EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

CERN-INTC-2012-003 ; INTC-P-320

Neutron capture cross section of ^{25}Mg and its astrophysical implications

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[6]*Oak Ridge National Laboratory, Physics Division, Oak Ridge, USA*
[7]*Istituto Nazionale di Fisica Nucleare, Trieste, Italy*
[8]*EC-JRC, Institute for Reference Materials and Measurements, Belgium*

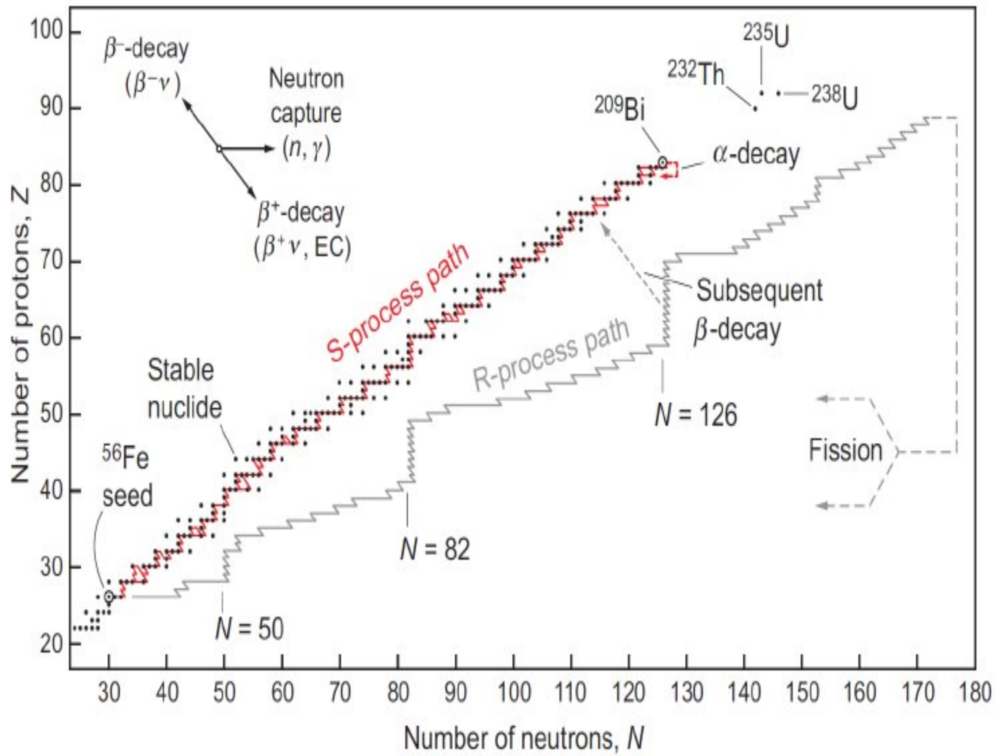
Spokesperson: C. Massimi
Technical coordinator: E. Berthoumieux

Outline

- Introduction / Motivations
  - Nuclear Astrophysics: *s* process
  - Constraints on $^{22}Ne(\alpha,n)^{25}Mg$
- Previous campaign: results and limitations
- Proposal
  - $^{25}Mg(n,\gamma)$ and $^{25}Mg(n,tot)$

Introduction

The *s* process and Mg stable isotopes



Introduction

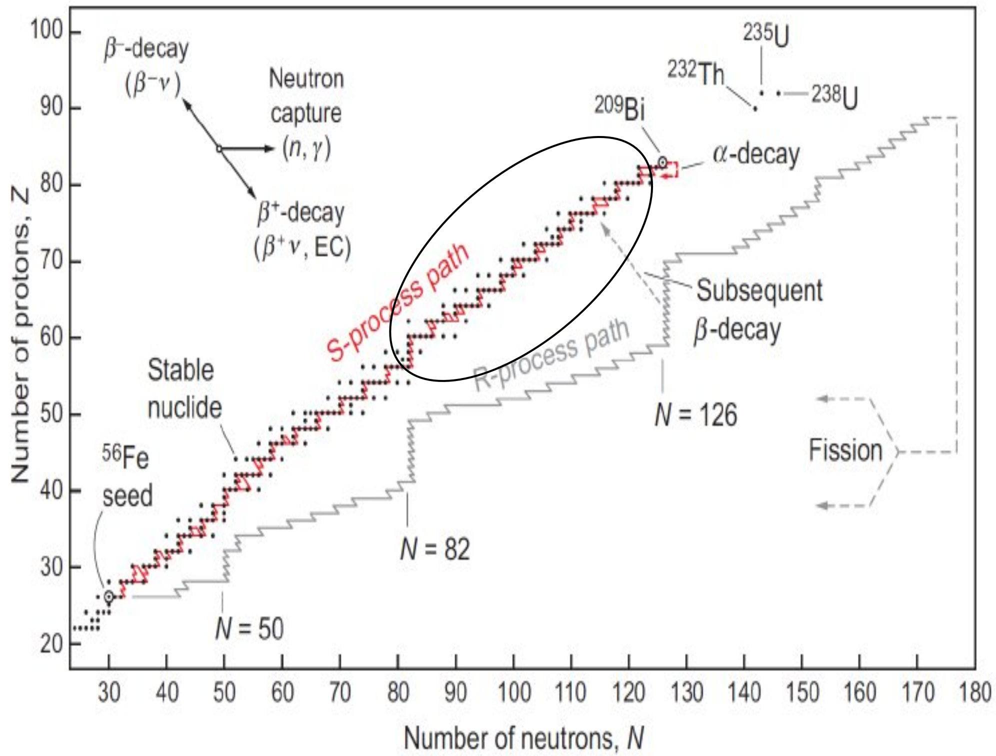
The *s* process and Mg stable isotopes

"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**



Introduction

The *s* process and Mg stable isotopes

"Main component"

^{22}**Ne(α,n)**^{25}**Mg** is a **neutron source** in **AGB stars**:

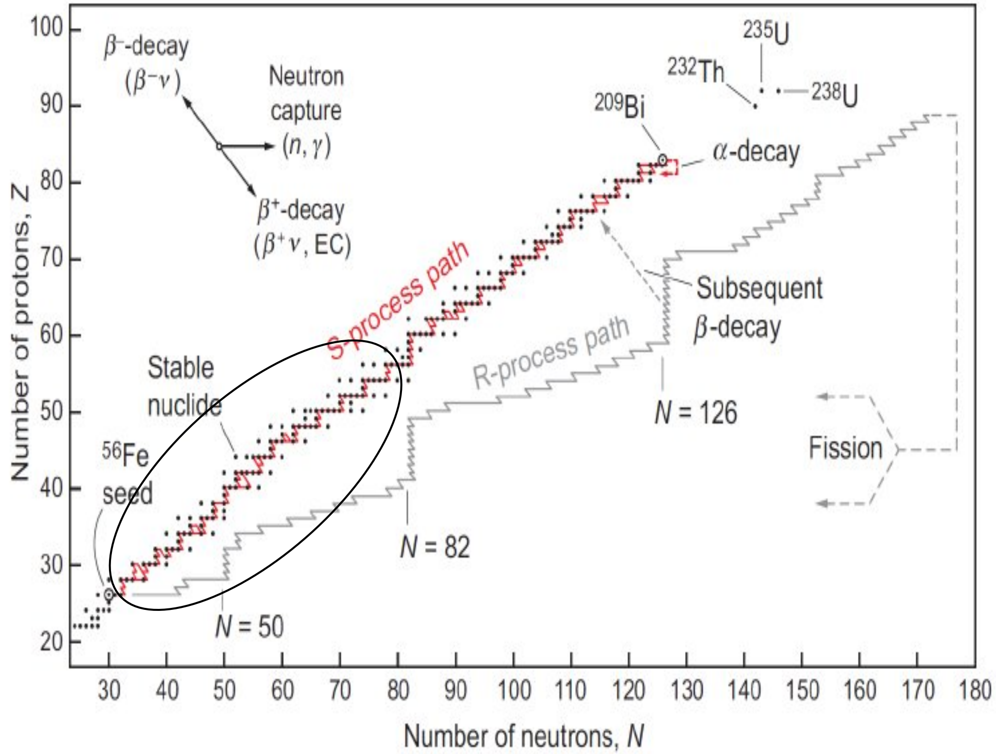
$1M_{sun} < M < 3M_{sun}$

– **kT=8 keV and kT=25 keV**

"Weak component"

^{22}**Ne(α,n)**^{25}**Mg** is the **main neutron source** in **massive stars:** $M > 10 - 12M_{sun}$

– **kT=25 keV and kT=90 keV**



Motivations

1. **^{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 that is the basic s-process seed for the production of heavy isotopes (and on heavier elements).

2. Several attempts to **determine the rate** for the **^{22}Ne(α,n)^{25}Mg** reaction either through direct ^{22}Ne(α,n)^{25}Mg measurement or indirectly, via ^{26}Mg(γ,n)^{25}Mg or charged particle transfer reactions. In both cases **the cross-section is very small** in the energy range of interest.
   - **The main uncertainty** of the reaction rate determination comes from the **poorly known property of the states in ^{26}Mg.**

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

Motivation

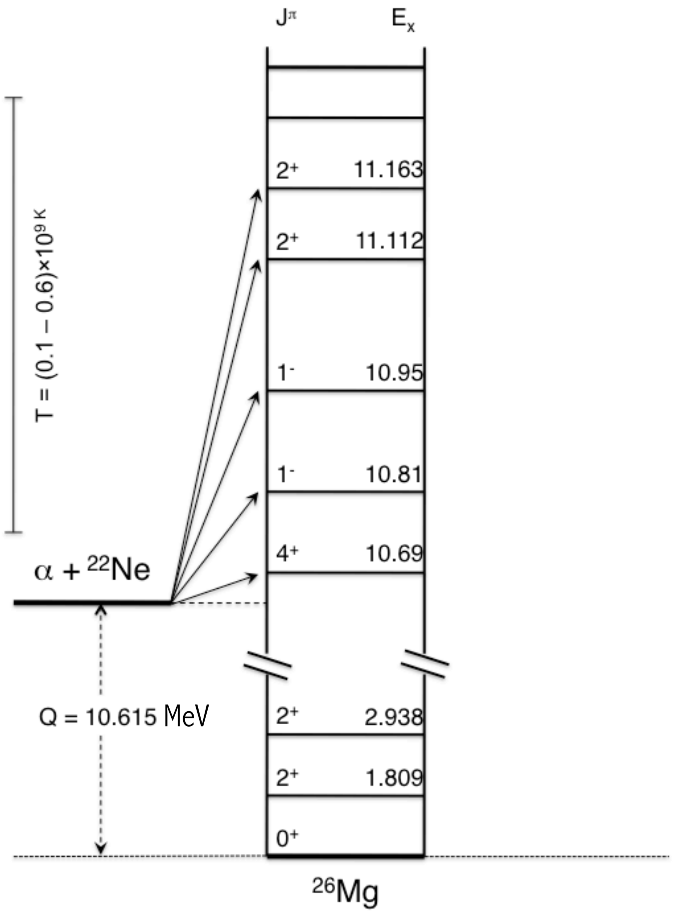
Constraints for the $^{22}Ne(\alpha,n)^{25}Mg$ reaction

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

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

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

Only **natural-parity** (0^+, 1^-, 2^+, 3^-, 4^+, …) **states in ^{26}Mg** can participate in the $^{22}Ne(\alpha,n)^{25}Mg$ reaction



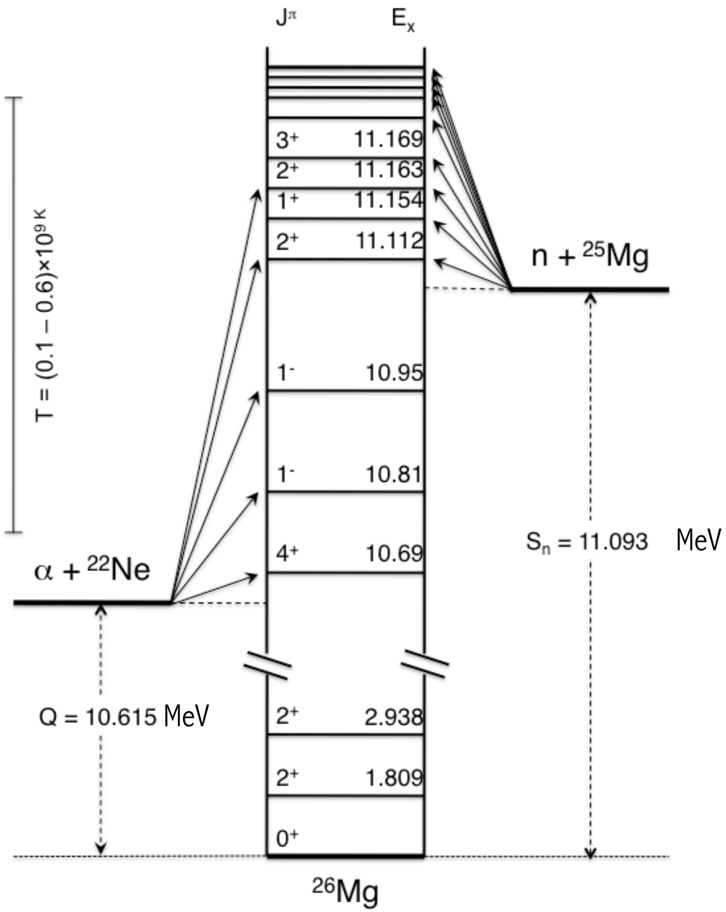
Motivation

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

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

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

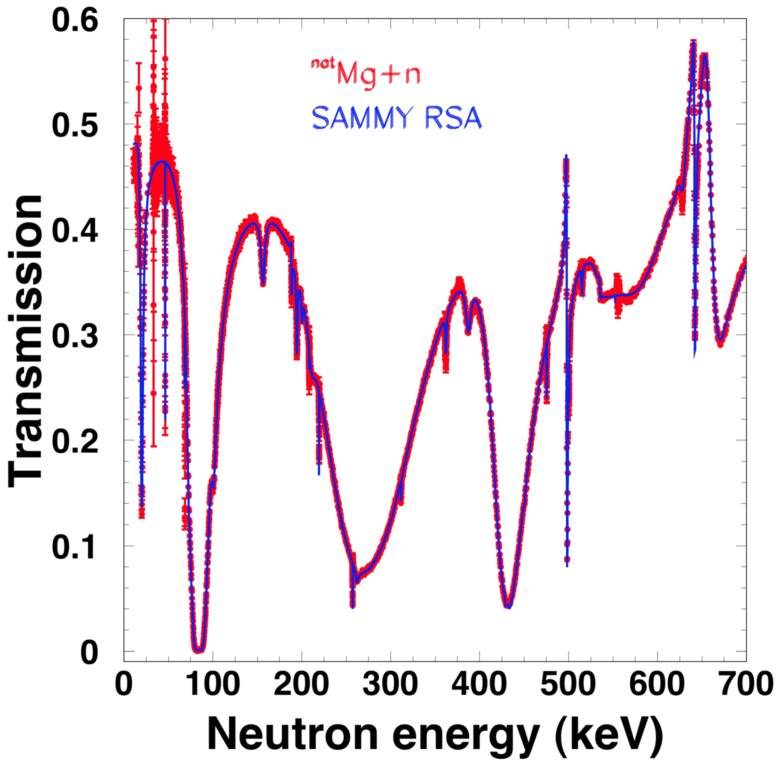
$$\vec{J} = 2 + \vec{\ell} \qquad \vec{J} = 3 + \vec{\ell}$$



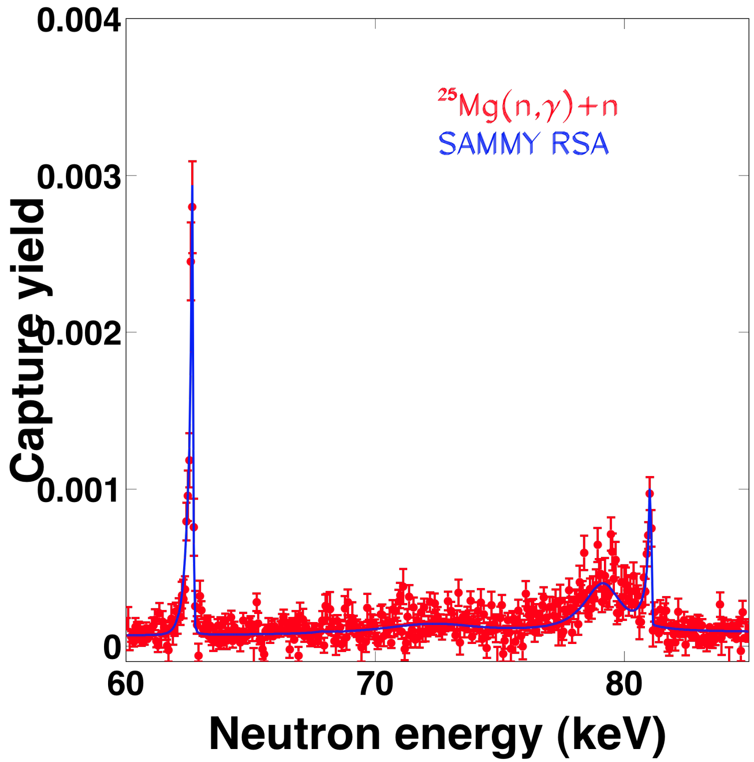
s-wave → J^π= **2⁺**, 3⁺
p-wave → J^π= **1⁻**, 2⁻, **3⁻**, 4⁻
d-wave → J^π= **0⁺**, 1⁺, **2⁺**, 3⁺, **4⁺**, 5⁺
States in ^{26}Mg populated by $^{25}Mg(n,\gamma)$ reaction

Previous campaign: results and limitations

Transmission - ORELA



Capture - n_TOF



Previous campaign: results I

MACS

Thermal energy (keV)	n_TOF*	Literature
	$^{24}Mg(n,g)$	
5	0.21±0.04 b	0.11 b
30	3.8±0.2 b	3.3±0.4 b
80	2.8±0.2 b	2.7 b
	$^{25}Mg(n,g)$	
5	3.5±0.4 b	4.8 b
30	**4.1±0.6 b**	6.4±0.4 b
80	**1.9±0.3 b**	4.4 b
	$^{26}Mg(n,g)$	
5	0.087±0.001 b	0.103 b
30	0.14±0.01 b	0.126±0.009 b
80	0.37±0.04 b	0.226 b

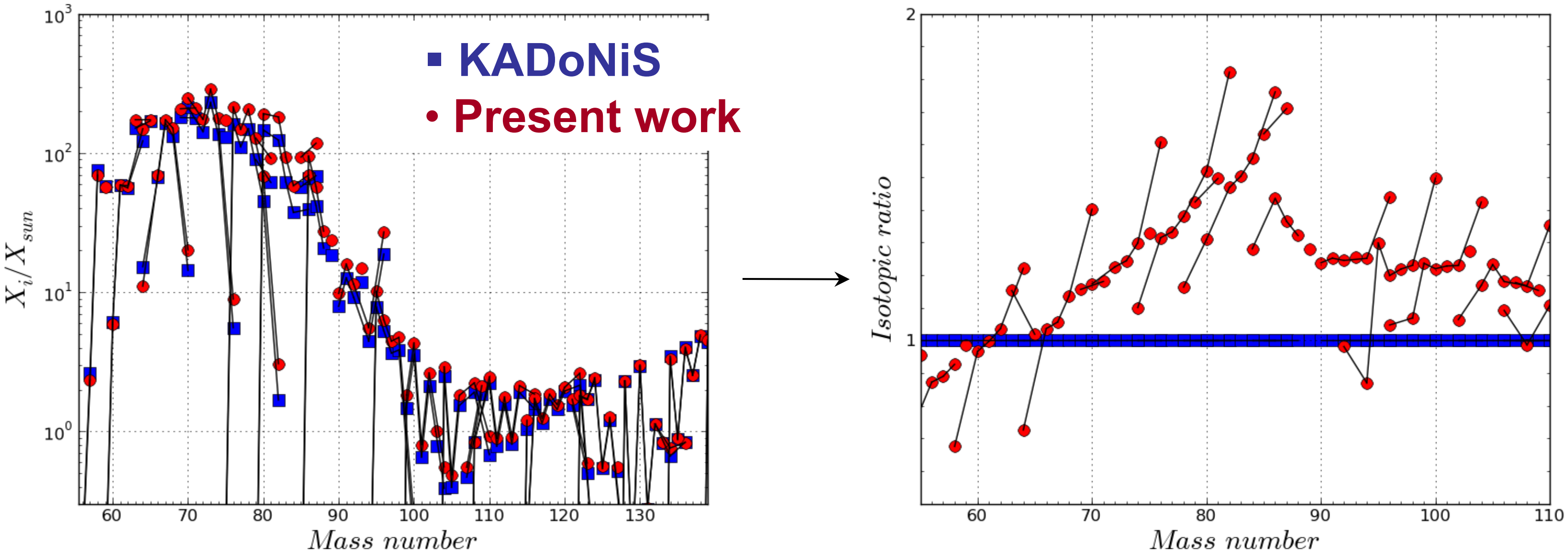
* Submmitted to Phys Rev. C

Previous campaign: results II

s-process abundances

Reduced poisoning effect.

Lower MACS of ^{25}Mg → higher neutron density



Abundance distribution of the weak *s* process

Small impact on AGB abundances

* Submmitted to Phys Rev. C

Previous campaign: results III

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

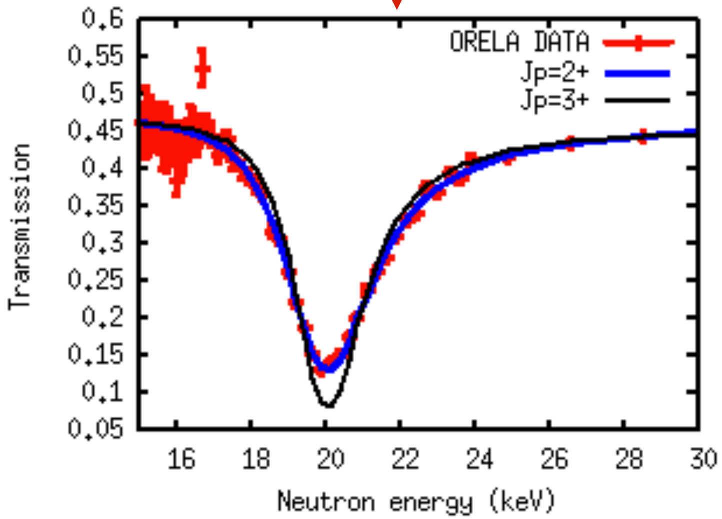
$^{25}Mg(n,\gamma)^{26}Mg$

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)

* Submmitted to Phys Rev. C

Previous campaign: results III

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



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

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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
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Previous campaign: results III

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

J^{π} uncertain

↓

NO information on $^{22}Ne(\alpha,n)^{25}Mg$

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

? (bracketing rows 81.117 to 311.57)

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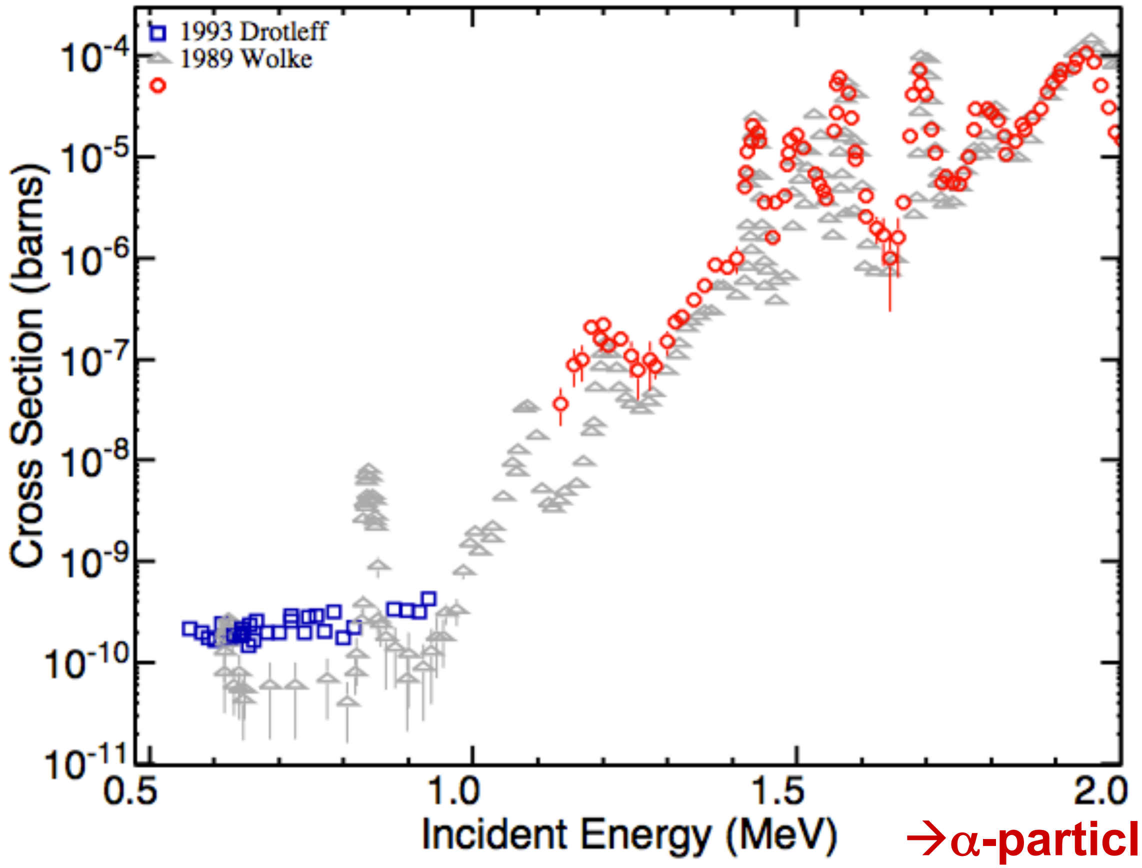
Previous campaign: results III

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

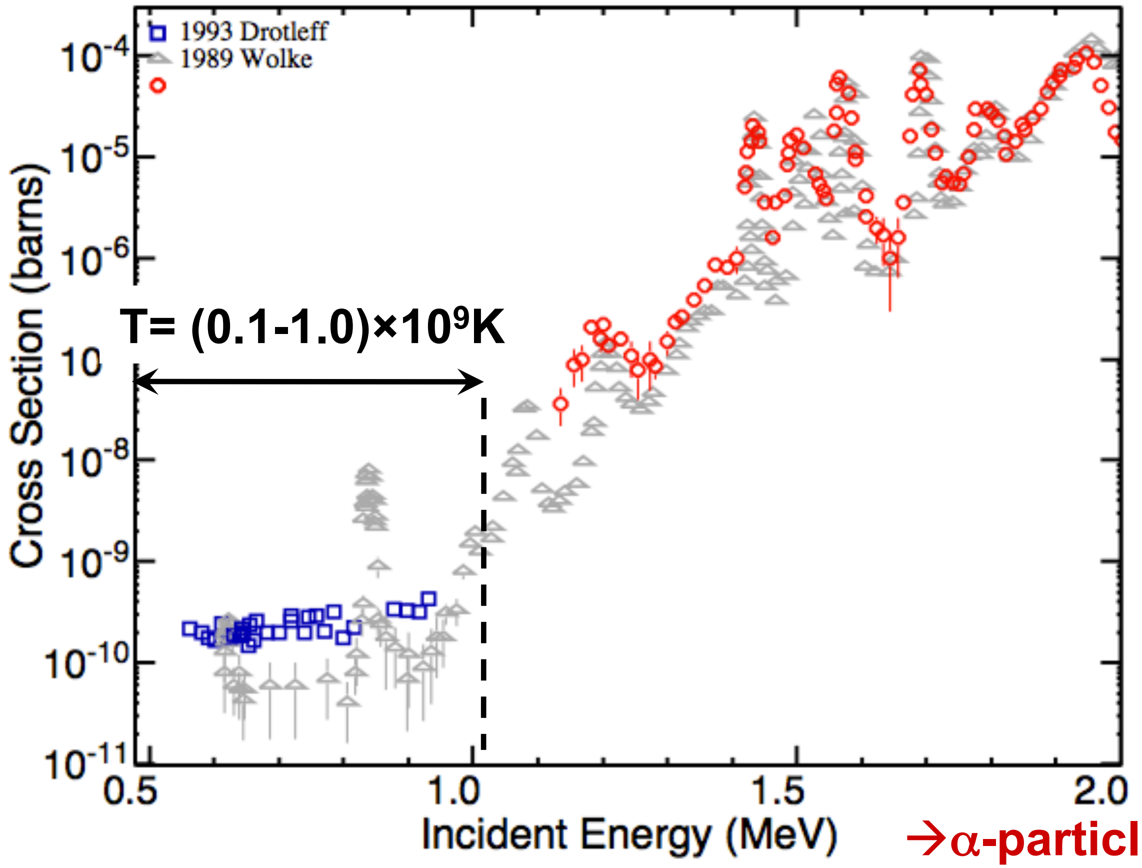
Q-value = - 480 keV



→α-particle energy Lab.

Previous campaign: results III

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



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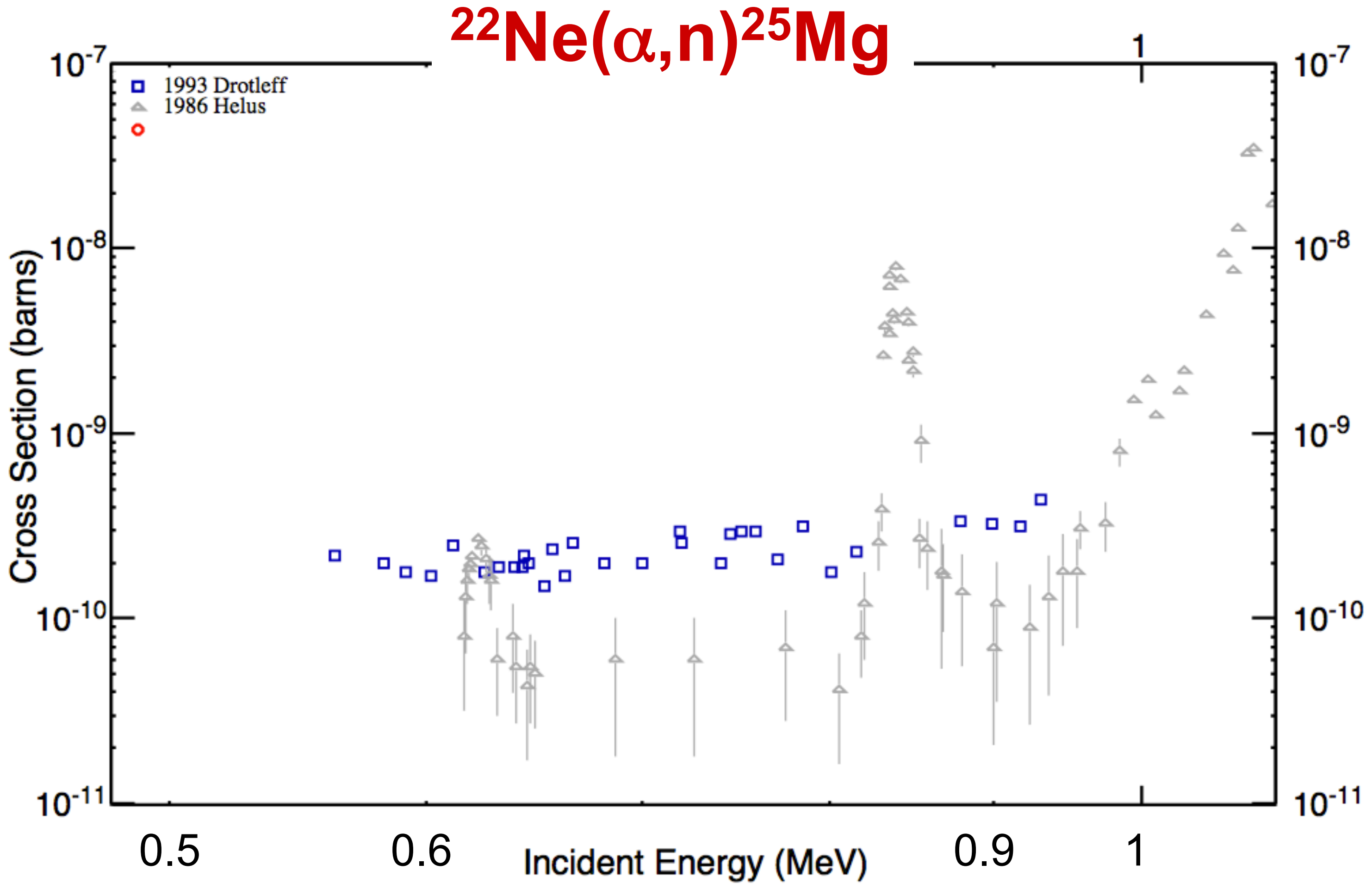
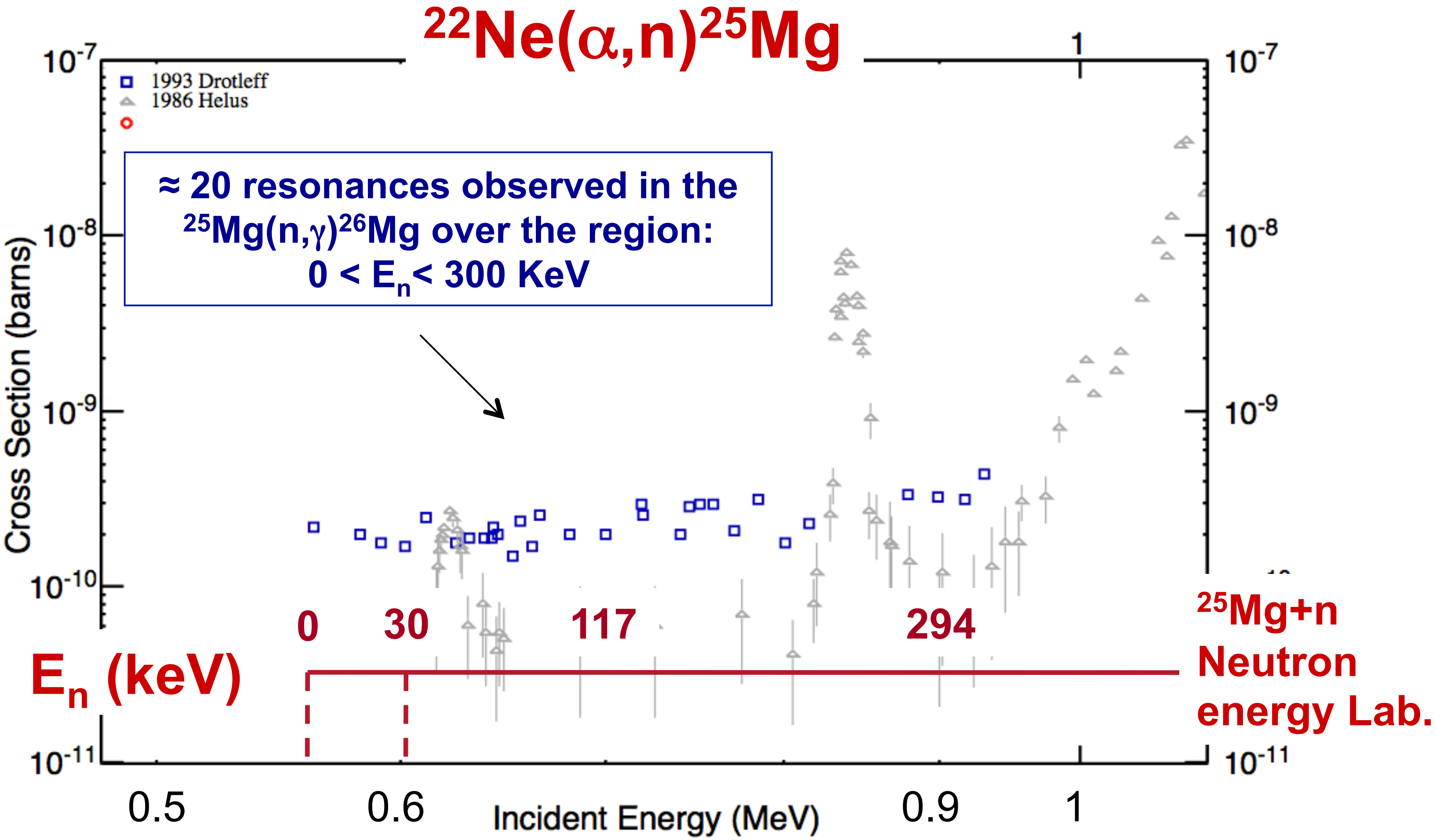
Previous campaign: results III

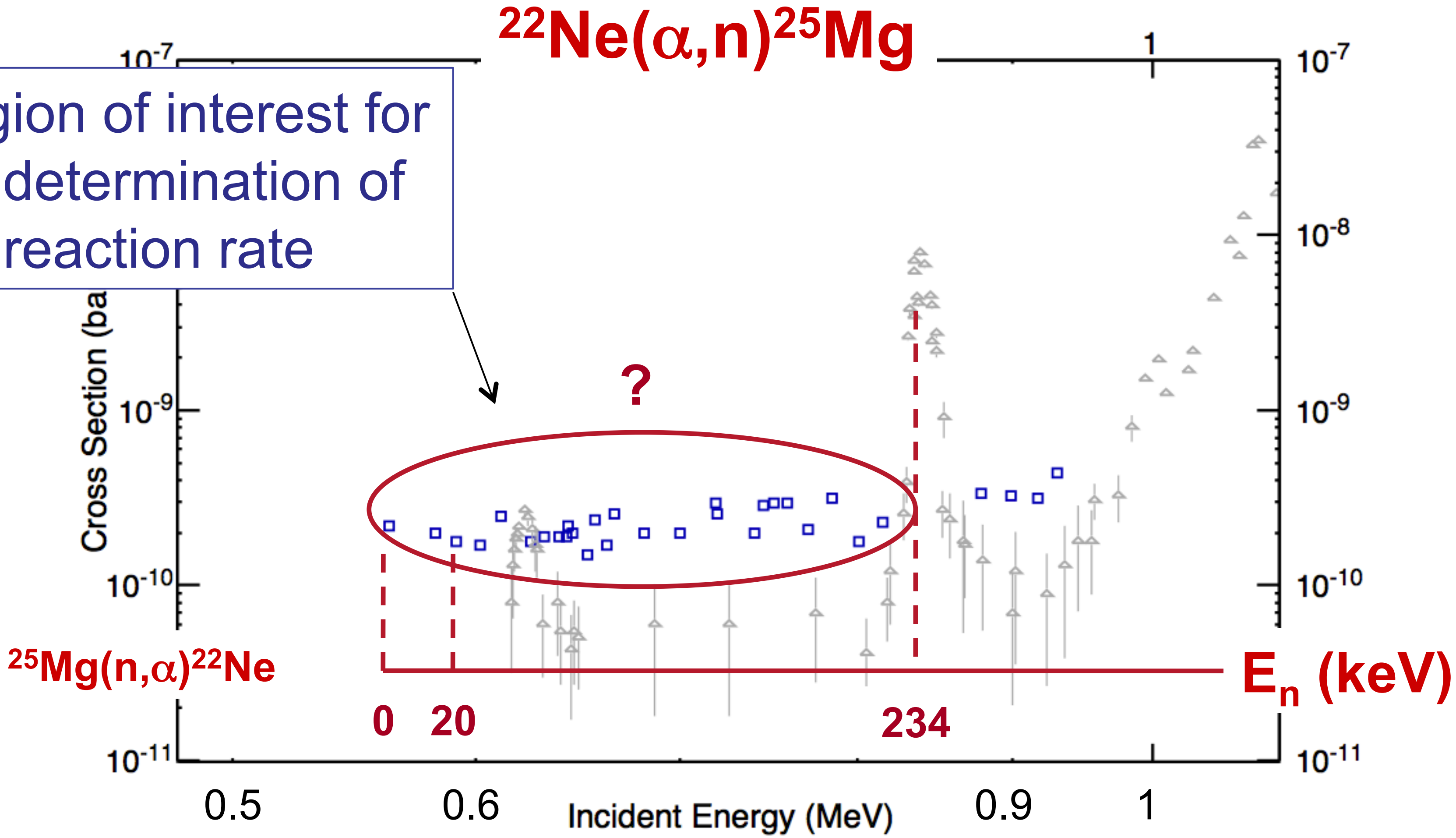


Previous campaign: results III



Previous campaign: results III

Region of interest for the determination of the reaction rate

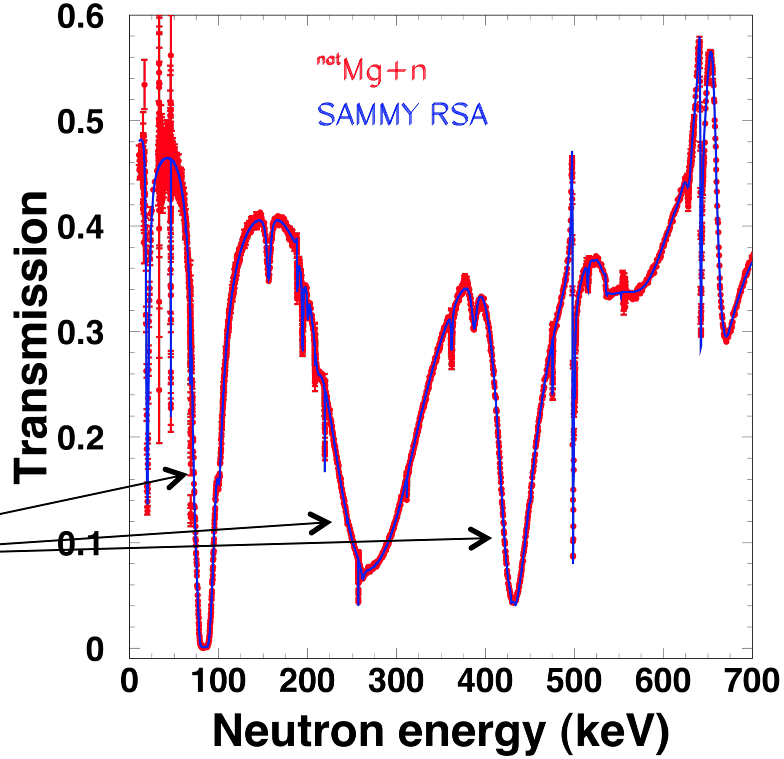


Previous campaign: limitations

1. **Sample**
   - MgO, powder sample
   - Transmission experiment on a ^{nat}Mg sample

2. **n_TOF facility Phase-I**:
   - Water as neutron moderator

^{24}**Mg**

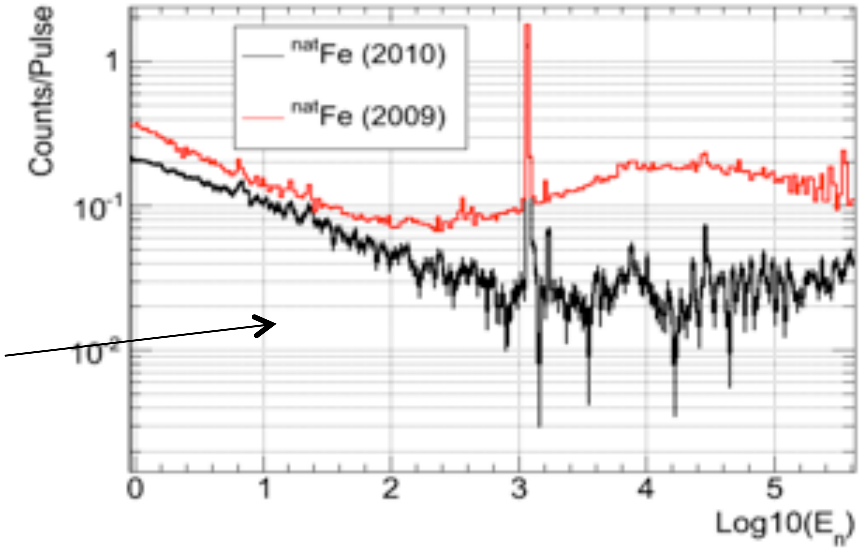


Proposal: improvements

1. **Sample**
   - metal ^{25}Mg-enriched sample
   - Transmission on the ^{25}Mg-enriched sample

2. **n_TOF facility Phase-II**:
   - Borated water as neutron moderator
   - New and improved detectors

- Water moderator
- Borated water moderator



Proposal

We propose to measure the **neutron capture cross section** of the stable **^{25}Mg** isotope. This experiment aims at the improvement of existing results for nuclear astrophysics:

- s-process path and abundances;
- constraints on the neutron source of the s process.

Additional measurements at the neutron time-of-flight facility GELINA operated by the European Commission

- Transmission measurement on the same sample will improve the analysis of the capture cross section eventually allowing for the spin assignment.
- Moreover dedicated measurements with HPGe detectors to detect single γ-ray transitions could be performed.

Proposal

Experimental program:

- Self-supporting (i. e. not compressed powder in a can) **metal ^{25}Mg-enriched sample**:
  - Material: Mg-25;
  - Chemical Form: Mg metal disc (3-cm diameter);
  - Isotopic enrichment: 97.86%;
  - Quantity: 8.8 g;

- The cross section will be determined up to about 300 keV by means of C_6D_6 liquid scintillators

Proposal

Experimental program:

The request for the **number of protons** is based on previous measurements with C_6D_6 :

- 1.6×10^{18} protons → ^{25}Mg
- 0.4×10^{18} protons → Au (normalization), C (background), Pb (background), sample holder (background)

According to the previous capture measurements we request a total of $\mathbf{2\times10^{18}}$ protons

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Additional slides

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

R. Longland *et al.*, Phys. Rev. C **80,** 055803, 2009
"Nuclear resonance fluorescence"

Before the 62.727-keV resonance was thought to be 1^-

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

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Additional slides

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

The reaction rate of the neutron source can be calculated:

$$N_A\langle\sigma v\rangle_r \cong \frac{1.54\times10^5(2J+1)\Gamma_\alpha}{A^{3/2}T_9^{3/2}e^{11.605E_R/T_9}}$$

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

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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)

Additional slides

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

The reaction rate of the neutron source can be calculated:

$$N_A\langle\sigma v\rangle_r \cong \frac{1.54\times10^5(2J+1)\Gamma_\alpha}{A^{3/2}T_9^{3/2}e^{11.605E_R/T_9}}$$

- E_R from (n,γ)
- Γ_α No information from neutron spectroscopy → different values assumed

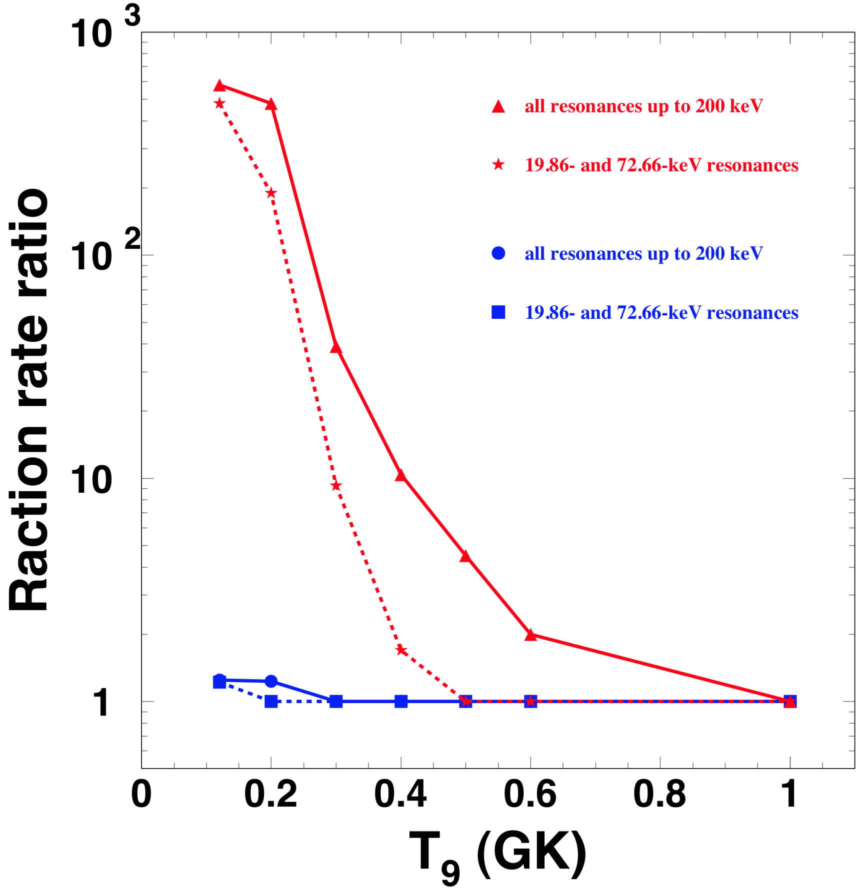
$^{25}Mg(n,\gamma)^{26}Mg$

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)

Additional slides

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

With respect to recommended value from NACRE

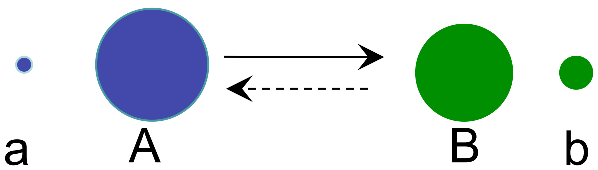


Upper limit for Γ_α

Lower limit for Γ_α

Additional slides

The $^{25}Mg(n,\alpha)^{22}Ne$ **(Q-value=480 keV)** cross-section is linked to the $^{22}Ne(\alpha,n)^{25}Mg$



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

Energy region of interest:
$0 < E_n < 300$ keV