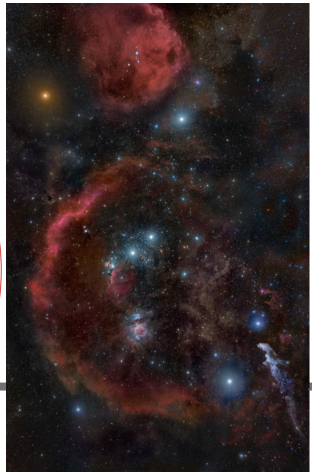
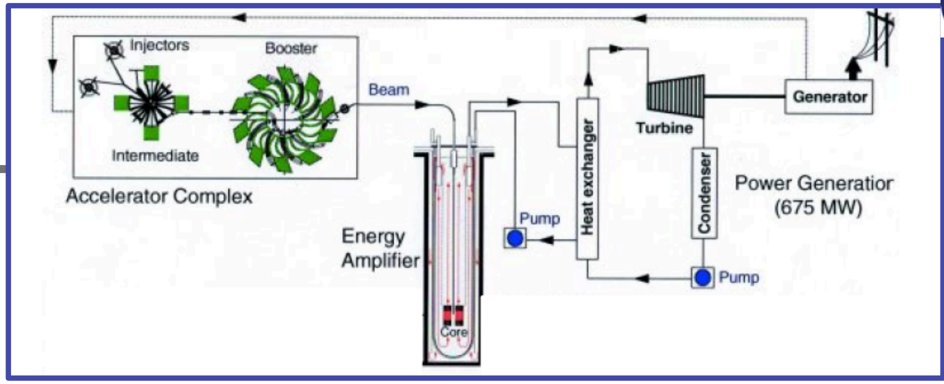




Neutron physics at CERN: n_TOF

Cristian Massimi

Bologna, 30/10/2015

Outline

- **The n_TOF project**

  Collaboration, objectives, timeline, basic parameters, instrumentation

- **INFN contribution to n_TOF**

  Proposals, detectors, and data analysis

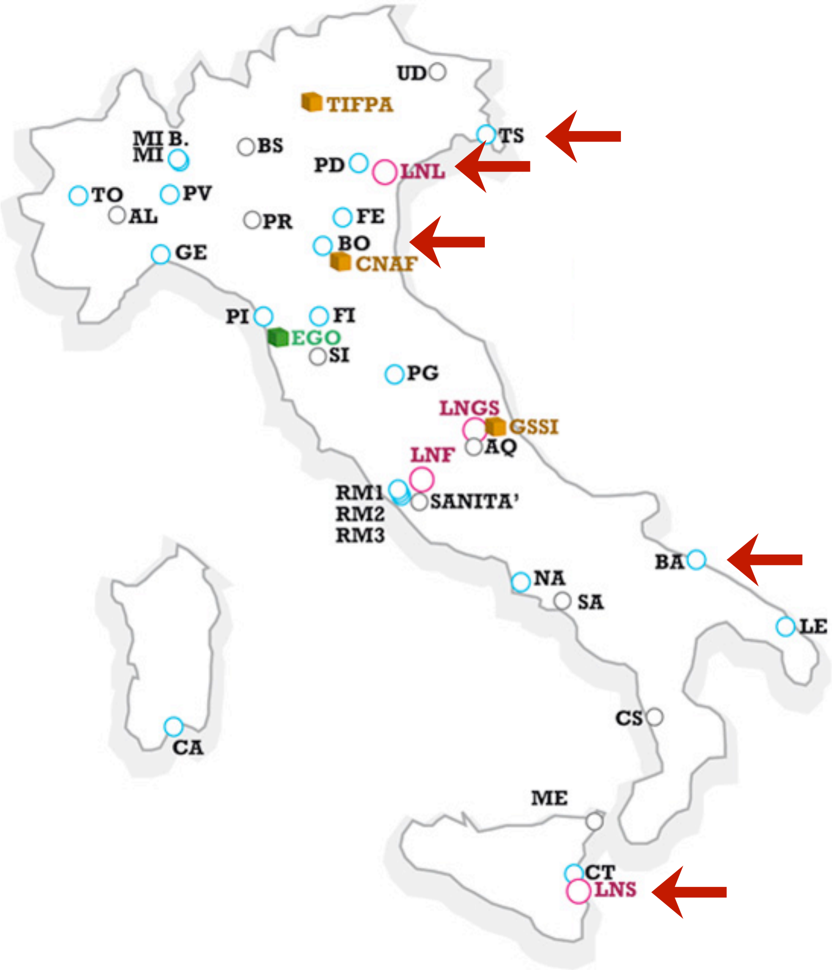
- **The role of Bologna – INFN section**

  Results and prespectives

The n_TOF project

1. Atominstitut, Technische Universität Wien, Austria
2. University of Vienna, Faculty of Physics, Austria
3. European Commission JRC, Institute for Reference Materials and Measurements (IRMM)
4. Department of Physics, Faculty of Science, University of Zagreb, Croatia
5. Charles University, Prague, Czech Republic
6. Centre National de la Recherche Scientifique/IN2P3 - IPN, Orsay, France
7. Commissariat à l'Énergie Atomique (CEA) Saclay - Irfu, Gif-sur-Yvette, France
8. Johann-Wolfgang-Goethe Universität, Frankfurt, Germany
9. Karlsruhe Institute of Technology, Campus Nord, Institut für Kernphysik, Karlsruhe, Germany
10. National Technical University of Athens (NTUA), Greece
11. Aristotle University of Thessaloniki, Thessaloniki, Greece
12. Bhabha Atomic Research Centre (BARC), Mumbai, India
13. ENEA Bologna e
14. Dipartimento di Fisica, e Astronomia, Università di Bologna
15. Sezione INFN di Bologna, INFN Bari, Bologna, LNL, Trieste, LNS
16. Uniwersytet Łódzki, Lodz, Poland
17. Instituto Tecnológico e Nuclear, Instituto Superior Técnico, Universidade Técnica de Lisboa, Portugal
18. Horia Hulubei National Institute of Physics and Nuclear Engineering – Bucharest, Romania
19. Centro de Investigaciones Energeticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
20. Instituto de Fìsica Corpuscular, CSIC-Universidad de Valencia, Spain
21. Universitat Politecnica de Catalunya, Barcelona, Spain
22. Universidad de Sevilla, Spain
23. Universidade de Santiago de Compostela, Spain
24. Department of Physics and Astronomy - University of Basel, Basel, Switzerland
25. European Organization for Nuclear Research (CERN), Geneva, Switzerland
26. Paul Scherrer Institut, Villigen PSI, Switzerland
27. University of Manchester, Oxford Road, Manchester, UK
28. University of York, Heslington, York, UK

The n_TOF project



Bari

M. Barbagallo, N. Colonna, M. Mastromarco, A. Mazzone, G. Tagliente, V. Variale, L. Damone

Bologna (INFN - UNIBO - ENEA)

D. Castelluccio, G. Clai, S. Lo Meo, C. Massimi, F. Mingrone, G. Vannini, A. Ventura

LNL

P.F. Mastinu

LNS

L. Cosentino, P. Finocchiaro, A. Musumarra

Trieste

P. Milazzo, F. Matteucci

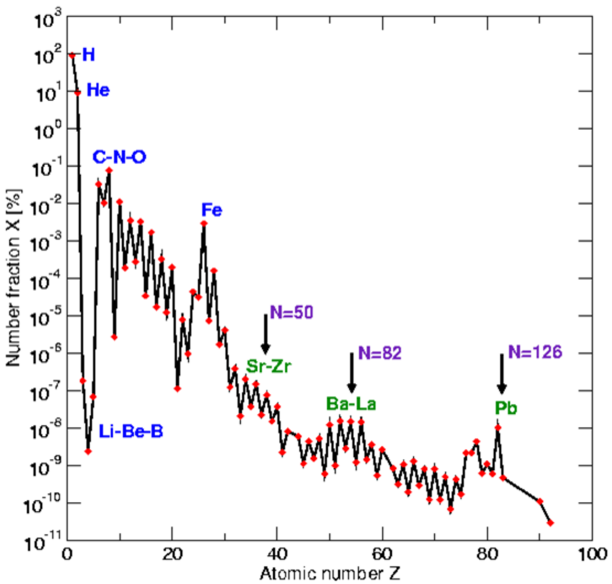
~ 12 FTE

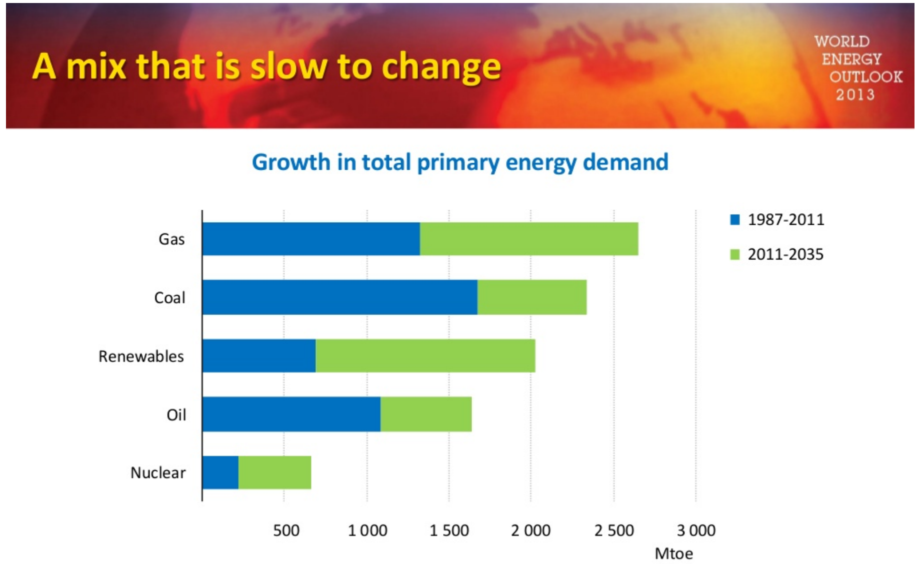
The n_TOF project

Nuclear Data for Science and Technology

How the elements are synthesized in the Universe?

- Stellar nucleosynthesis (**s process**)
- Cosmochronology
- Stellar thermodynamics
- **Big Bang nucleosynthesis**





Today's share of fossil fuels in the global mix, at 82%, is the same as it was 25 years ago; the strong rise of renewables only reduces this to around 75% in 2035

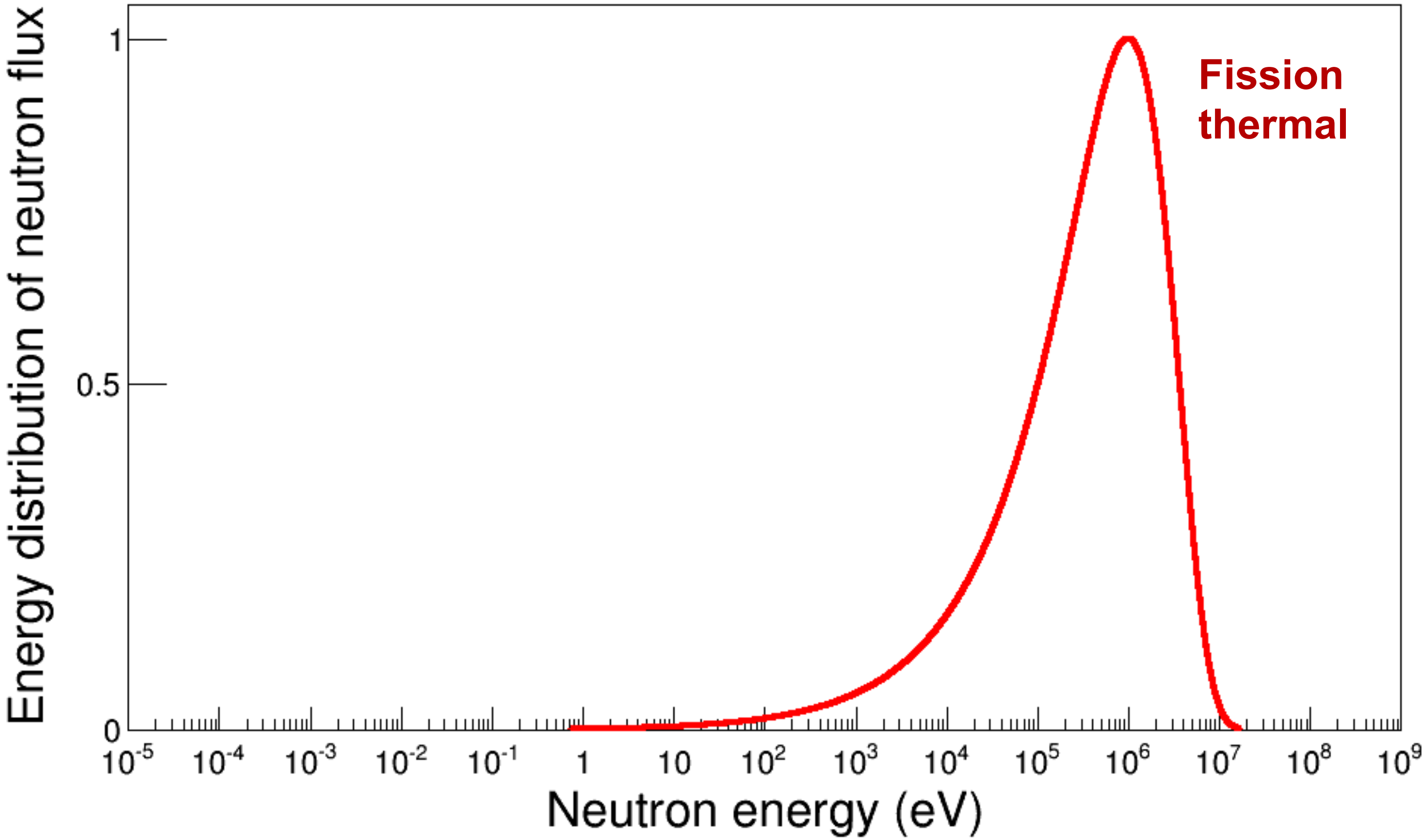
Nuclear technology / medicine

- Transmutation of nuclear waste
- Gen-IV reactors
- Accelerator Drives System (ADS)
- Neutron Capture Therapy (NCT)

The n_TOF project

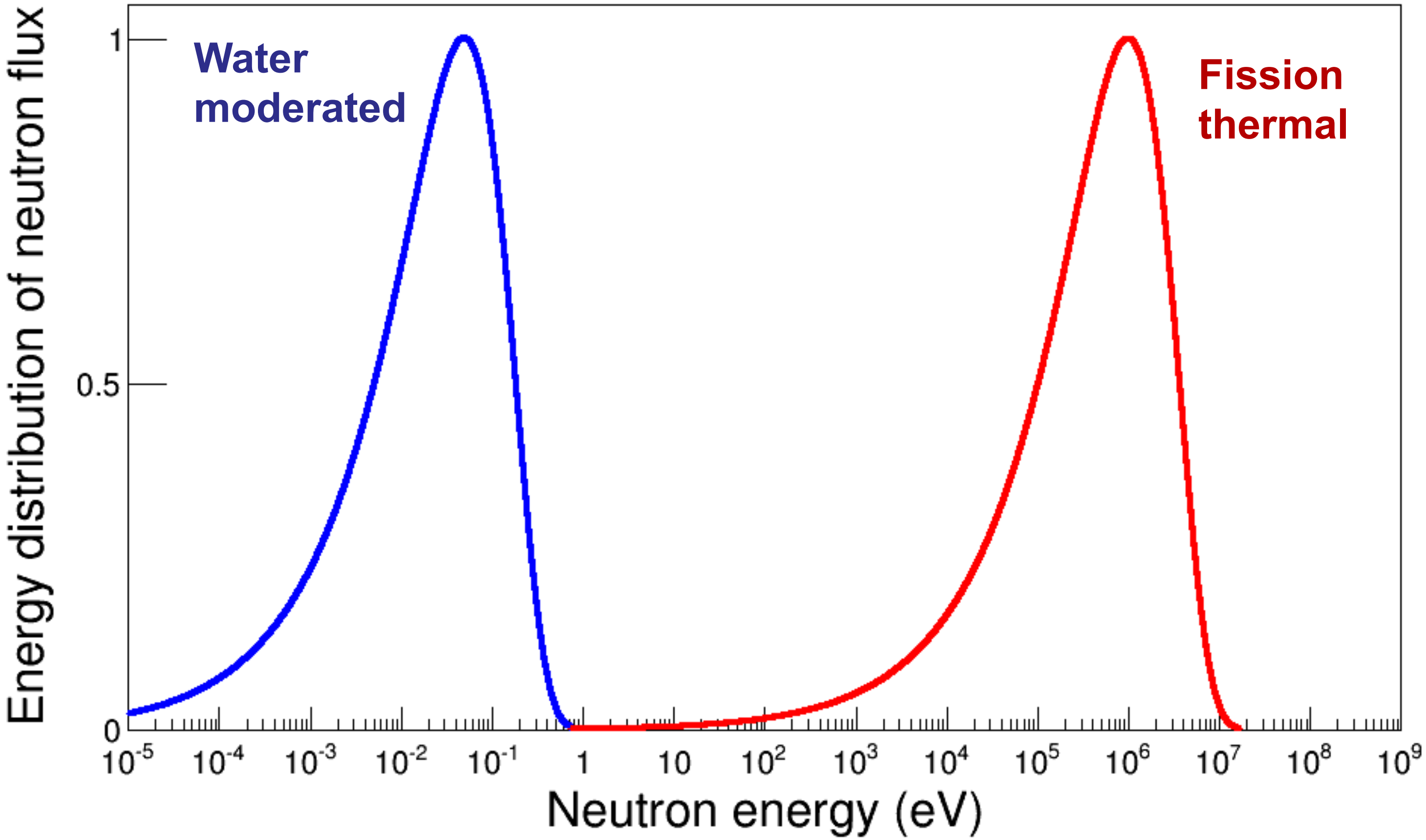
Istituto Nazionale di Fisica Nucleare

Nuclear Data for Science and Technology



The n_TOF project

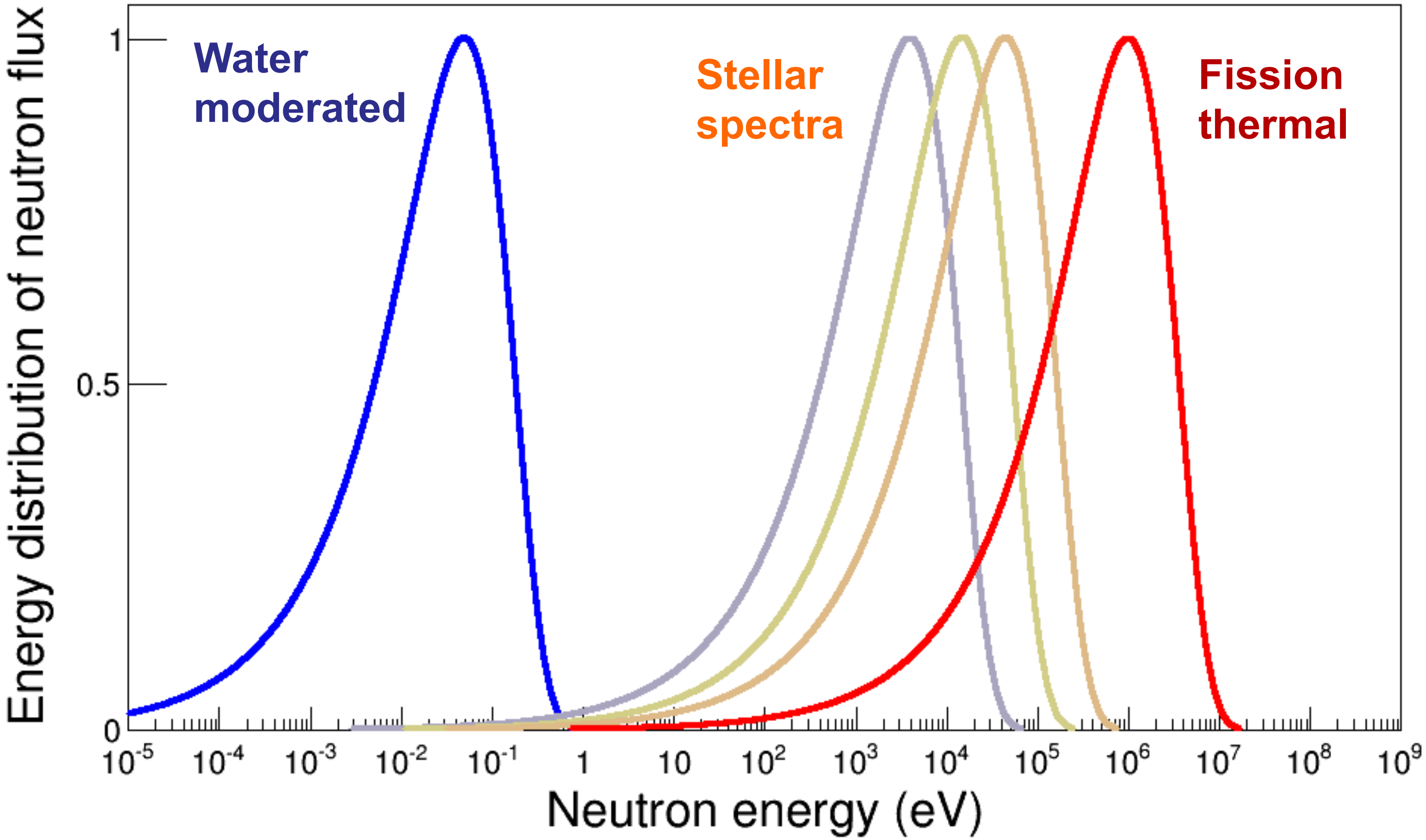
Nuclear Data for Science and Technology



The n_TOF project

Istituto Nazionale di Fisica Nucleare

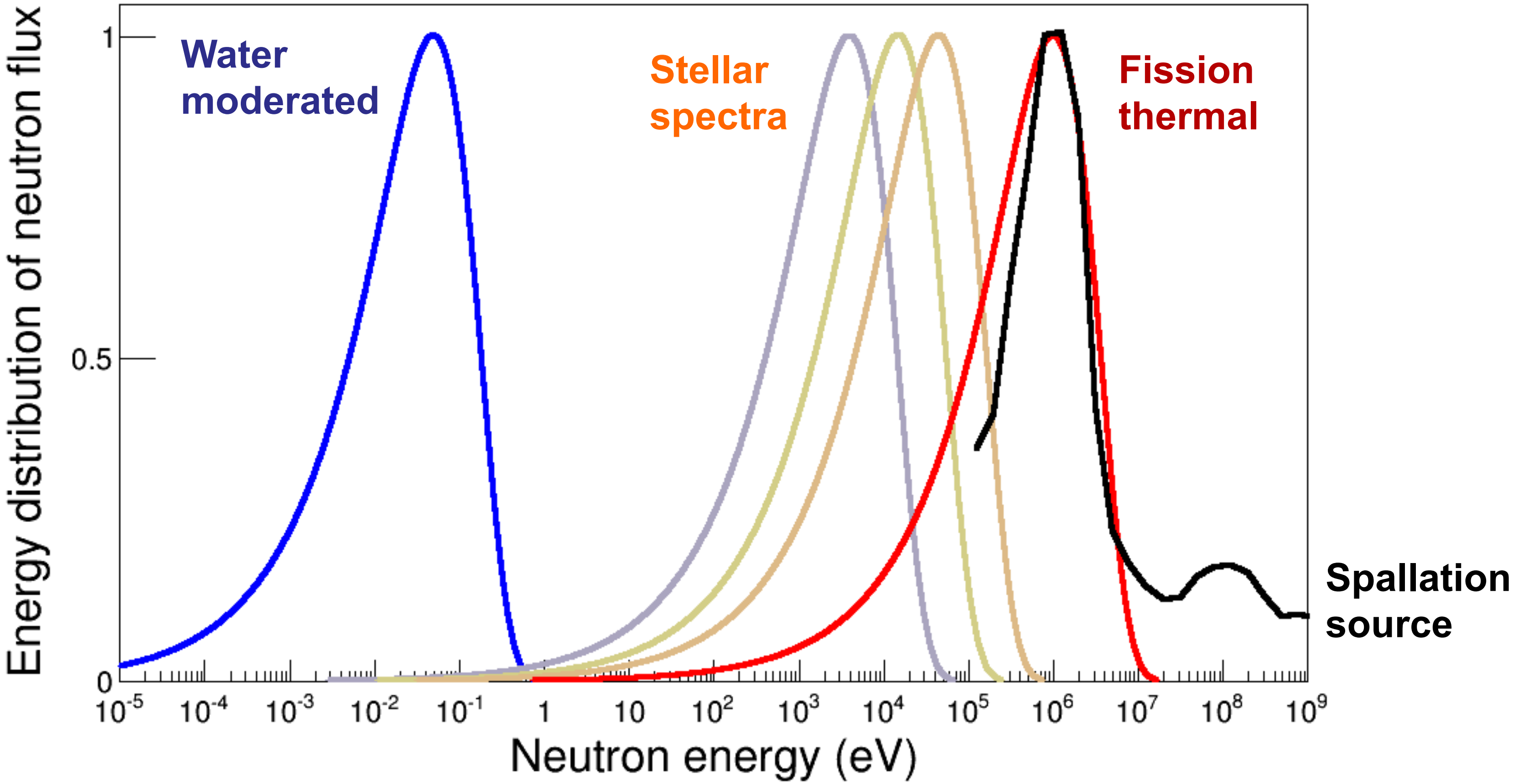
Nuclear Data for Science and Technology



The n_TOF project

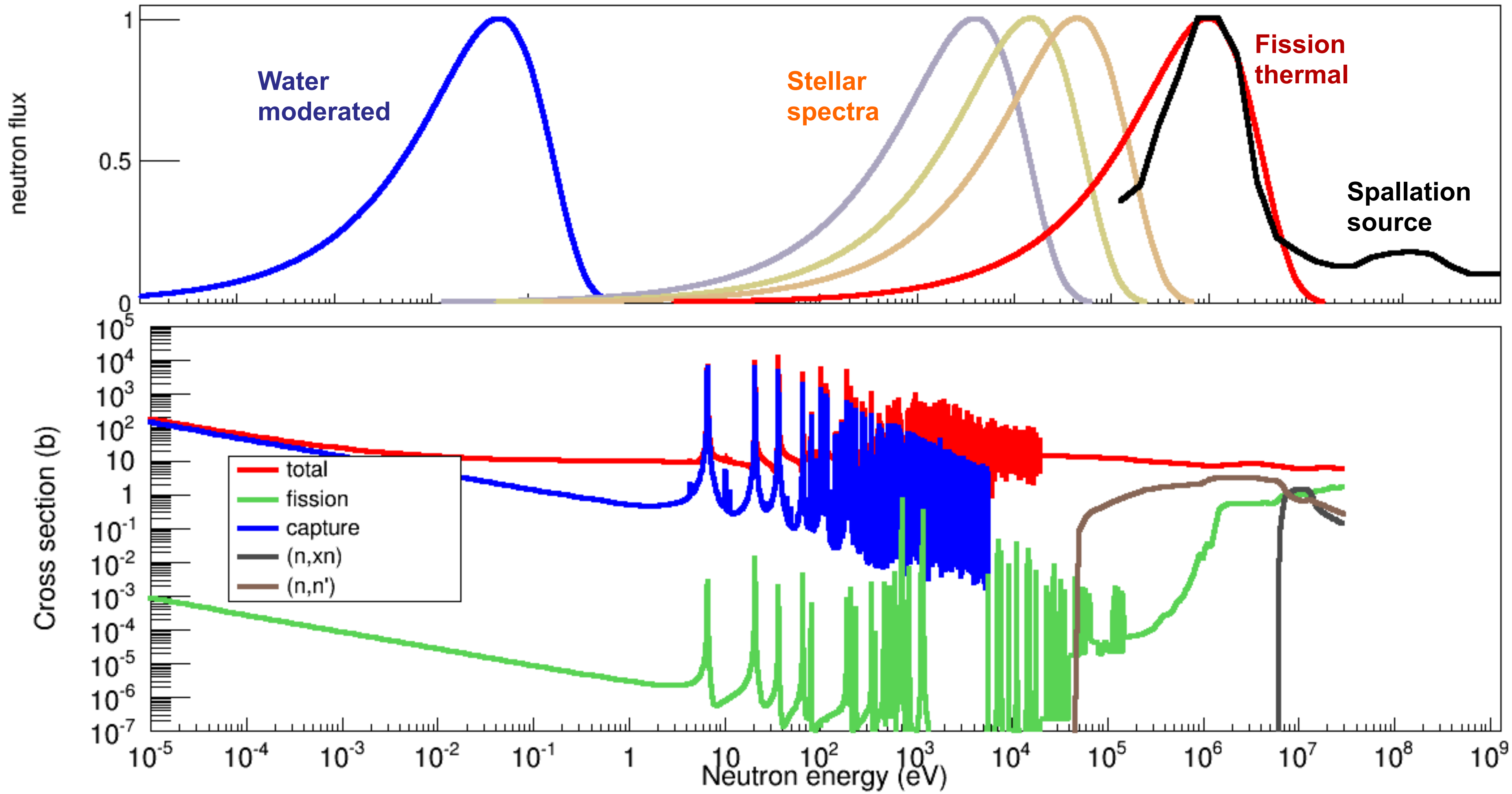
Istituto Nazionale di Fisica Nucleare

Nuclear Data for Science and Technology



The n_TOF project

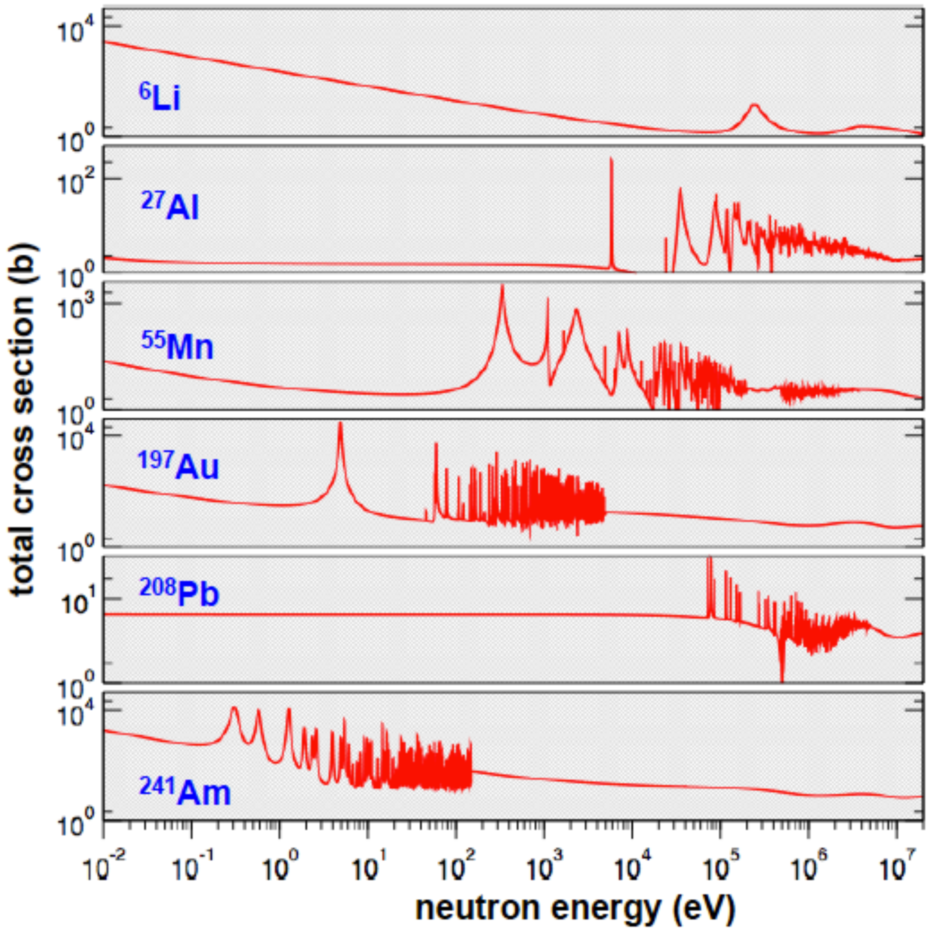
Nuclear Data for Science and Technology



The n_TOF project

Istituto Nazionale di Fisica Nucleare

Nuclear Data for Science and Technology



The quest for accurate nuclear data

- Cross section: capture, fission, inelastic
- Multiplicity and energy spectrum of neutron
- Delayed neutron
- Fission fragments: mass distribution
- β decay

So far, only data relevant to U/Pu thermal reactor are present. New needs:

1. High neutron energies (fast reactors)
2. Radioactive isotopes (*e.g.* involved in the fuel cycle)
3. New fuel cycle (U/Th)

The n_TOF project

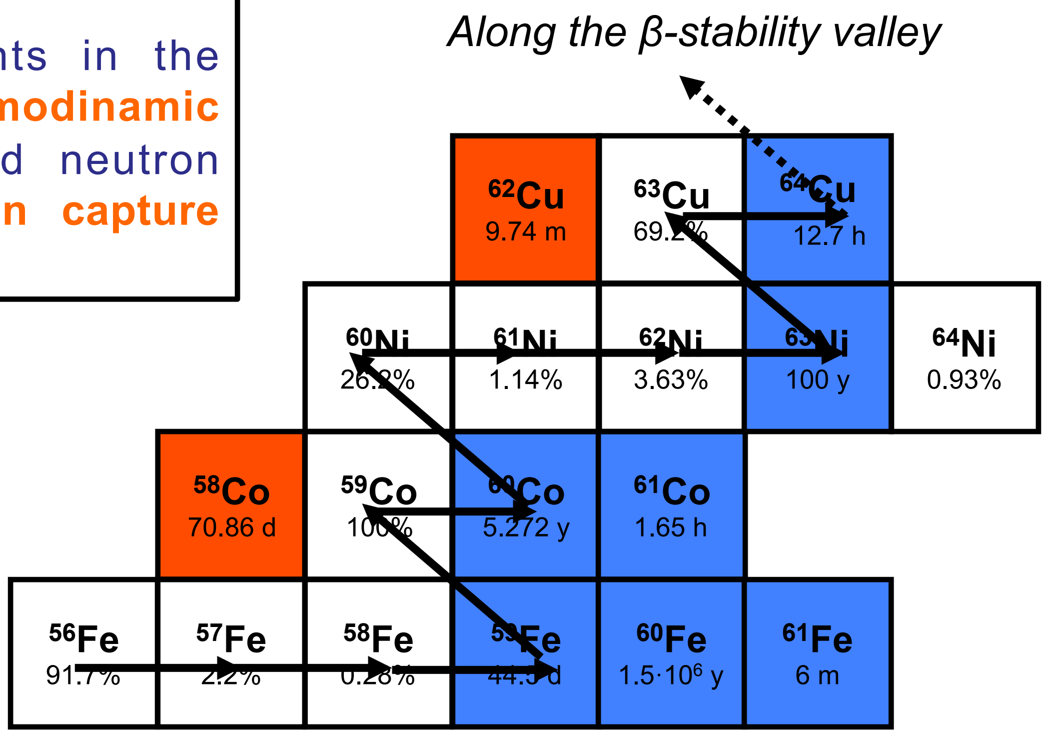
Nuclear Data for Science and Technology

s-process nucleosynthesis proceeds through **neutron captures** and successive **β-decay.**

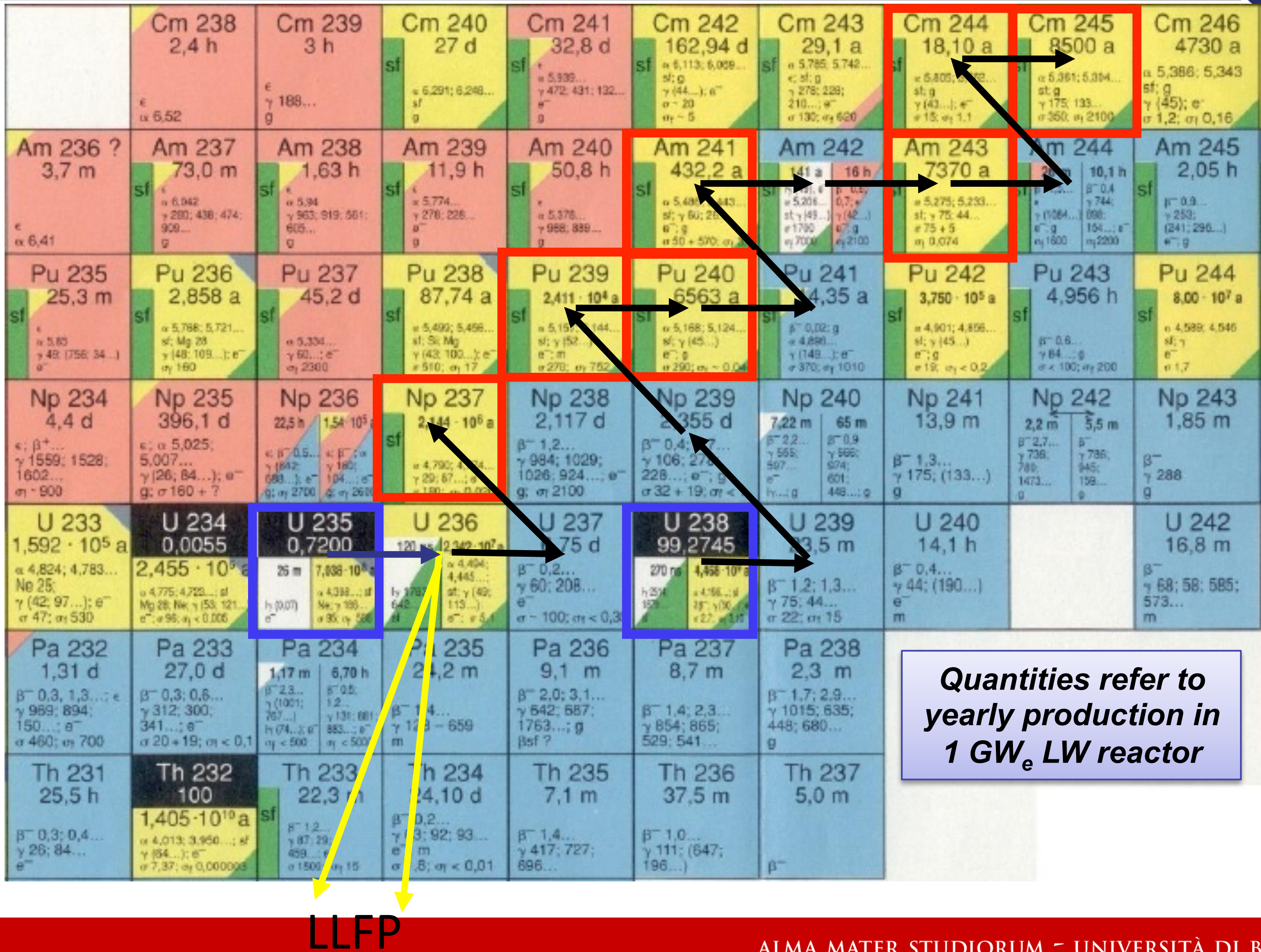
The abundance of elements in the Universe depends on **thermodinamic conditions** (temperture and neutron density) and on the **neutron capture cross-sections.**

σ(n, γ) is a key quantity

s process



The n_TOF project



Quantities refer to yearly production in 1 GW_e LW reactor

$^{244,\,245}$Cm
1.5 Kg/yr

^{241}Am: 11.6 Kg/yr
^{243}Am: 4.8 Kg/yr

^{239}Pu: 125 Kg/yr

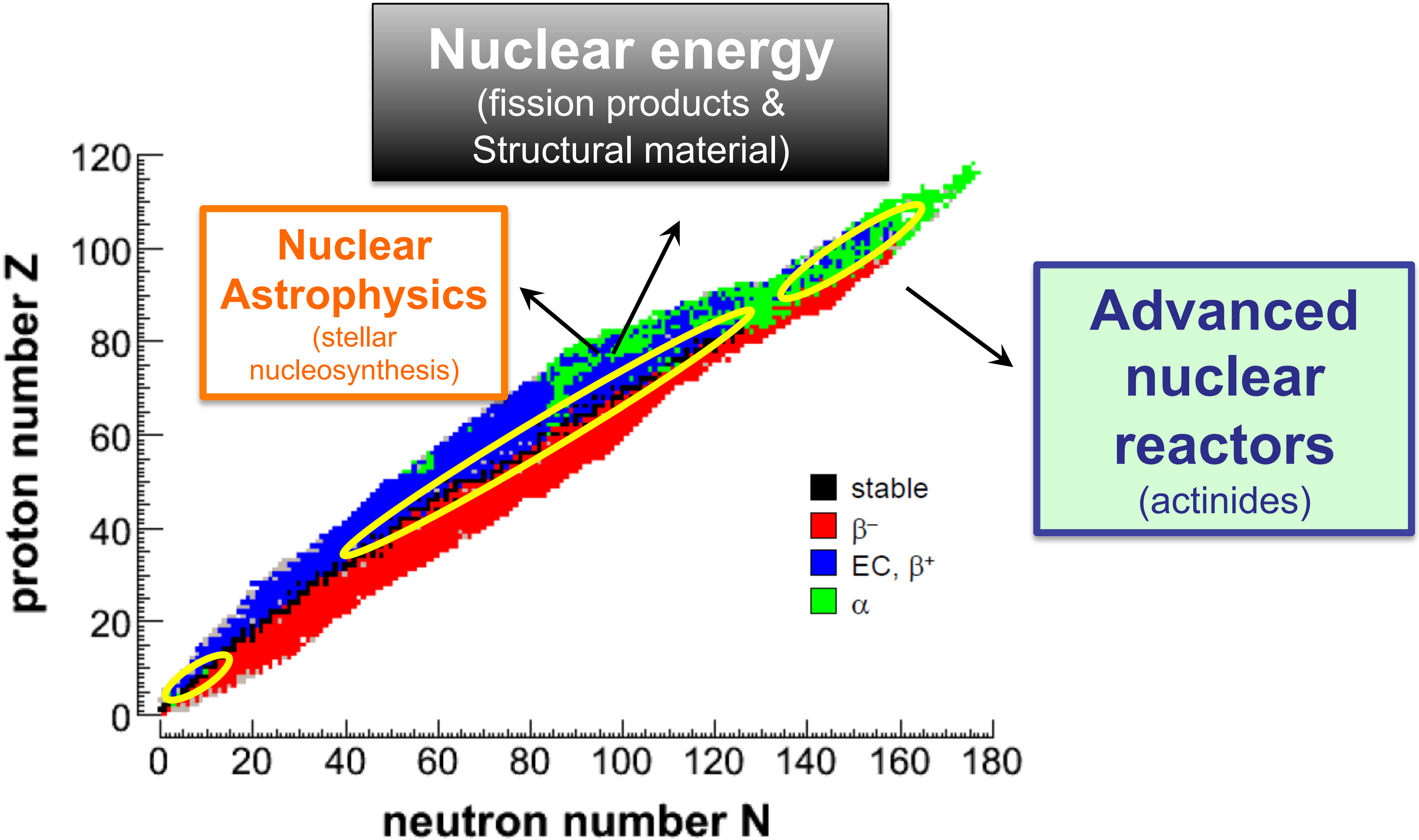
^{237}Np: 16 Kg/yr

LLFP
76.2 Kg/yr

The n_TOF project

Istituto Nazionale di Fisica Nucleare

Nuclear Data for Science and Technology



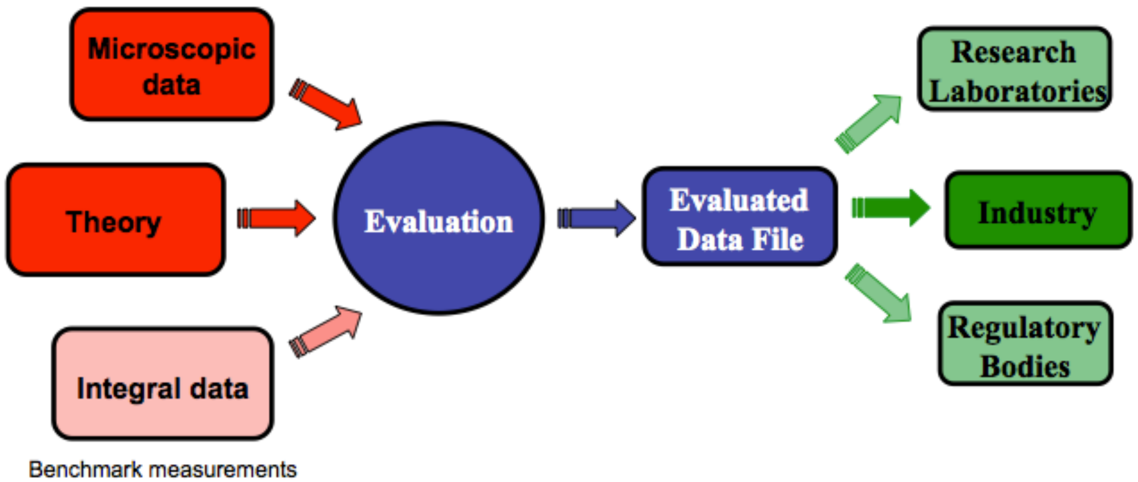
nTOF

The n_TOF project

INFN Istituto Nazionale di Fisica Nucleare

Nuclear Data for Science and Technology

The **European Commission** encourages and finances research in nuclear physics applied to the construction of new reactors (EURATOM).



FP VII EURATOM

Topic: Fission-2009-2.3.2: Improved nuclear data for advanced reactor systems.
The combination of advanced simulation systems and more precise nuclear data will allow optimising the use of and need for experimental and demonstration facilities in the design and deployment of new reactors. A concerted effort including new nuclear data measurements, dedicated benchmarks (i.e. integral experiments) and improved evaluation and modelling is needed in order to achieve the required accuracies. **The project shall aim to obtain high precision nuclear data for the major actinides present in advanced reactor fuels**, to reduce uncertainties in new isotopes in closed cycles with waste minimisation and to better assess the uncertainties and correlations in their evaluation.

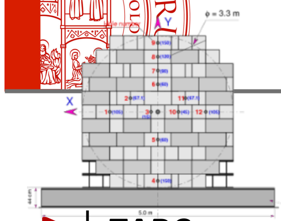
n_TOF

The n_TOF project

INFN Istituto Nazionale di Fisica Nucleare

Timeline

1996 — 2015



1995-1997 — **TARC** experiment

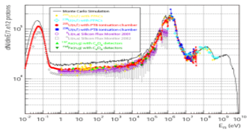
1997 — **Concept** by C.Rubbia CERN/ET/Int. Note 97-19

May 1998 — **Feasibility** CERN/LHC/98-02+Add

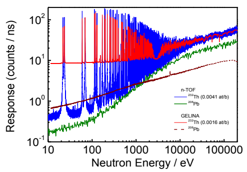
Aug 1998 — **Proposal** submitted

1999 — **Construction** started

2000 — **Commissioning**



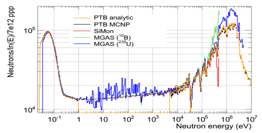
2001-2004 — **Phase I** Isotopes Capture: 25 Fission: 11



2004-2007 — **Problem** Investigation

2008 — **New Target** construction

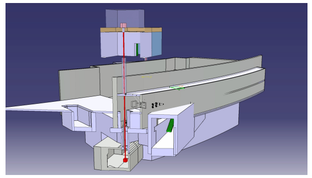
May 2009 — **Commissioning**



2009 - 2012 — **Phase II** Isotopes Capture: 14 Fission: 3 (n,cp): 2

2010 — **Upgrades:** Borated-H_2O Class-A Second Line

2011 — **EAR2** Design and Construction



July 2014 — **Commissioning**

2015 — **Phase-3**

n_TOF

The n_TOF project

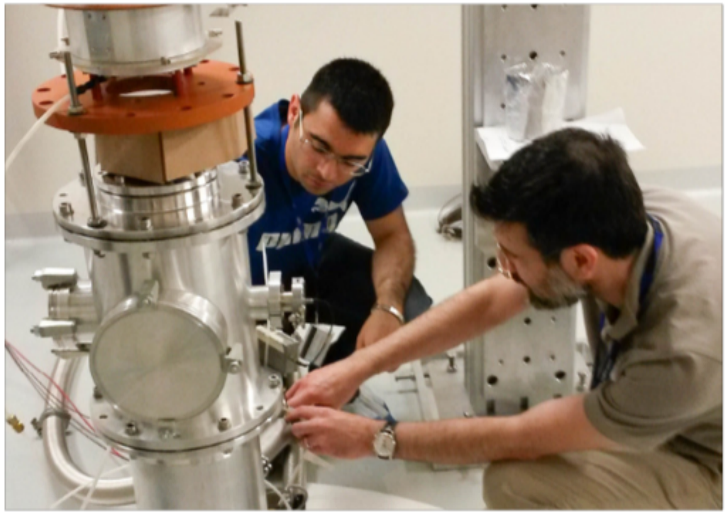
Istituto Nazionale di Fisica Nucleare

CERN Bulletin

Issue No. 32-34/2014 - Monday 4 August 2014
More articles at: http://bulletin.cern.ch

THE FIRST NEUTRON BEAM HITS EAR2

On 25 July 2014, about a year after construction work began, the Experimental Area 2 (EAR2) of CERN's neutron facility n_TOF recorded its first beam. Unique in many aspects, EAR2 will start its rich programme of experimental physics this autumn.



The last part of the EAR2 beamline: the neutrons come from the underground target and reach the top of the beamline, where they hit the samples.

GETTING TO KNOW INTERNATIONAL GENEVA

Over recent years, CERN has been tightening its links with fellow organisations in Geneva's vibrant international community.

(Continued on page 2)

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Getting to know international Geneva 1
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The light at the end of the tunnel gets brighter 5

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Training 6
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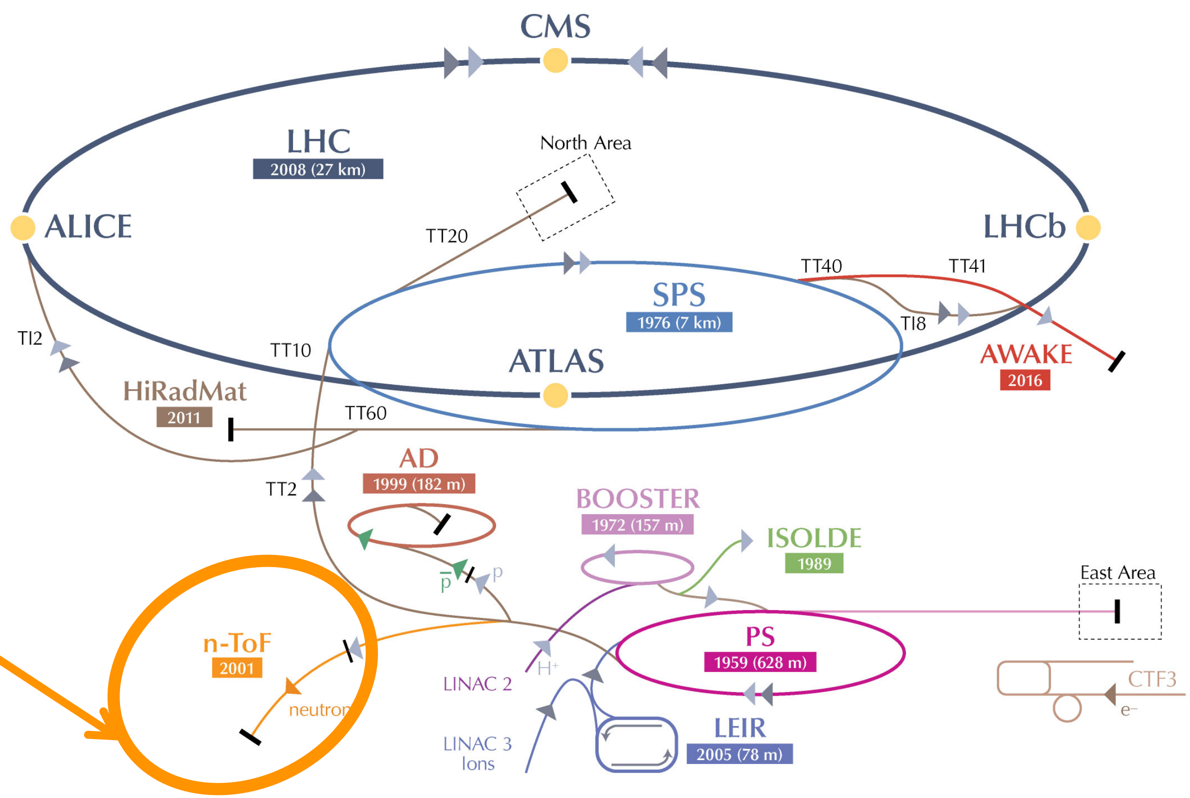
Take note 8

nTOF

The n_TOF project

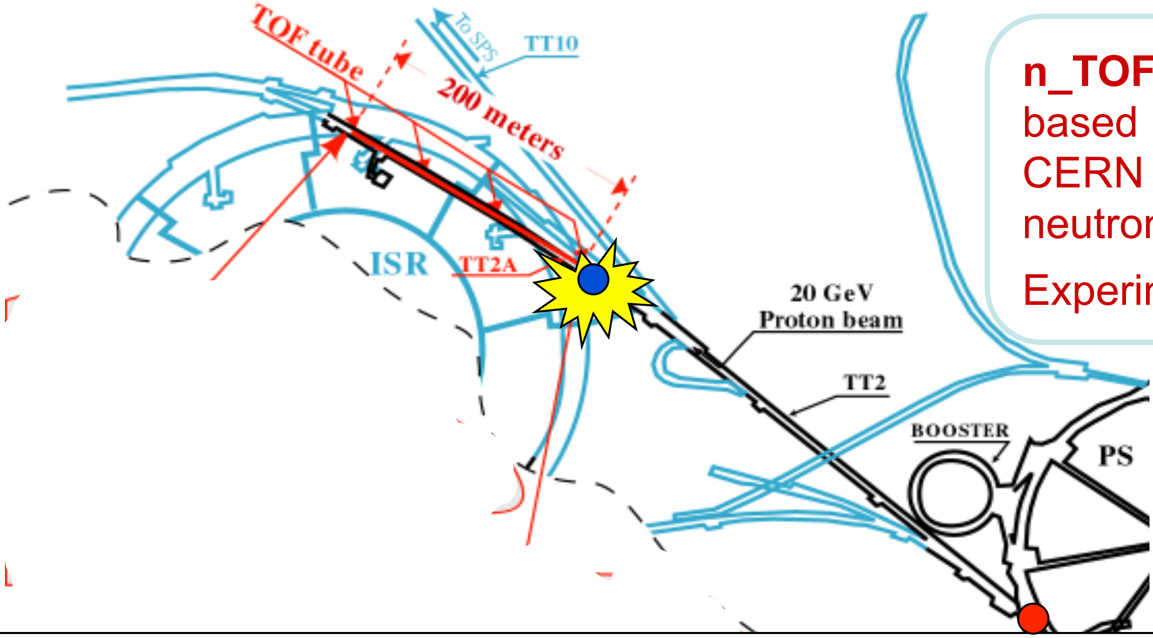


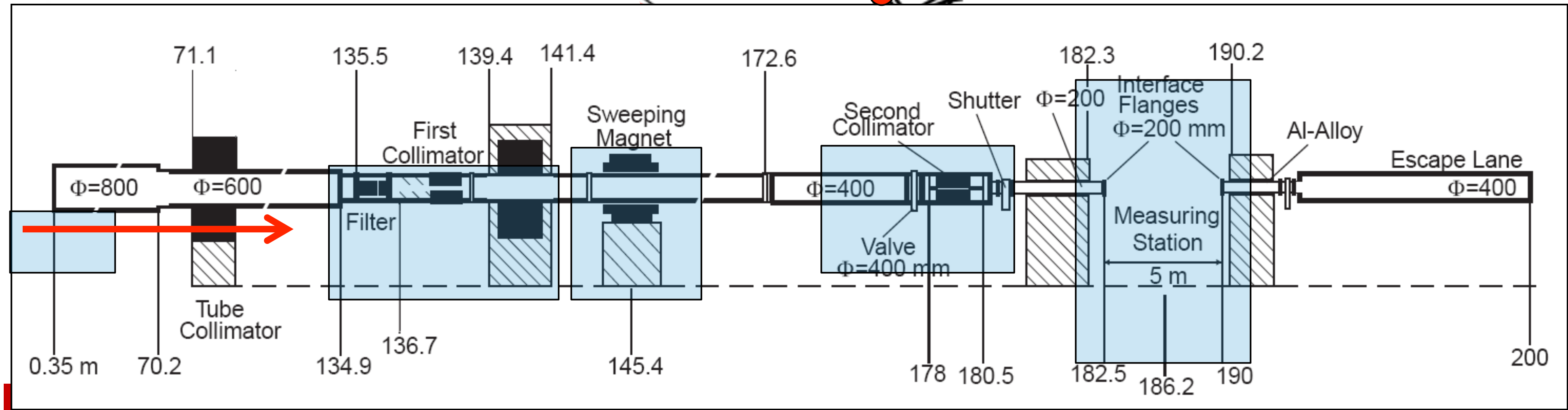
Neutron Time-Of- Flight facility: **n_TOF**

The n_TOF project

n_TOF is a **spallation** neutron source based on **20 GeV/c protons** from the CERN PS hitting a **Pb block** (~300 neutrons per proton and ~ $7x10^{12}$ ppp).

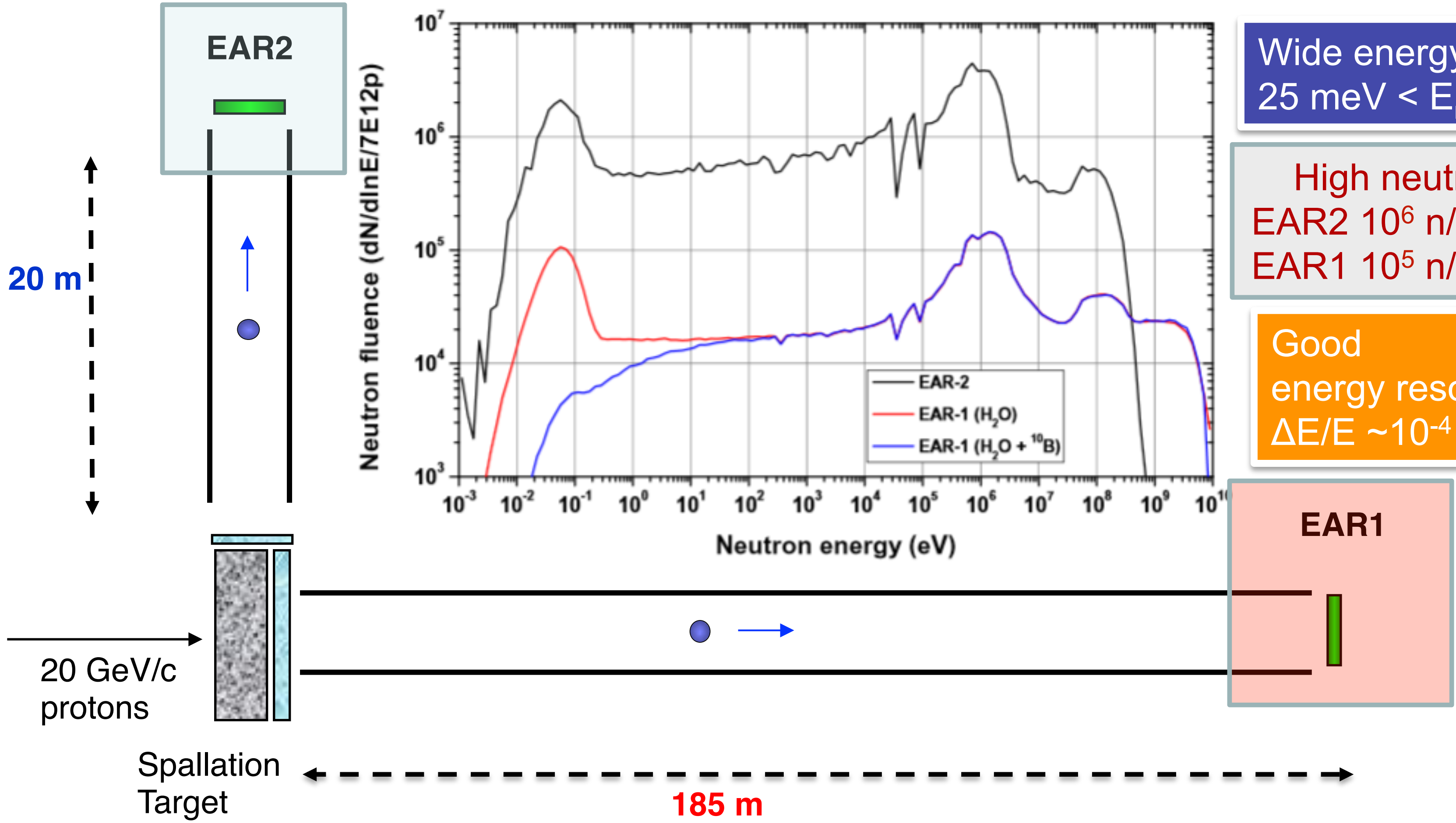
Experimental area at **185 m** and **18.5 m**.





The n_TOF project

The advange of n_TOF are a direct consequence of the characteristics of the **PS proton beam**: **high energy, high peak current, low duty cycle.**



Wide energy range:
25 meV < E_n < 1 GeV

High neutron flux
EAR2 10^6 n/cm^2/pulse
EAR1 10^5 n/cm^2/pulse

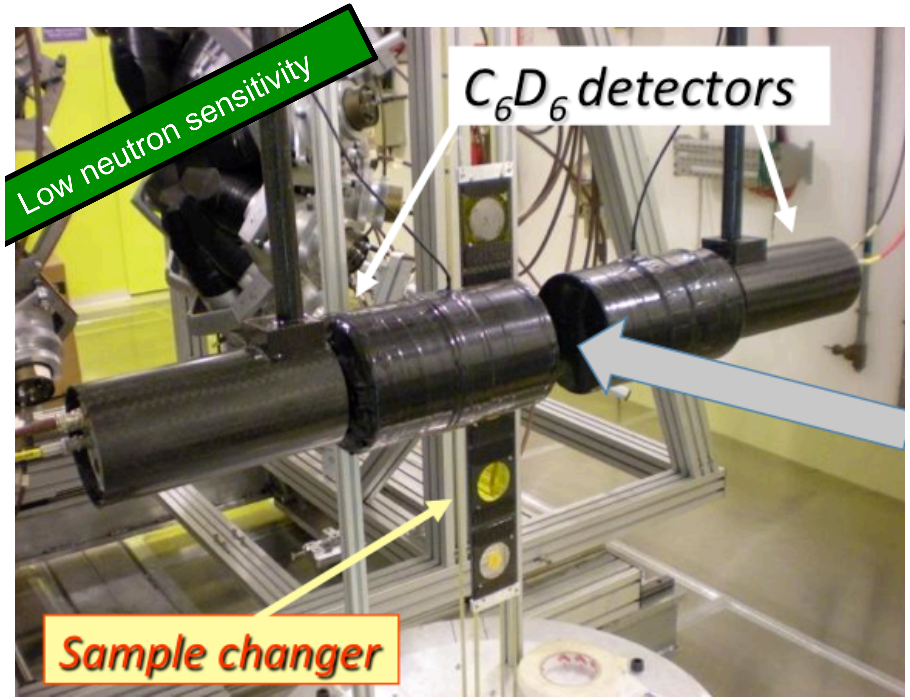
Good energy resolution
$\Delta E/E \sim 10^{-4}$ @ EAR1

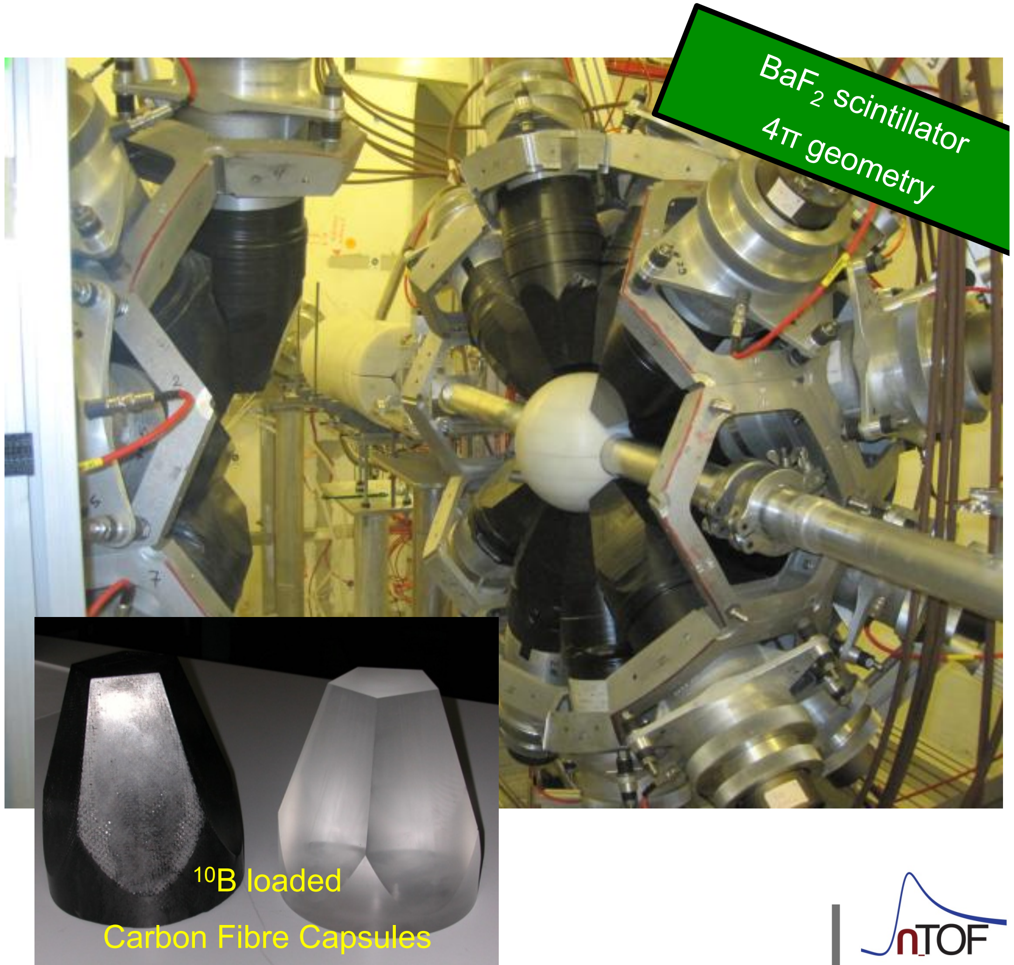
The n_TOF project

Istituto Nazionale di Fisica Nucleare

Detectors: radiative capture

Capture reactions are measured by detecting γ-rays emitted in the de-excitation process. **Two different systems**, to minimize different types of background

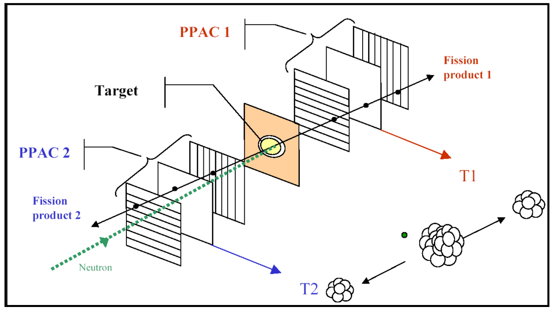




The n_TOF project

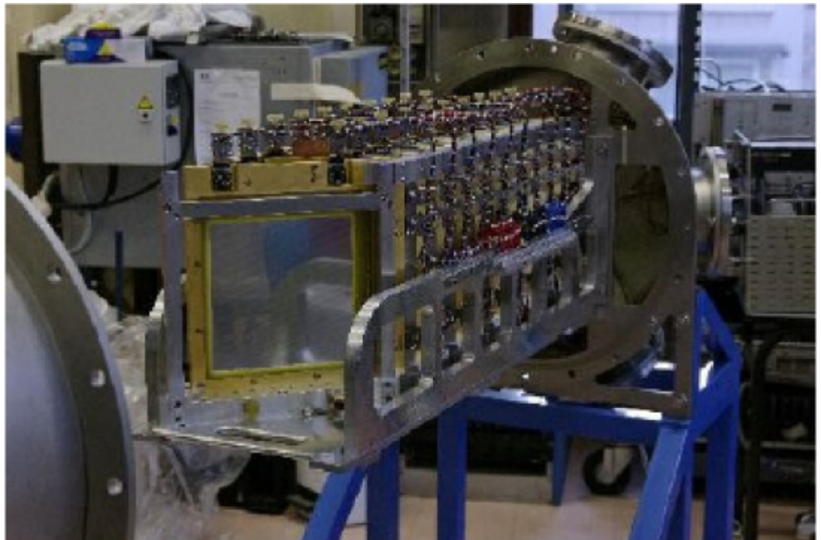
Detectors: fission

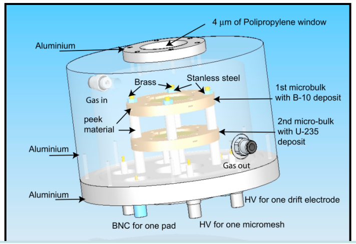
Several systems have been used for detecting fission fragments.
The main **problem** in fission measurements is the **background** due to **α-decay**.

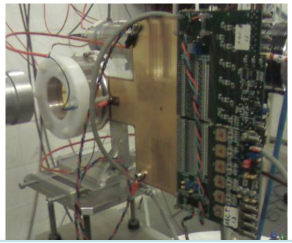


Parallel Plate Avalanche Counters (PPAC)

- Fission fragments detected **in coincidence**
- Very good rejection of α-background

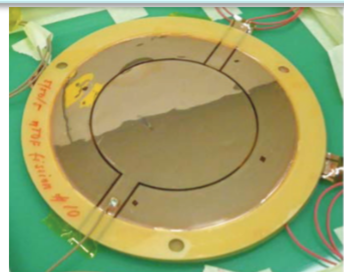


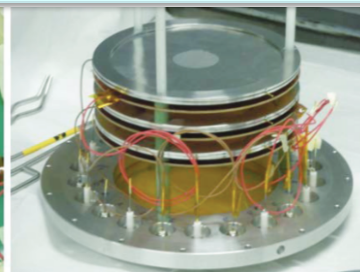




Micromegas chamber

- low-noice, high-gain, radiation-hard detector

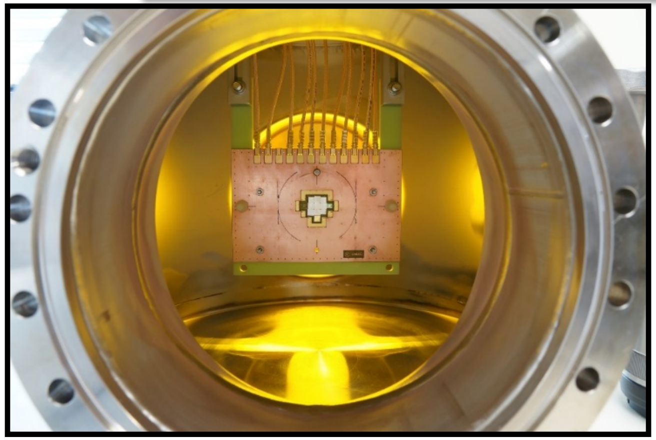




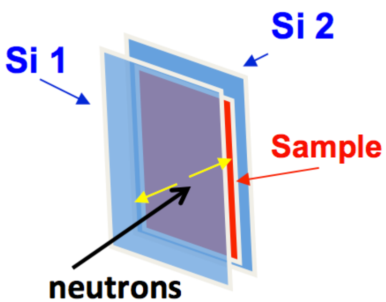
The n_TOF project

Detectors: (n, p) and (n, α) reactions

Gas and solid state detectors are used for detecting charged particles, depending on the energy region of interest and the Q-value of the reaction

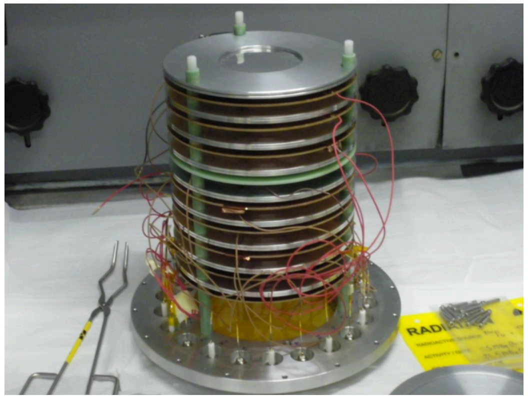


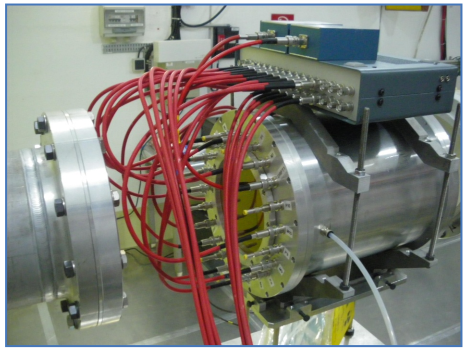
Silicon detectors
Silicon sandwich
Diamond detector
ΔE-E Telescopes



Micromegas chamber

- low-noice, high-gain, radiation-hard detector



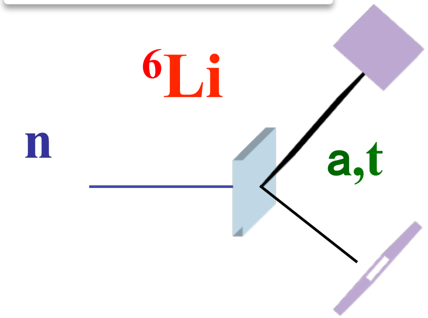


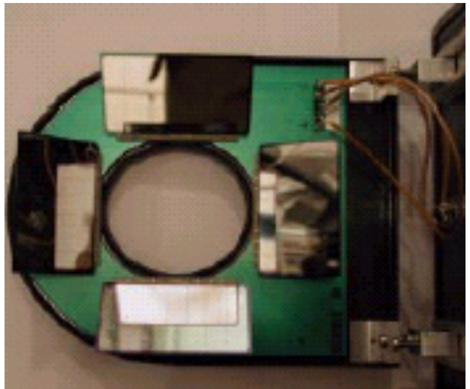
INFN @ n_TOF

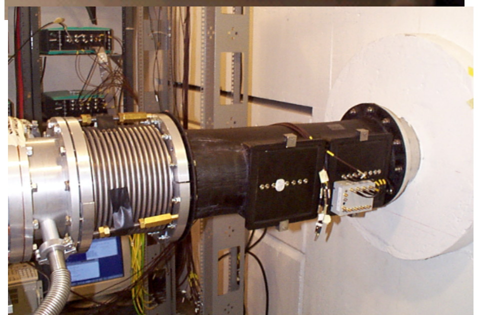
SiMon – EAR1

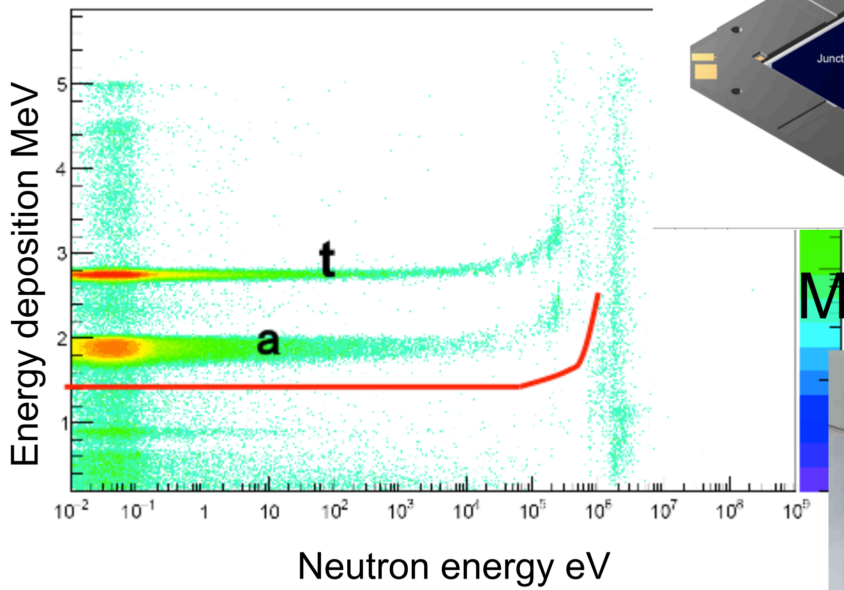
Detector for the neutron flux

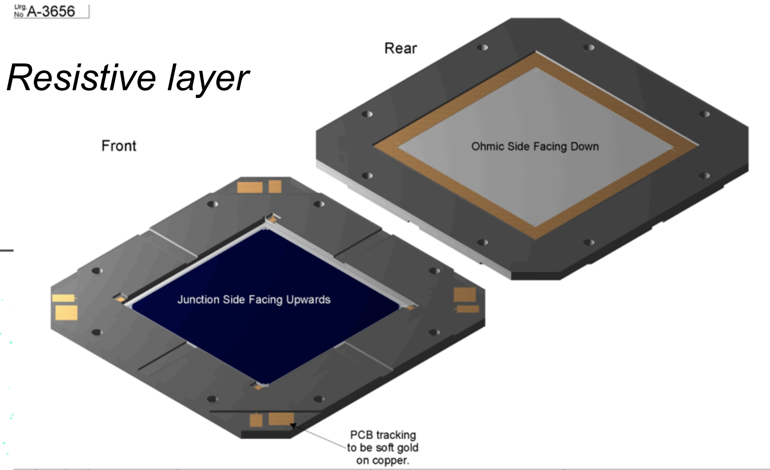
SiMon – EAR2











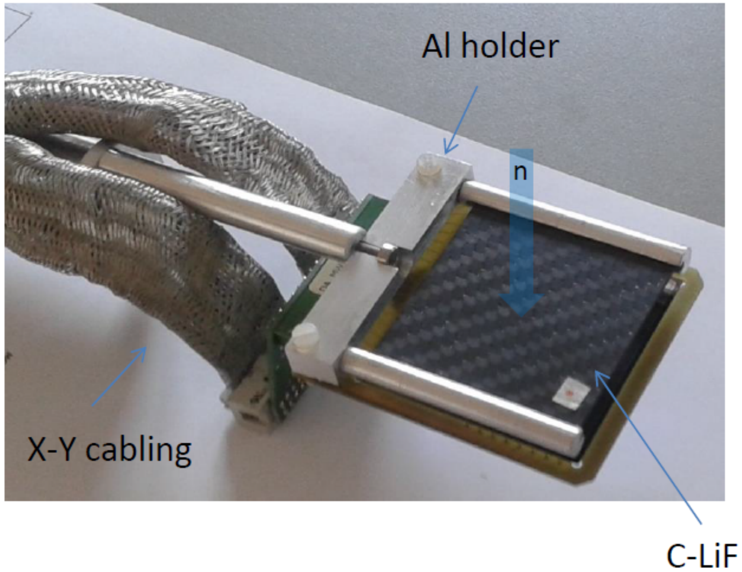
Monitor + profile

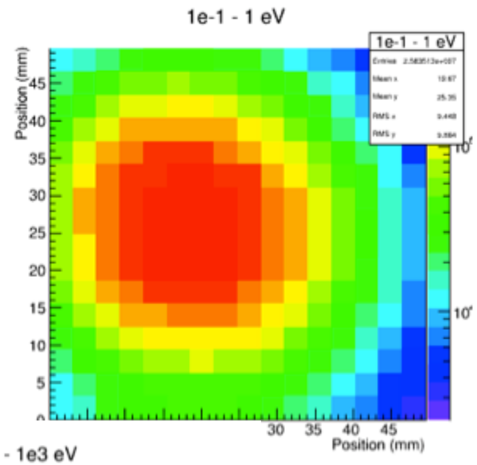
INFN @ n_TOF

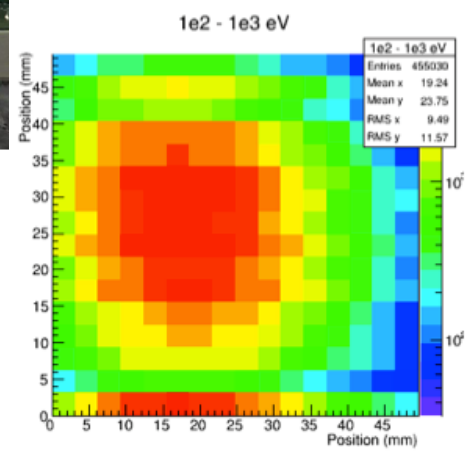
Detector for the neutron flux

The **spatial distribution** of neutrons as a function of energy has been measured by means of a **double side silicon strip detector** (DSSSD).

- 16 x 16 Si sensor strips
- 3 mm wide strips, 500 mm thick
- 50 x 50 mm² X-Y grid
- LiF converter

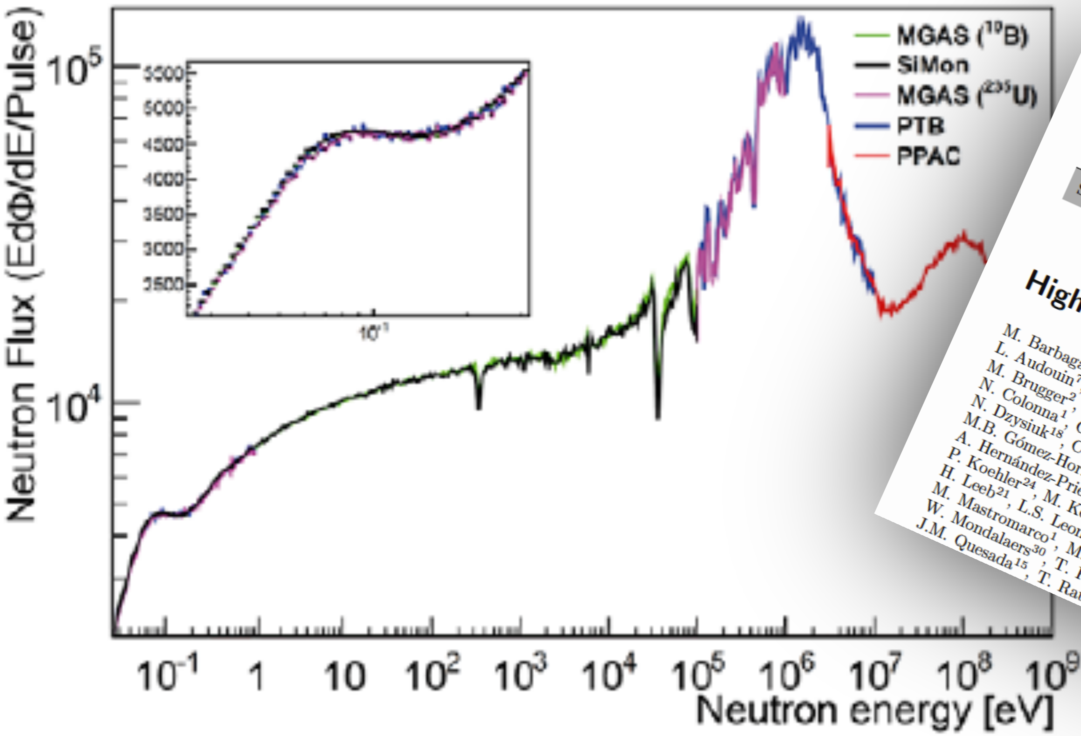


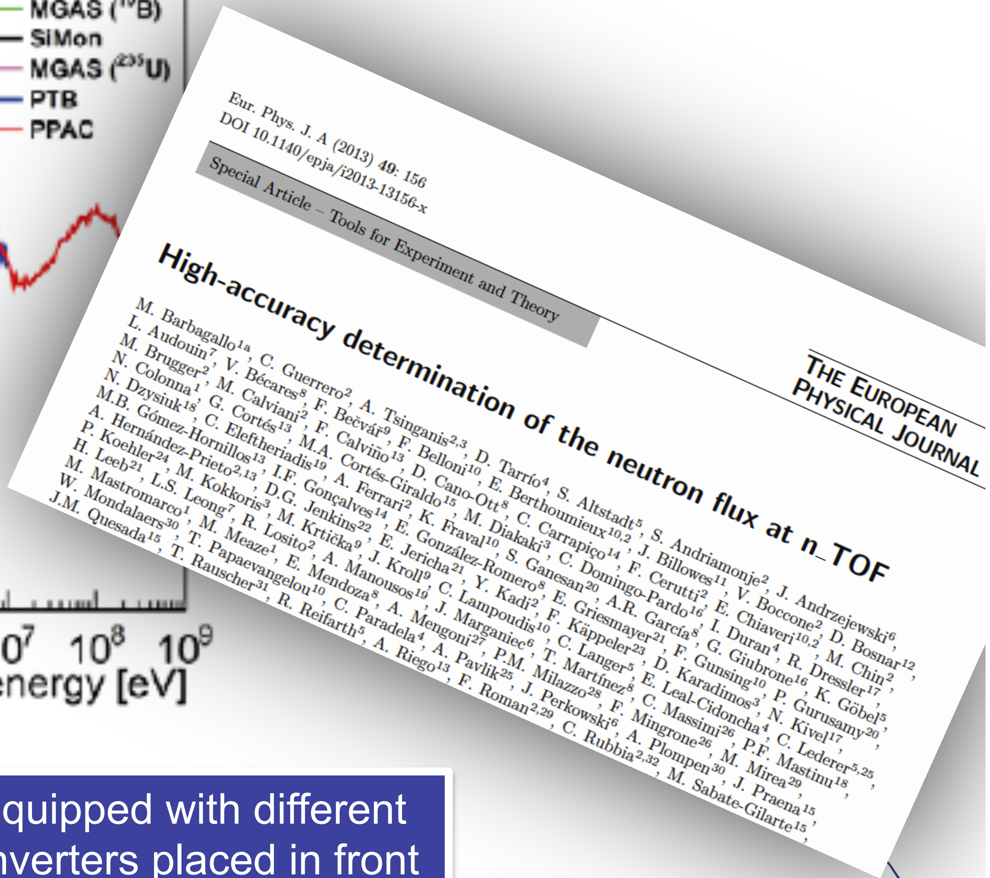




INFN @ n_TOF

Study of the neutron flux





Eur. Phys. J. A (2013) 49: 156
DOI 10.1140/epja/i2013-13156-x

Special Article – Tools for Experiment and Theory

THE EUROPEAN PHYSICAL JOURNAL

High-accuracy determination of the neutron flux at n_TOF

M. Barbagallo[1a], C. Guerrero[2], A. Tsinganis[2,3], D. Tarrío[4], S. Altstadt[5], S. Andriamonje[2], J. Andrzejewski[6], L. Audouin[7], V. Bécares[8], F. Bečvář[9], F. Belloni[10], E. Berthoumieux[10,2], J. Billowes[11], V. Boccone[2], D. Bosnar[12], M. Brugger[2], M. Calviani[2], F. Calviño[13], D. Cano-Ott[8], C. Carrapiço[14], F. Cerutti[2], E. Chiaveri[10,2], M. Chin[2], N. Colonna[1], G. Cortés[13], M.A. Cortés-Giraldo[15], M. Diakaki[3], C. Domingo-Pardo[16], I. Duran[4], R. Dressler[17], N. Dzysiuk[18], C. Eleftheriadis[19], A. Ferrari[2], K. Fraval[10], S. Ganesan[20], A.R. García[8], G. Giubrone[16], K. Göbel[5], M.B. Gómez-Hornillos[13], I.F. Gonçalves[14], E. González-Romero[8], E. Griesmayer[21], C. Guerrero[2], F. Gunsing[10], P. Gurusamy[20], A. Hernández-Prieto[2,13], D.G. Jenkins[22], E. Jericha[21], Y. Kadi[2], F. Käppeler[23], D. Karadimos[3], N. Kivel[17], P. Koehler[24], M. Kokkoris[3], M. Krtička[9], J. Kroll[9], C. Lampoudis[10], C. Langer[5], E. Leal-Cidoncha[4], C. Lederer[5,25], H. Leeb[21], L.S. Leong[7], R. Losito[2], A. Manousos[19], J. Marganiec[6], T. Martínez[8], C. Massimi[26], P.F. Mastinu[18], M. Mastromarco[1], M. Meaze[1], E. Mendoza[8], A. Mengoni[27], P.M. Milazzo[28], F. Mingrone[26], M. Mirea[29], W. Mondalaers[30], T. Papaevangelou[10], C. Paradela[4], A. Pavlik[25], J. Perkowski[6], A. Plompen[30], J. Praena[15], J.M. Quesada[15], T. Rauscher[31], R. Reifarth[5], A. Riego[13], F. Roman[2,29], C. Rubbia[2,32], M. Sabate-Gilarte[15],

Reaction	Energy range of standard
H(n,n)	da 1 keV a 20 MeV
^{3}He(n,t)	da 0.0253 eV a 50 keV
^{6}Li(n,α)	da 0.0253 eV a 1 MeV
^{10}B(n,α)	da 0.0253 eV a 1 MeV
^{197}Au(n,γ)	0.0253 eV e da 0.2 MeV a 2.5 MeV
^{235}U(n,f)	0.0253 eV e da 0.15 MeV a 200 MeV
^{238}U(n,f)	da 2 MeV a 200 MeV

Detectors equipped with different neutron converters placed in front of the sensible layer or volume

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Detector for (n, γ) reaction

n_TOF Internal Report (June 2013)

New C_6D_6 detectors: reduced neutron sensitivity and improved safety

P.F. Mastinu[1], R. Baccomi[2], E. Berthoumieux[3], D. Cano-Ott[4], F. Gramegna[1], C. Guerrero[5], C. Massimi[6], P.M. Milazzo[2], F.Mingrone[6], J. Praena[7], G. Prete[1], A.R. García[4]

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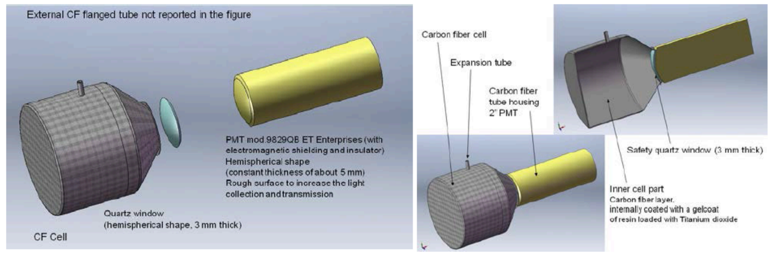
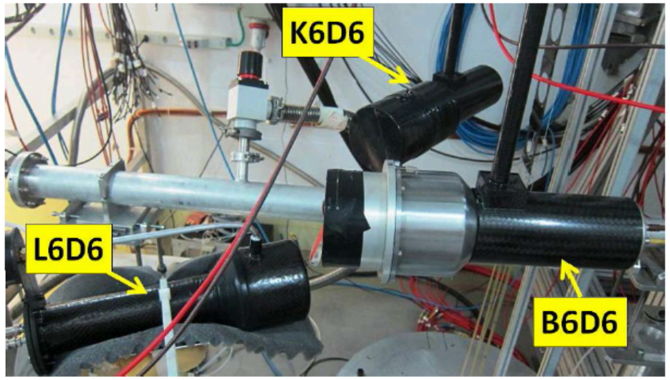
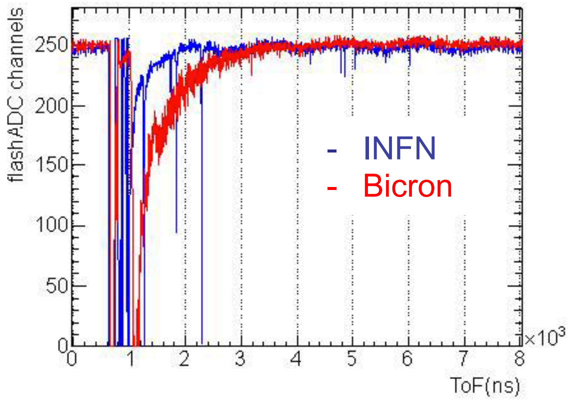
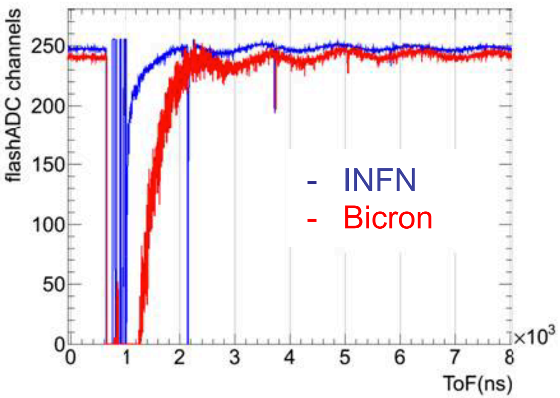
[6] Dipartimento di Fisica e Astronomia, Università di Bologna and Sezione INFN di Bologna, Italy
[7] Universidad de Sevilla, Spain

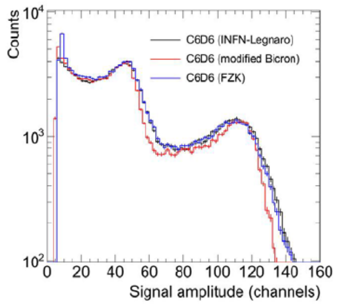
(The n_TOF Collaboration, http://cern.ch/nTOF)











n_TOF

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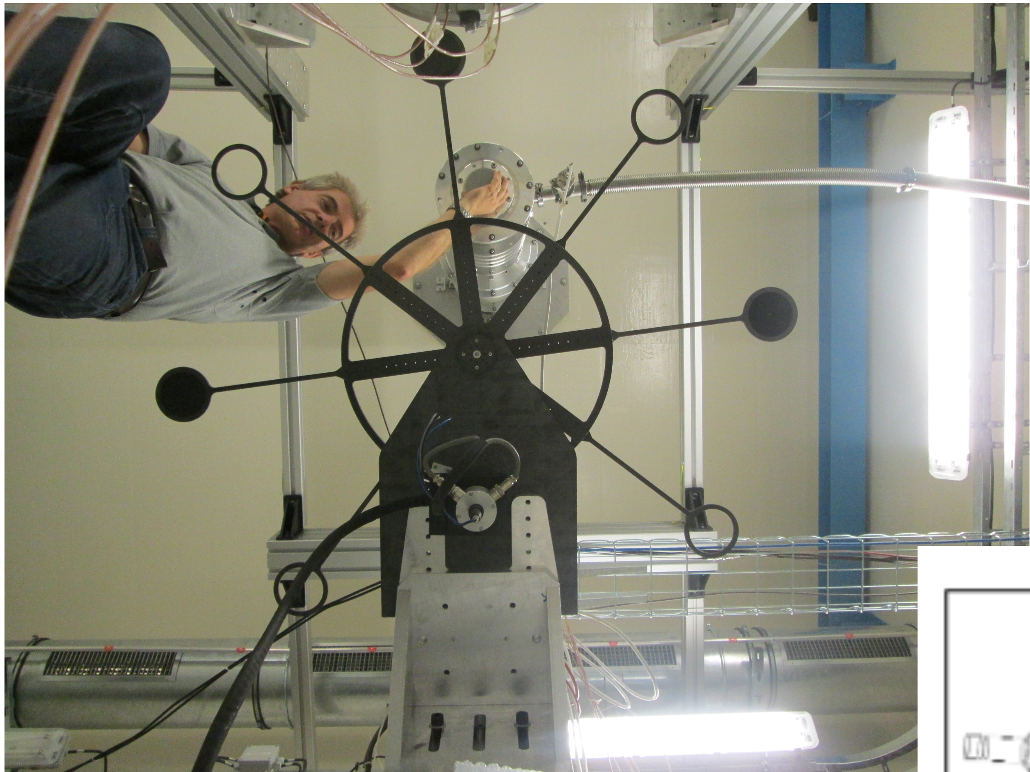
Other in kind contributions

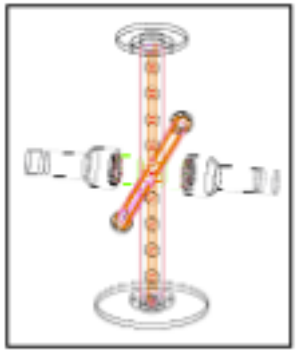
Remote Sample Exchanger

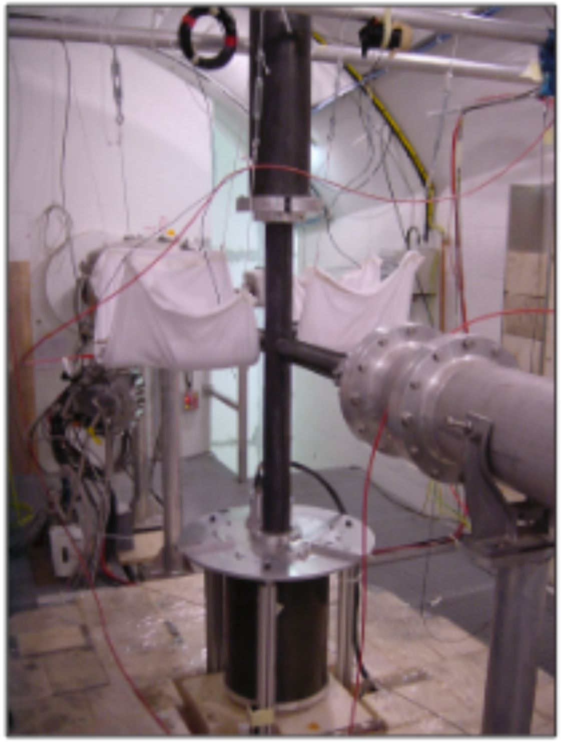
- Mechanical motion
- LabView software



EAR2

EAR1





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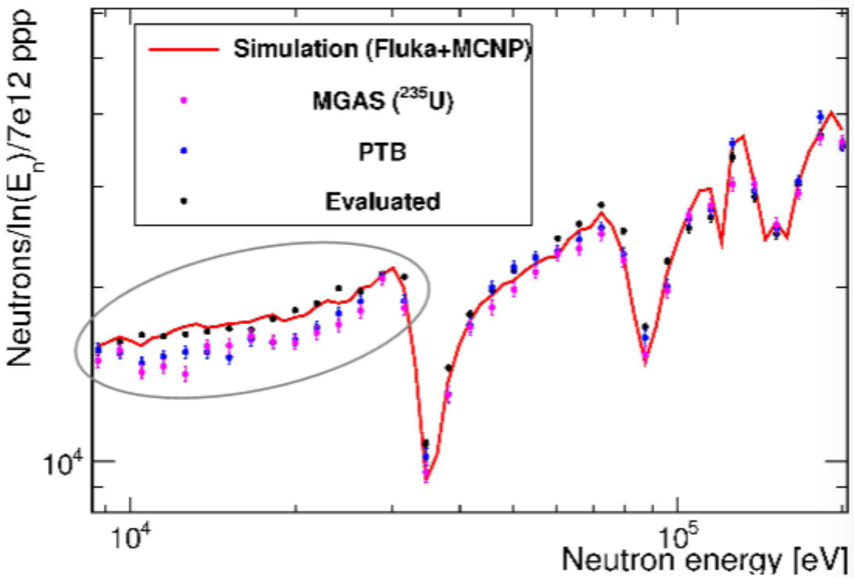
Proposal and realization of experiments



^{235}U(n, f) is considered a well known cross section and is a standard at thermal and from 150 keV to 200 MeV

→ Large deviation observed: $10 < E_n < 40$ keV

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

High accuracy measurement of the ^{235}U(n,f) reaction cross-section in the 10-30 keV neutron energy range

May 26, 2014

M. Barbagallo[1], M. Mastromarco[1], N. Colonna[1], L. Cosentino[2], P. Schillebeeckx[3], E. Berthoumieux[4], P. Finocchiaro[2], A. Musumarra[2], C. Massimi[5], P.M. Milazzo[6] , G. Tagliente[1],J. Andrzejewski[7], A. Tsinganis[8], R. Vlastou[8] and the n_TOF Collaboration[9]

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Spokesperson(s): [M. Barbagallo] (massimo.barbagallo@ba.infn.it)
Technical coordinator: O. Aberle (Oliver.Aberle@cern.ch)

Abstract

The analysis of the neutron flux of n_TOF (in EAR1) revealed an anomaly in the 10-30 keV neutron energy range. While the flux extracted on the basis of the ^{6}Li(n,t)^{4}He and ^{10}B(n,α)^{7}Li reactions mostly agreed with each other and with the results of FLUKA simulations of the neutron beam, the one based on the ^{235}U(n,f) reaction was found to be systematically lower, independently of the detection system used. A possible explanation is that the ^{235}U(n,f) cross-section in that energy region, where in principle should be known with an uncertainty of 1%, may be systematically overestimated. Such a finding, which has a negligible influence on thermal reactors, would be important for future fast critical or subcritical reactors. Furthermore, its interest is more general, since the ^{235}U(n,f) reaction is often used at that energy to determine the neutron flux, or as reference in measurements of fission cross section of other actinides. We propose to perform a high-accuracy, high-resolution measurement of the ^{235}U(n,f) cross section in EAR1@n_TOF, to clarify this issue.

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Istituto Nazionale di Fisica Nucleare

Proposal and realization of experiments

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Measurement of ^{7}Be(n,α)^{4}He and ^{7}Be(n,p)^{7}Li cross sections for the Cosmological Lithium Problem

Request for a test beam at n_TOF and sample preparation at ISOLDE

May 27, 2014

M. Barbagallo[1], A. Musumarra[2], A. Mengoni[3], L. Cosentino[2], P. Finocchiaro[2], N. Colonna[1], D. Schumann[4], R. Dressler[4], S. Lo Meo[3], C. Massimi[5], F. Mingrone[5], J. Andrzejewski[6], J. Praena[7], P. Zugec[8], P.M. Milazzo[9], T. Stora[10], E. Chiaveri[10], M. Calviani[10], C. Lederer[11], the n_TOF collaboration[10]

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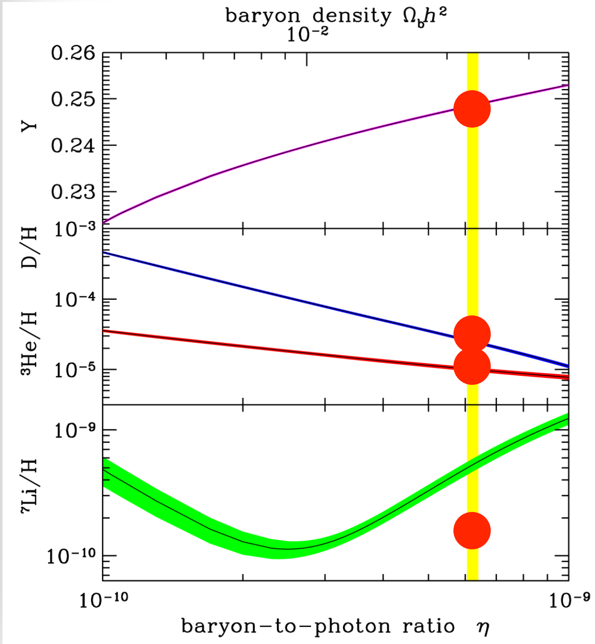
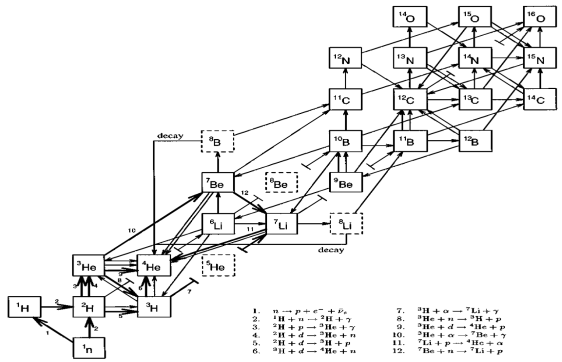
A. Musumarra [musumarra@lns.infn.it]
Technical coordinator: O. Aberle [Oliver.Aberle@cern.ch]

Abstract: We propose to measure in the second experimental area of n_TOF the ^{7}Be(n,α)^{4}He and ^{7}Be(n,p)^{7}Li reaction in a wide energy range. Both reactions are of interest for the long-standing "Cosmological ^{7}Li problem" in Big Bang Nucleosynthesis (BBN).

BBN successfully predicts the abundances of primordial elements such as ^{4}He, D and ^{3}He. Large **discrepancy** for ^{7}**Li**, which is produced from electron capture decay of ^{7}**Be**





~ 95% of ^{7}**Li** is produced by the decay of ^{7}**Be** ($T_{1/2}$=53.2 d)

n_TOF

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Istituto Nazionale di Fisica Nucleare

Proposal and realization of experiments

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Measurement of ^{7}Be(n,α)^{4}He and ^{7}Be(n,p)^{7}Li cross sections for the Cosmological Lithium Problem

Request for a test beam at n_TOF and sample preparation at ISOLDE

May 27, 2014

M. Barbagallo[1], A. Musumarra[2], A. Mengoni[3], L. Cosentino[2], P. Finocchiaro[2], N. Colonna[1], D. Schumann[4], R. Dressler[4], S. Lo Meo[3], C. Massimi[5], F. Mingrone[5], J. Andrzejewski[6], J. Praena[7], P. Zugec[8], P.M. Milazzo[9], T. Stora[10], E. Chiaveri[10], M. Calviani[10], C. Lederer[11], the n_TOF collaboration[10]

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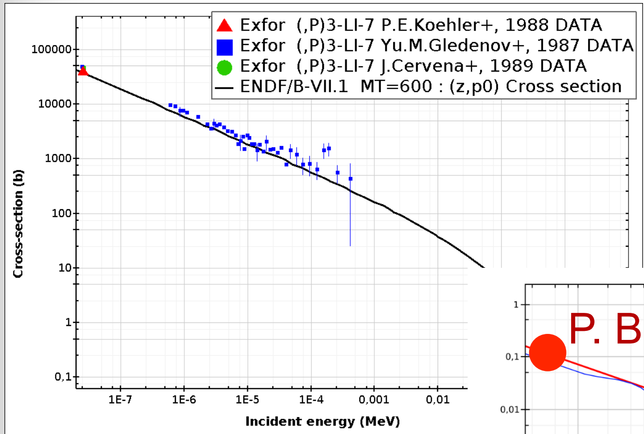
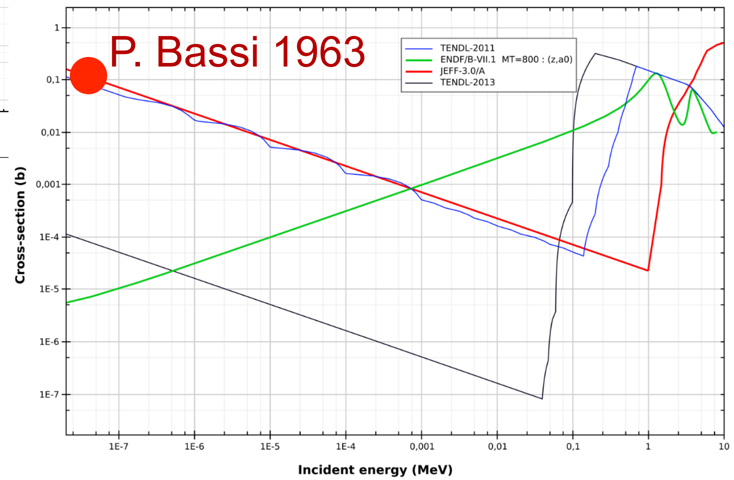
^{7}Be is destroyed by (n, p) (≈97%) and (n, α) (≈2.5%)

With a 10 times higher destruction rate of ^{7}Be the cosmological lithium problem could be solved (nuclear)



^{7}Be(n, p)

^{7}Be(n,α)



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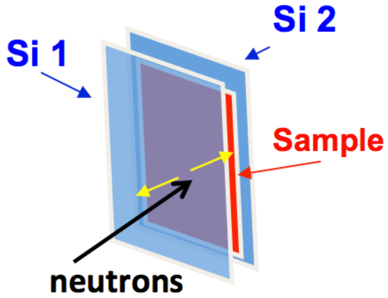
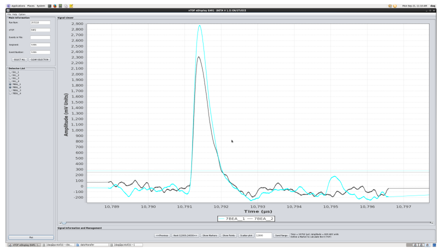
Proposal and realization of experiments

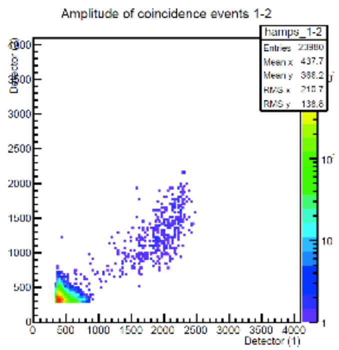
The (n, α) reaction produces **two α-particles** emitted back-to-back with **several MeV energy** (Q-value=19 MeV)

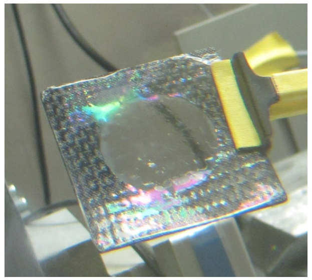
2 Sandwiches of **silicon detector** (140 mm,3x3cm^2) with ^{7}Be sample in between **directly inserted in the neutron beam**

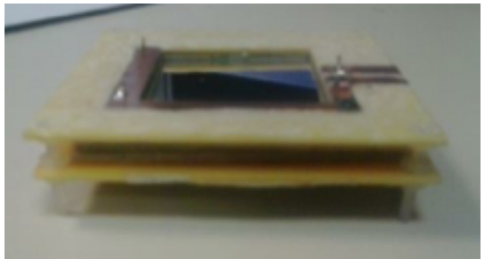
Coincidence technique: strong background rejection

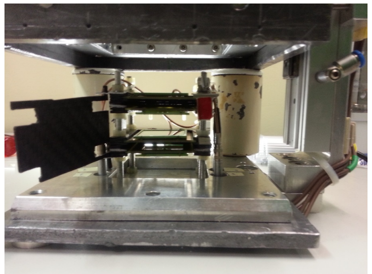


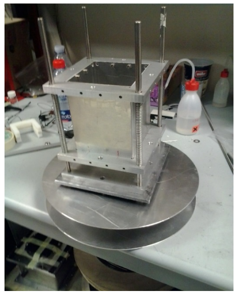


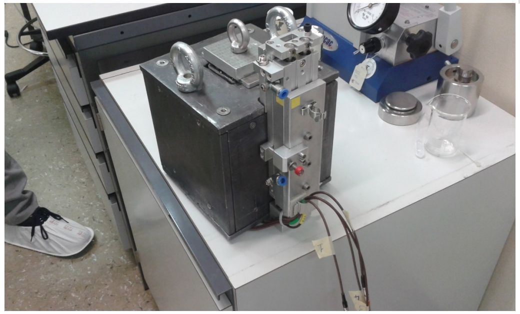












nTOF

INFN @ n_TOF

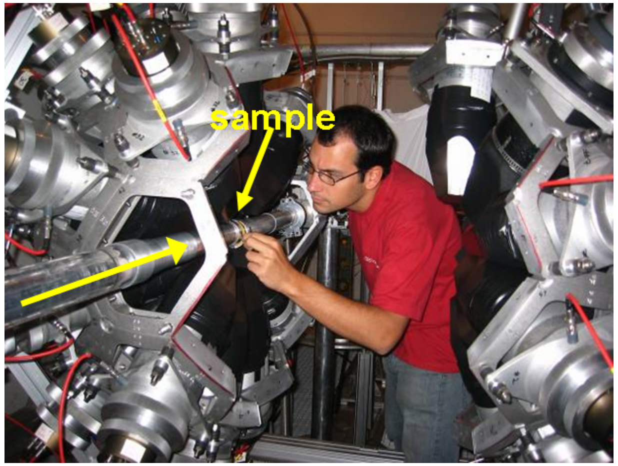
Publications

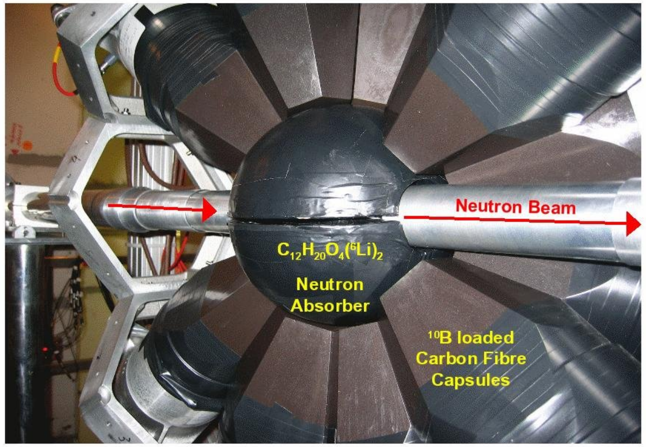
- Physical Review Letter (2) → INFN ½ + ½
- Energy & Environmental Science (1) → INFN 1
- Phisical Review C (33) → INFN 14
- The European Physical Journal A (7) → INFN 4
- Nuclear Instruments and Methods (16) → INFN 8
- Nuclear Data Sheets (20) → INFN 4
- Others (n) → INFN (n/2)
- Proceedings (n^2) → INFN ($n^2/2$)

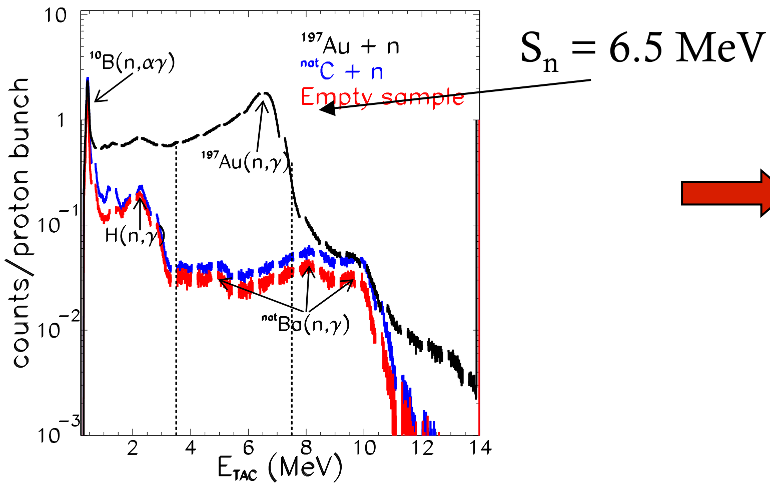
The n_TOF Collaboration ~ 100 researchers
INFN ~ 10 researchers

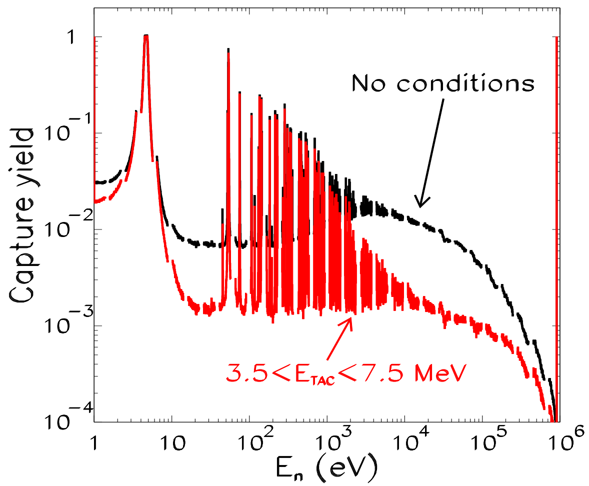
INFN – Bo @ n_TOF

1st publication using the 4π detector: $^{197}Au(n,\gamma)$









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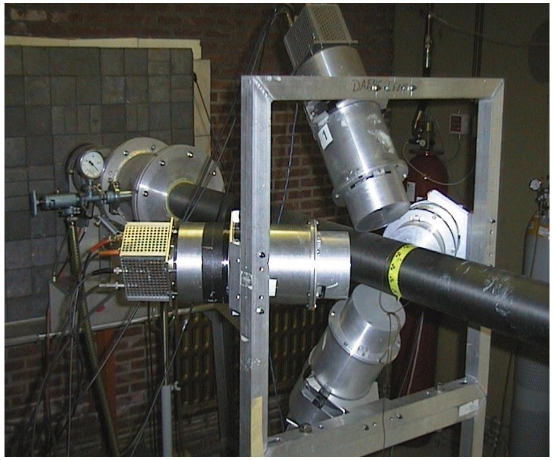
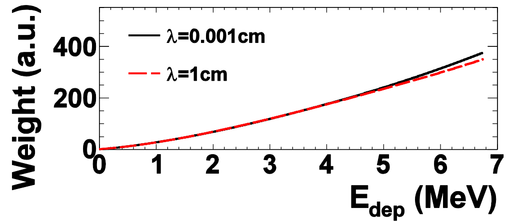
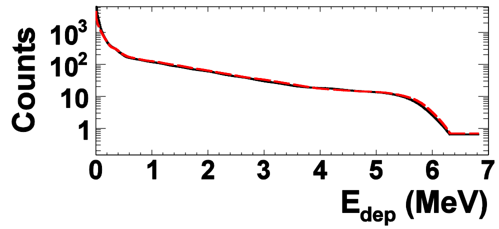
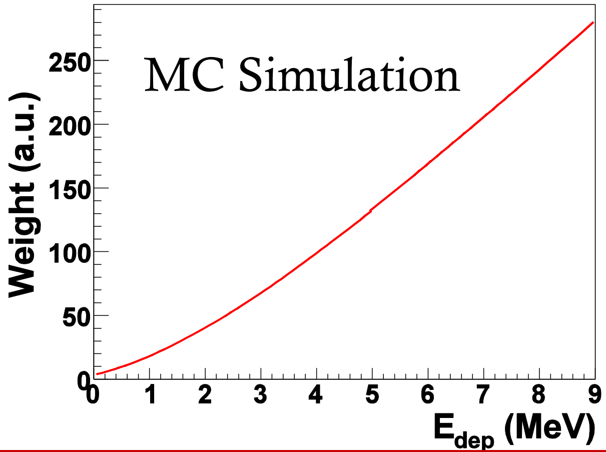
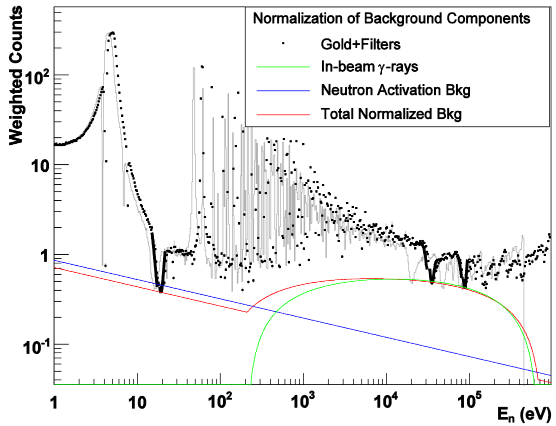
1st comparison using both BaF_2 and C_6D_6: $^{197}Au(n,\gamma)$











INFN – Bo @ n_TOF

Istituto Nazionale di Fisica Nucleare

Reference Cross Section for Astrophysics

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- Mass ... INA,
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Karlsruhe Astrophysical Database of Nucleosynthesis in Stars

s-process [Standards] [Logbook] [FAQ] [Links] [Disclaimer] [Contact] p-process

Available isotopes for Gold (Z=79)

^{197}Au ^{198}Au

Go to isotope [ ] Go!

Recommended MACS30 (Maxwellian Averaged Cross Section @ 30keV)

$$^{197}Au\,(n,\gamma)^{198}Au$$

Total MACS at 30keV: 612.8 ± 7.0 mb

Cross sections do not include stellar enhancement factors!

History

Version	Total MACS [mb]	Partial to gs [mb]	Partial to isomer [mb]
1.0	612.8 ± 7.0	-	-
0.0	582 ± 9	-	-

(Version 0.0 corresponds to Bao et al.)

Comment

Au-197 is used as standard for most astrophysical cross section measurements. Unfortunately, it is at the moment only a standard in the thermal region and between E(n)= 200 keV and 2.8 MeV (au197). Recent measurements at nTOF (CL11, CM10) and GELINA (MBD14) show a discrepancy of about 5% to the previously used standard value at kT= 30 keV from RaK88 and Mac82e.
The new recommended standard cross section for the astrophysical energy region was derived between kT= 5 and 50 keV by the weighted average of the GELINA measurement of MBD14 and the nTOF measurement of CL11,CM10. The uncertainty in this energy range was taken from MBD14. For the energies between kT= 60-100 keV we used the average of the recent libraries (jeff32, jendl40, endfb71) and the uncertainty from the standard deviation given in jeff32 and endfb71.
The previous standard value used for activations with the Li-7(p,n)Be-7 reaction at E(p)= 1912 keV was 586 (9) mb, the so-called "Ratynski value" (RaK88). At this energy the neutrons are collimated in a forward cone of 120 degree opening angle and resemble a quasi-stellar neutron spectrum of kT= 25 keV. With the new results this value would change to 632 (9) mb.

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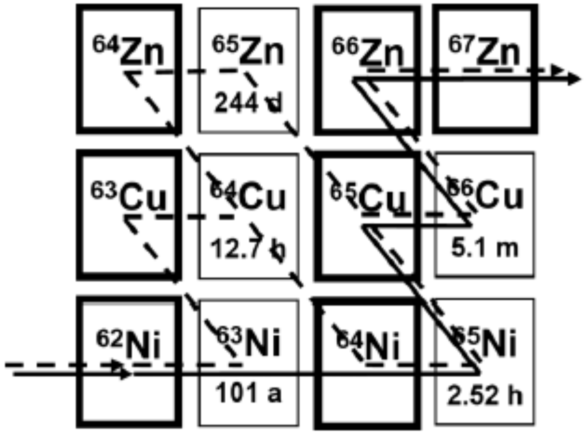
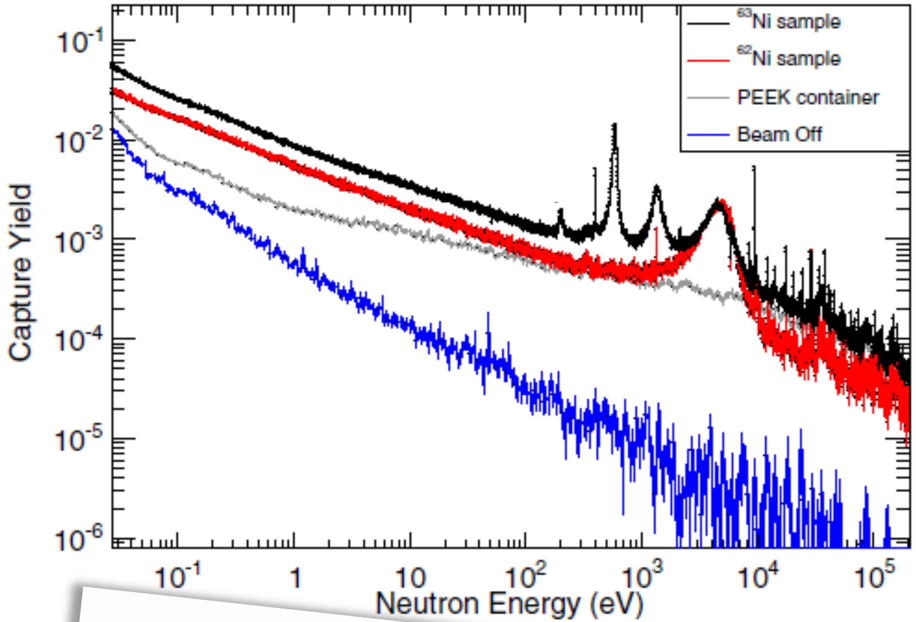


^{63}Ni ($t_{1/2}$=100 y) represents the **first branching point** in the s-process, and determines the **abundance** of **^{63,65}Cu**

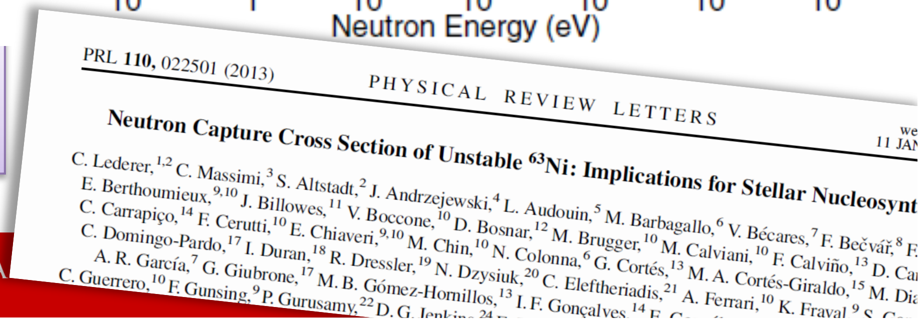
^{62}Ni sample (1g) irradiated **in thermal reactor** (1984 and 1992), leading to enrichment in **^{63}Ni** of **~13 %** (131 mg)

In 2011 ~ **15.4 mg ^{63}Cu** in the sample (from ^{63}Ni decay).

After **chemical** separation at PSI, **^{63}Cu** contamination <**0.01 mg**



First high-resolution measurement of ^{63}Ni(n,g) in the astrophysical energy range.


PRL 110, 022501 (2013) PHYSICAL REVIEW LETTERS

Neutron Capture Cross Section of Unstable ^{63}Ni: Implications for Stellar Nucleosynt

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E. Berthoumieux,[9,10] J. Billowes,[11] V. Boccone,[10] D. Bosnar,[12] M. Brugger,[10] M. Calviani,[10] F. Calviño,[13] D. Ca
C. Carrapiço,[14] F. Cerutti,[10] E. Chiaveri,[9,10] M. Chin,[10] N. Colonna,[6] G. Cortés,[13] M. A. Cortés-Giraldo,[15] M. Di
C. Domingo-Pardo,[17] I. Duran,[18] R. Dressler,[19] N. Dzysiuk,[20] C. Eleftheriadis,[21] A. Ferrari,[10] K. Fraval,[9]
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INFN Istituto Nazionale di Fisica Nucleare

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

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

January 4, 2012

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1. **CONSTRAINTS for ^{22}Ne(α, n)**
   ^{25}Mg: it 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 **J$^{\pi}$** of ^{26}Mg states can be deduced.

2. **NEUTRON POISON: ^{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 (the basic s-process seed for the production of heavy isotopes).

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

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

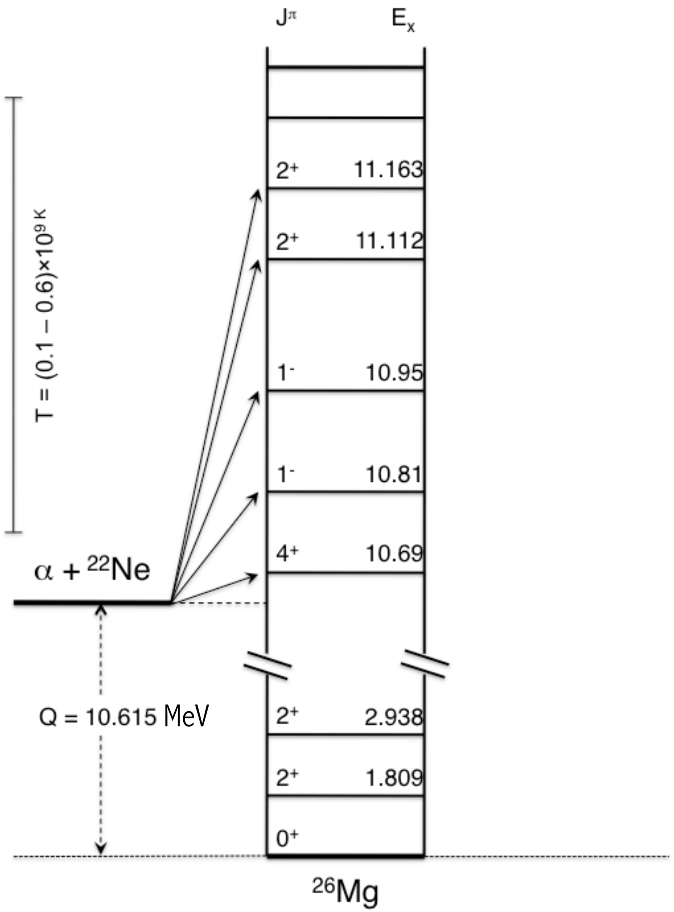
Only **natural-parity states in ^{26}Mg** can participate in the $^{22}Ne(\alpha,n)^{25}Mg$ reaction

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

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

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

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



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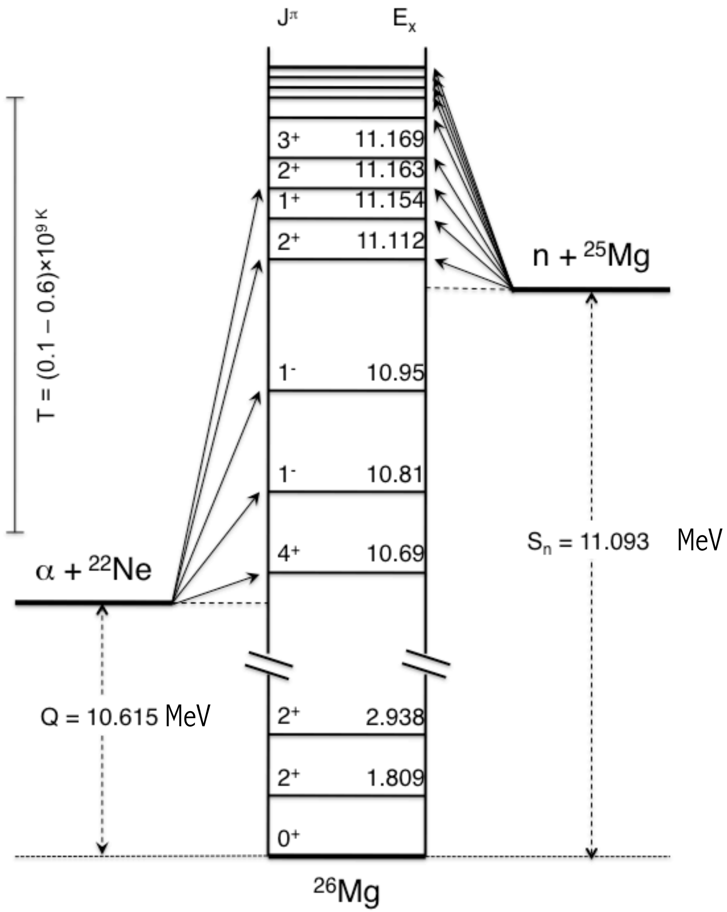
Constraints for the $^{22}Ne(\alpha, n)^{25}Mg$ reaction

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= **<u>2^+</u>**, 3^+

p-wave → J^π= **<u>1^-</u>**, 2^-, **<u>3^-</u>**, 4^-

d-wave → J^π= **<u>0^+</u>**, 1^+, **<u>2^+</u>**, 3^+, **<u>4^+</u>**, 5^+

States in ^{26}Mg populated by ^{25}Mg+n reaction

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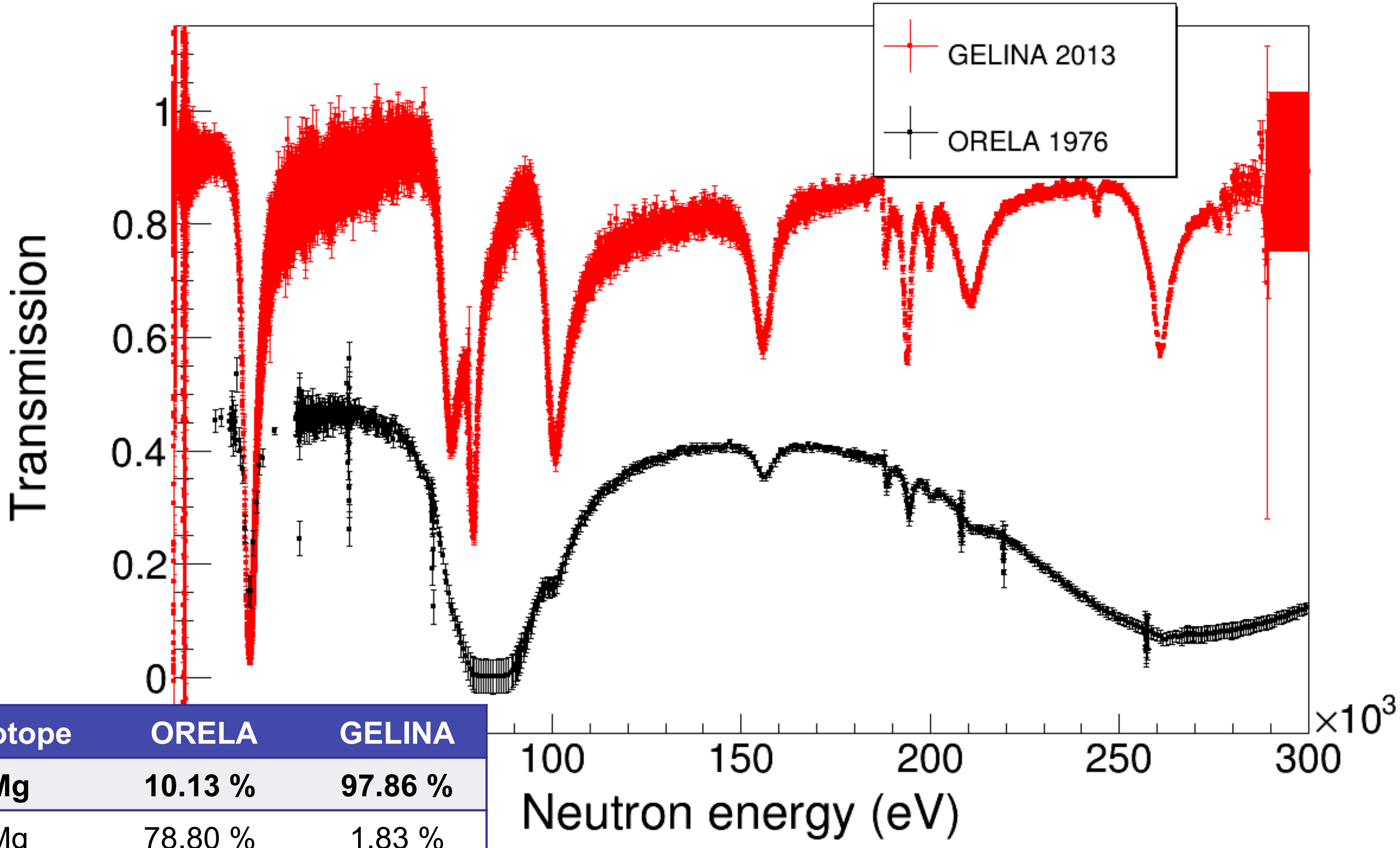

Isotope	ORELA	GELINA
^{25}Mg	**10.13 %**	**97.86 %**
^{24}Mg	78.80 %	1.83 %
^{26}Mg	11.17 %	0.31 %

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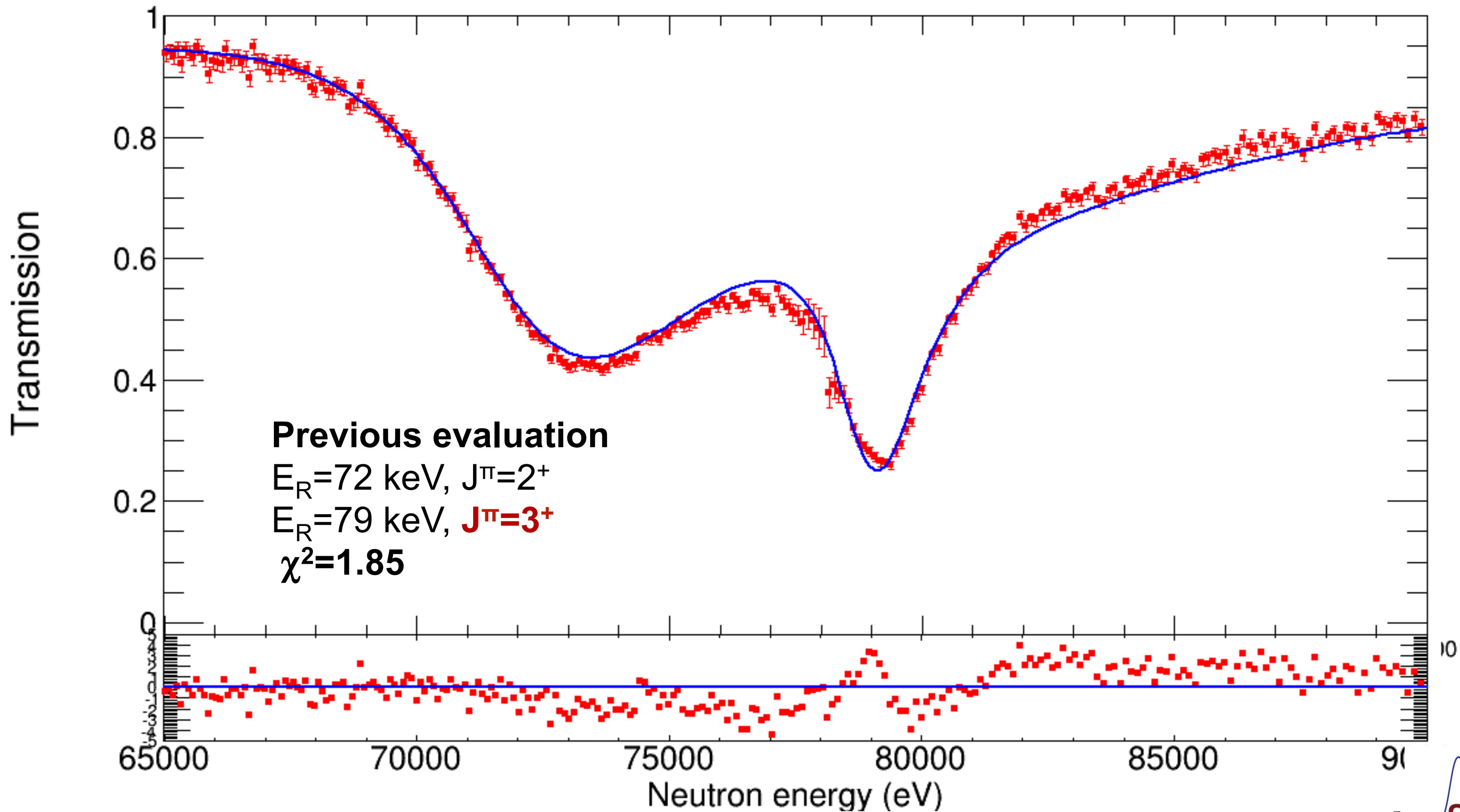

Transmission
Neutron energy (eV)
Previous evaluation
E_R=72 keV, J^π=2+
E_R=79 keV, J^π=3+
χ^2=1.85

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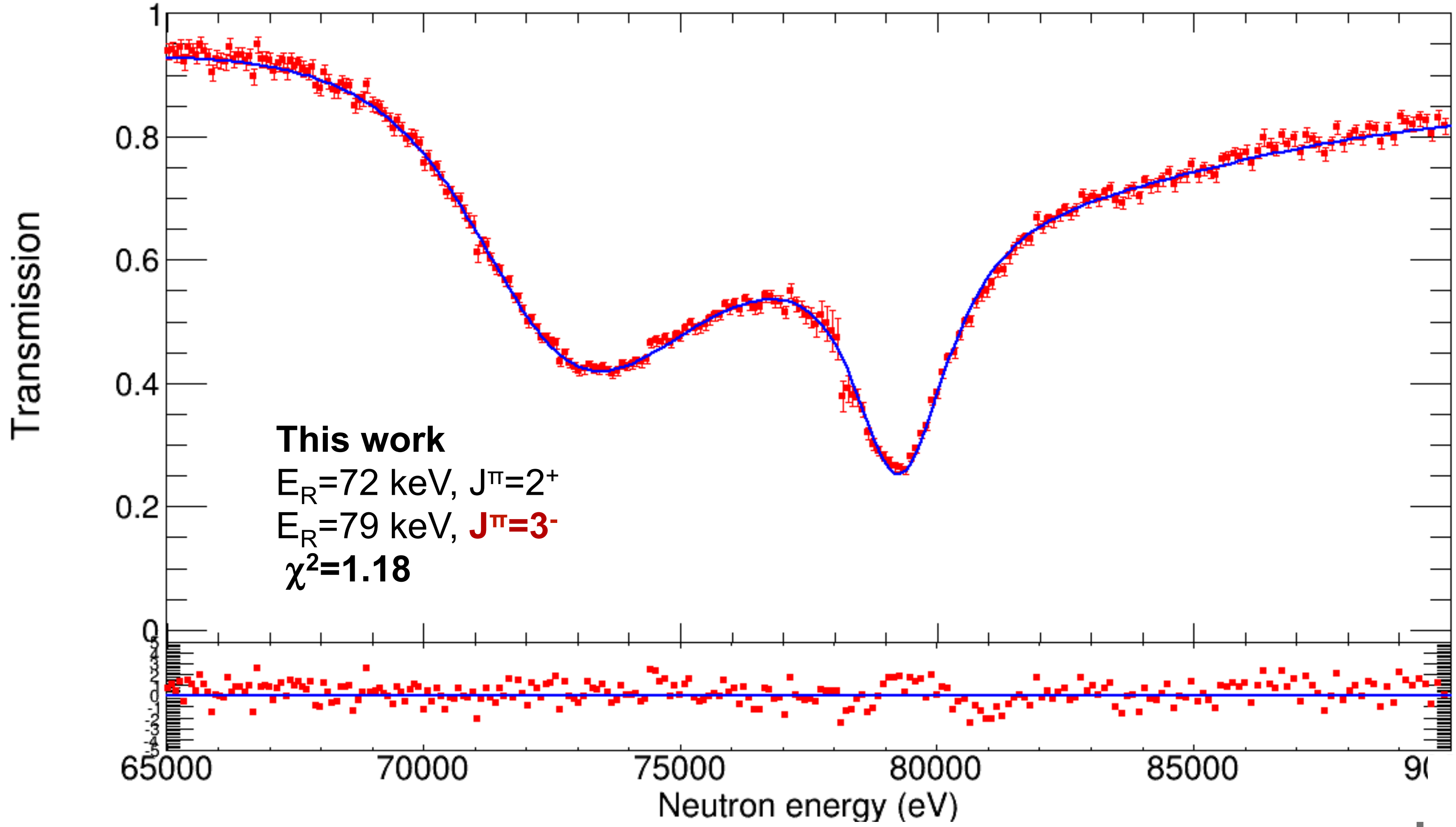
Experimental evidence of natural spin parity



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PhD on $^{238}U(n, \gamma)$

Neutron capture cross section measurement of ^{238}U at the n_TOF CERN facility with C_6D_6 scintillation detectors in the energy region from 1 eV to 700 keV

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L. Audouin,[7] M. Barbagallo,[3] V. Bécares,[8] F. Bečvář,[9] F. Belloni,[10] E. Berthoumieux,[10,11] J. Billowes,[12]
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P. Koehler,[25] M. Kokkoris,[16] M. Krtička,[9] J. Kroll,[9] C. Lampoudis,[10] C. Langer,[5] E. Leal-Cidoncha,[18]
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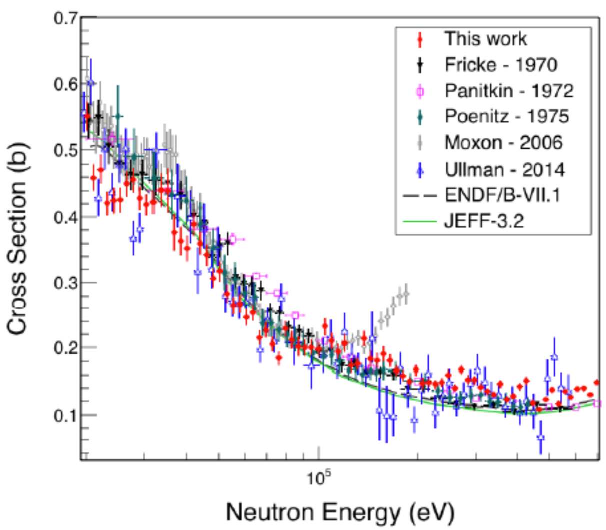
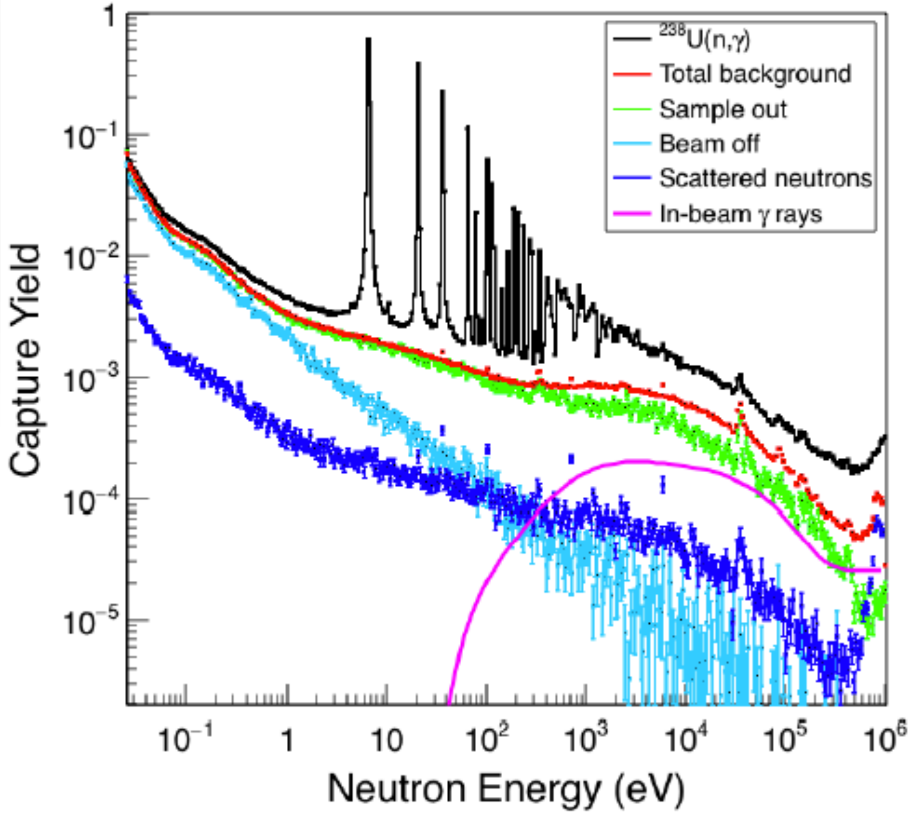
T. Martínez,[8] P.F. Mastinu,[28] M. Mastromarco,[3] E. Mendoza,[8] A. Mengoni,[27] P.M. Milazzo,[29] M. Mirea,[30]
W. Mondalaers,[31] C. Paradela,[18] A. Pavlik,[26] J. Perkowski,[6] A. Plompen,[31] J. Praena,[15] J.M. Quesada,[15]
T. Rauscher,[32] R. Reifarth,[5] A. Riego,[13] M.S. Robles,[18] C. Rubbia,[11,33] M. Sabaté-Gilarte,[15] R. Sarmento,[14]
A. Saxena,[21] P. Schillebeeckx,[31] S. Schmidt,[5] D. Schumann,[19] G. Tagliente,[3] J.L. Tain,[17] D. Tarrío,[18]
L. Tassan-Got,[7] A. Tsinganis,[11] S. Valenta,[9] V. Variale,[3] P. Vaz,[14] A. Ventura,[2] M.J. Vermeulen,[23]
V. Vlachoudis,[11] R. Vlastou,[16] A. Wallner,[26] T. Ware,[12] M. Weigand,[5] C. Weiß,[22] and T. Wright[12]
(The n_TOF Collaboration (www.cern.ch/ntof))





"One of the most accurate measurements and analysis procedure"

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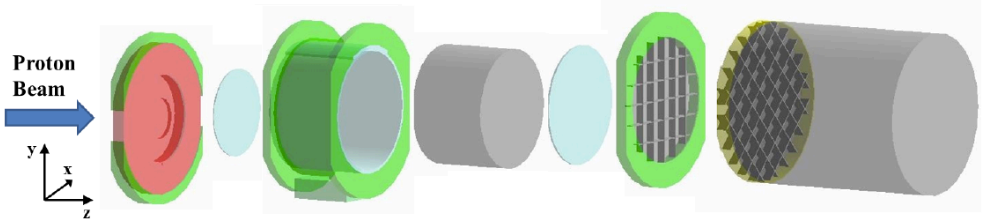
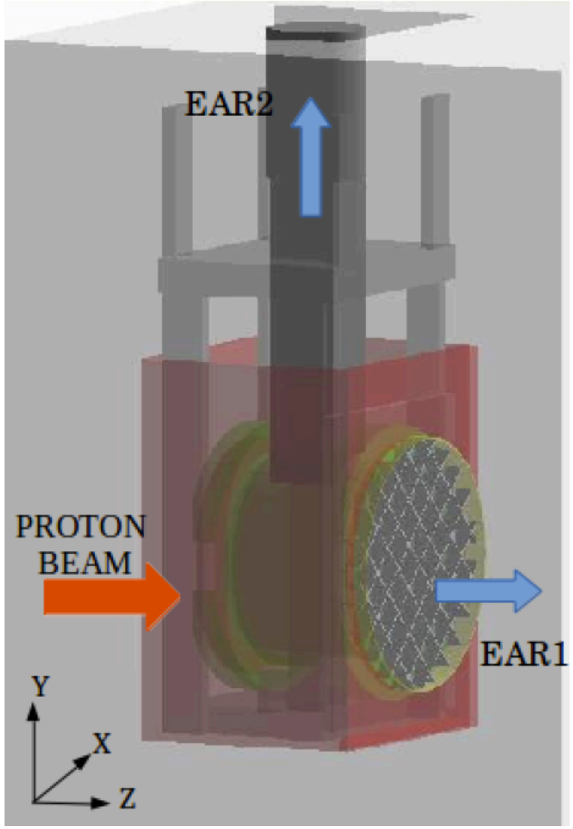
GEANT4 simulation of the n_TOF neutron source



GEOMETRY: spallation target, coolant and moderator systems separated, the support structures and the concrete pit in which it is mounted.

2 SCORING PLANES: towards EAR1 and EAR2 (at the entrance of the beam pipe).

MODERATOR: borated water is made with 4.2% in weight of H_3BO_3, with a ^{10}B enrichment of 90%.



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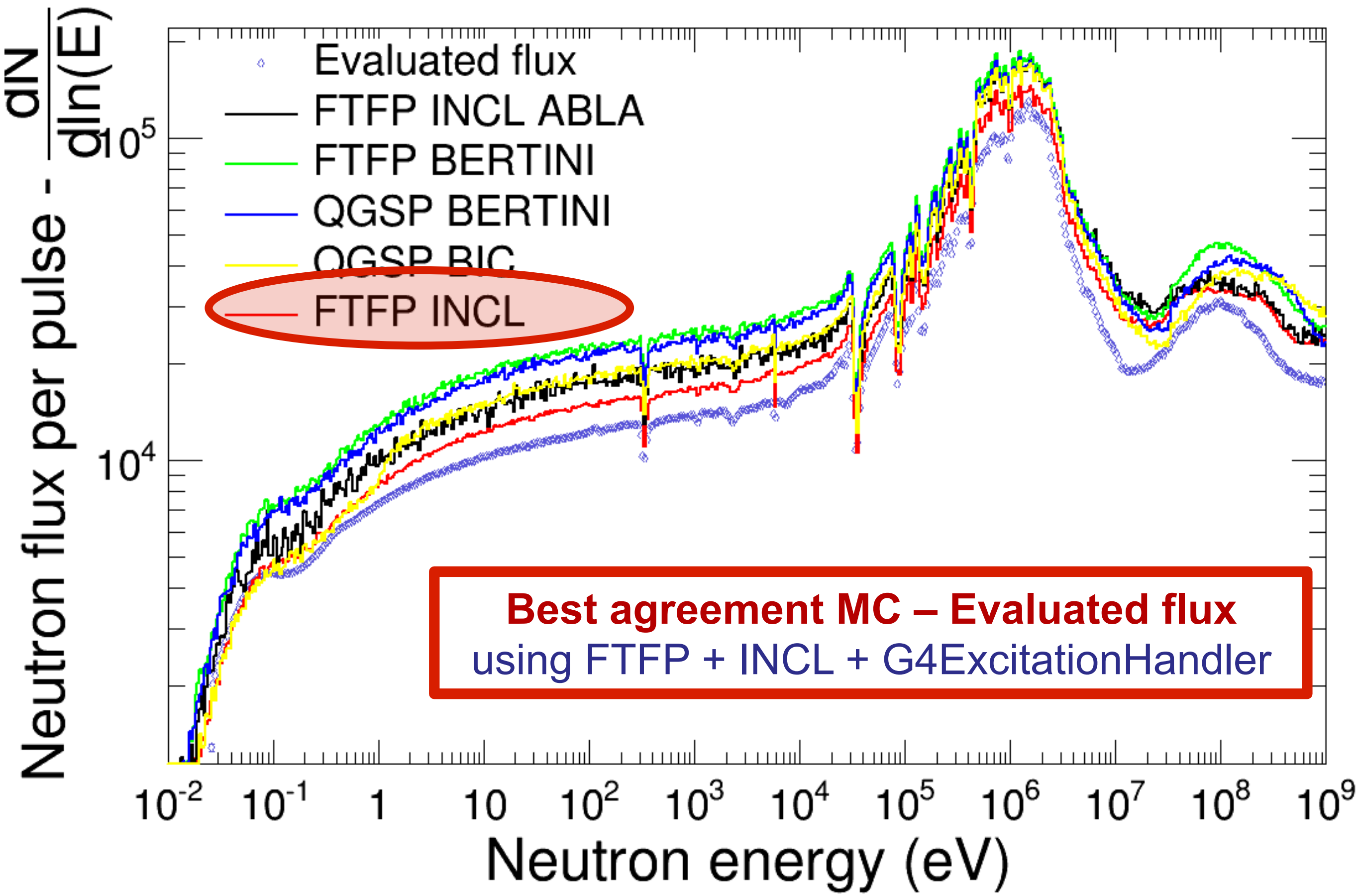
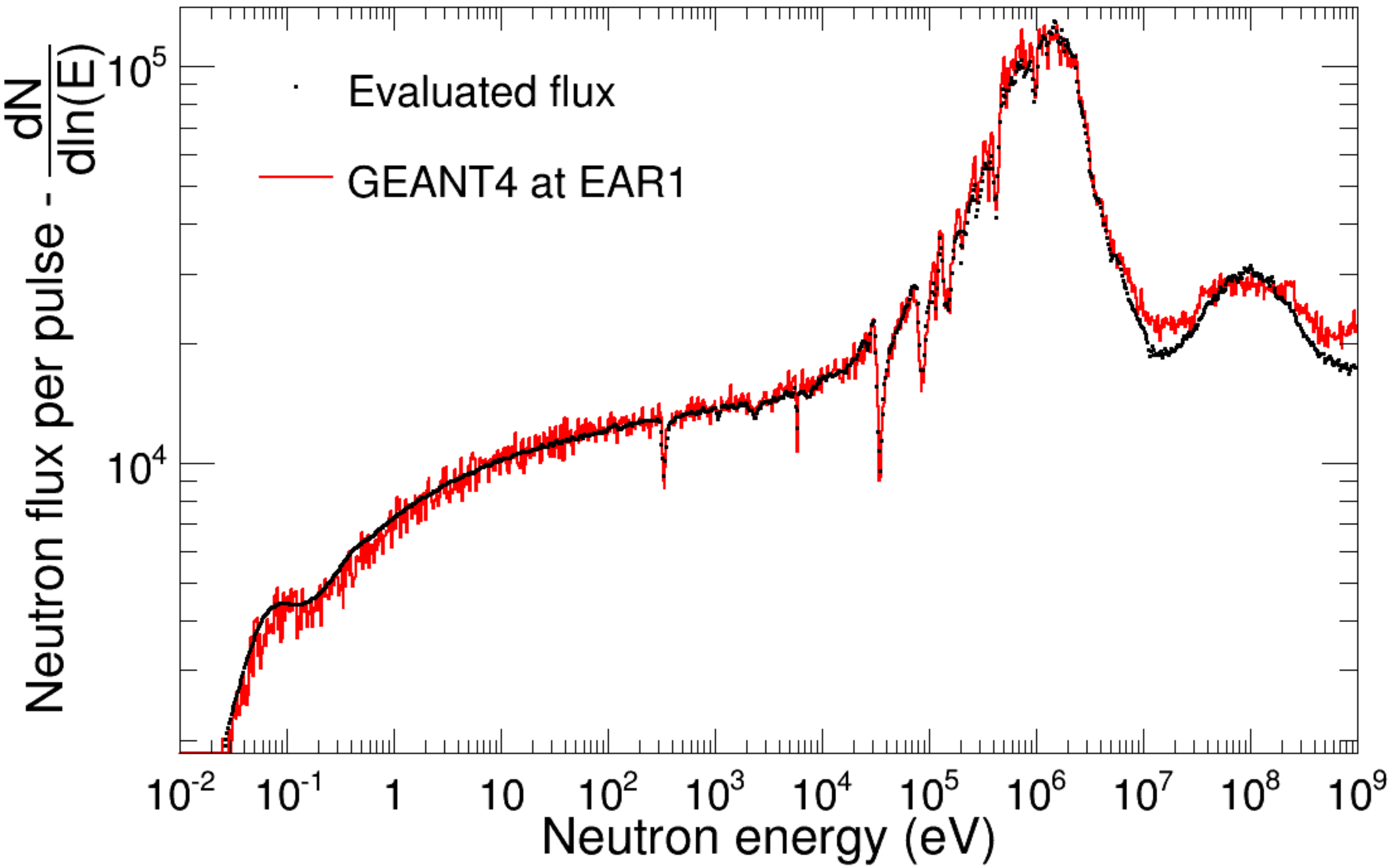
GEANT4 simulation of the n_TOF neutron source



GEANT4 simulation of the n_TOF neutron source



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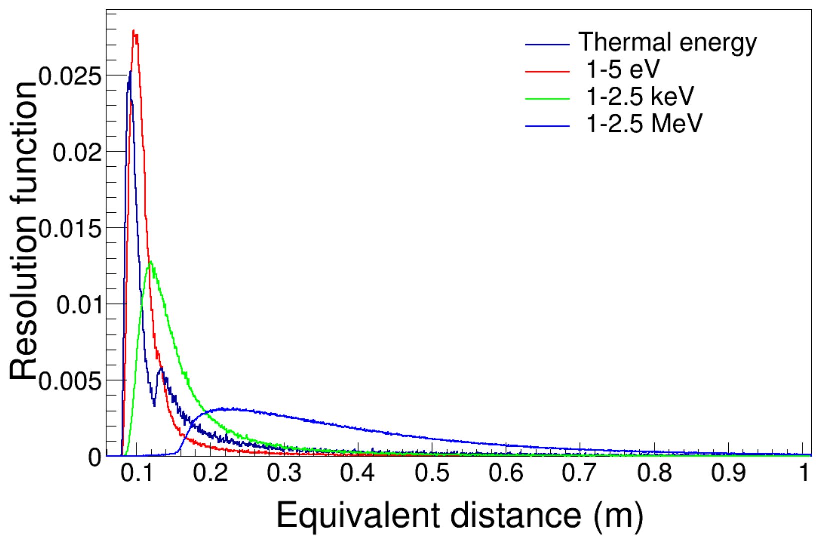
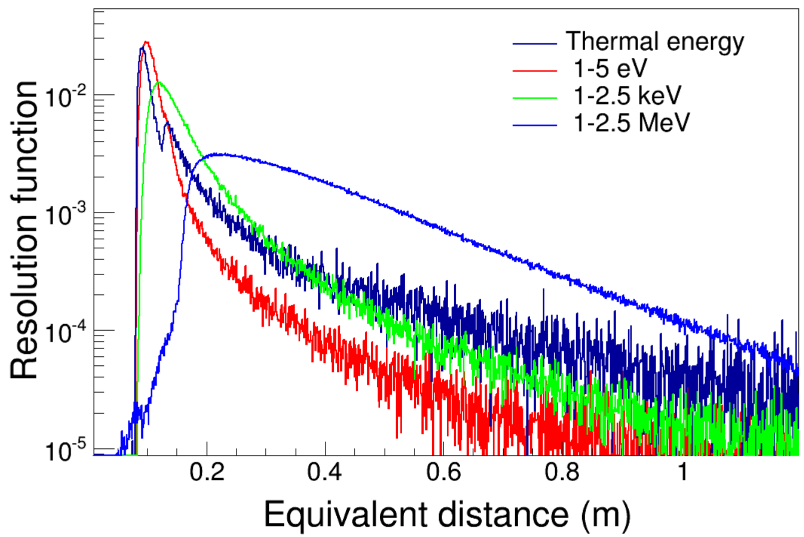
Resolution function, impact on resonances





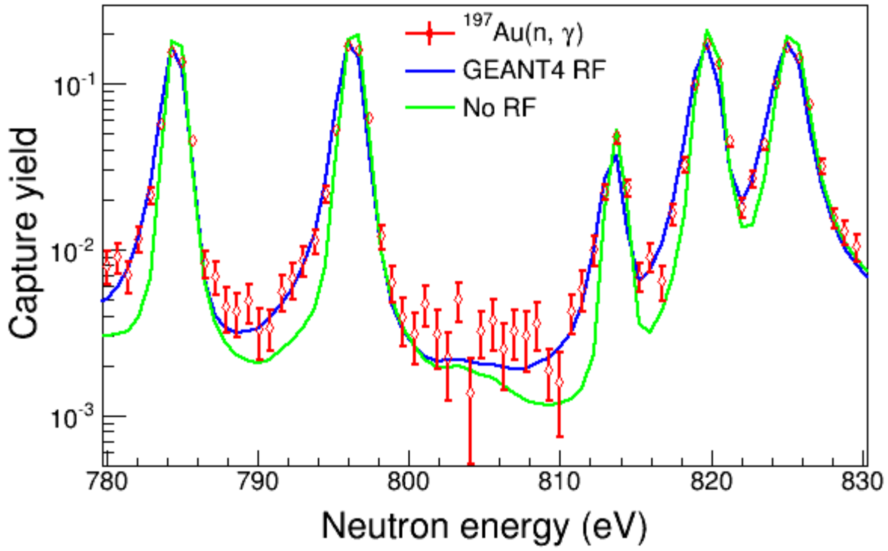
$$\lambda = v t_{\mathrm{mod}}$$

Equivalent distance

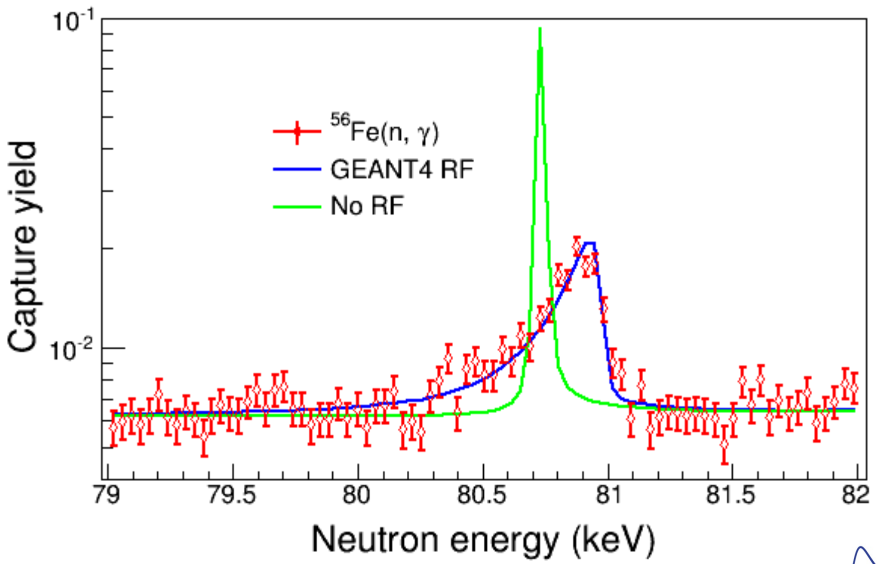
Velocity at the scoring plane

Time spent by the neutron inside the target assembly

Resolution function, impact on resonances

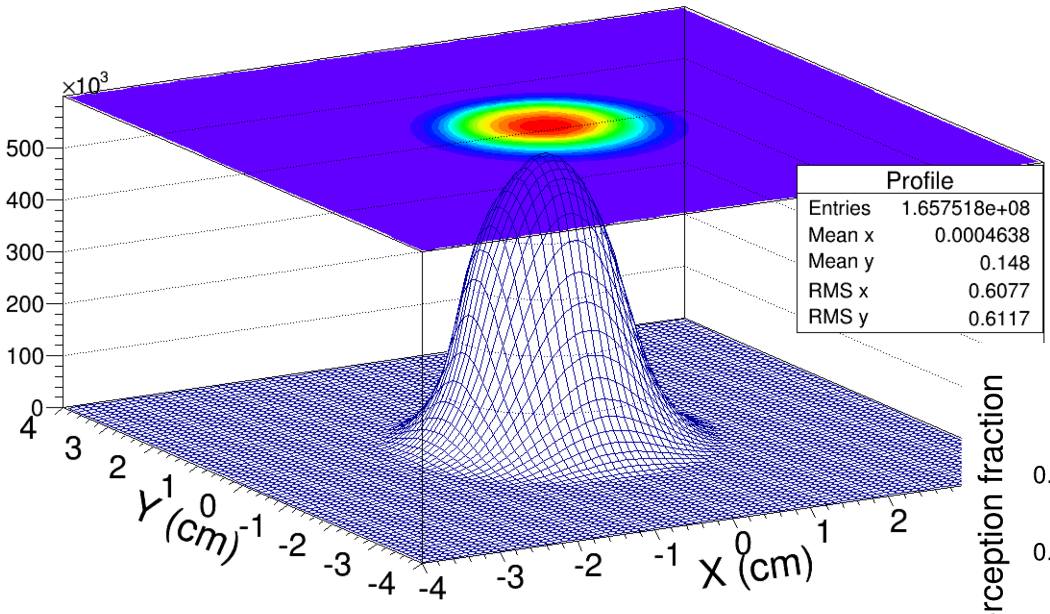


The stochastic process of **moderation** inside the neutron-producing target causes a **broadening of** the **energy** distribution of neutrons reaching the experimental area at a given TOF.

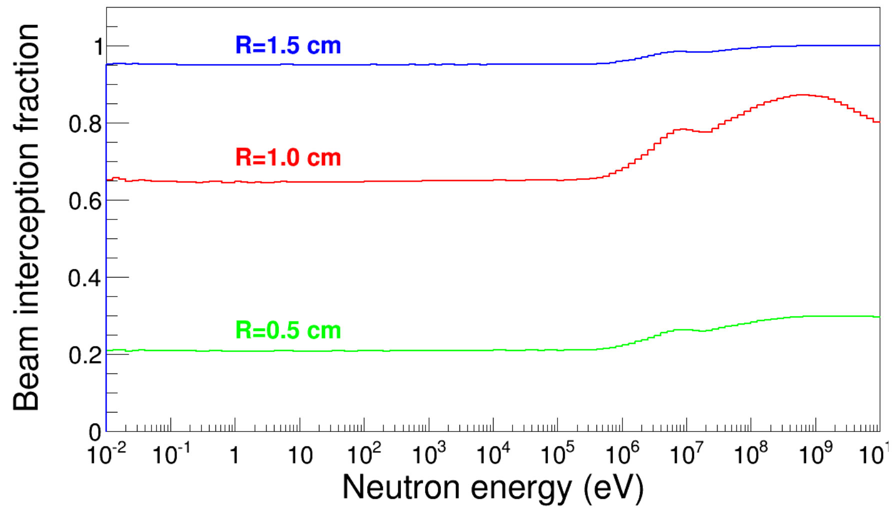


Well-known neutron resonances of ^{197}Au and ^{56}Fe

Beam Profile



at **185.2 m**
Gaussian beam profile
RMS ~ 6 mm



Radius (cm)	BIF at 185.2 m (flat region)	BIF at 185.2 m (E_n=1 MeV)
0.5	0.21	0.22
1.0	0.65	0.68
1.5	0.95	0.96

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Proposals for experiments in the next year …

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Measurement of the neutron capture cross section for ^{155}Gd and ^{157}Gd for Nuclear Technology

May 5, 2015

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Technical coordinator:
Oliver Aberle (oliver.aberle@cern.ch)

Abstract: We propose to measure the neutron capture cross-section of ^{155}Gd and ^{157}Gd from thermal to 1 MeV neutron energy. The main motivation is related to the need of accurate data for applications to nuclear reactors, but new data could also be useful for recent developments in Neutron Capture Therapy, and for new detector concepts in neutrino research. The measurement should be performed in EAR-1 with cutting edge C_6D_6 detectors specifically designed for n_TOF. Since the cross section of these two isotopes changes by orders of magnitude as a function of neutron energy, two highly-enriched samples for each isotope will be measured: a very thin one up to 100 meV, and a thicker one for cross section determination above 100 meV.

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Measurement of the neutron capture cross section of gadolinium even isotopes relevant to Nuclear Astrophysics

May 5, 2015

Cristian Massimi[1,2], Federica Mingrone[1], Sergio Cristallo[3], Donato Maurizio Castelluccio[1,4], Nicola Colonna[5], Sergio Lo Meo[1,4], Gianni Vannini[1,2]

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Abstract:

We propose to measure the neutron capture cross-section of the stable isotopes ^{152}Gd, ^{154}Gd, ^{156}Gd, ^{158}Gd and ^{160}Gd. This experiment aims at the improvement of existing data of interest for nuclear astrophysics. The measurement will be carried out under similar conditions of previous measurements successfully completed at n_TOF with an optimized detection set-up: a cutting edge detector especially designed for accurate (n,γ) measurement will be exploited in combination with a series of isotopically enriched samples. Concerning the correction related to isotopic impurities, we count on taking advantage of the result of the measurement on the ^{155}Gd(n, γ) and ^{157}Gd(n, γ), subject of a different proposal.

n_TOF

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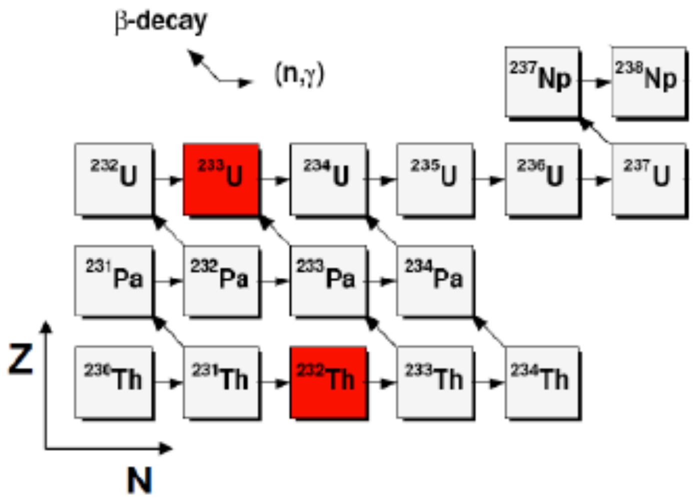
Th/U fuel cycle

$$^{232}\mathrm{Th} + \mathrm{n} \longrightarrow {}^{233}\mathrm{Th} \xrightarrow{\beta^-\ (22\ min)} {}^{233}\mathrm{Pa} \xrightarrow{\beta^-\ (27\ d)} {}^{233}\mathrm{U}$$



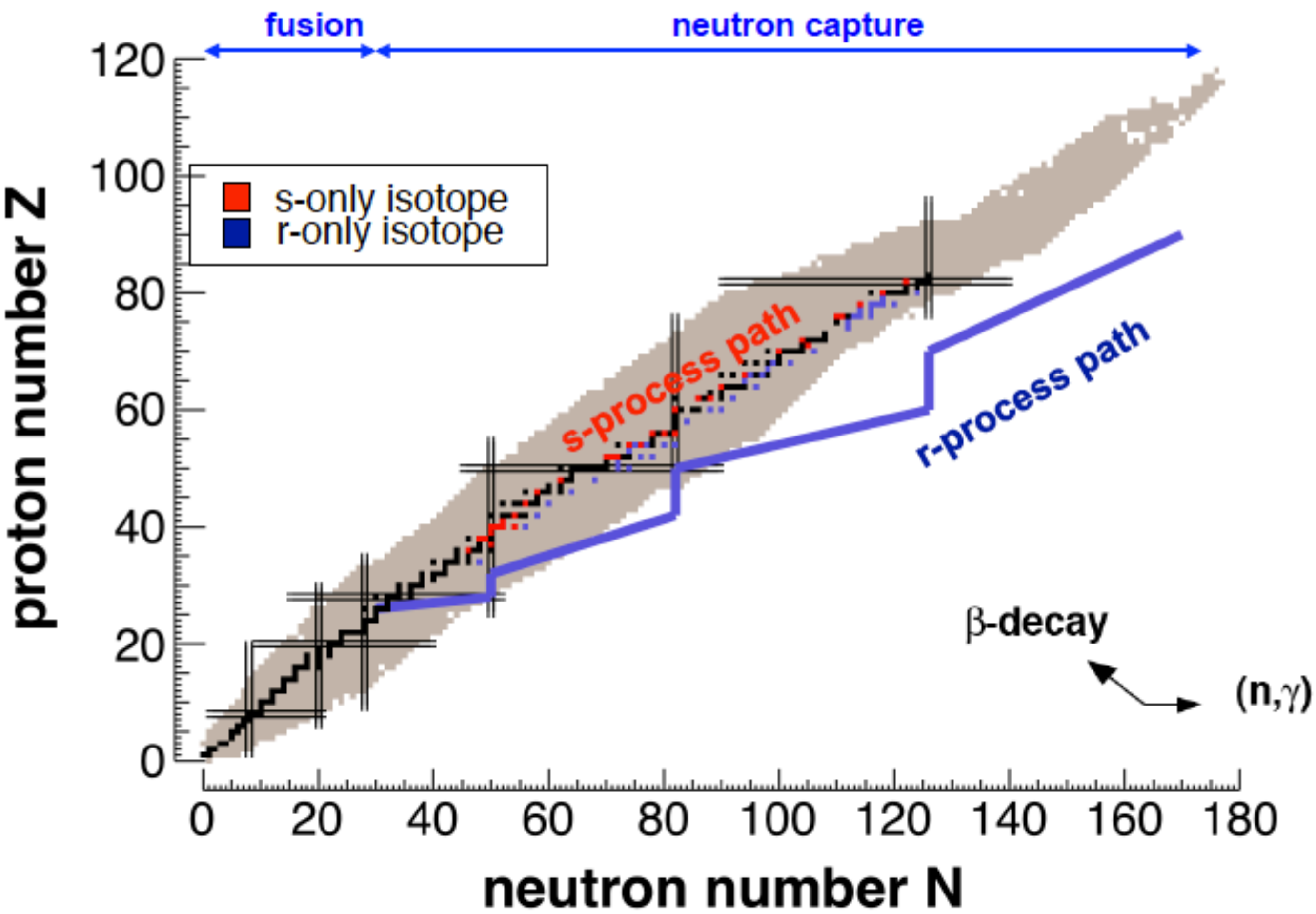
Il ^{232}Th è l'isotopo **fertile**: a seguito della cattura neutronica (e successivi decadimenti β), produce il ^{233}U, **isotopo fissile**.

Necessarie sezioni d'urto accurate su ^{232}Th(n,γ) e ^{233}U(n,f), ma non solo.

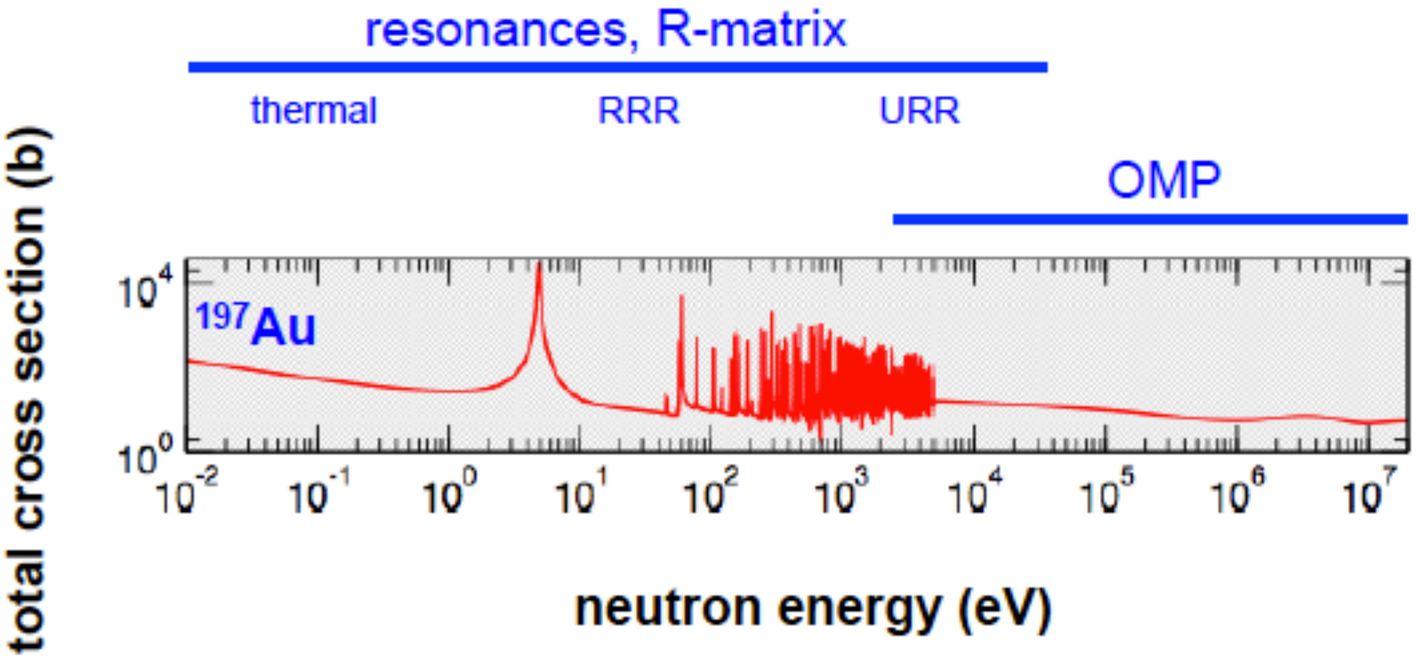
Importante le sezioni d'urto di cattura e fissione del ^{233}Pa, molto difficile da misurare direttamente.

s- and r- process

Stellar nucleosynthesis (s-, r-process)



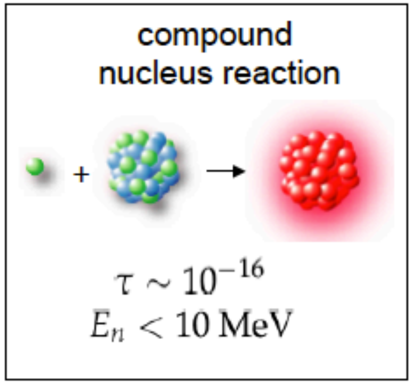
CN reaciton

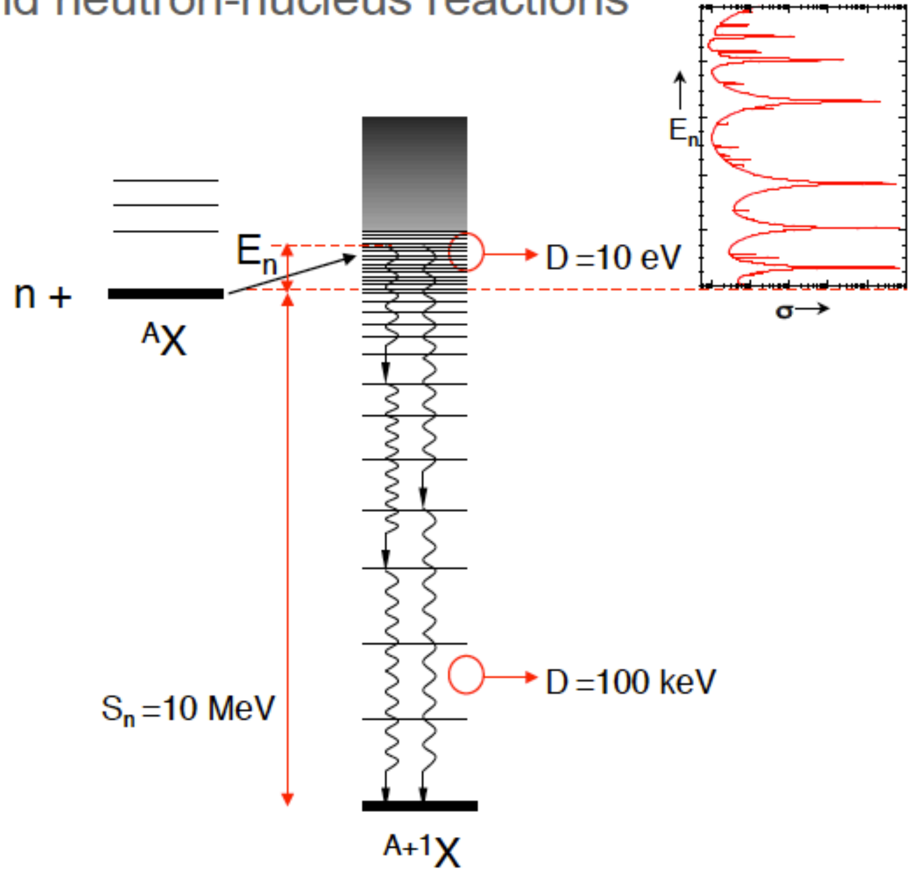


resonances, R-matrix
thermal
RRR
URR
OMP
^{197}Au
total cross section (b)
neutron energy (eV)

CN reaciton

Compound neutron-nucleus reactions





CN reaciton

The R-matrix formalism

saclay

The Breit-Wigner Single Level approximation:

total cross section:

$$\sigma_c = \pi \bar{\lambda}_c^2 g_c \left(4 \sin^2 \phi_c + \frac{\Gamma_\lambda \Gamma_{\lambda c} \cos 2\phi_c + 2(E - E_\lambda - \Delta_\lambda)\Gamma_{\lambda c} \sin 2\phi_c}{(E - E_\lambda - \Delta_\lambda)^2 + \Gamma_\lambda^2/4} \right)$$

neutron channel: $c = n$

only capture, scattering, fission: $\Gamma_\lambda = \Gamma = \Gamma_n + \Gamma_\gamma + \Gamma_f$

other approximations: $\ell = 0 \quad \cos\phi_c = 1 \quad \sin\phi_c = \rho = ka_c \quad \Delta_\lambda = 0$

total cross section:

potential / interference / elastic / capture / fission

$$\sigma_T(E) = 4\pi R'^2 + \pi \bar{\lambda}^2 g \left(\frac{4\Gamma_n (E - E_0) R'/\bar{\lambda} + \Gamma_n^2 + \Gamma_n \Gamma_\gamma + \Gamma_n \Gamma_f}{(E - E_0)^2 + (\Gamma_n + \Gamma_\gamma + \Gamma_f +)^2/4} \right)$$

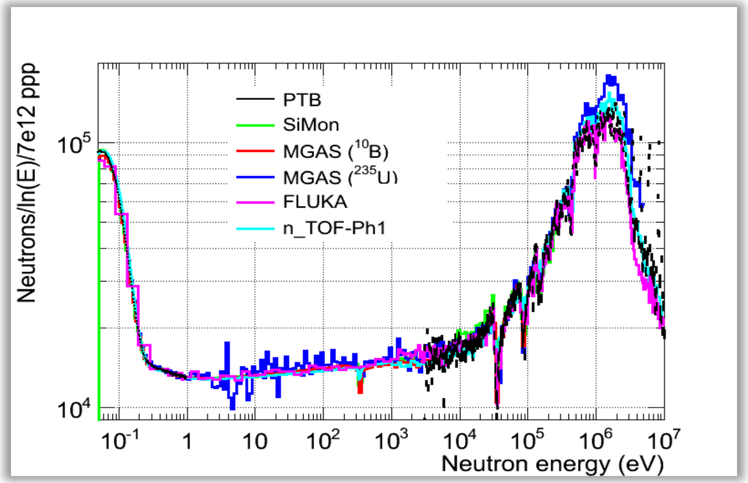
total width

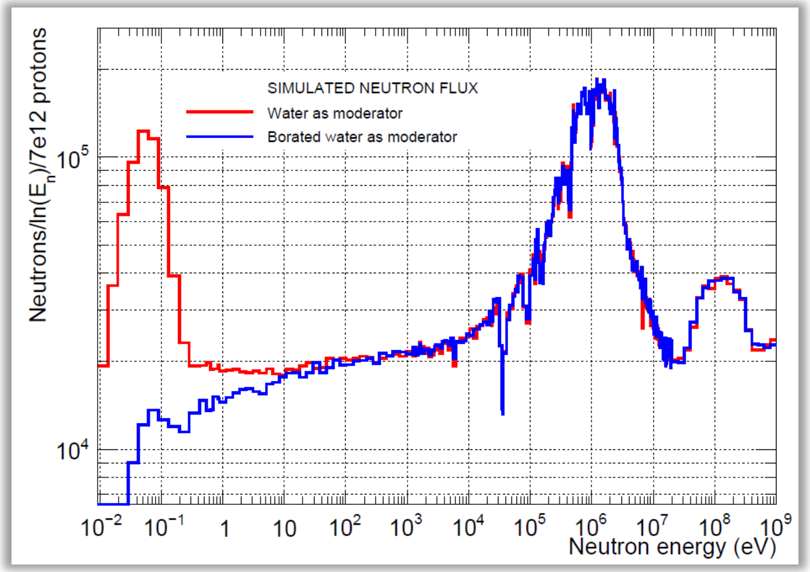
Flux

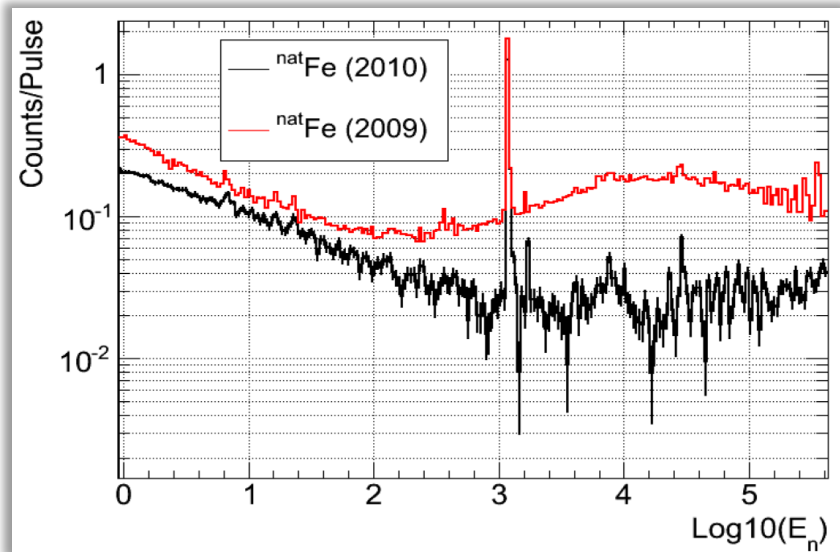
The flux was measured for each target, with **four** different systems based on **^{6}Li, ^{10}B and ^{235}U.**

Measurements were repeated for the **^{10}B-water moderator** (the thermal peak in the flux is suppressed).

The use of borated water suppresses the 2.2 MeV g-rays from $^{1}H(n,g)^{2}H$. Background reduced by a factor of 10 in some energy regions!



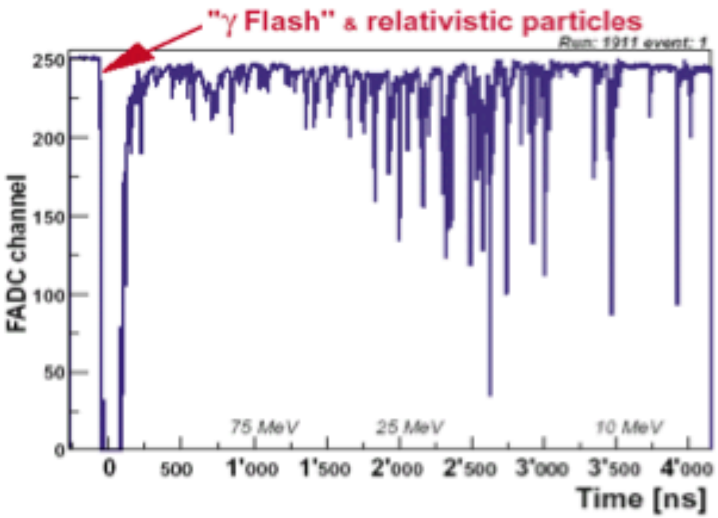


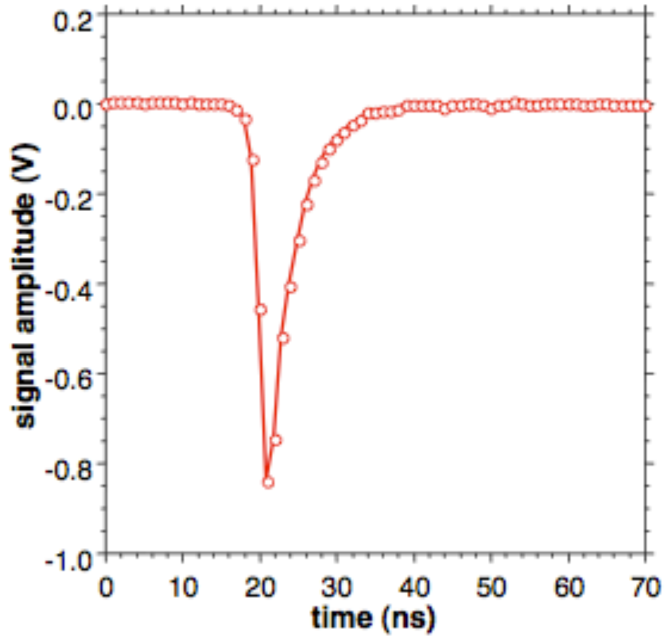


DAQ - fADC

Data acquisition

Detector signal sampling, Acqiris digitizers

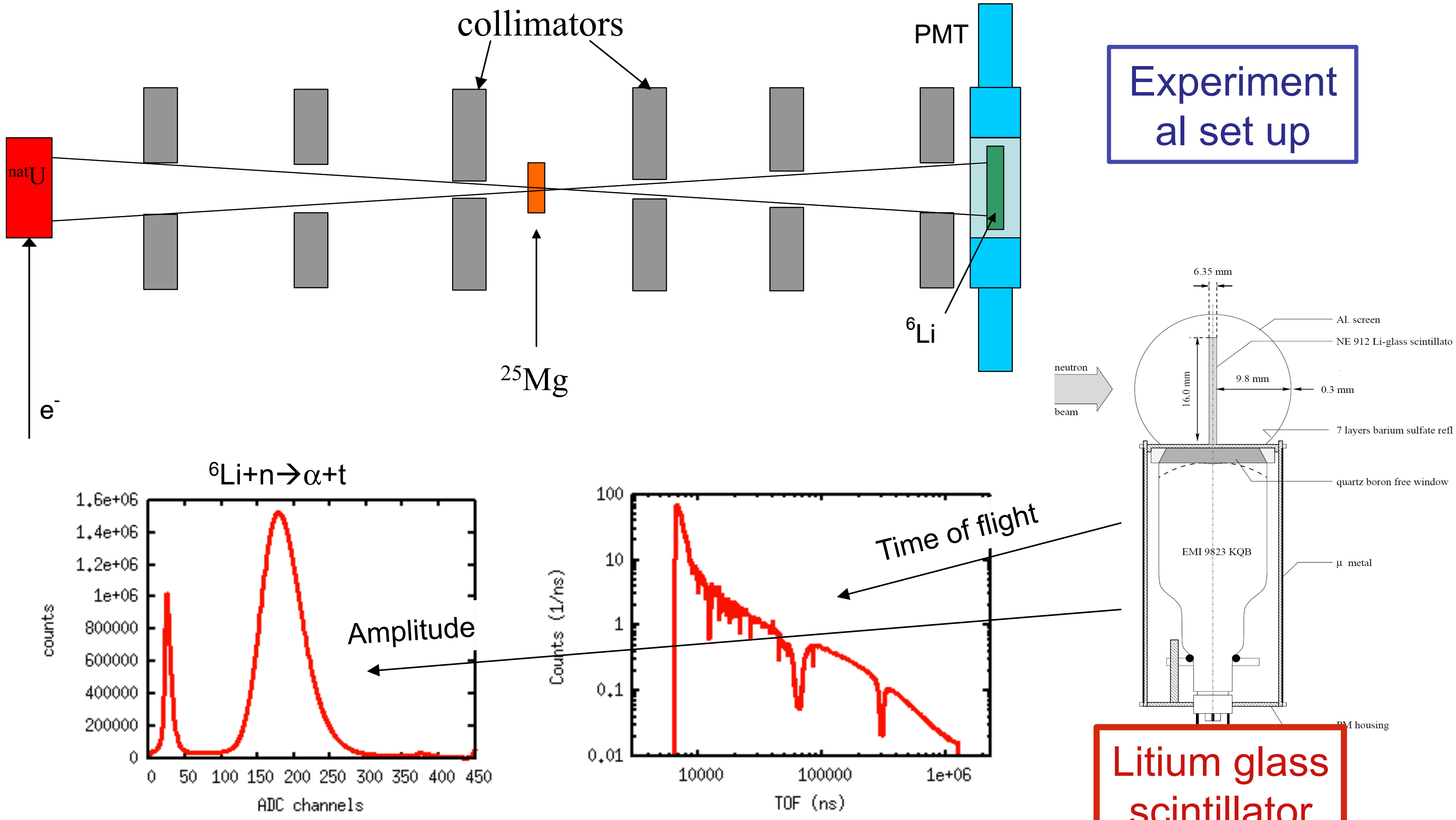




$^{25}Mg(n, tot)$ @ GELINA

New Measurement

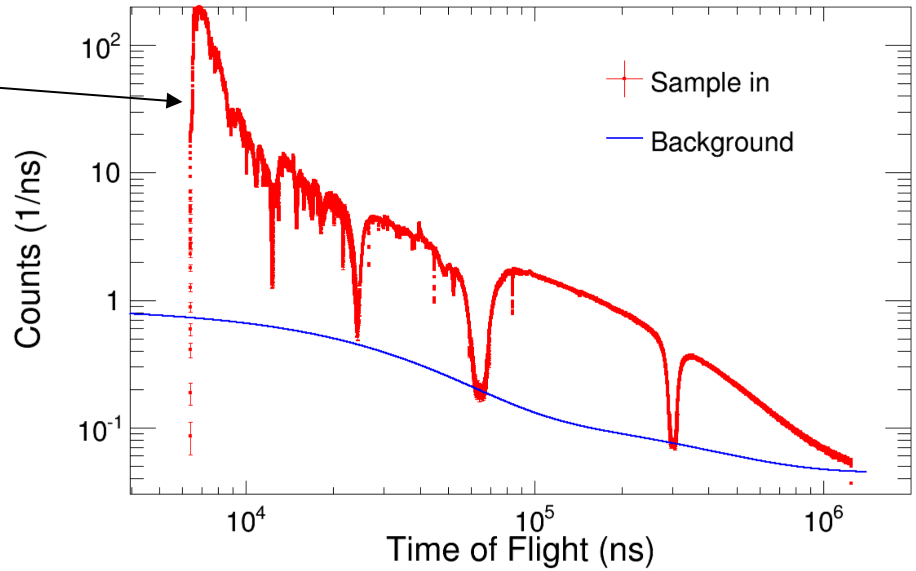
Experimental set up

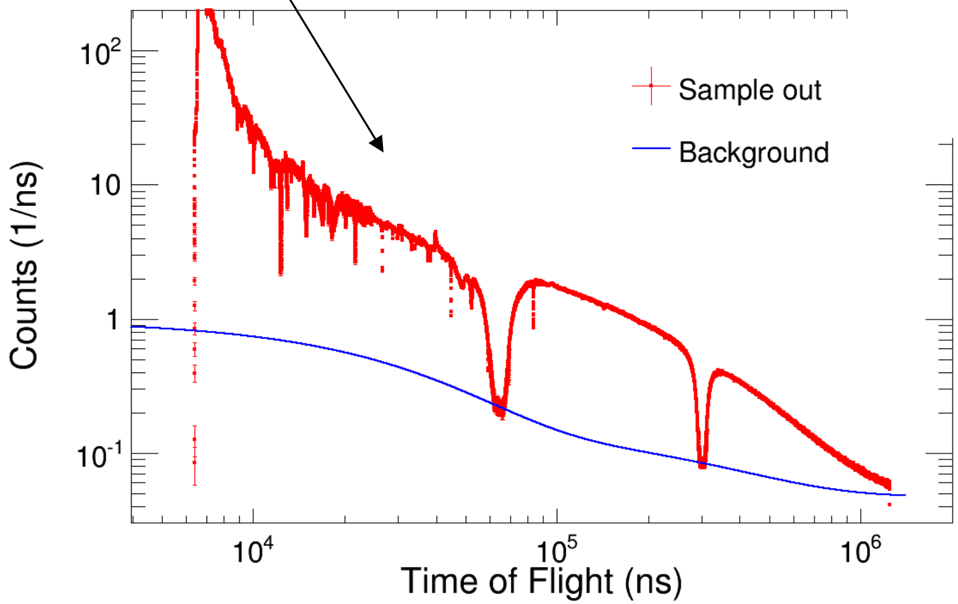


Litium glass scintillator

New Measurement

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





Background determined by **black resonance** technique:

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

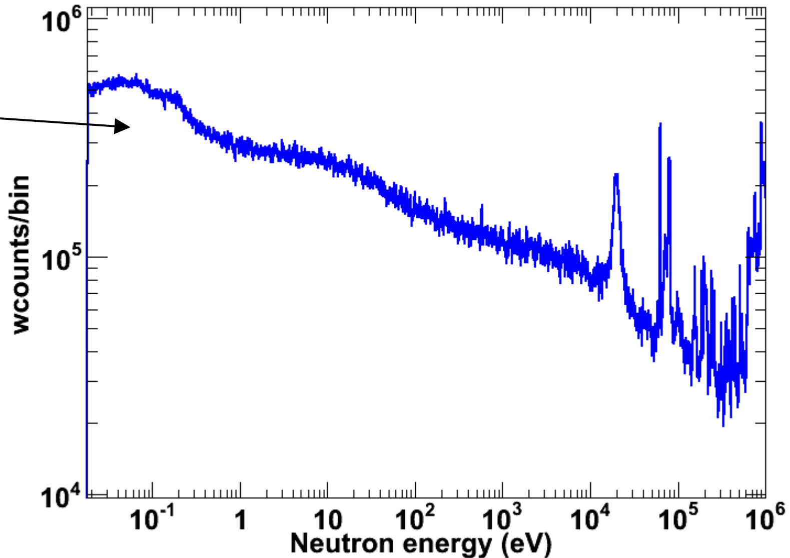
^{25}Mg(n, γ) @ n_TOF

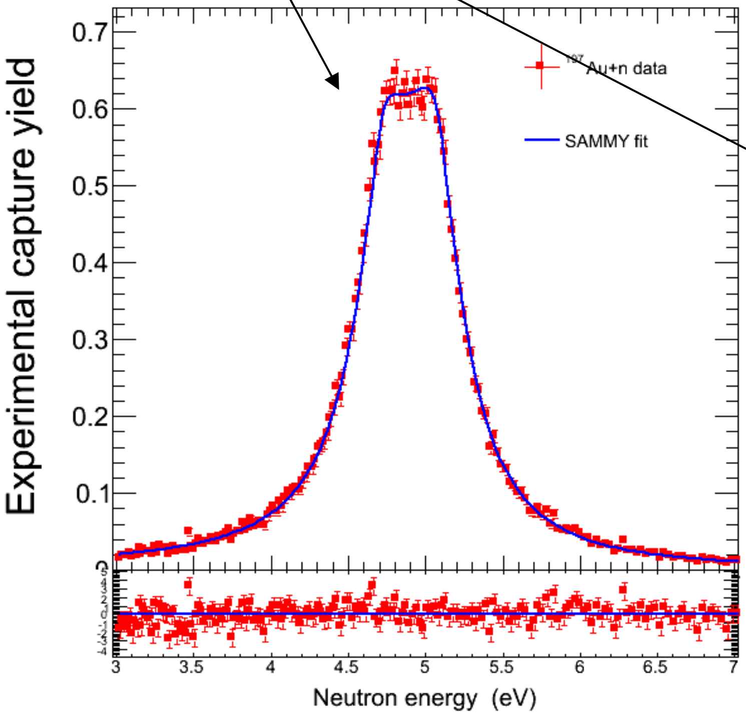
Data Analysis

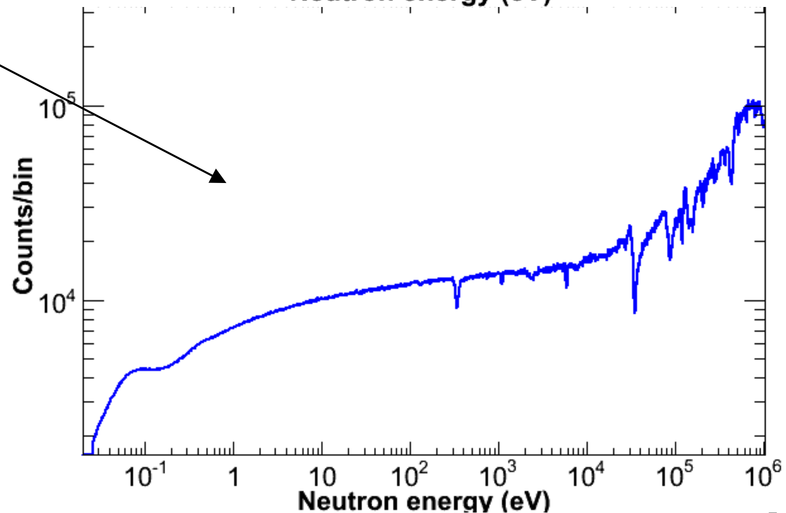
Istituto Nazionale di Fisica Nucleare

Experimental capture yield

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

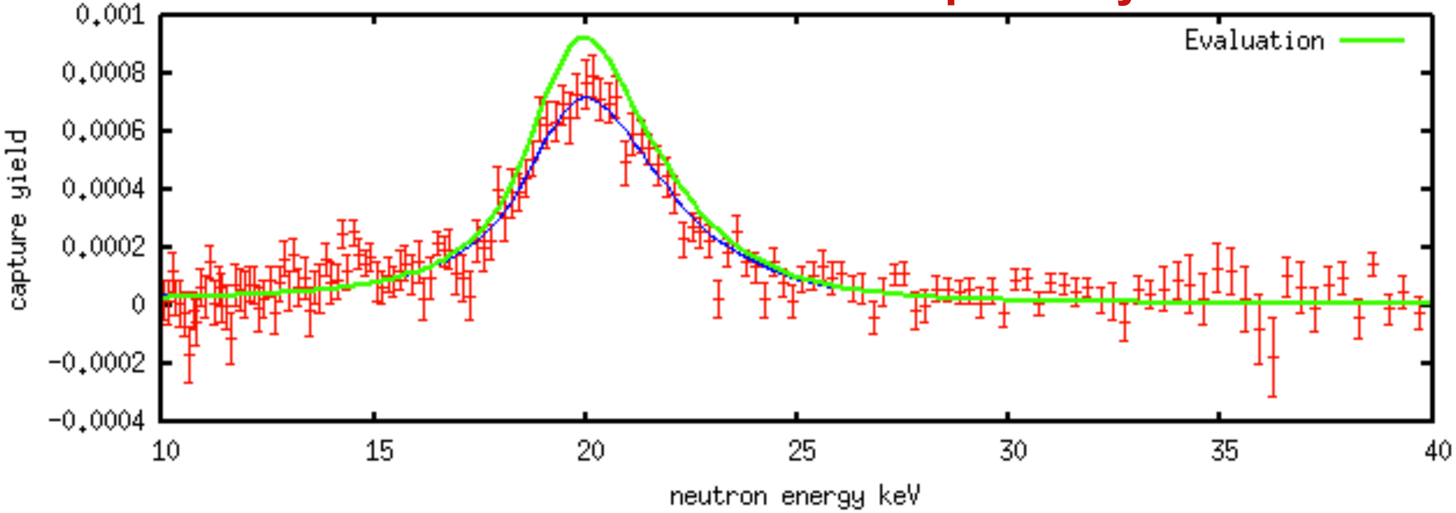




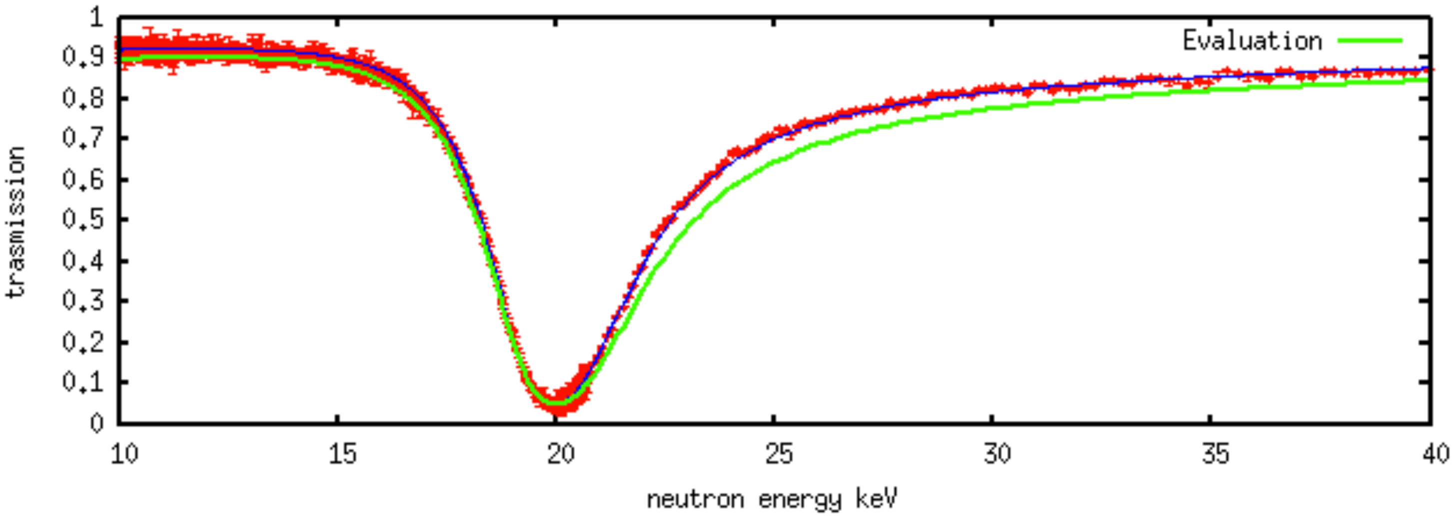


Data Analysis

Simultaneous Resonance Shape Analysis



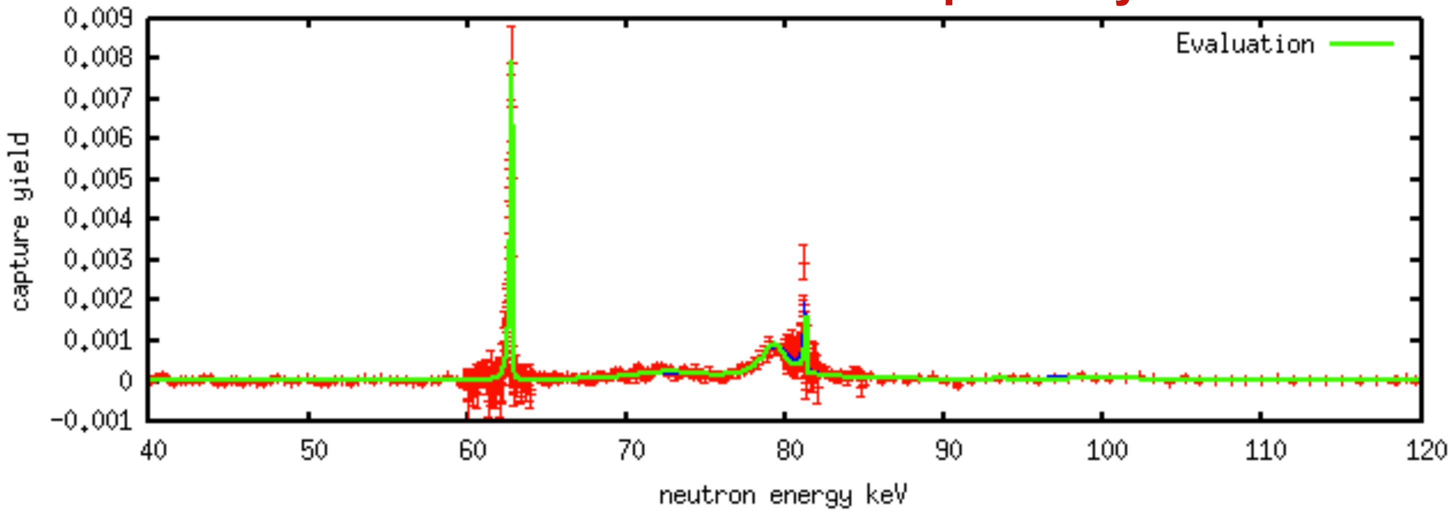
$^{25}Mg(n, \gamma)$ @ n_TOF



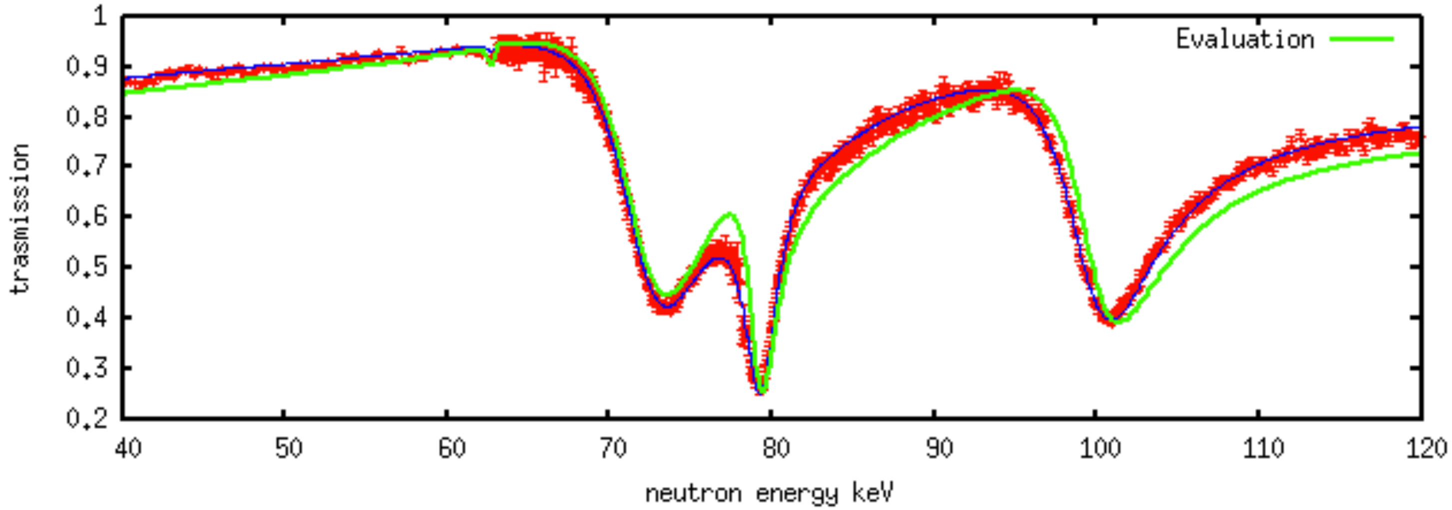
$^{25}Mg(n, tot)$ @ GELINA

Data Analysis

Simultaneous Resonance Shape Analysis



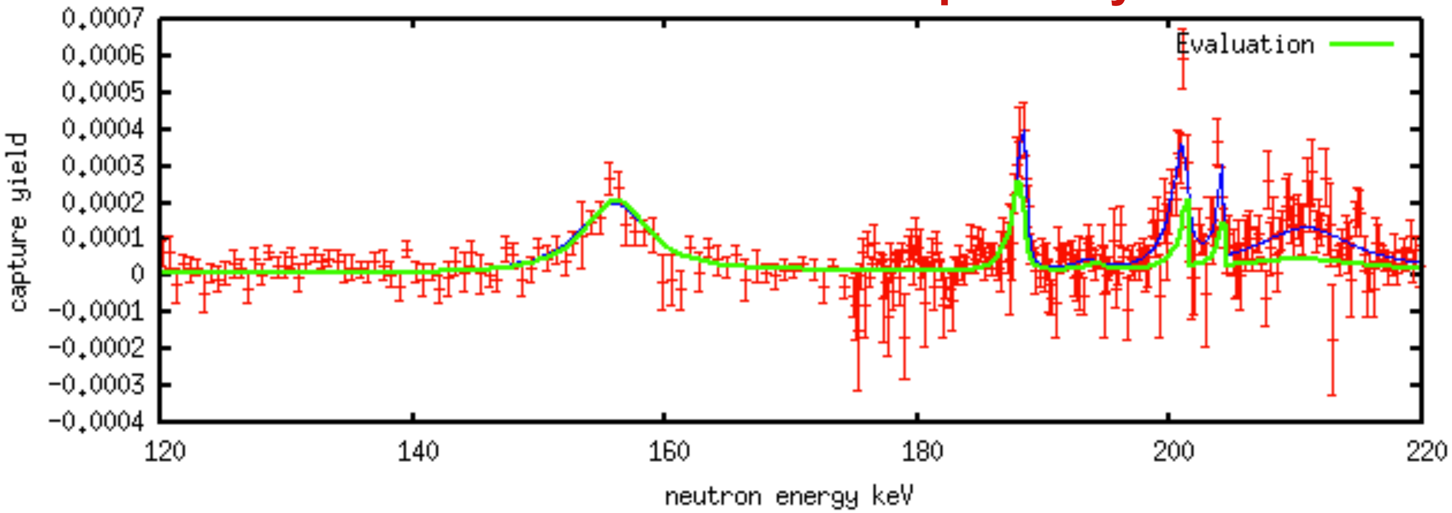
^{25}Mg(n, γ) @ n_TOF



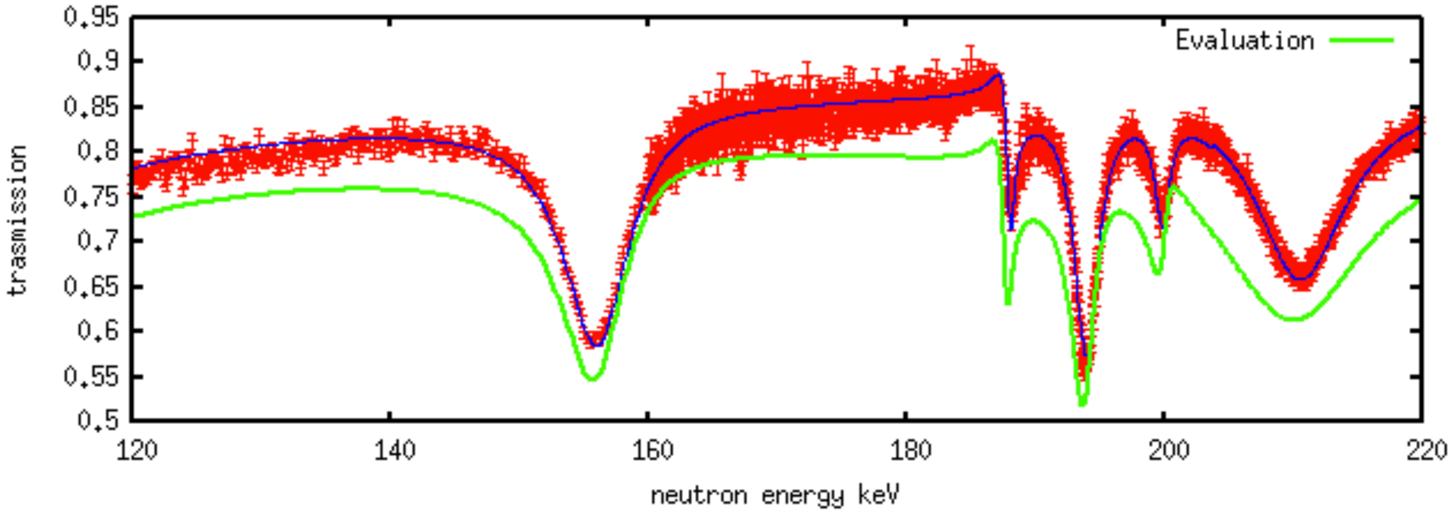
^{25}Mg(n, tot) @ GELINA

Data Analysis

Simultaneous Resonance Shape Analysis



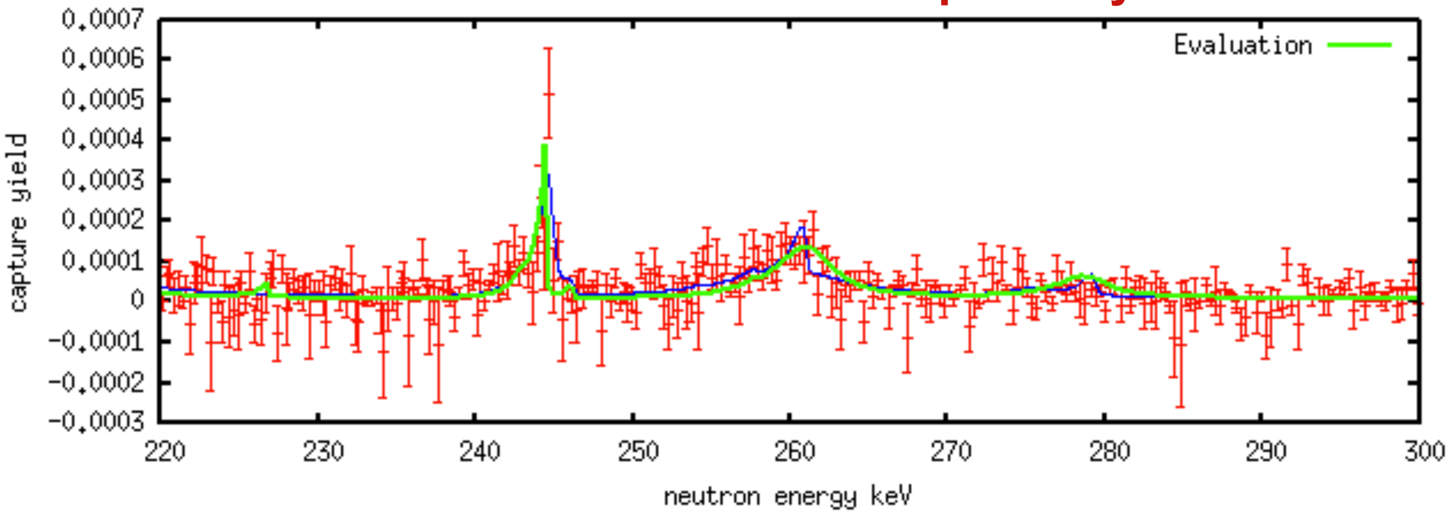
^{25}Mg(n, γ) @ n_TOF



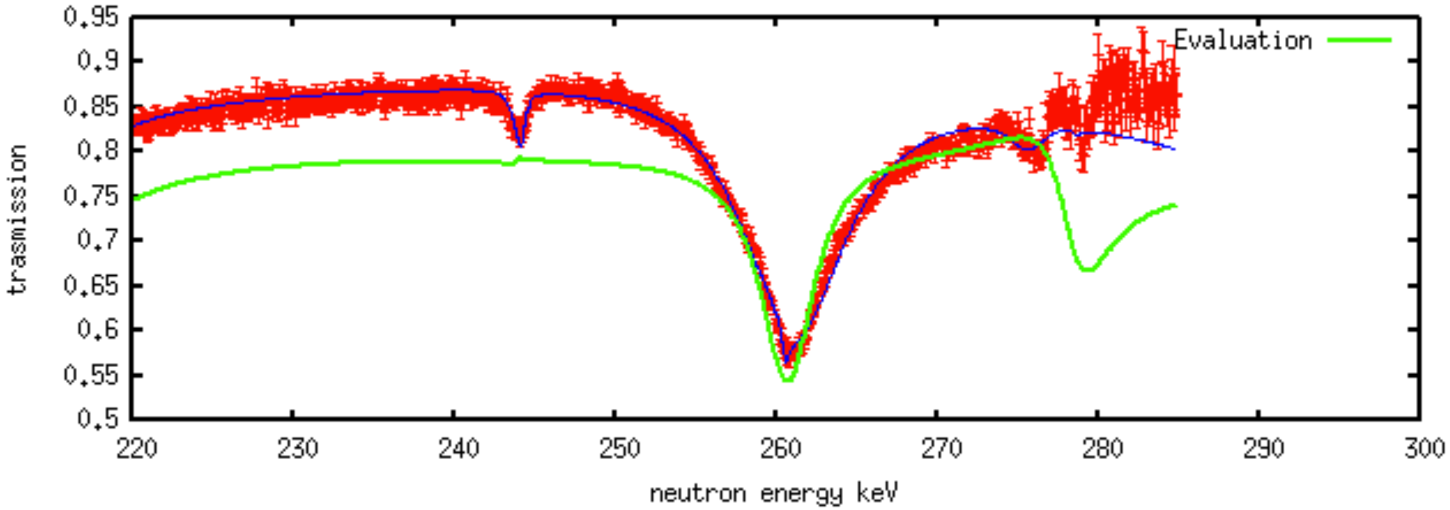
^{25}Mg(n, tot) @ GELINA

Data Analysis

Simultaneous Resonance Shape Analysis



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

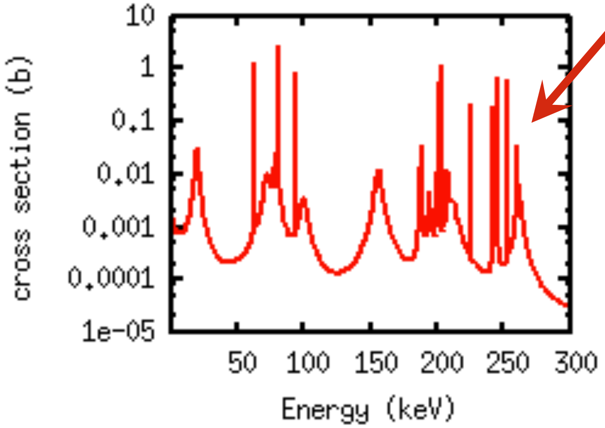


$^{25}Mg(n, tot)$ @ GELINA

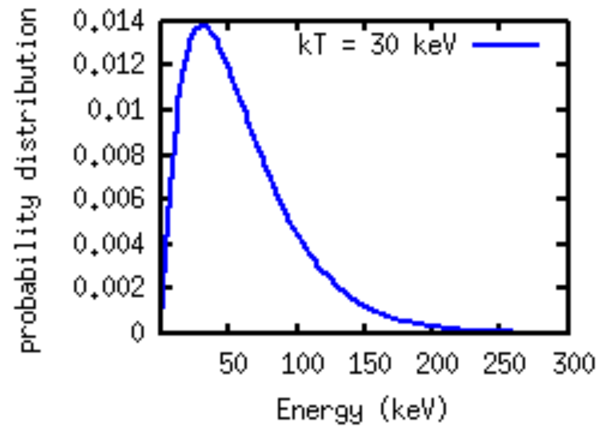
Results

$^{25}Mg(n, \gamma)^{26}Mg$ resonances → **R-matrix** parameterization of the **cross section**

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)



Convoluted with **neutron** stellar **flux**



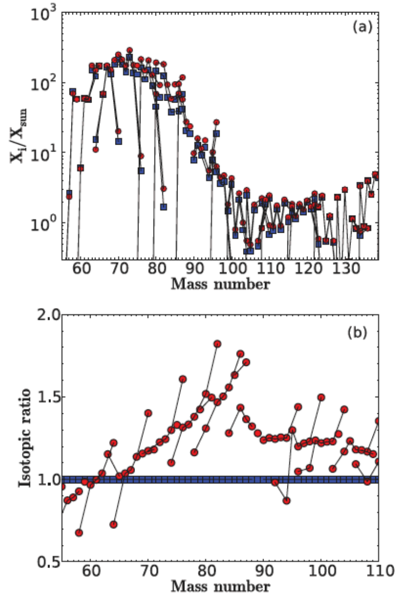
MACS and reaction rate

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

Results

Istituto Nazionale di Fisica Nucleare

Stellar site	Temperature keV	MACS (Massimi 2003)	MACS (KADoNiS)	MACS Massimi 2012
He - AGB	8	**4.9±0.6 mb**	4.9 mb	**4.3 mb**
He - AGB	23	**3.2±0.2 mb**	6.1 mb	**4.3 mb**
30	30	**4.1±0.6 mb**	6.4±0.4 mb	**4.1 mb**
He – Massive	25	**3.4±0.2 mb**	6.2 mb	**4.2 mb**
C - Massive	90	**2.6±0.3 mb**	4.0 mb	**2.5 mb**



Old Sample, oxide powder

Capture

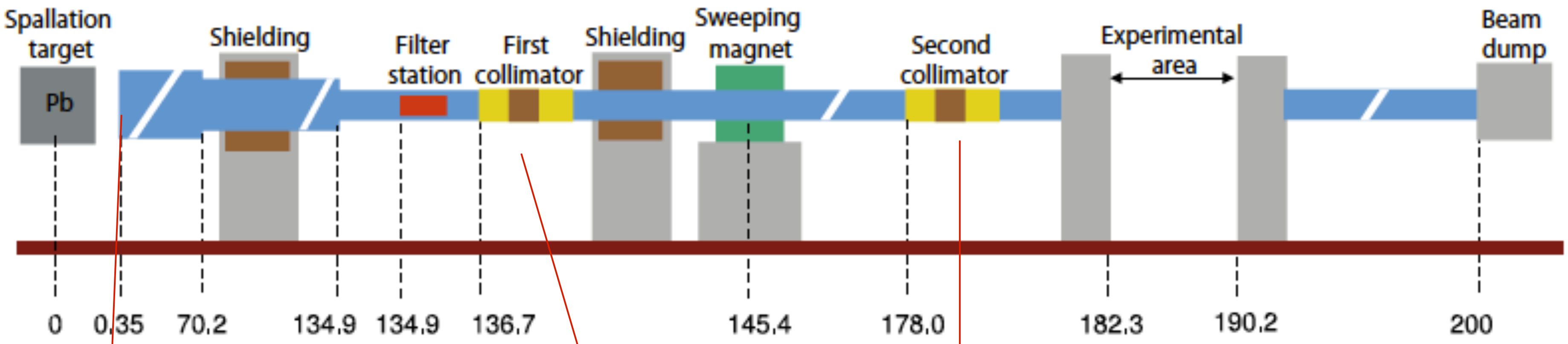
New Sample, metal disc

Capture + transmission

nTOF

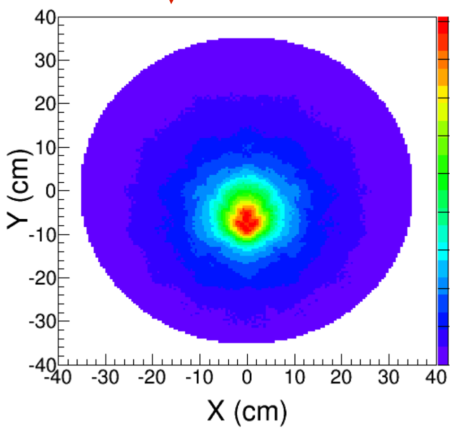
MC and resampling

n_TOF beam line



R=5,5 cm

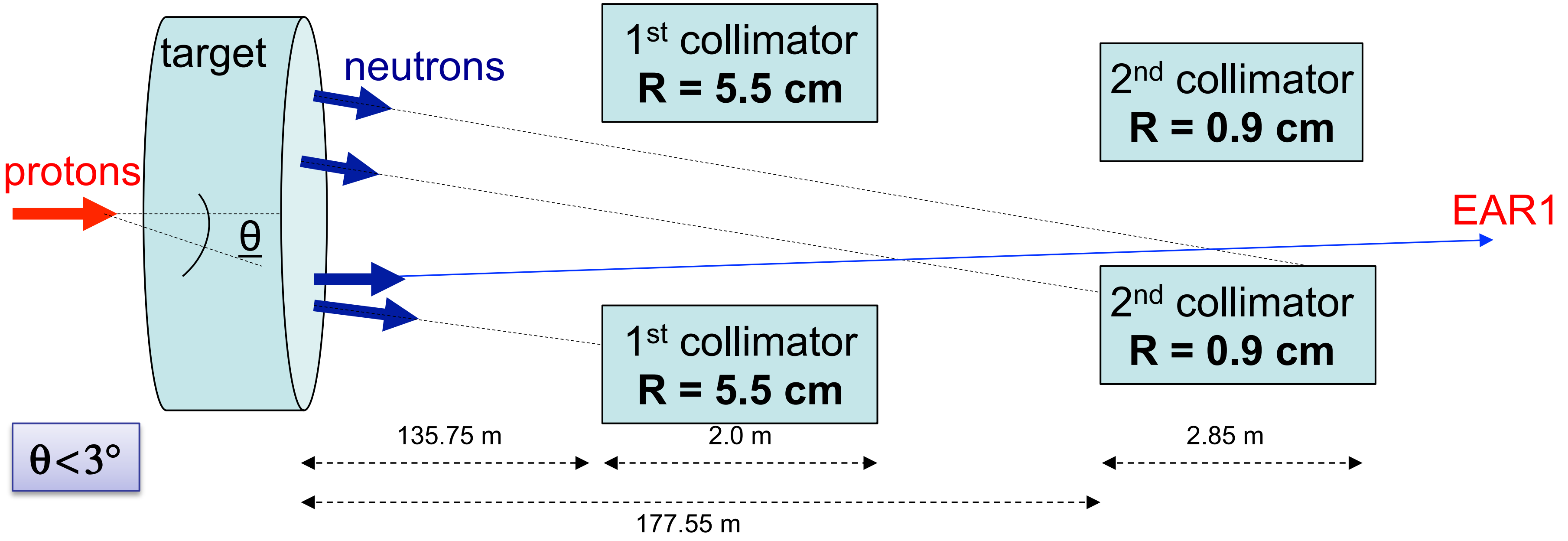
R=0,9 cm



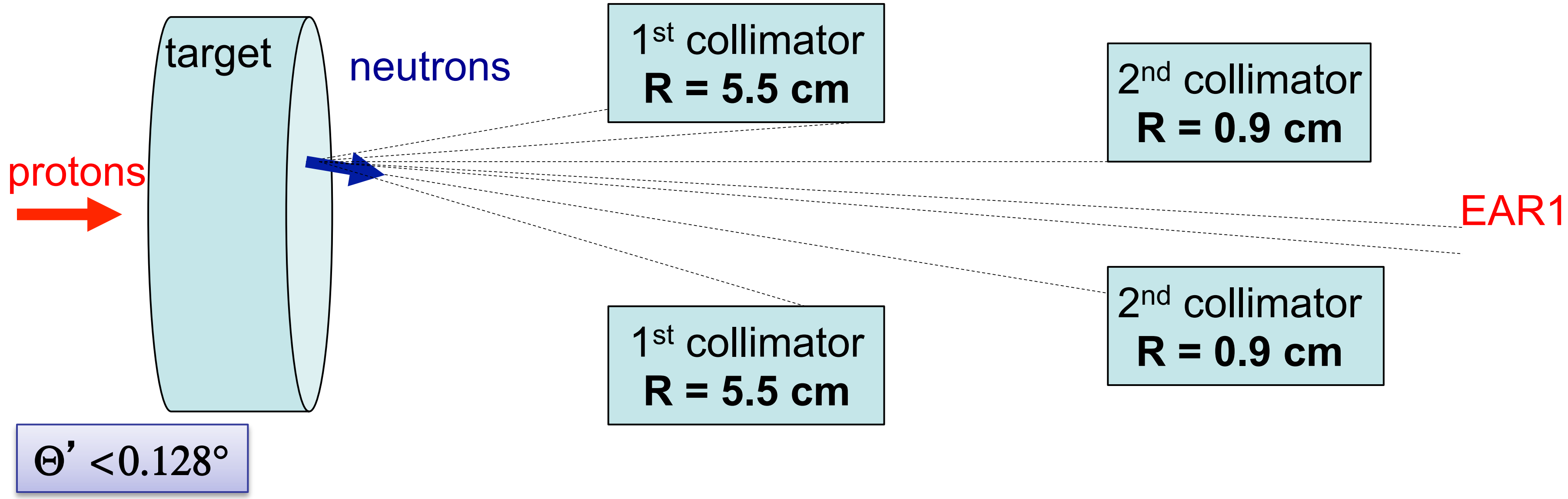
Ω ~10^{-8} sr
5×10^{6} protons → 1 neutron

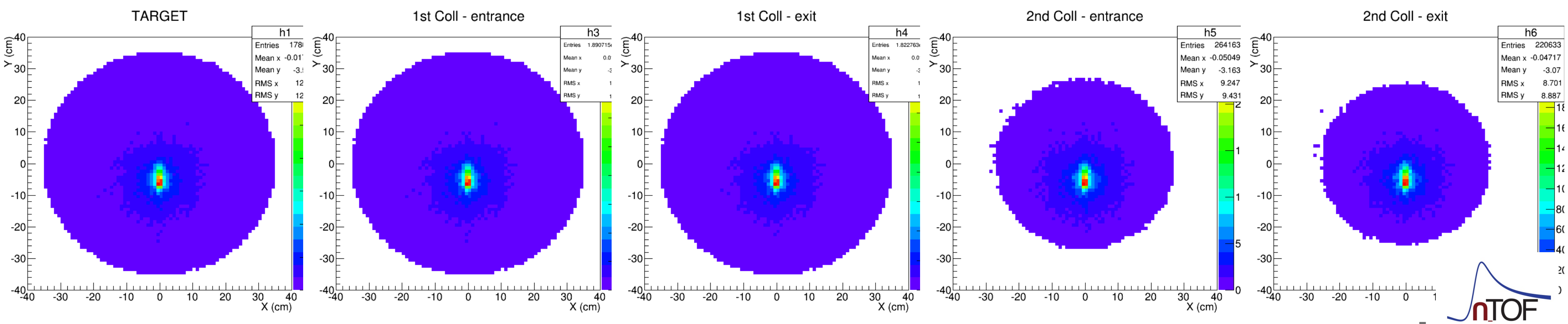
1/2 week CPUs = 10^{6} protons !!!

MC and resampling



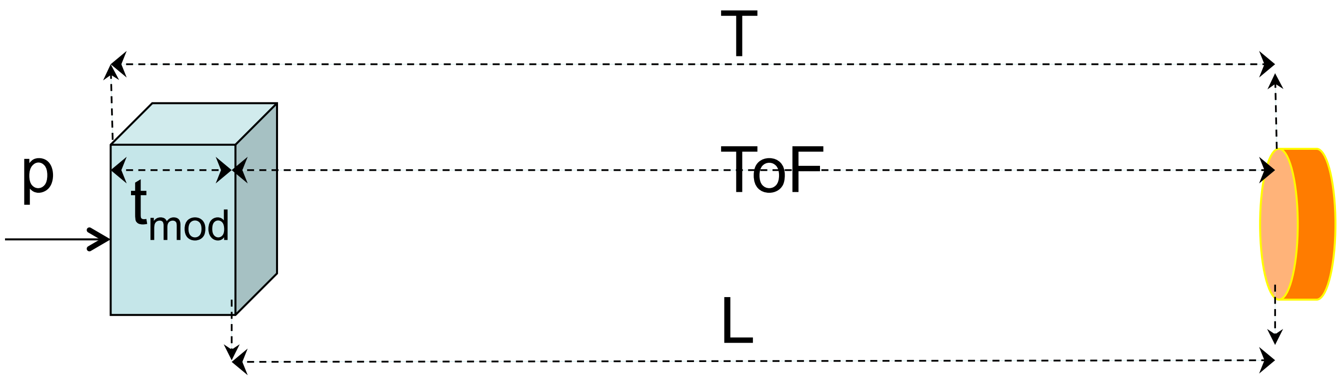
MC and resampling





Time to energy

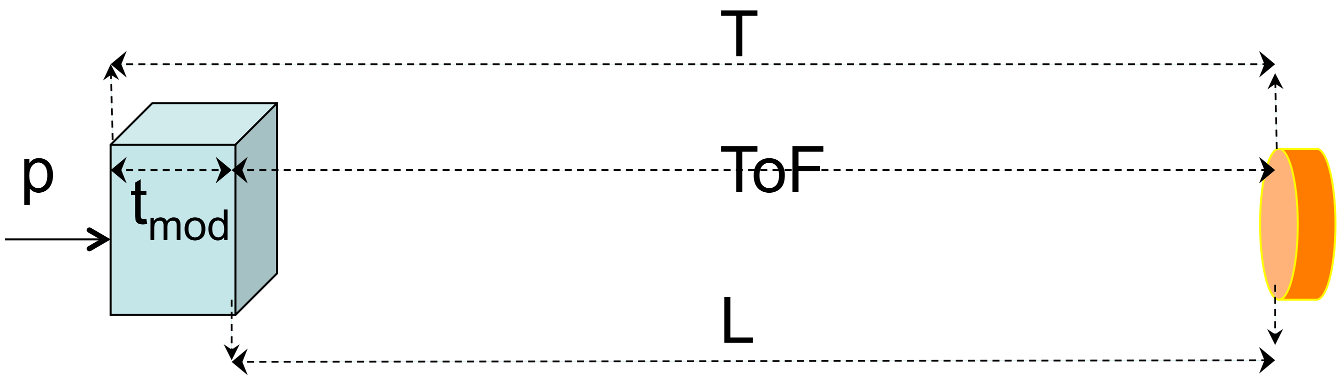
$$E_n = \frac{1}{2} m \left(\frac{L}{ToF} \right)^2$$



$$E_n = \frac{1}{2} m \left(\frac{L}{T - t_{mod}} \right)^2$$

Time to energy

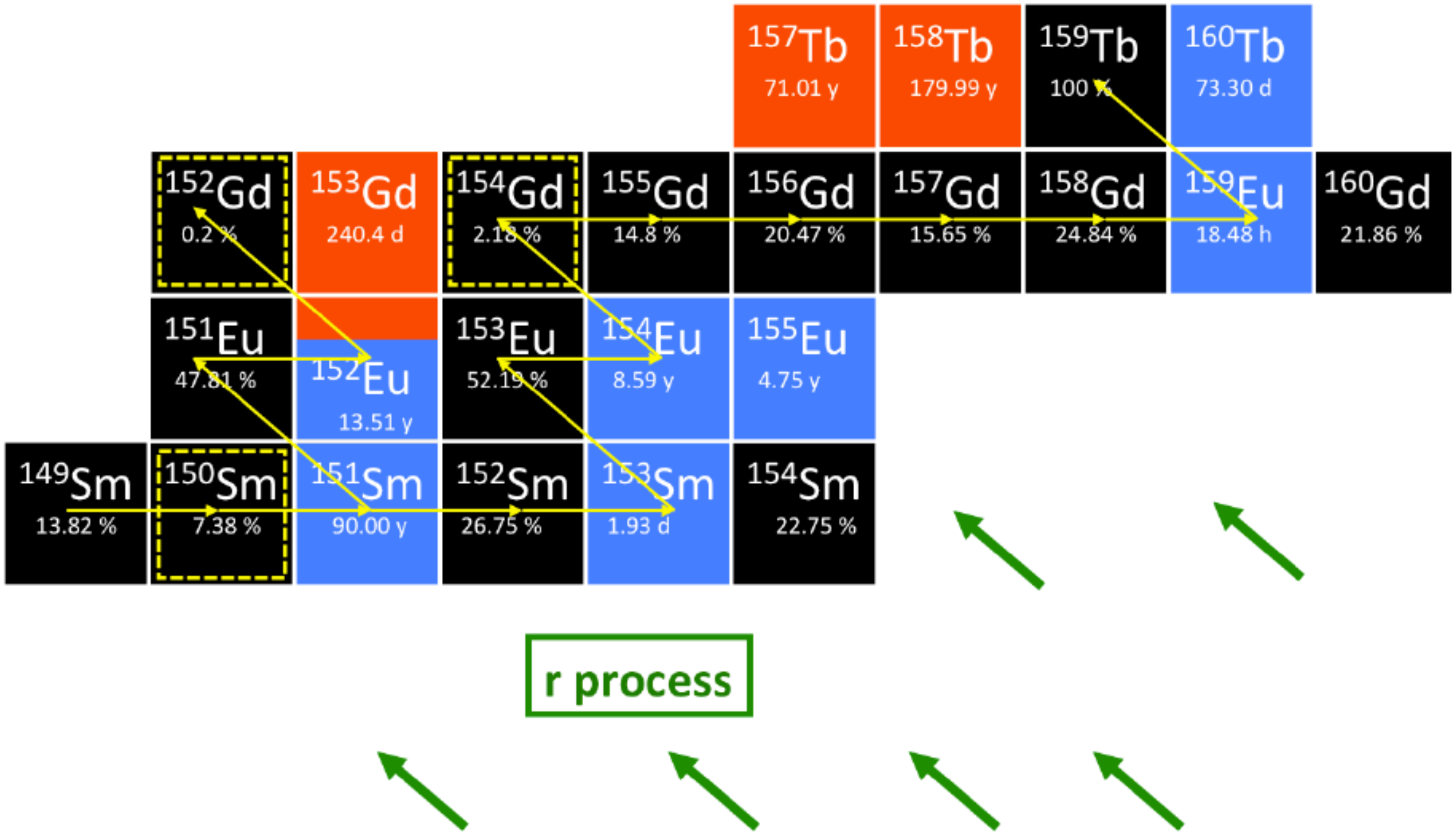
$$E_n = \frac{1}{2} m \left(\frac{L}{ToF} \right)^2$$



$$E_n = \frac{1}{2} m \left(\frac{L}{T - t_{mod}} \right)^2$$

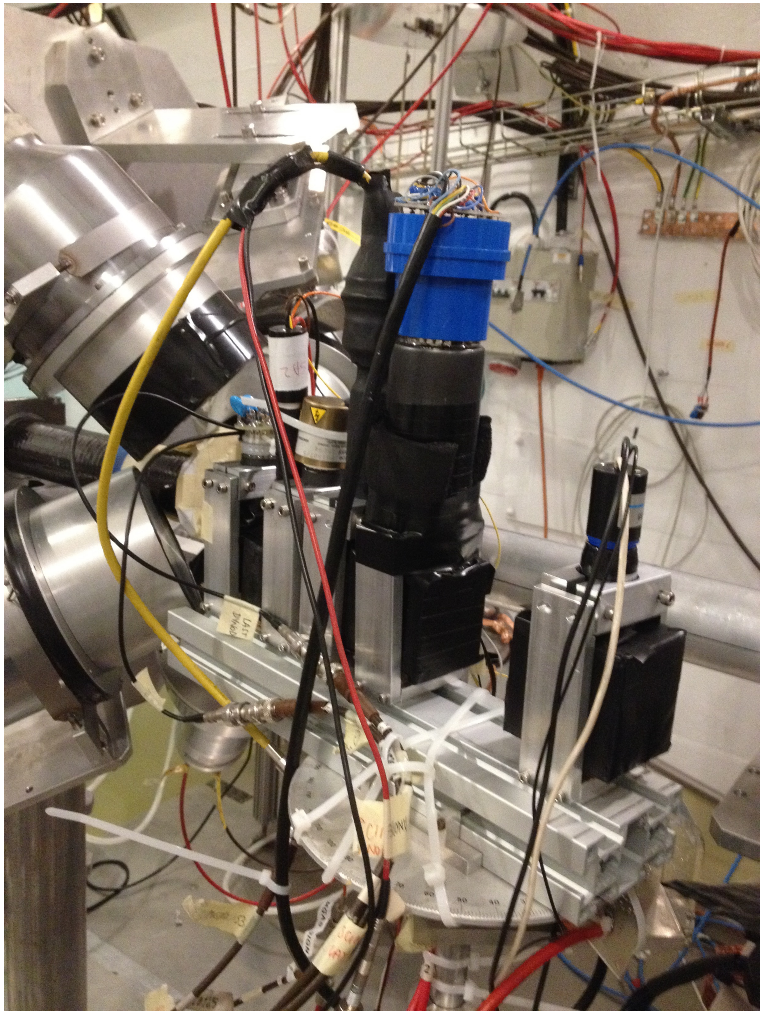
$$v = \frac{L}{ToF} = \frac{L}{T - t_{mod}} \Rightarrow v \times (T - t_{mod}) = L \Rightarrow vT = L + vt_{mod} = L + \lambda \Rightarrow v = \frac{L + \lambda}{T}$$

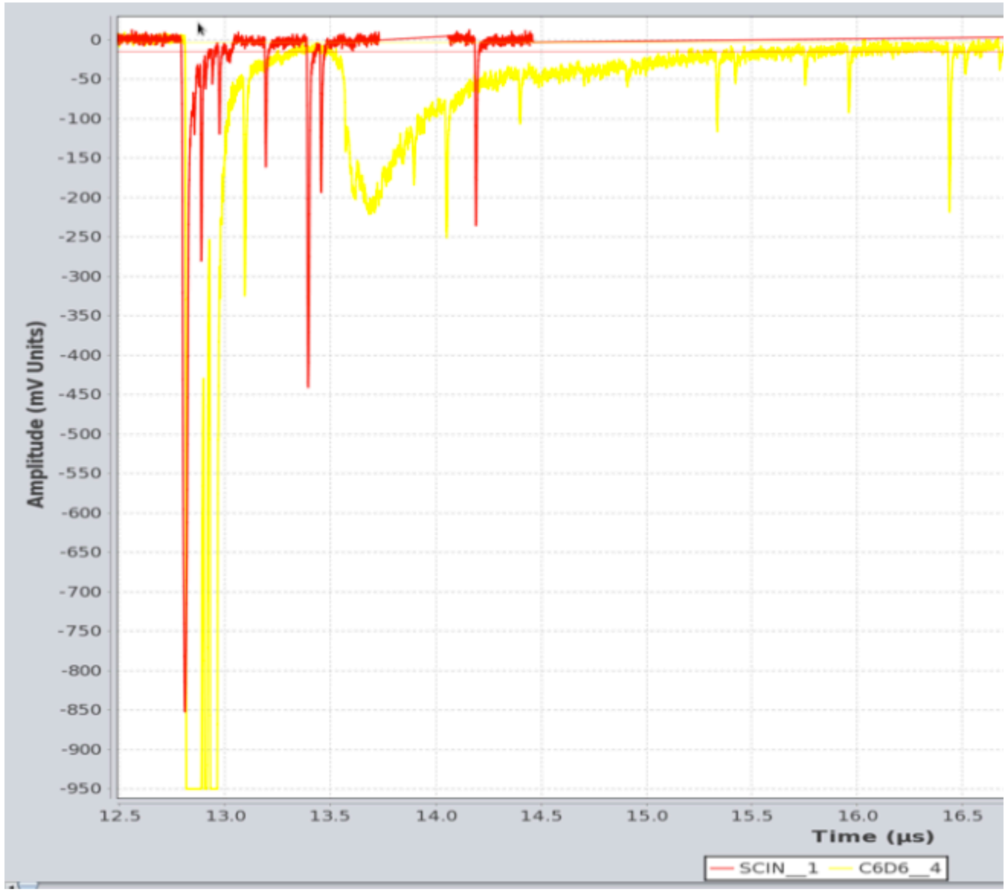
Gd



157Tb
71.01 y
158Tb
179.99 y
159Tb
100 %
160Tb
73.30 d
152Gd
0.2 %
153Gd
240.4 d
154Gd
2.18 %
155Gd
14.8 %
156Gd
20.47 %
157Gd
15.65 %
158Gd
24.84 %
159Eu
18.48 h
160Gd
21.86 %
151Eu
47.81 %
152Eu
13.51 y
153Eu
52.19 %
154Eu
8.59 y
155Eu
4.75 y
149Sm
13.82 %
150Sm
7.38 %
151Sm
90.00 y
152Sm
26.75 %
153Sm
1.93 d
154Sm
22.75 %
r process

PRT





Amplitude (mV Units)
0
-50
-100
-150
-200
-250
-300
-350
-400
-450
-500
-550
-600
-650
-700
-750
-800
-850
-900
-950
12.5
13.0
13.5
14.0
14.5
15.0
15.5
16.0
16.5
Time (µs)
SCIN__1
C6D6__4