New experimental measurement of the $^{24,25,26}Mg(n,\gamma)$ reaction cross-section at n_TOF

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**) www.cern.ch/n_TOF*

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Outline

- Introduction and Motivation
- Mg in literature
- Measurement at n_TOF: Laboratory and detectors
- Data analysis
- Preliminary results
- Conclusions

Introduction

Nuclear astrophysics:

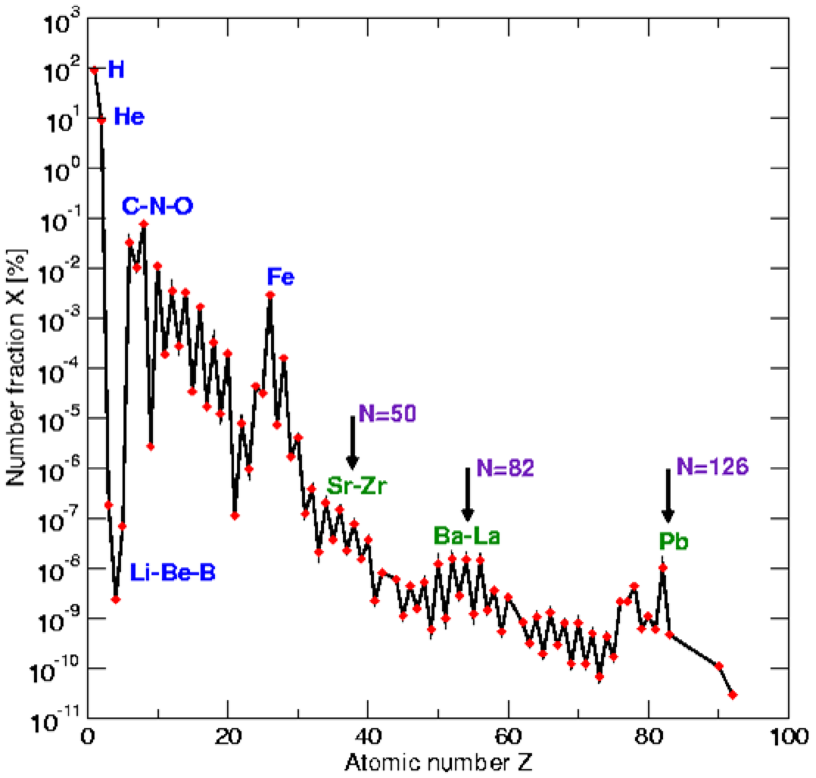
nucleosynthesis of elements

1. Big Bang (H, D, ^{3,4}He, ^{6,7}Li)
2. Nuclear fusion (A<60)
3. **Neutron capture (A>60)**

Depending on the stellar conditions

- The slow neutron-capture process (**s-process**): low neutron density → neuton capture time longer than β-decay half-lives
- The rapid neutron-capture process (**r-process**)

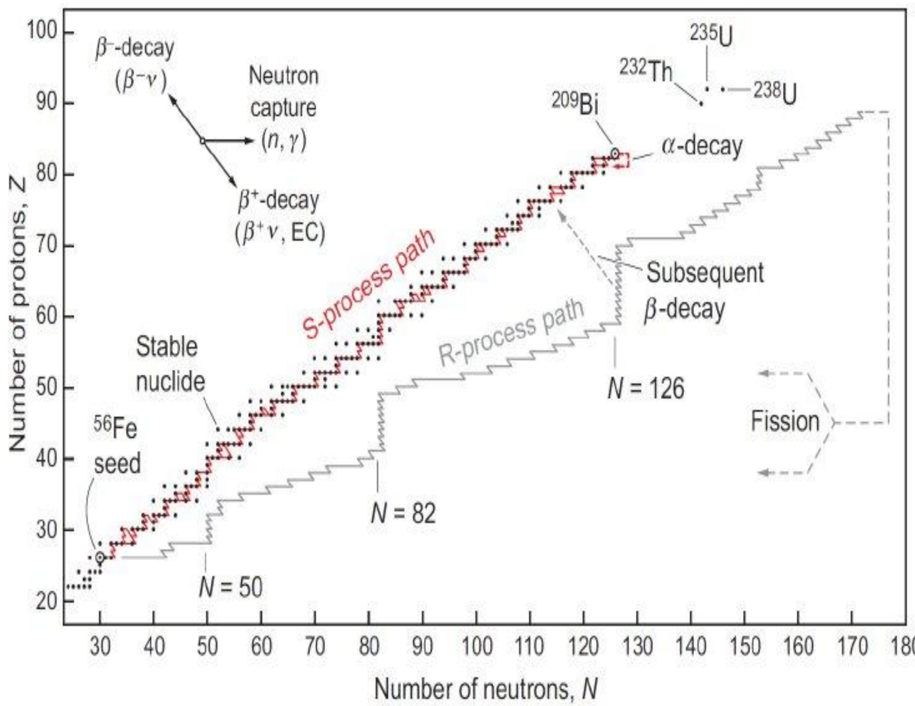
Solar system elemental abundances



Introduction

The s-process

- is responsible for the **production** of about half of the **elemental abundances beyond Iron** that we observe today.
- Most of the **s-process isotopes** between iron and strontium (60 < A < 90) are **produced in massive stars** (M > 10 – 12 M_{sun}) where the **$^{22}Ne(\alpha,n)^{25}Mg$** reaction is the main **neutron source**.
- Beyond strontium, the **s-process abundances** are mostly produced in low mass Asymptotic Giant Branch stars (**AGB stars**, 1.2M_{sun}<M<3M_{sun}), where the **neutrons** are **provided** by the **$^{13}C(\alpha,n)^{16}O$** reaction and by the partial activation of the **$^{22}Ne(\alpha,n)^{25}Mg$** reaction.



The **reaction path** follows the **stability valley** → the resulting **abundances** are determined by the respective neutron-capture **cross-section**

Introduction

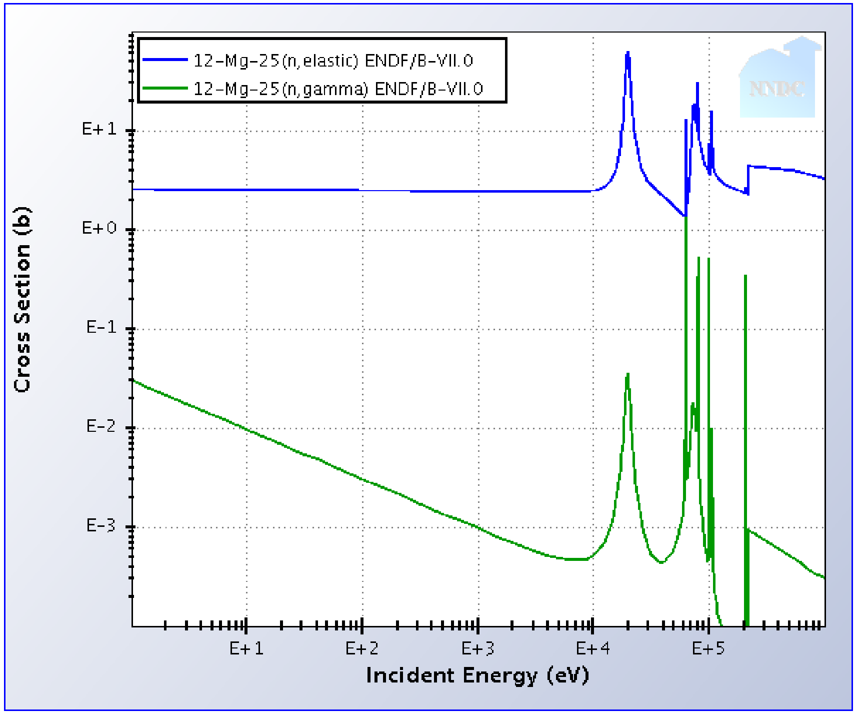
The s-process and the capture cross-section

- Cross-section data is the most important nuclear physics input for s-process studies: Reaction rate = n <σv>
- Neutron energy: Maxwell-Boltzmann distribution

Laboratory measurements are required in the energy range $0.1 < E_n < 300$ keV.

Example: → $E_n = kT$ (e. g. $T=3\times10^8$ K → $E_n = 26$ keV)

n + ^{25}Mg cross-sections



Motivations

The s-process and the Mg(n,γ) reaction

- **^{25}Mg** is the most important **neutron poison** due to neutron capture on ^{25}Mg in competition with neutron capture on ^{56}Fe that is the basic s-process seed for the production of heavy isotopes.
- For this reason, a **precise knowledge of the ^{25}Mg(n, γ)^{26}Mg cross section is required** to properly simulate **s-process** nucleosynthesis in stars.
- Several attempts to **determine the rate** for the reaction **^{22}Ne(α,n)^{25}Mg** 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→ **No results** have been **reported**.
- The main uncertainty of the reaction rate comes from the poorly known property of the states in ^{26}Mg. Information can come from neutron measurements (knowledge of J^{π} for the ^{26}Mg states).

Mg data in literature

The **small**, resonance dominated, **cross-section** of light nuclei are **difficult to measure:**

- **Few measurement** are present in literature
- **Capture data** suffer from severe **systematic uncertainties**

- The **available** experimental **data** for ^{24,25,26}Mg are essentially based on a time-of-flight measurement performed at ORELA:
  - very high-resolution **transmission** measurement (200-m flight path, metallic Mg sample, plastic scintillator)
  - high-resolution **capture** measurement (40-m flight path, 97.9% enriched sample, fluorocarbon scintillators)

- The **thermal-neutron capture cross section** was measured at the Los Alamos Omega West reactor (by neutron **activation**)

Mg data in literature

Evaluations:

- Existing **evaluations** are **based** on **JENDL3.3 (by T. Asami)**
- **JENDL 4** (2010) is **not updated**
- **Resonance parameters** in resolve resonance region are taken **from BNL (Mughabghab)** and negative resonances were added to reproduce the measured thermal cross-section

Evaluation does not consider:
- the photoneutron cross-section measurement $^{26}Mg(\gamma,n)^{25}Mg$ by Berman *et al.*(PRL 1969), → J^{π}
- a recent work by P. E. Koehler (PRC, 2002) → R-matrix analysis of existing measurements

Sizeable discrepancies between Asami and Koehler

	Thermal-neutron cross section: Evaluation	Measurements
^{24}Mg	50 mb	54.1 ± 1.3 mb
^{25}Mg	190 mb	200 ± 3 mb
^{26}Mg	38 mb	39.0 ± 0.8 mb

New measurement at n_TOF

Aim of this capture measurement:

- neutron capture cross-section measurements were performed at n_TOF (**Phase I**) to improve (n, γ) cross-section of the Mg isotopes.

- **Resonance shape analysis** (RSA) to parameterize the cross sections in terms of the R-matrix formalism
- Determination of the **Maxwellian-averaged capture cross-section.**

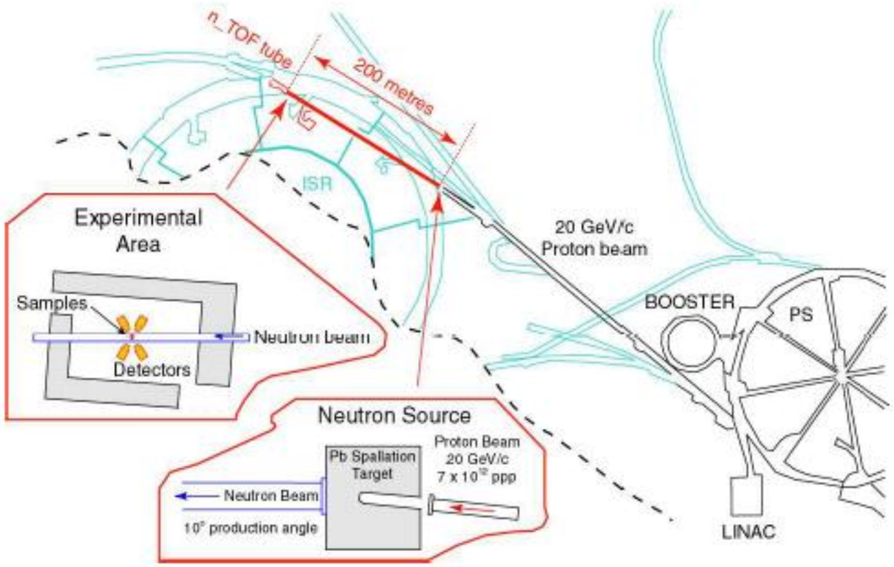
Simultaneous RSA on:

- ***capture data*** *from the measurement performed at the* ***n_TOF*** *facility* ***at CERN*** *and*
- ***transmission data*** *from the* ***ORELA*** *facility.*

n_TOF facility at CERN

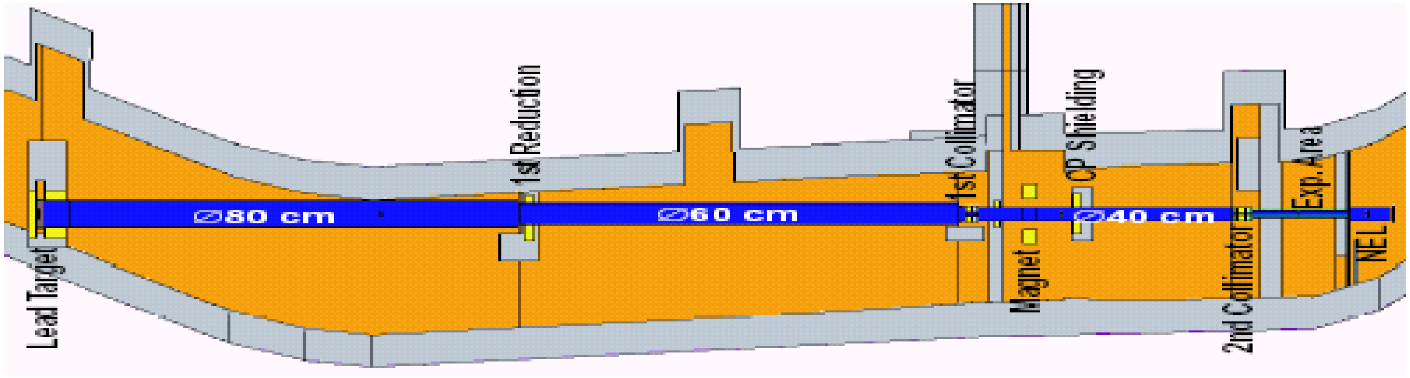
Pulsed neutron source: spallation of 20-GeV/c protons from CERN PS

- Neutron-producing target: 80x80x60 cm lead block
- Cooling and moderation: 5-cm water
- Flight path length: 180 m
- protons per burst: 7×10^{12}
- Proton burst duration: 6 ns
- Neutrons per protons ≈ 300



High neutron flux	**10^5 n/cm^2/pulse**
Wide energy range	**1 eV < E_n < 250 MeV**
Good energy resolution	**$\Delta E / E \sim 10^{-4}$ (up to keV)**
Low repetition rate	**~ 0.25 Hz**

n_TOF facility at CERN



2 collimators, 3 shielding walls, 1 sweeping magnet

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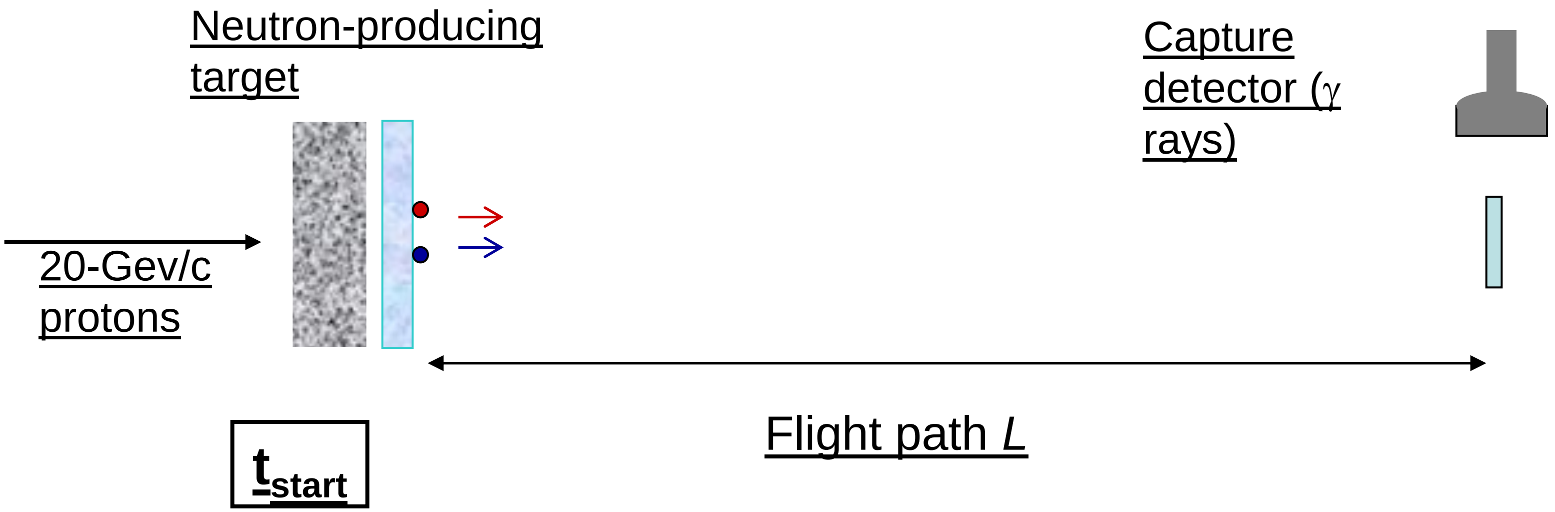
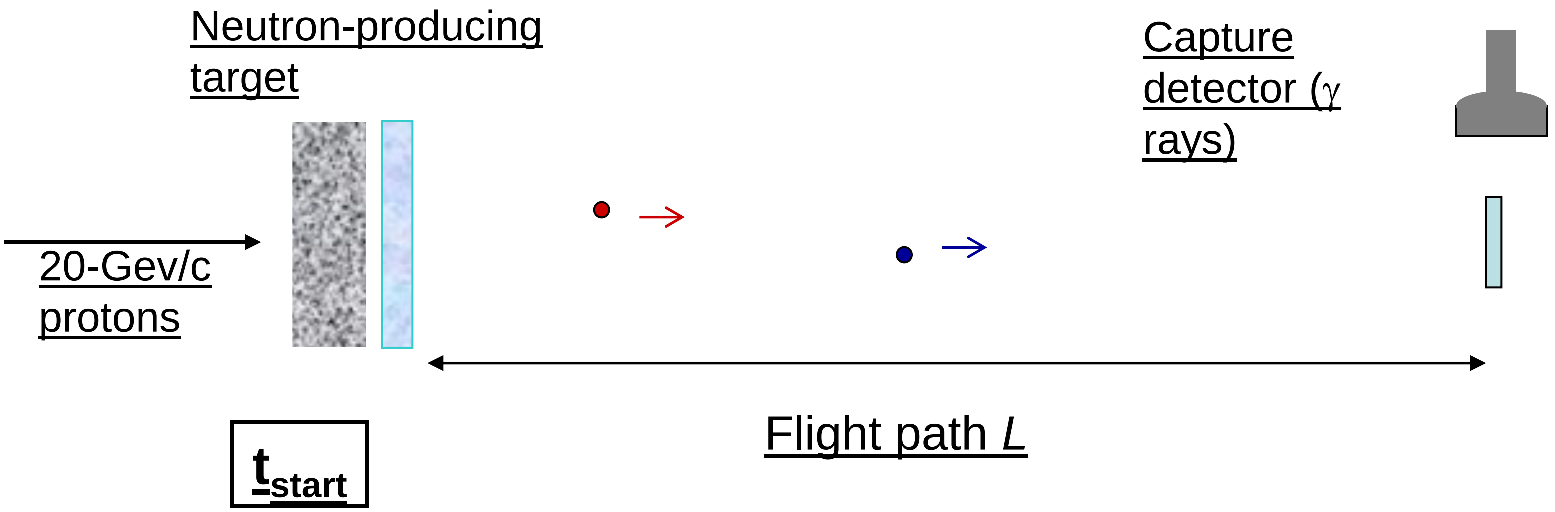
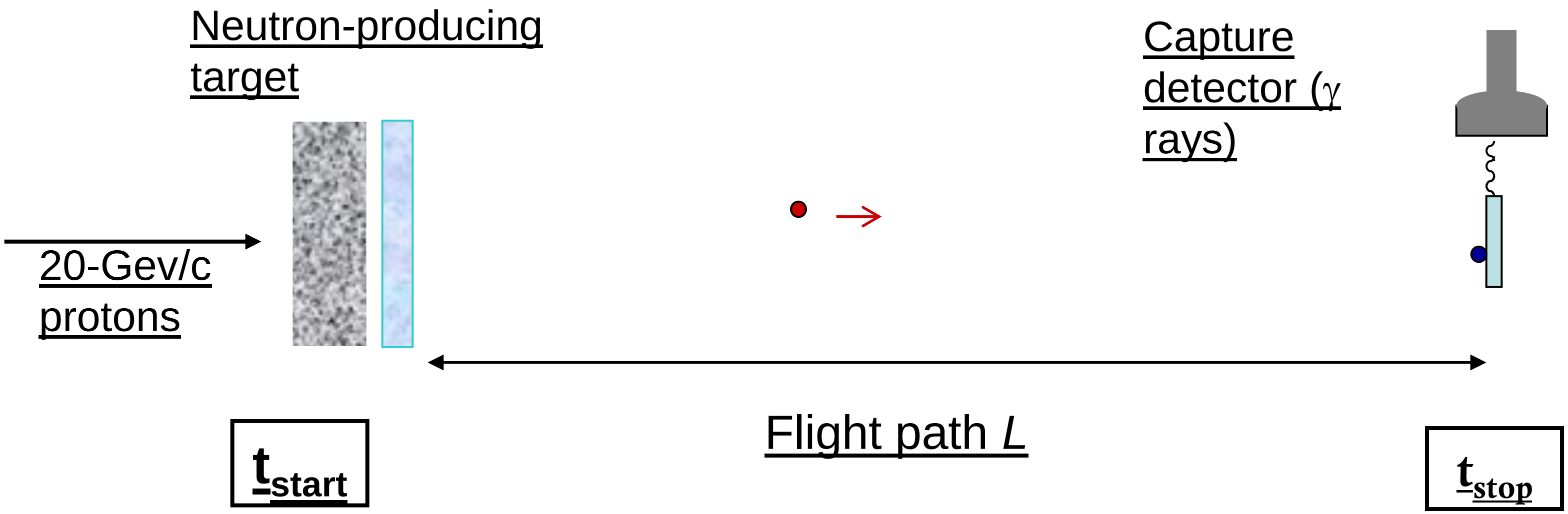
TOF technique



TOF technique



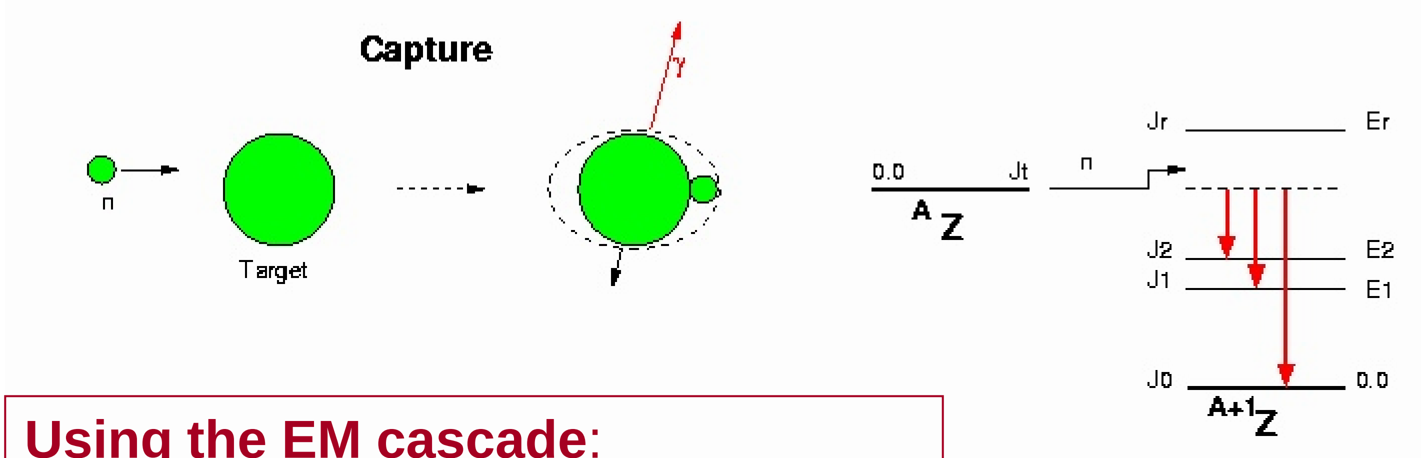
TOF technique



$$ToF = t_{stop} - t_{stop}$$

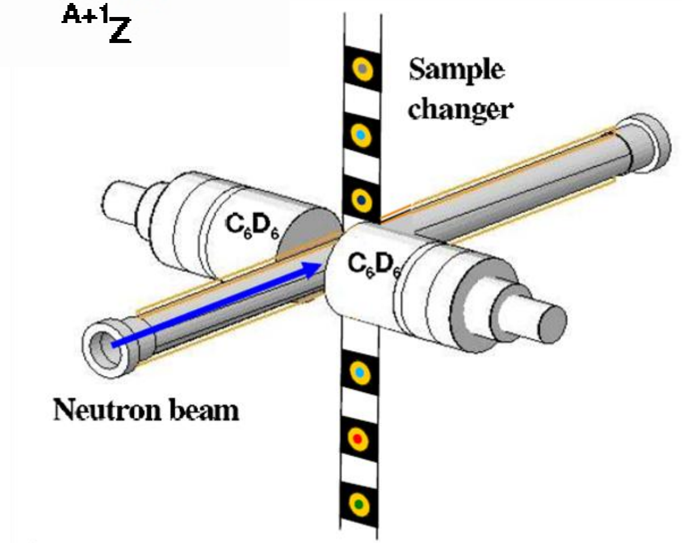
$$E_n = ½ \, m \, v^2 = \alpha^2 \, L^2 / (ToF)^2$$

Capture detectors



Using the EM cascade:

- prompt γ rays following the capture events are detected



The ***total energy detection*** principle was used, applying the ***pulse height weighting method,*** requires:

1) **low efficiency detector**
2) **efficiency proportional to γ-ray energy**

Capture detectors

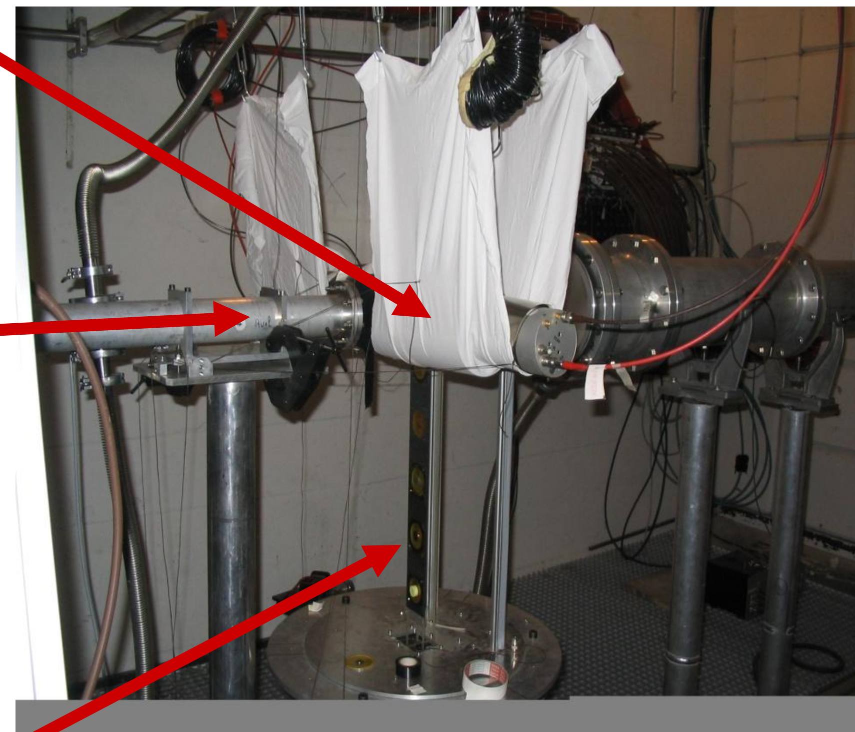
Especially designed detectors to minimize the background due to sample-scattered neutrons

- C_6D_6 liquid scintillators
- Boron free
- carbon fiber detector holder
- carbon fiber sample holder

Proper detector when capture << elastic

C_6D_6

n



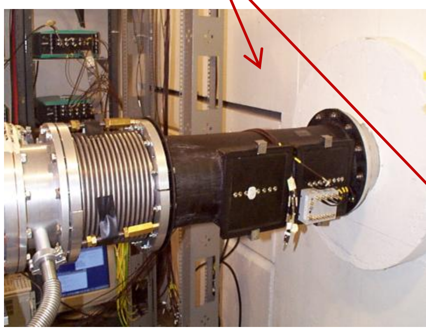
Sample holder

Flux detectors

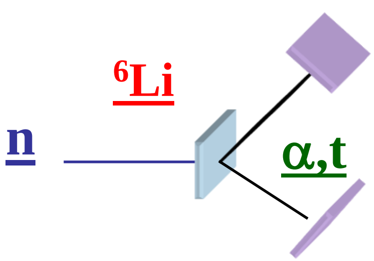
Two detectors:

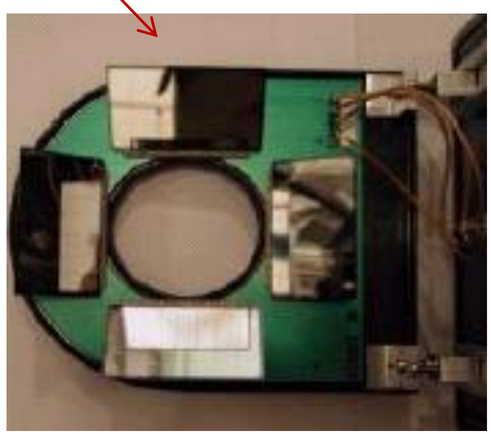
1) ^{235}U fission chamber

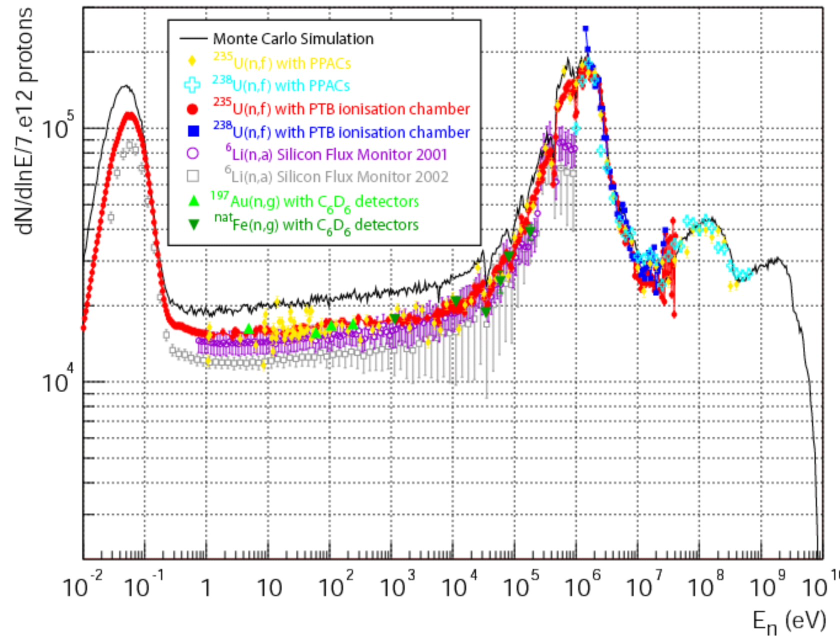
2) SiMon detector, using $^{6}Li(n,\alpha)t$



Also used as neutron monitor





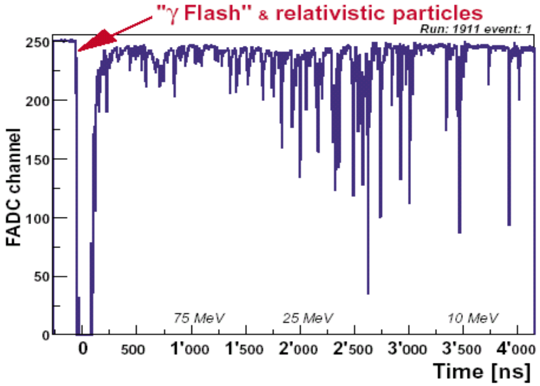


- Mylar foil with thin ^{6}Li deposit (200 µg/cm2)
- Silicon detector out of the beam
- Carbon fiber chamber

Acquisition system

n_TOF DAQ based on Flash ADC

- 500 MSample/s (500 MHz bandwidth), 16 MB buffer memory
- Zero Suppression software
- Commercial Aqiris



Offline Analysis of signals to deduce the information on tof, amplitude, …

- single signal
- fitting procedure in case of signal pile-up

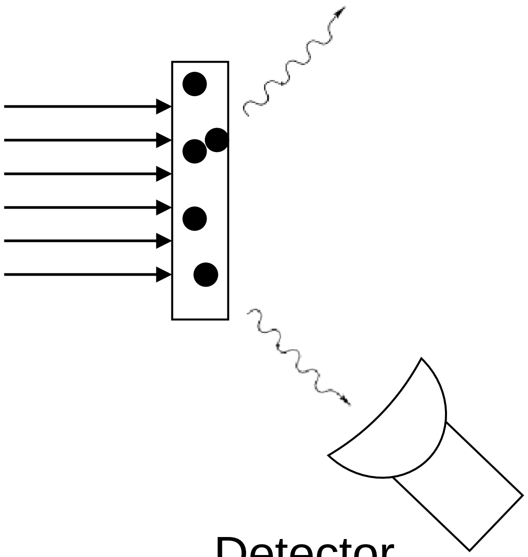
Data analysis

Mg samples 2.2-cm in diameter.
Oxide sample sealed in an **aluminum** canning.

Sample	Isotopic abundance of:			Mass	Areal	Type
ID	^{24}Mg	^{25}Mg	^{26}Mg	(g)	Density (at/b)	
^{24}Mg	78.7%	10.13%	11.17%	5.2393	0.03415	Metallic
^{25}Mg	3.05%	95.20%	1.20%	3.1924	0.01234	Oxide
^{26}Mg	2.46%	1.28%	96.26%	3.2301	0.012189	Oxide

Data analysis

The capture yield



The counts recorded by the capture detector, the C_6D_6, are related to the capture yield Y_γ (the fraction of neutron beam that undergoes capture reactions):

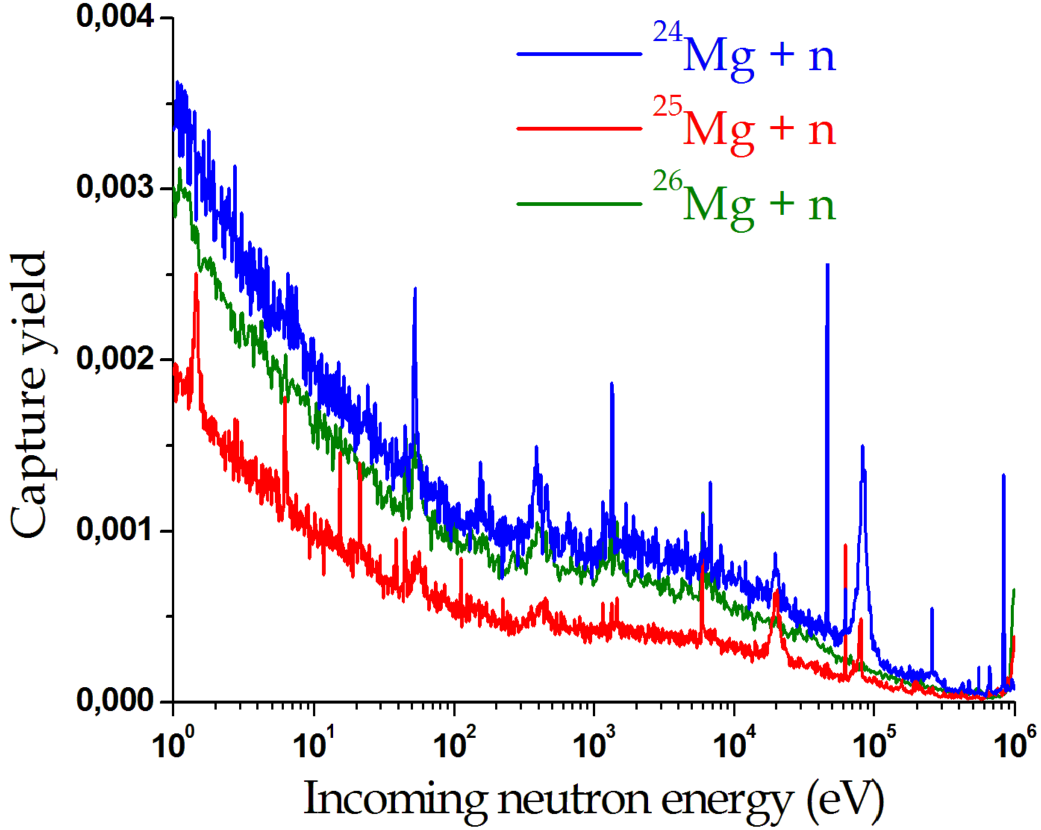
$C_\gamma = \varepsilon_\gamma \times Y_\gamma \times A \times \varphi_n$

- φ_n neutron flux
- ε_γ detection efficiency
- A effective area
- Y_γ capture yield

The self-shielding corrected yield is related to the capture cross-section:

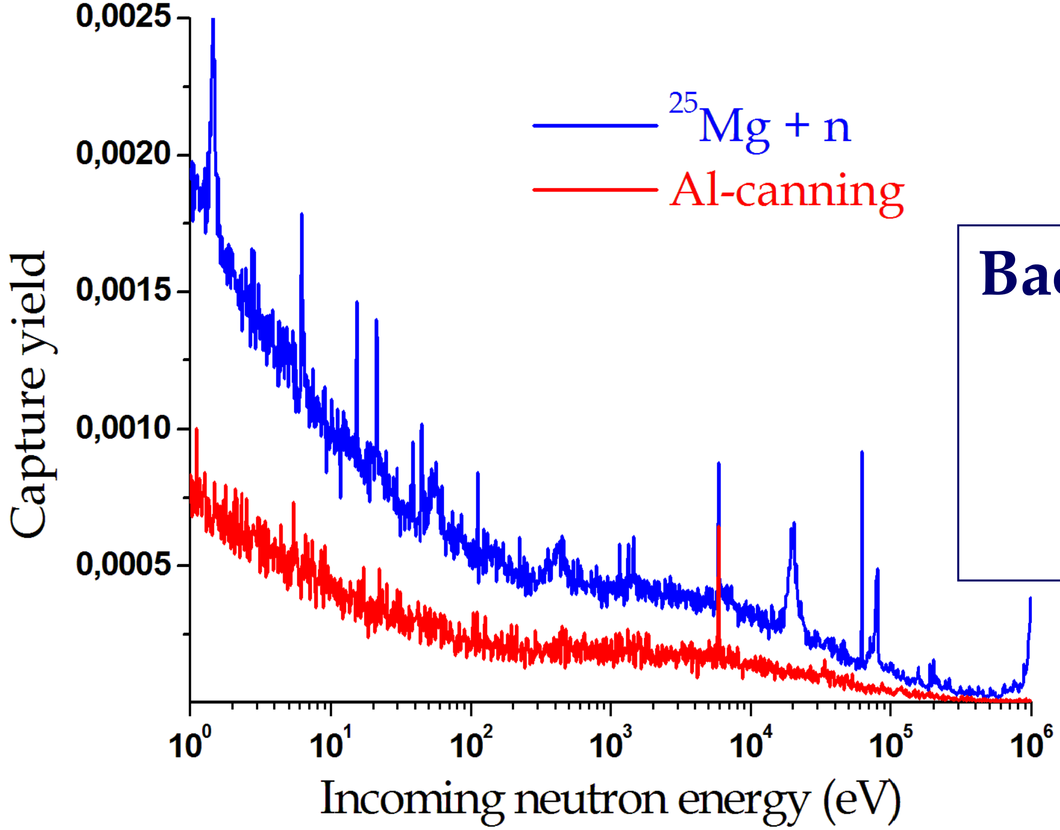
$$Y_\gamma = (1 - e^{-n\sigma_{tot}}) \frac{\sigma_\gamma}{\sigma_{tot}}$$

Data analysis



Normalization:
the capture detector (C_6D_6) and the neutron monitor (SiMon) were calibrated to about 1% accuracy by saturating the 4.9-eV resonance in Gold with a 0.25-mm thick sample.

Data analysis

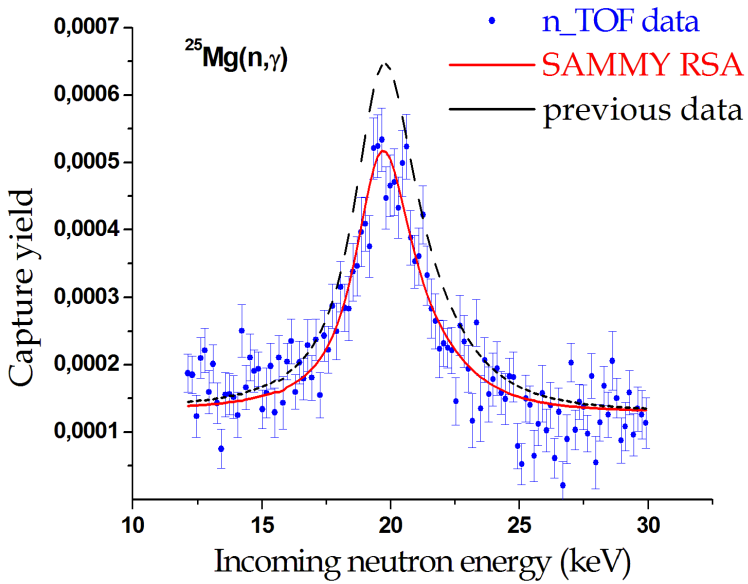


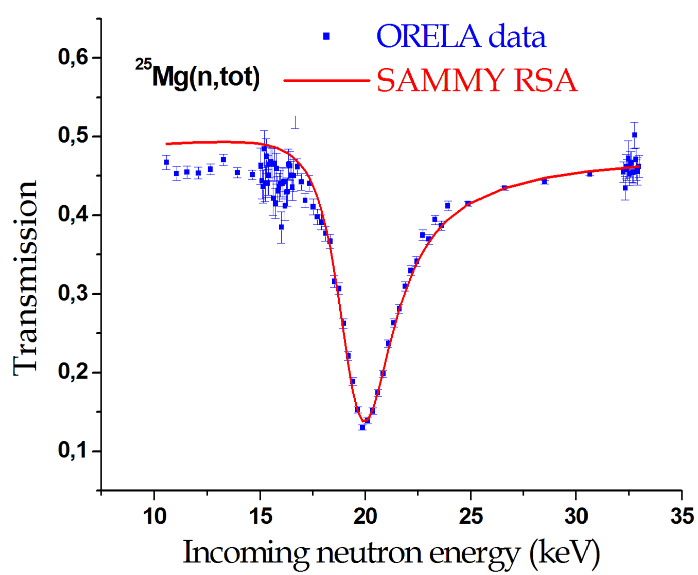
Background contributions:

- Al-canning
- γ-rays travelling in the beam
- sample-scattered neutrons

Resonance shape Analysis

The data are fitted using the R-matrix code SAMMY to extract resonance parameters





Preliminary results

- Resonance parameters of the $^{24}Mg(n,\gamma)$, $^{25}Mg(n,\gamma)$, $^{26}Mg(n,\gamma)$ reaction cross-sections have been determined.

- Sizable differences have been found respect to the existing evaluation, JENDL4 (2010), resulting in Maxwellian-averaged capture cross-sections (MACS), which are considerably different compared to previous measurements and compilations.

- Studies of the direct capture component demonstrated that this mechanism contributes at most 1 mb to the MACS of each isotope.

Conclusions

- The present (n,γ) measurement improves the cross section data on Mg isotopes.
- From preliminary analyses we find that the MACS of ^{25}Mg isotope is lower than reported previously.
- The contribution of the direct capture mechanism was calculated, it is not negligible.
- The respective changes of the stellar (n, γ) rates for the Mg isotopes are expected to have a significant impact on the neutron balance of the *s* process.

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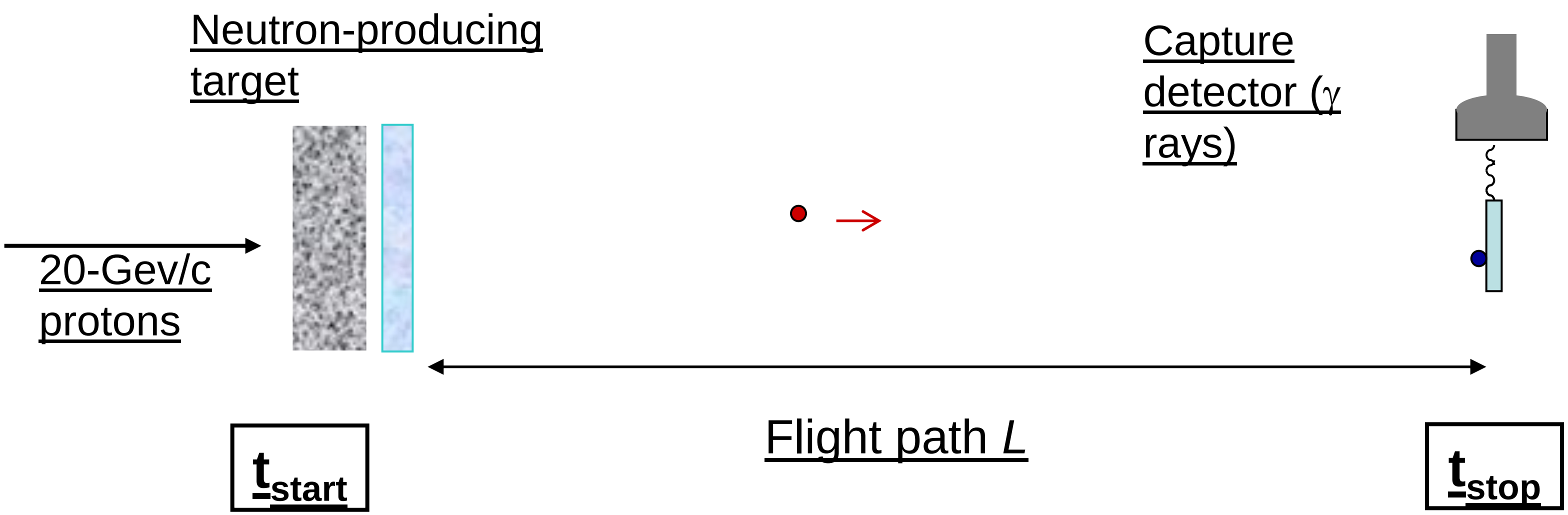
Motivations

The reaction ^{22}**Ne(α,n)**^{25}**Mg**

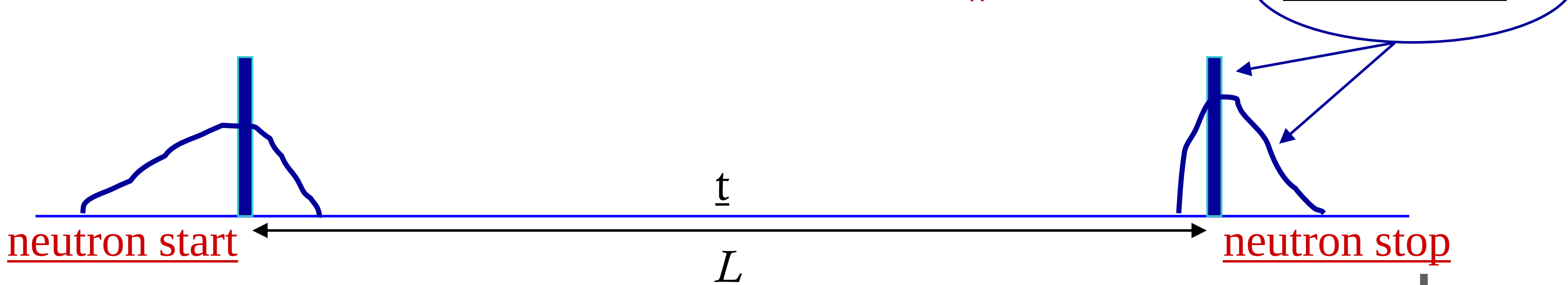
Element	J^{π}
^{22}Ne	0^+
^{4}He	0^+

Only **natural-parity** (0^+, 1^-, 2^+) **states in** ^{26}**Mg** can participate in the ^{22}Ne(α,n)^{25}Mg reaction, so only a subset of ^{26}Mg states in the relevant energy range observed via neutron reactions can contribute to the reaction rate

TOF technique

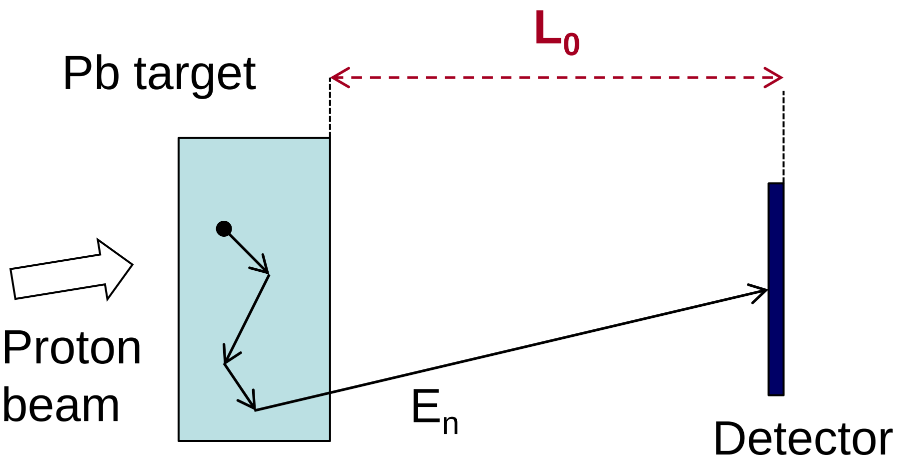


The time distribution of the *start*- and *stop*-signal introduces un uncertainty in the TOF → E_n

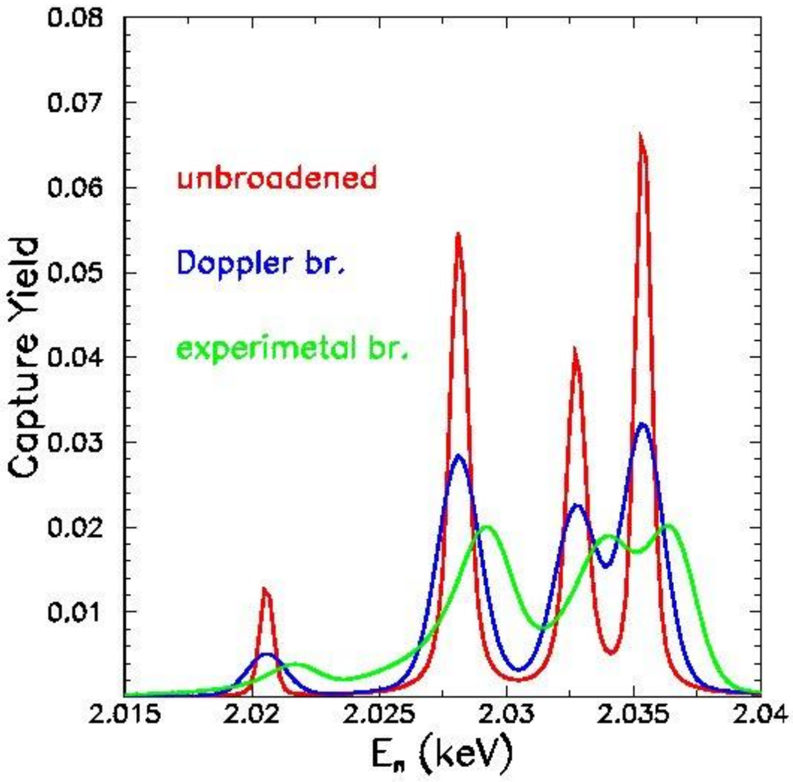


TOF technique

Energy resolution



L = L₀ + Lm



$$\frac{\Delta E_n}{E_n} = \frac{2}{L}\sqrt{(\Delta L)^2 + 1.9 E_n (\Delta t)^2}$$