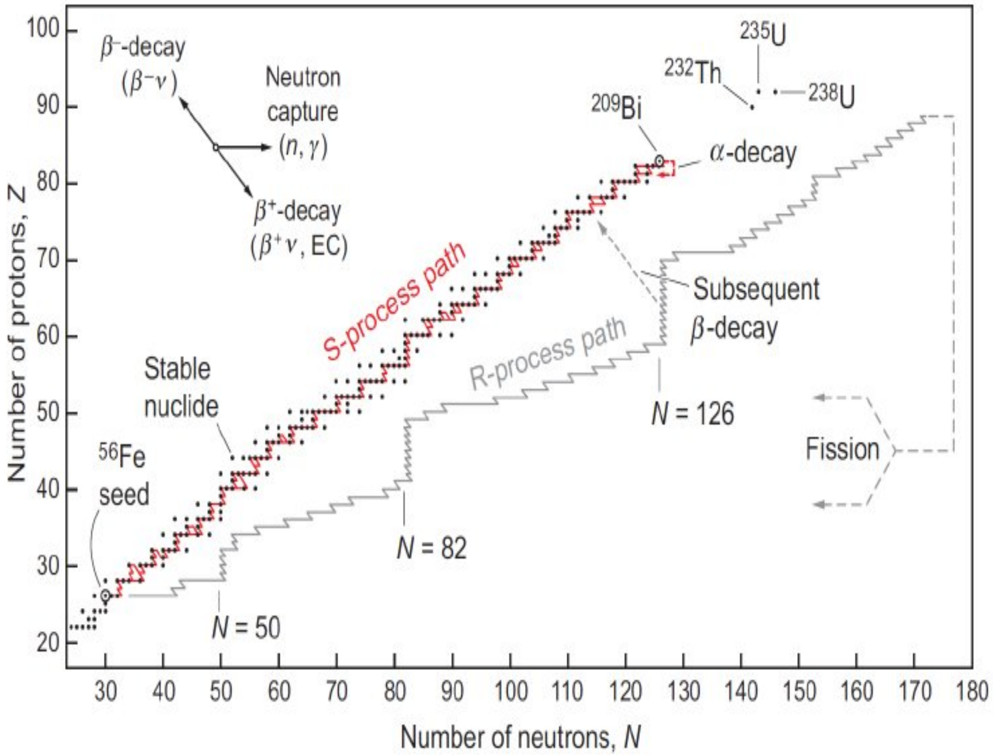
^{25}Mg in the s-process – II

^{25}**Mg** is one of the most important **neutron poisons**

Neutron capture on Mg stable isotopes affects the process of neutron capture on ^{56}Fe, the basic s-process seed for the production of heavy isotopes.

From neutron time of flight measurements:

→ ^{25}**Mg(n,γ) cross section**



^{25}Mg campaign

^{25}Mg is crucial for s-process both as involved as a **neutron poison** and in **neutron production**

Elements abundance strongly depends on the n+Mg cross sections, and in particular on the balance between:

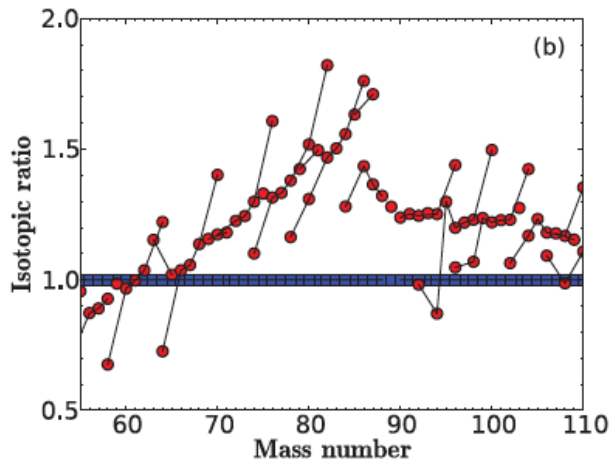
- Production of ^{25}Mg via ^{22}Ne(α,n)^{25}Mg
- Formation of ^{26}Mg via ^{25}Mg(n,γ)^{26}Mg

Old 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]

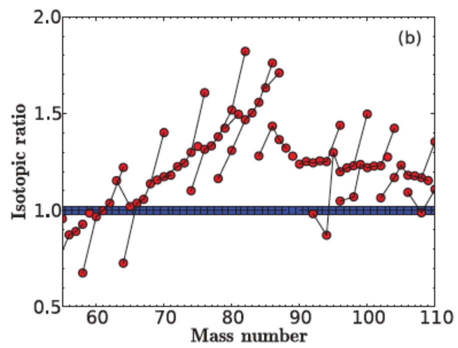


Old 2003 measurement

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

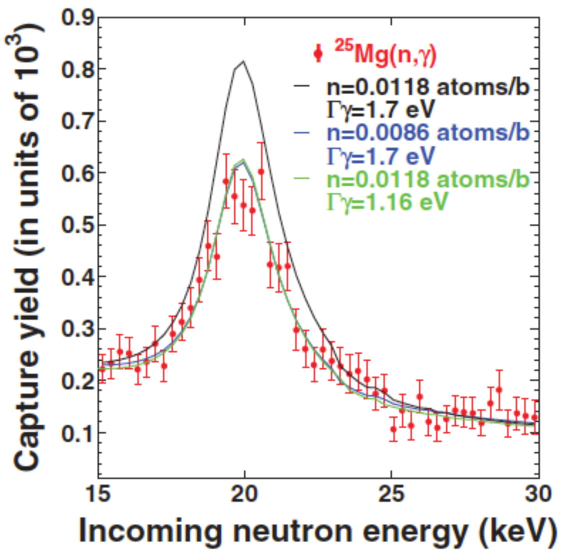
Resonance neutron-capture cross sections of stable magnesium isotopes and their astrophysical implications

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]



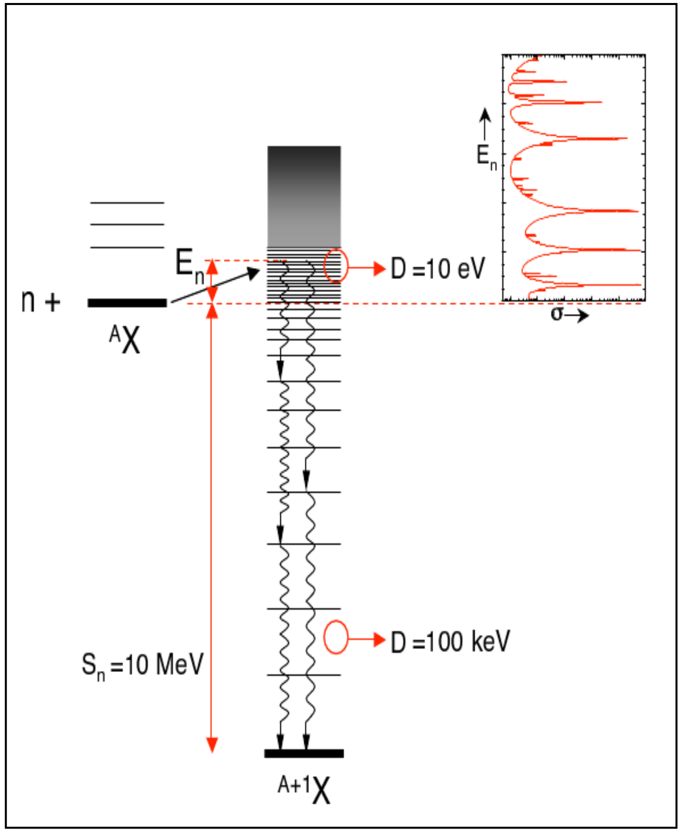
PROBLEMS:

- **Oxide Sample** → Large uncertainty in the Mg mass
- **Powder Sample** → Al canning + Areal density uncertainty
- **High impurities** → ^{24}Mg ~ 3%, ^{26}Mg ~ 1.2%



New 2012 measurement:
EXPERIMENTAL TECHNIQUE

Using a Time of Flight (TOF) technique, the cross section is determined through the measurement of **the reaction yield $Y_R(E_n)$**:



$$Y = N \frac{C_w}{\varepsilon\ \Phi}$$

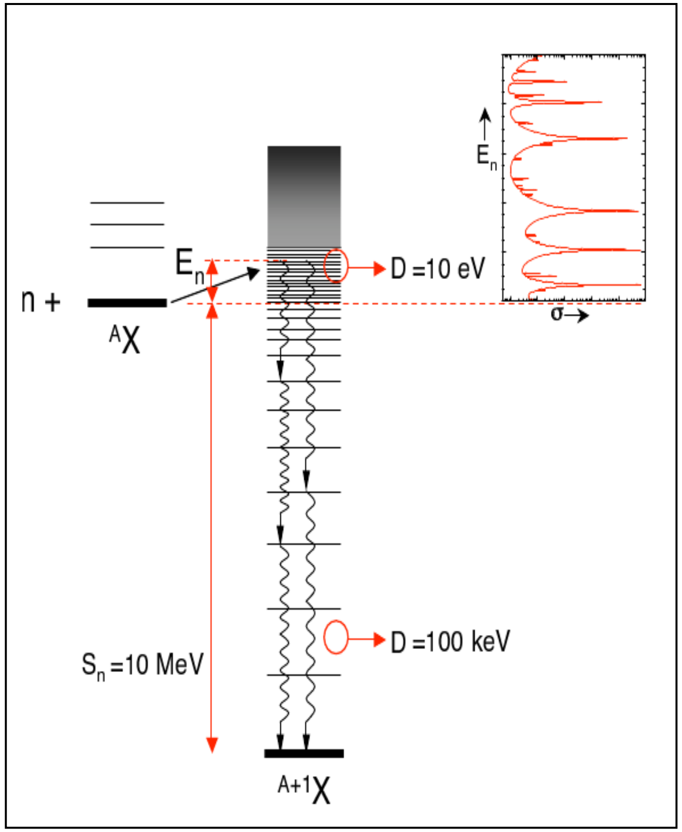
- ***N:*** normalization factor to obtain an absolute capture yield
- ***C_w:*** weighted counts background subtracted
- **Φ:** incident neutron fluence
- **$\varepsilon = k \times E_c$:** detection efficiency

The experimental yield can be expressed in terms of **total (σ_{tot})** and **capture (σ_γ)** cross section:

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

New 2012 measurement: EXPERIMENTAL TECHNIQUE

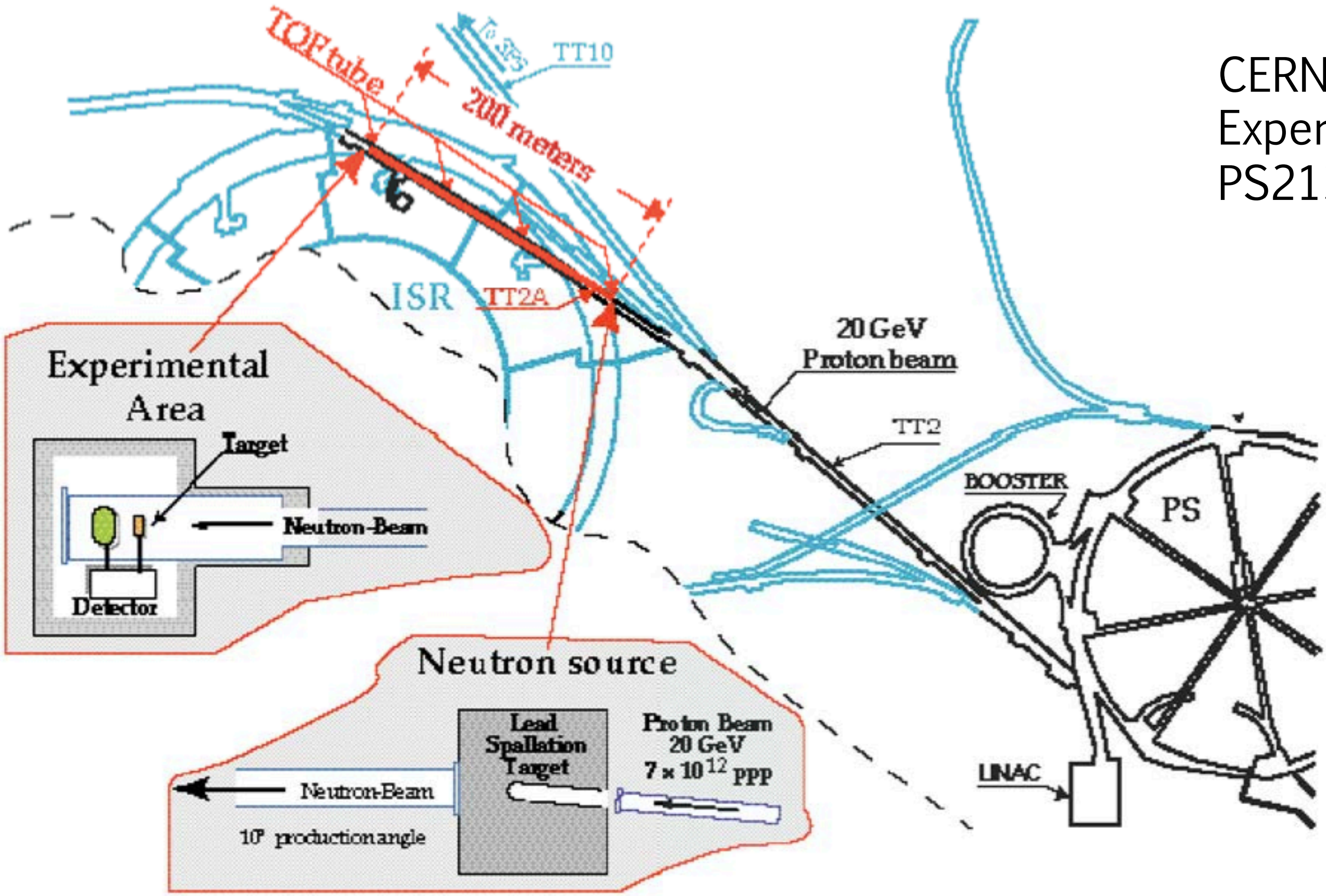
Detection efficiency independent from γ spectrum multiplicity and from γ-ray energy distribution



$$\varepsilon_c = \sum \varepsilon_\gamma = k \cdot \left(B_n + E_n^{(cm)}\right)$$

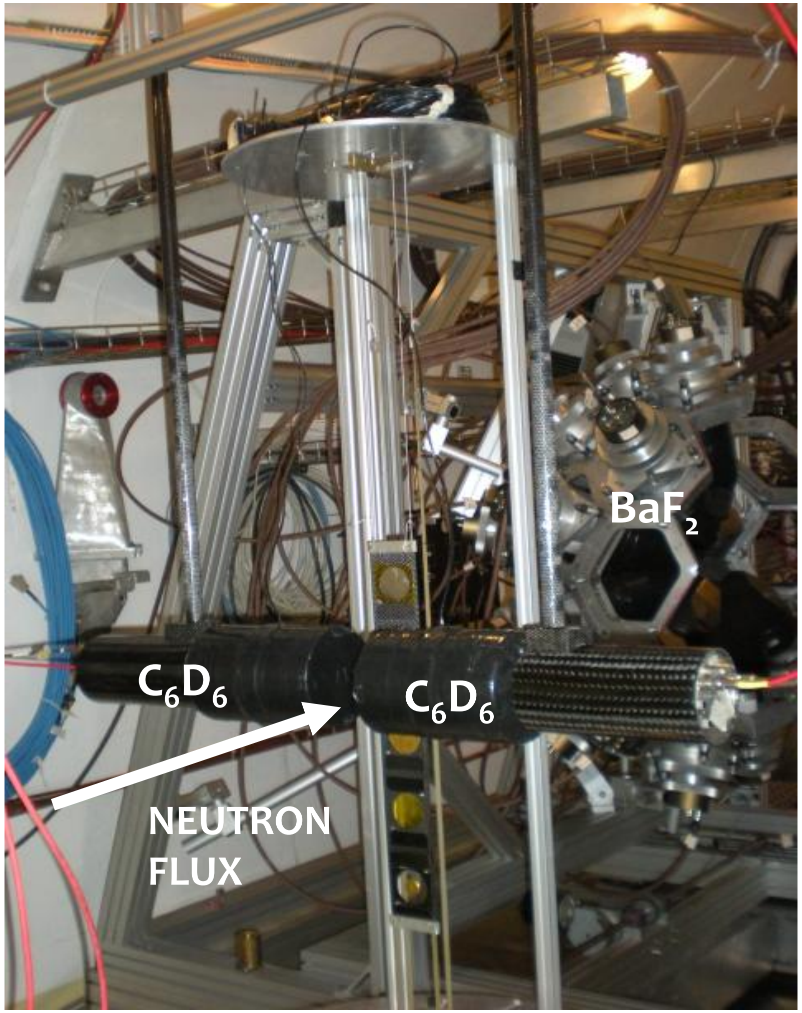
- **Total Absorption Detection**
  - E_γ ~ 100 %
  - 4π geometry detectors
- **Total Energy Detection**
  - Low detection efficiency ε_γ
  - Low solid angle

New 2012 measurement: THE n_TOF FACILITY



CERN
Experiment
PS213

New 2012 measurement:
EXPERIMENTAL SET–UP



Two different setups for capture measurements

- **Total Absorption Calorimeter**
  - 40 BaF2 crystals in a 4π geometry
  - Detects the entire γ cascade (together with background n)
- **Two C_6D_6 scintillation detectors**
  - Optimized for an extremely low neutron sensitivity $(\varepsilon_n/\varepsilon_\gamma < 4 \cdot 10^{-5})$
  - Only one γ–ray detected per cascade → "Total Energy Detection System" with PHWT

New 2012 measurement: SAMPLE

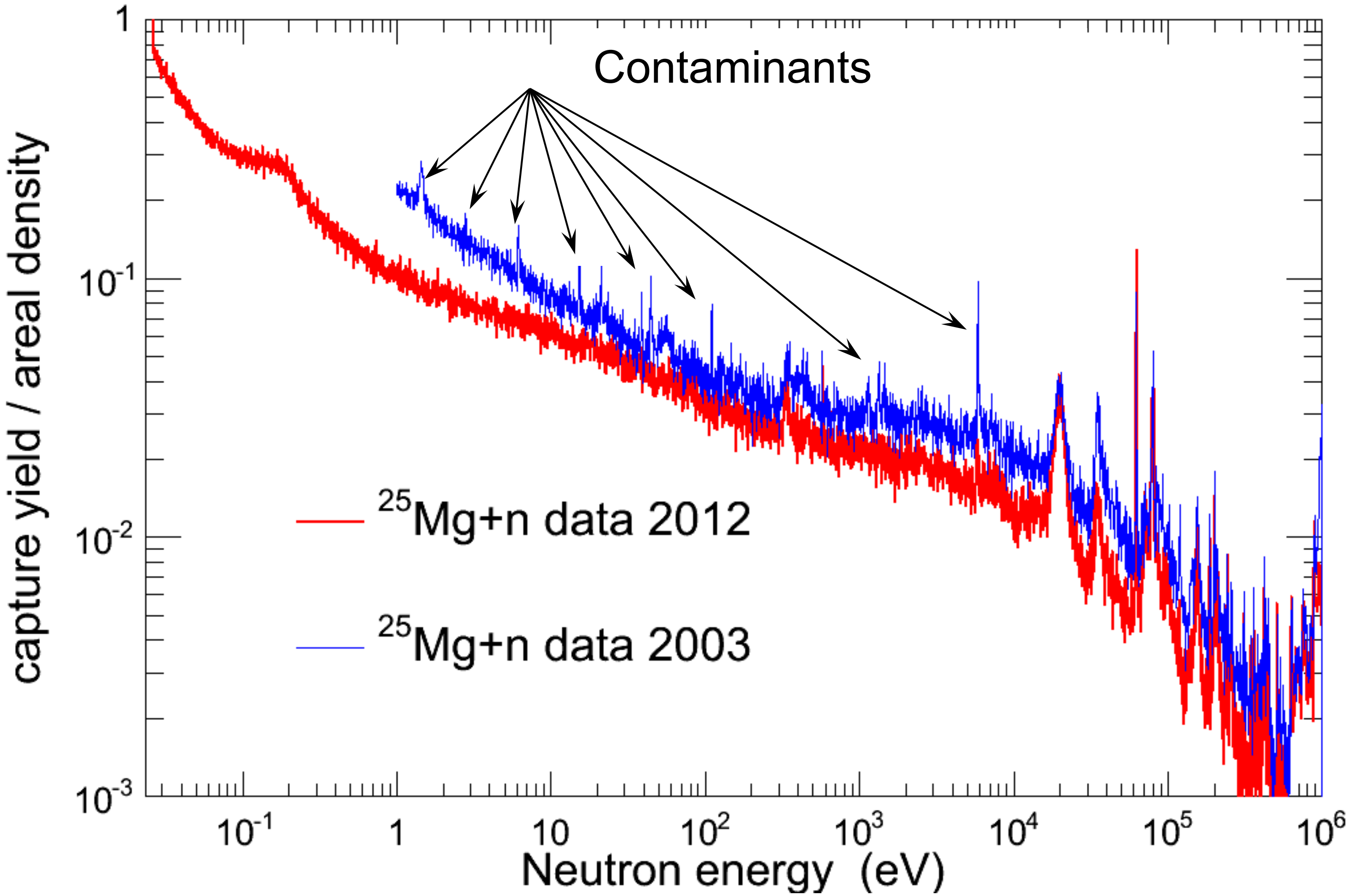
Self-supporting metal ^{25}Mg-enriched sample

Only 2 μm kapton layer

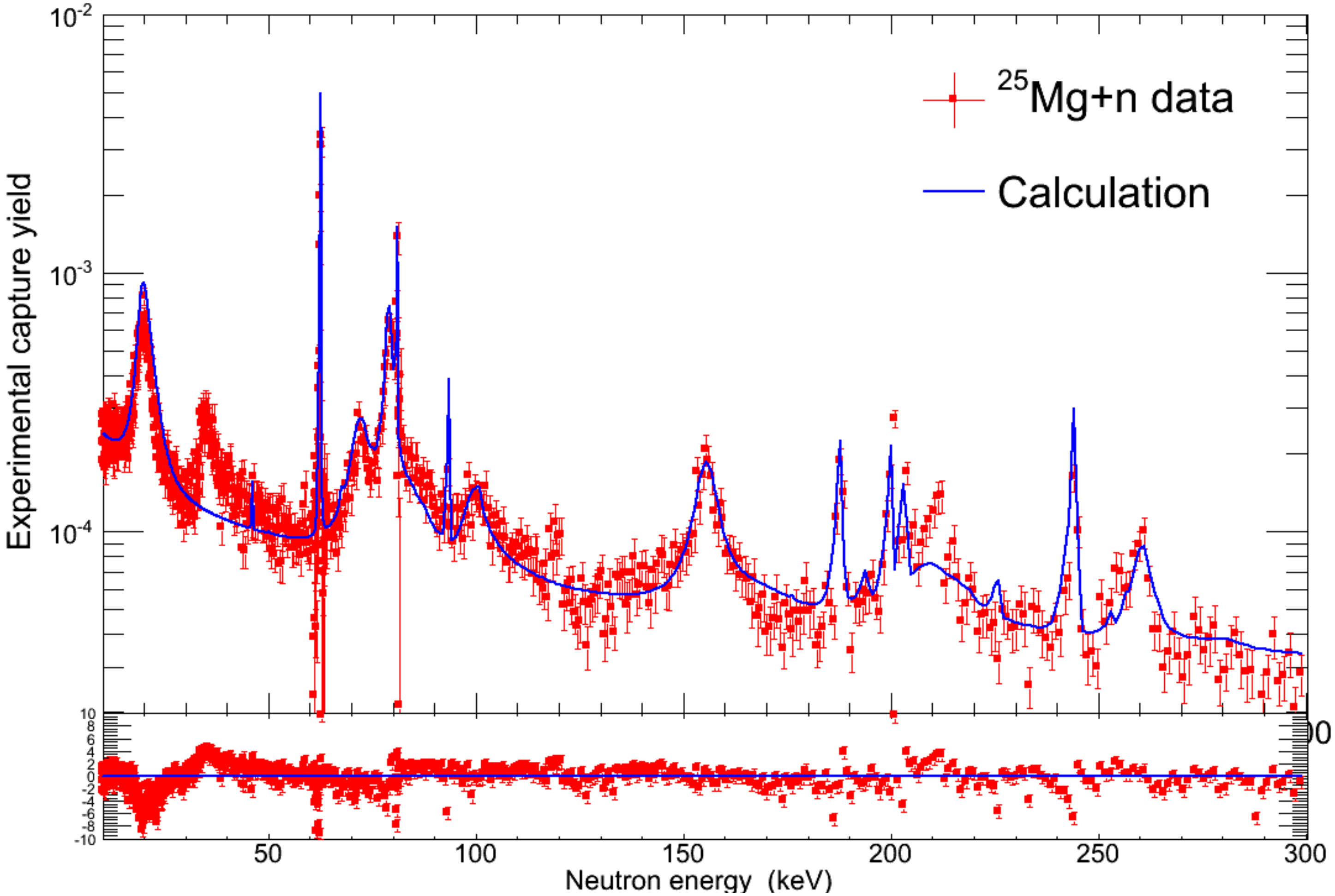
Property	Value
Mass Mg	3.94 g
Diameter	20 mm
Thickness	7 mm
Areal density	3.00×10^{-2} at/b
Isotopic composition	^{25}Mg ~ 97.86% ^{24}Mg ~ 1.83% ^{26}Mg ~ 0.31%

National Isotope Development Center (ORNL, USA)

Preliminary results: OLD vs NEW



Preliminary results:
ASTROPHYSICAL ENERGIES



New 2012 measurement: TRANSMISSION MEASUREMENT

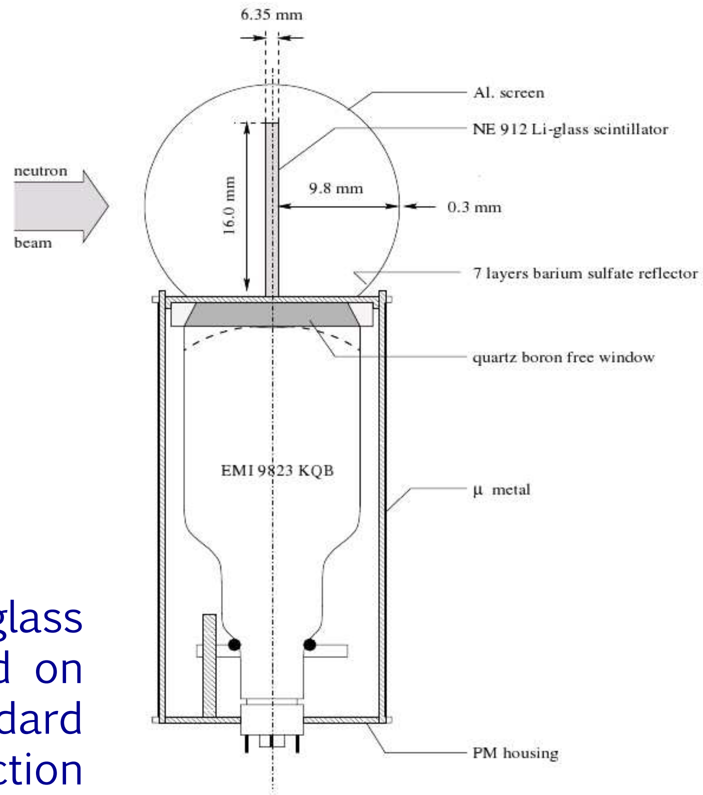
To have more complete and accurate results on 26Mg formation transmission measurement was performed at the GELINA Facility @ EC-JRC-IRMM.

The observed quantity is the fraction of the neutron beam that traverses the sample without any interaction:

$$T_{exp} = \frac{C_{in}}{C_{out}}$$

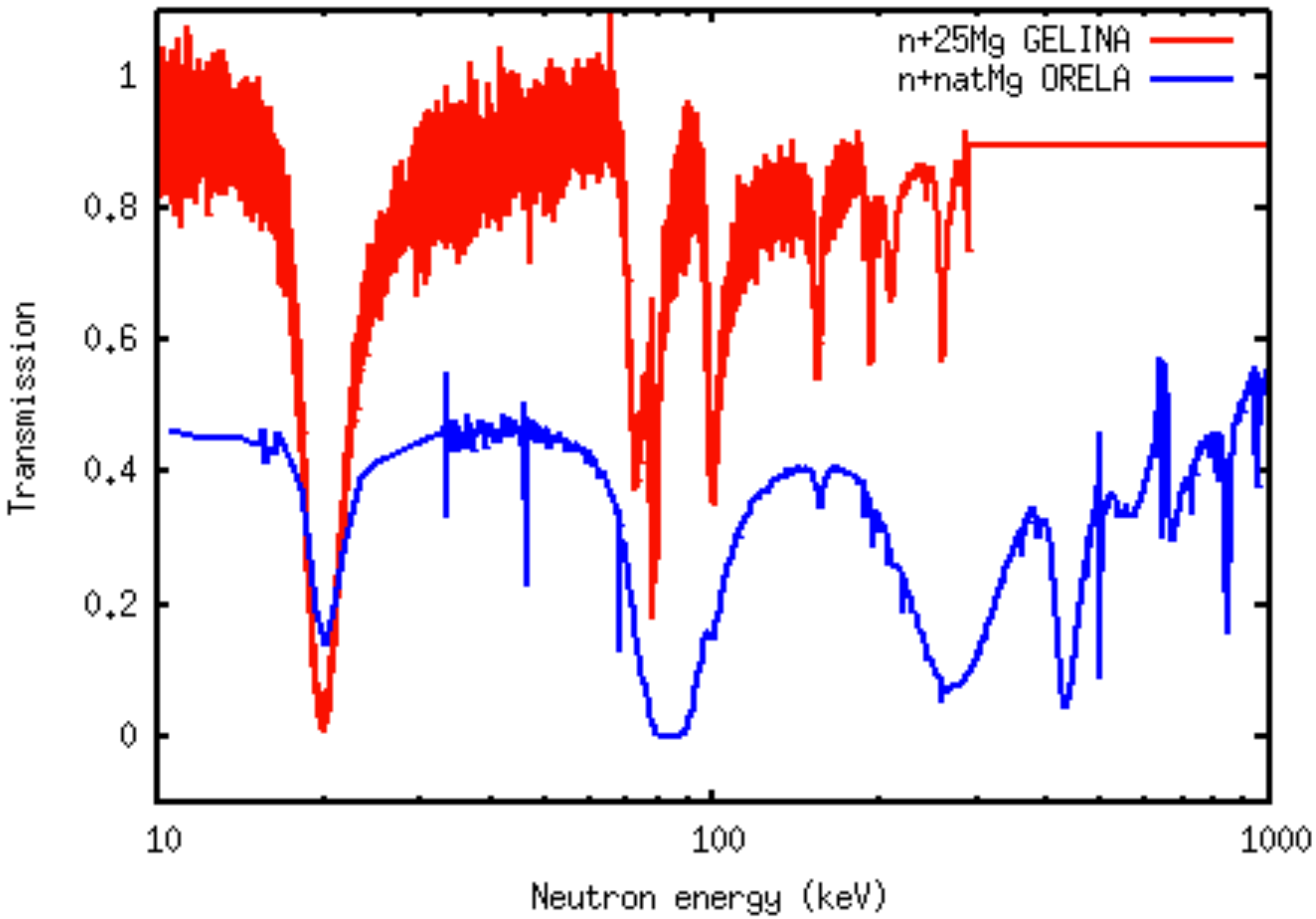
And it is related to the total cross section by:

$$T(E_n) = e^{-n\sigma_{tot}}$$

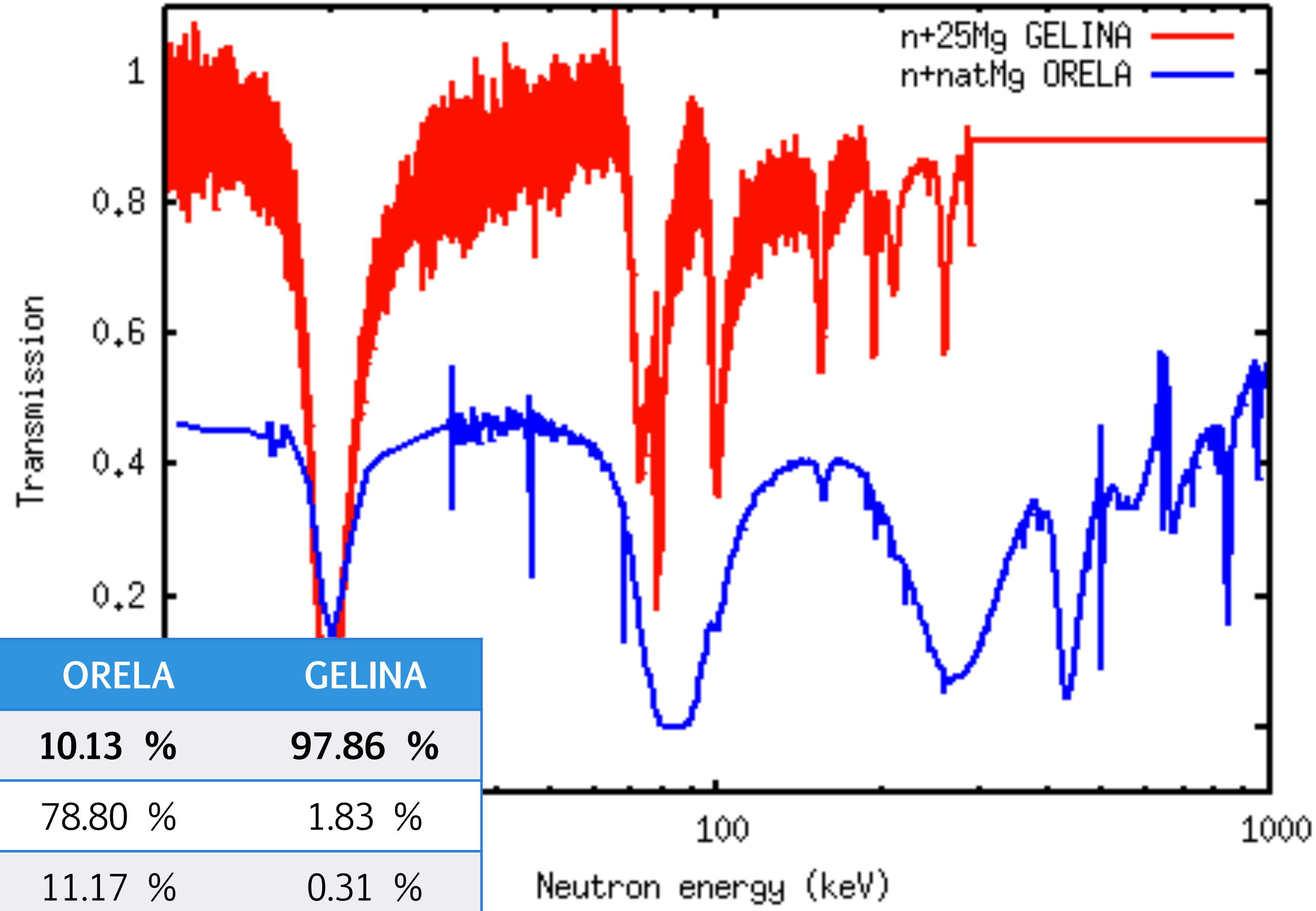


Lithium glass detectors, based on the ^{6}Li(n,α)t standard reaction

New 2012 measurement:
TRANSMISSION MEASUREMENT



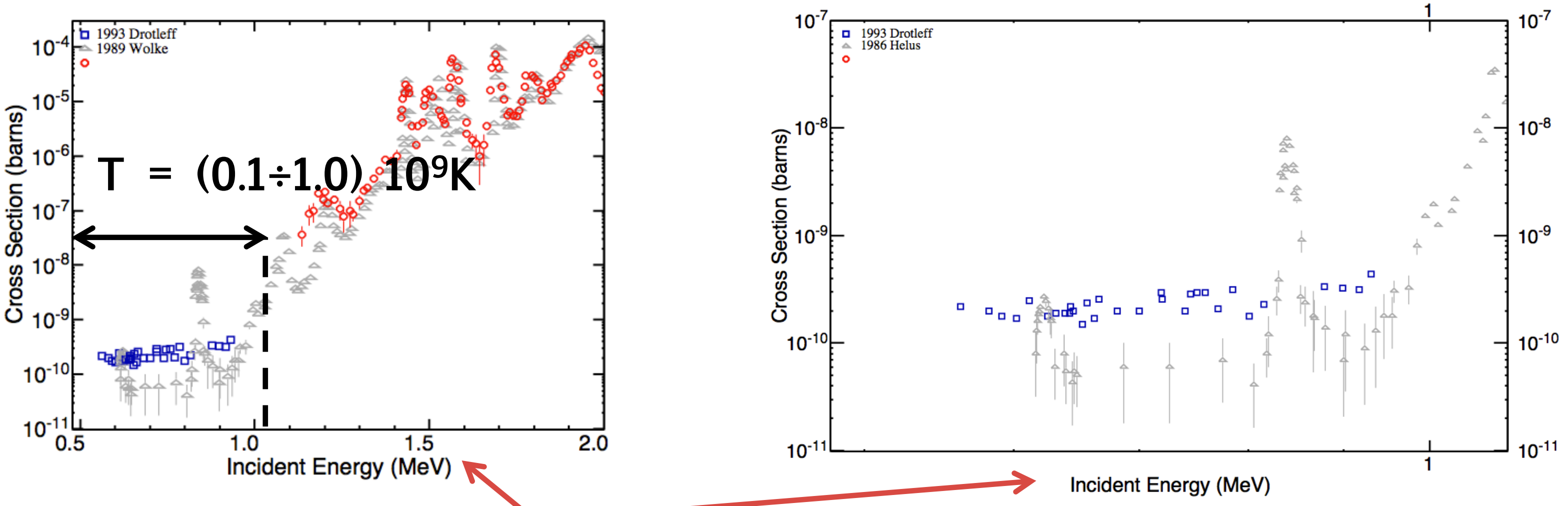
New 2012 measurement:
TRANSMISSION MEASUREMENT



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

A look onward:
$^{25}Mg(n,\alpha)^{22}Ne$ @ n_TOF EAR-2

To complete the comprehension of the role of ^{25}Mg isotope on stellar nucleosynthesis we plan to measure the reaction $^{25}Mg(n,\alpha)^{22}Ne$.
By means of the detailed balance procedure from this cross section we will be able to calculate the $^{22}Ne(\alpha,n)^{25}Mg$ one, which presents relevant inconsistencies in the low energy region.



α-particle LAB energy

Conclusions

- The ^{25}Mg(n,γ) reaction cross-section was measured at n_TOF in 2003 and in 2012 with an improved measurement set up.
- Additional (n,tot) measurement performed at GELINA facility.
- Final analysis will be a simultaneous resonance shape analysis of capture and transmission data:
  - Accurate ^{25}Mg(n,γ) cross section;
  - J^{π} information on ^{26}Mg.
- Proposal: ^{25}Mg(n,α)^{22}Ne reaction cross section measurement @ n_TOF–EAR2 in 2014

INFN Istituto Nazionale di Fisica Nucleare
ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA
n_TOF

THANK YOU FOR YOUR ATTENTION