Workshop on Basic research and
interdisciplinary applications with
small accelerators
Naples, Italy
17 – 18 January, 2018

Neutron beams produced by TANDEM and potential applications

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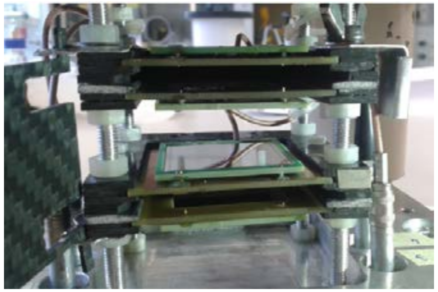
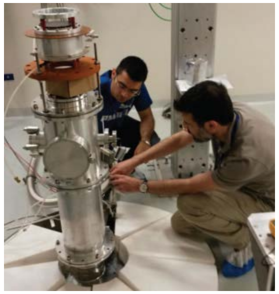
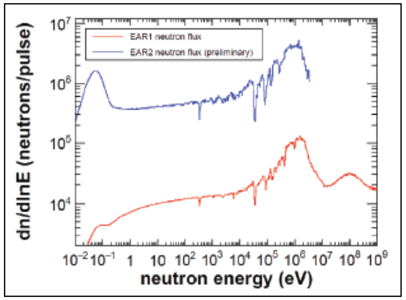
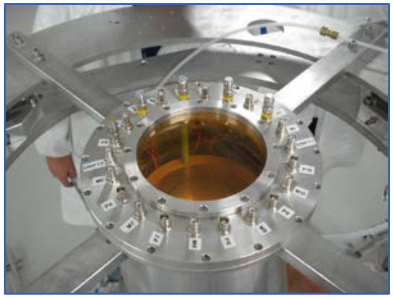








Outline

- **Motivations**

  nuclear Astrophysics, energy production, nuclear medicine, neutron imagine, etc…

- **Techniques**

  time-of-flight, activation, monoenergetic

Accelerator-based neutron facilities in the world

large scale (high energy) and small scale (low energy)

- **Some ideas**

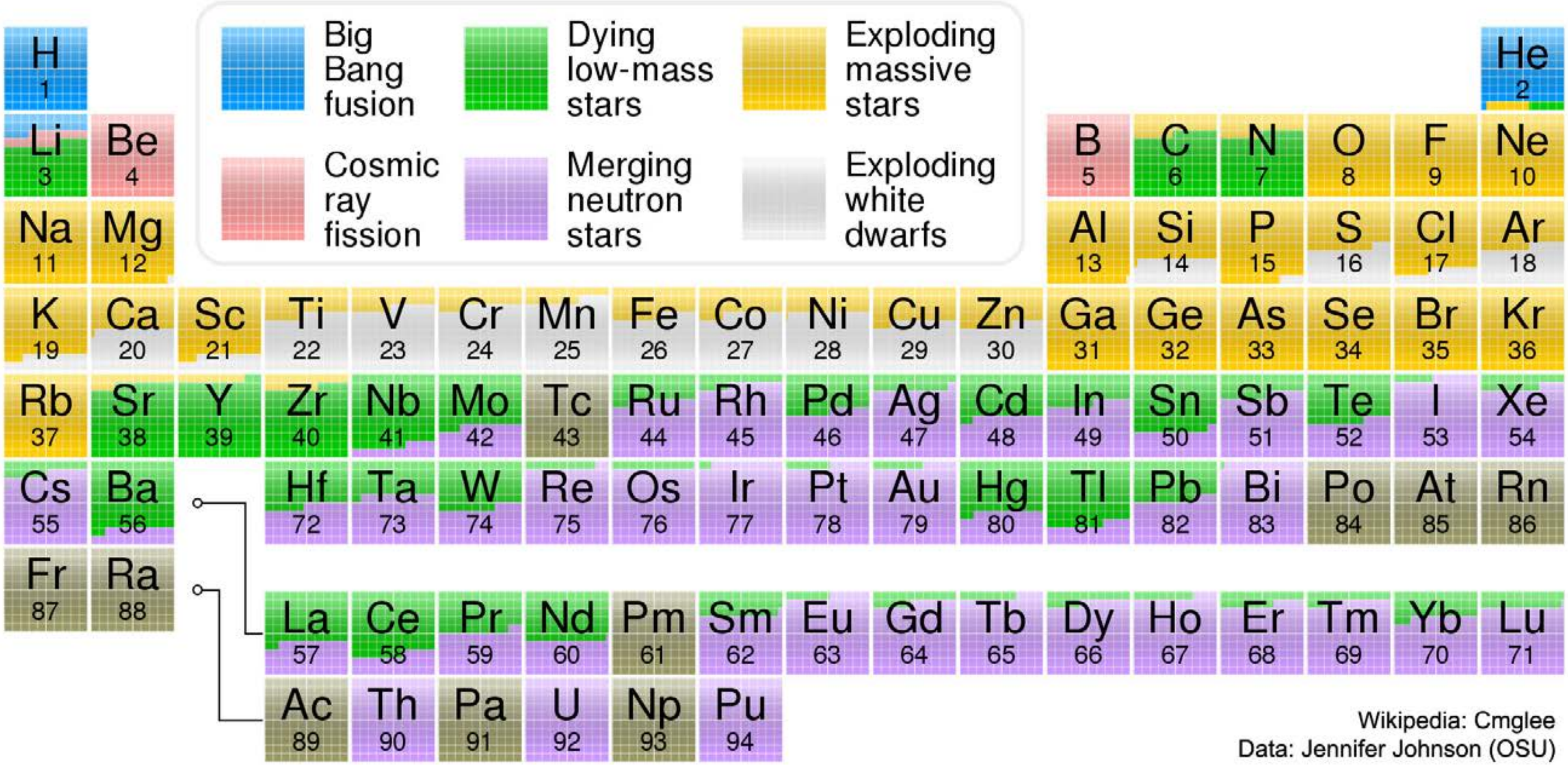
  lVNAA, atom counting, etc…

- **Summary**

Astronomy Picture of the day

NASA web site – 24 Ottobre 2017

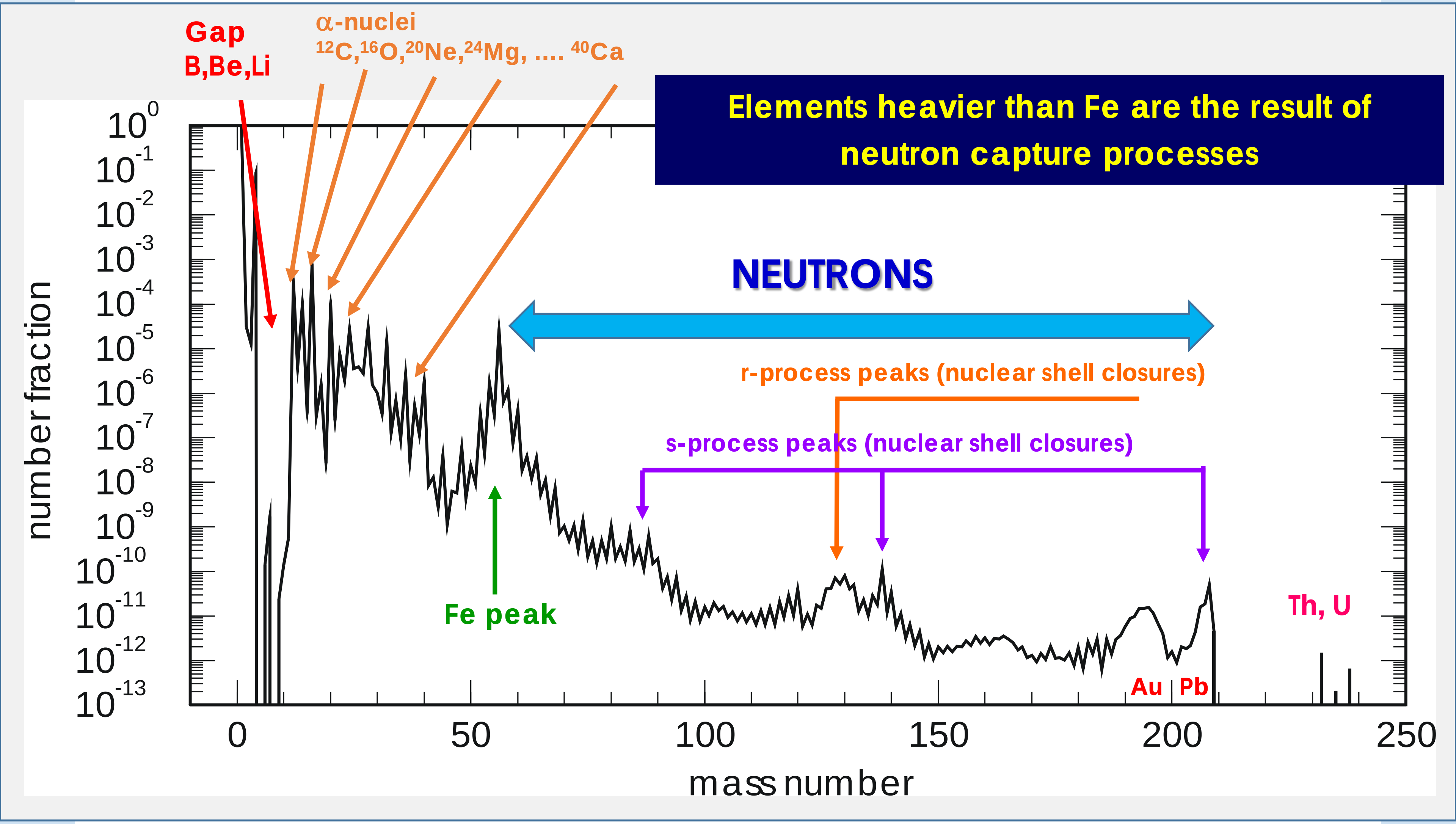
Where your elements came from



Wikipedia: Cmglee
Data: Jennifer Johnson (OSU)

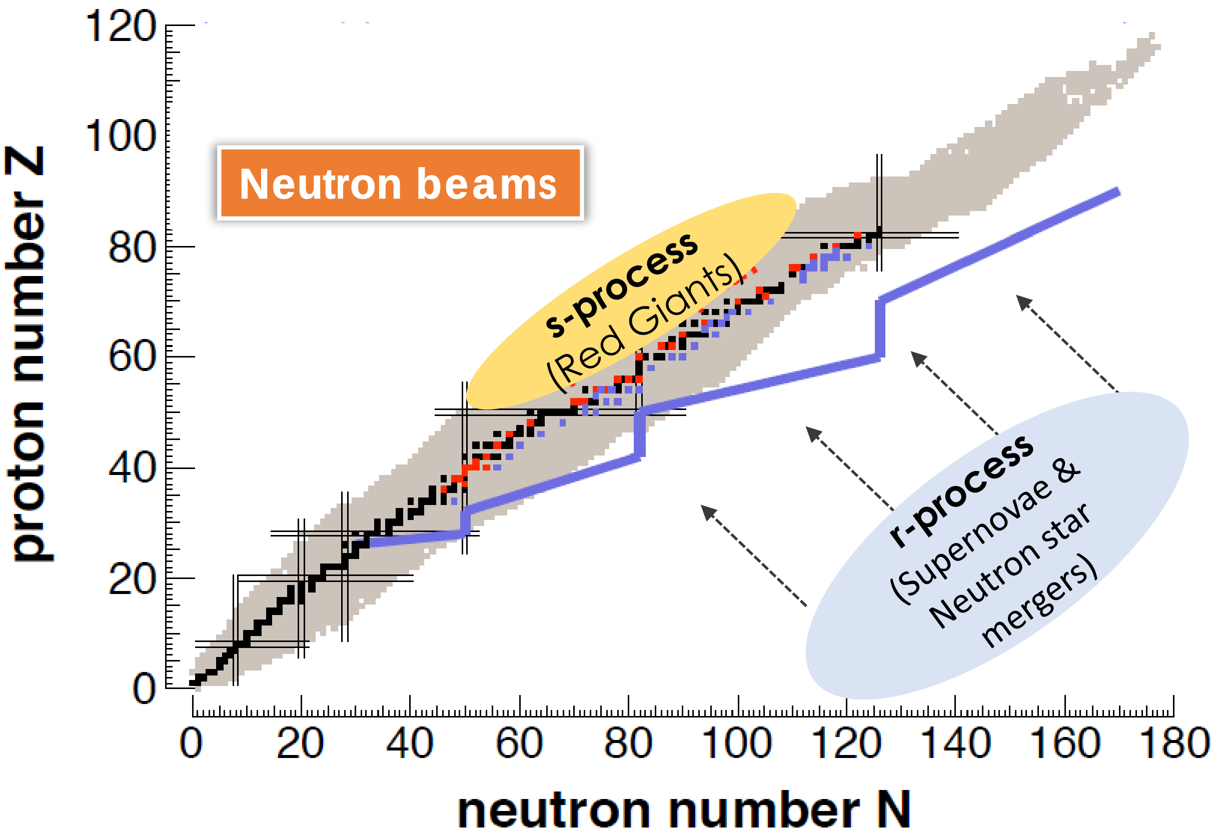
https://apod.nasa.gov/apod/ap171024.html

Nucleosynthesis of heavy elements



Elements heavier than Fe are the result of neutron capture processes

The stellar nucleosynthesis of heavy elements



s-process (slow process):

- **Capture times** long relative to decay time
- Involves mostly **stable isotopes**
- **N**$_n$ = 10^8 n/cm^3 , **kT** = 0.3 – 300 keV

r-process (rapid process):

- **Capture times** short relative to decay times
- Produces **unstable isotopes**
- **N**$_n$ = 10^{20-30} n/cm^3

Importance of s-process

How do we determine the contribution of the r-process to the solar abundance?

$$r = ?$$

A detailed knowledge of the s-process is a fundamental prerequisite for any calculation of the galactical chemical evolution, including the contribution from supernovae and neutron star mergers

The s-process

The abundance of elements in the Universe depends on:

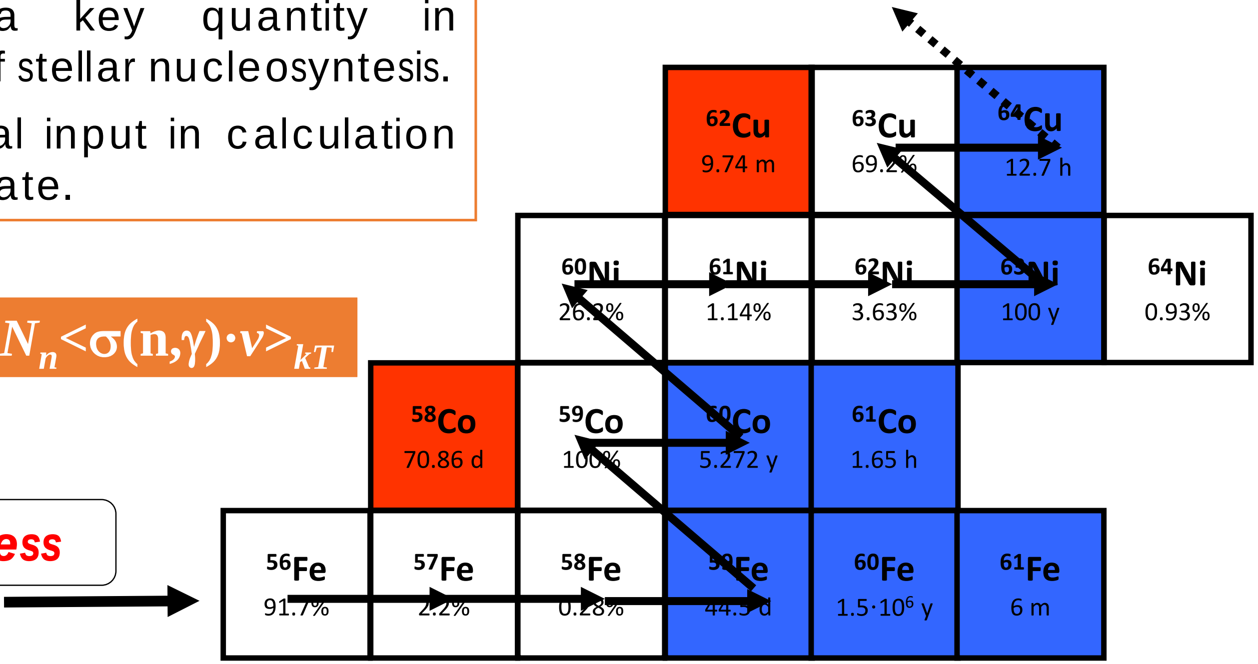
- **thermodinamic conditions** in stars (*temperture and neutron density*)
- **neutron capture cross-sections**

$\sigma(n,\gamma)$ is a key quantity in modelling of stellar nucleosynthesis.

Fundamental input in calculation of capture rate.

CR: $\lambda_n = N_n\langle\sigma(n,\gamma)\cdot v\rangle_{kT}$

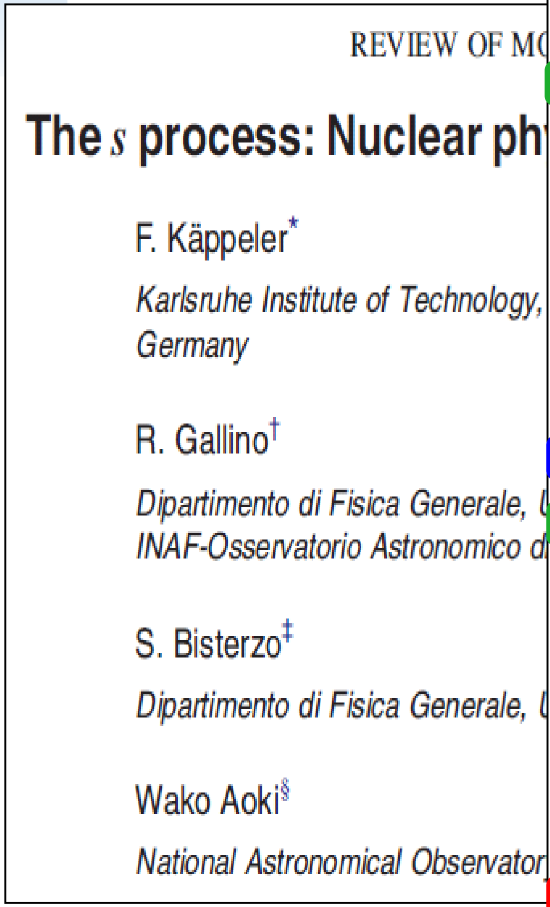
Along the β-stability valley



Accurate neutron capture cross-sections allow to:

- **refine models** of stellar nucleosynthesis in the Universe;
- obtain information on the **stellar environment and evolution**

Branching point isotopes at n_TOF



REVIEW OF M

The *s* process: Nuclear ph

F. Käppeler*

Karlsruhe Institute of Technology,
Germany

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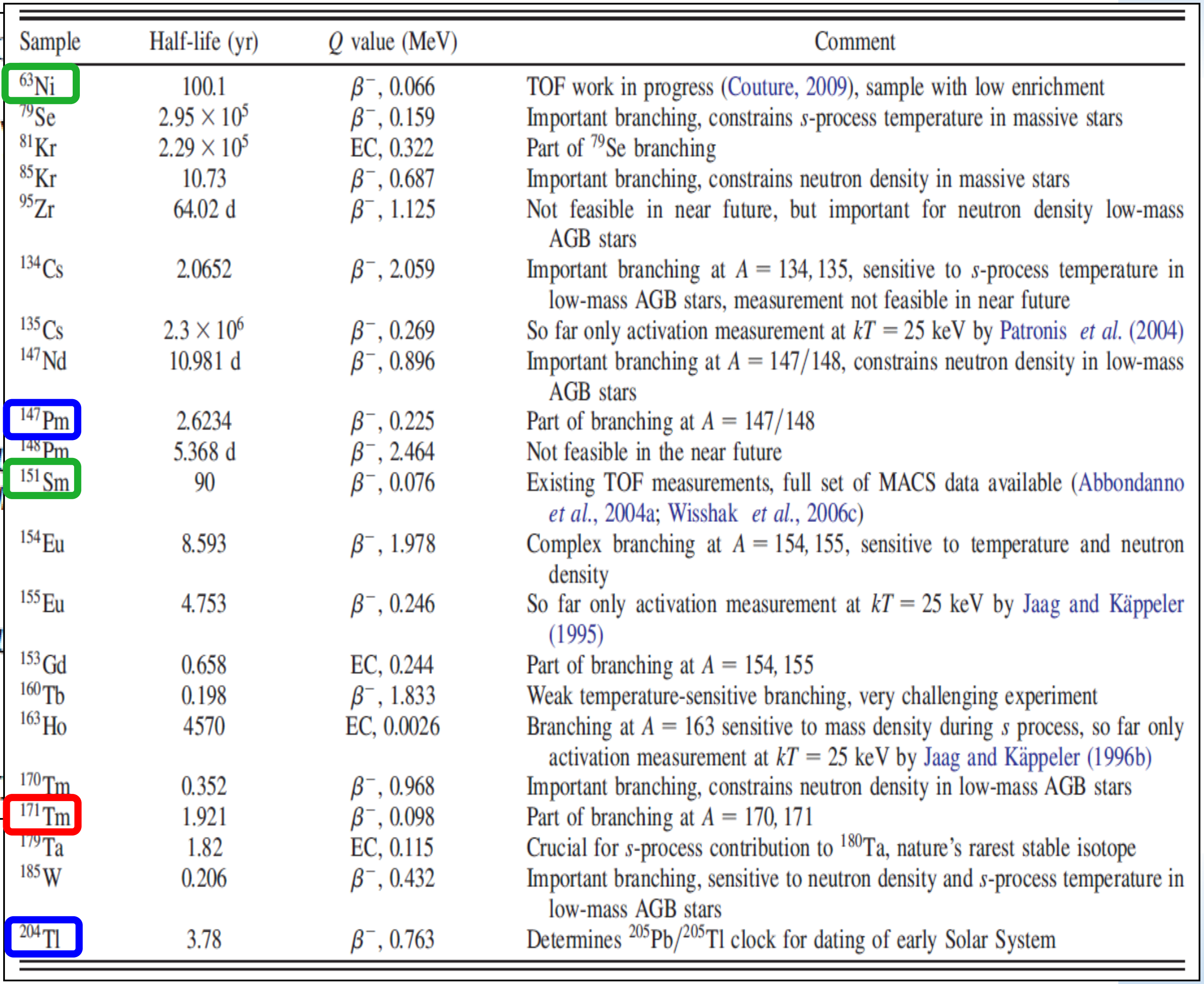
Dipartimento di Fisica Generale,
INAF-Osservatorio Astronomico d

S. Bisterzo‡

Dipartimento di Fisica Generale,

Wako Aoki§

National Astronomical Observator



Sample	Half-life (yr)	*Q* value (MeV)	Comment
^{63}Ni	100.1	β^-, 0.066	TOF work in progress (Couture, 2009), sample with low enrichment
^{79}Se	2.95×10^5	β^-, 0.159	Important branching, constrains *s*-process temperature in massive stars
^{81}Kr	2.29×10^5	EC, 0.322	Part of ^{79}Se branching
^{85}Kr	10.73	β^-, 0.687	Important branching, constrains neutron density in massive stars
^{95}Zr	64.02 d	β^-, 1.125	Not feasible in near future, but important for neutron density low-mass AGB stars
^{134}Cs	2.0652	β^-, 2.059	Important branching at $A = 134, 135$, sensitive to *s*-process temperature in low-mass AGB stars, measurement not feasible in near future
^{135}Cs	2.3×10^6	β^-, 0.269	So far only activation measurement at $kT = 25$ keV by Patronis *et al.* (2004)
^{147}Nd	10.981 d	β^-, 0.896	Important branching at $A = 147/148$, constrains neutron density in low-mass AGB stars
^{147}Pm	2.6234	β^-, 0.225	Part of branching at $A = 147/148$
^{148}Pm	5.368 d	β^-, 2.464	Not feasible in the near future
^{151}Sm	90	β^-, 0.076	Existing TOF measurements, full set of MACS data available (Abbondanno *et al.*, 2004a; Wisshak *et al.*, 2006c)
^{154}Eu	8.593	β^-, 1.978	Complex branching at $A = 154, 155$, sensitive to temperature and neutron density
^{155}Eu	4.753	β^-, 0.246	So far only activation measurement at $kT = 25$ keV by Jaag and Käppeler (1995)
^{153}Gd	0.658	EC, 0.244	Part of branching at $A = 154, 155$
^{160}Tb	0.198	β^-, 1.833	Weak temperature-sensitive branching, very challenging experiment
^{163}Ho	4570	EC, 0.0026	Branching at $A = 163$ sensitive to mass density during *s* process, so far only activation measurement at $kT = 25$ keV by Jaag and Käppeler (1996b)
^{170}Tm	0.352	β^-, 0.968	Important branching, constrains neutron density in low-mass AGB stars
^{171}Tm	1.921	β^-, 0.098	Part of branching at $A = 170, 171$
^{179}Ta	1.82	EC, 0.115	Crucial for *s*-process contribution to ^{180}Ta, nature's rarest stable isotope
^{185}W	0.206	β^-, 0.432	Important branching, sensitive to neutron density and *s*-process temperature in low-mass AGB stars
^{204}Tl	3.78	β^-, 0.763	Determines ^{205}Pb/^{205}Tl clock for dating of early Solar System

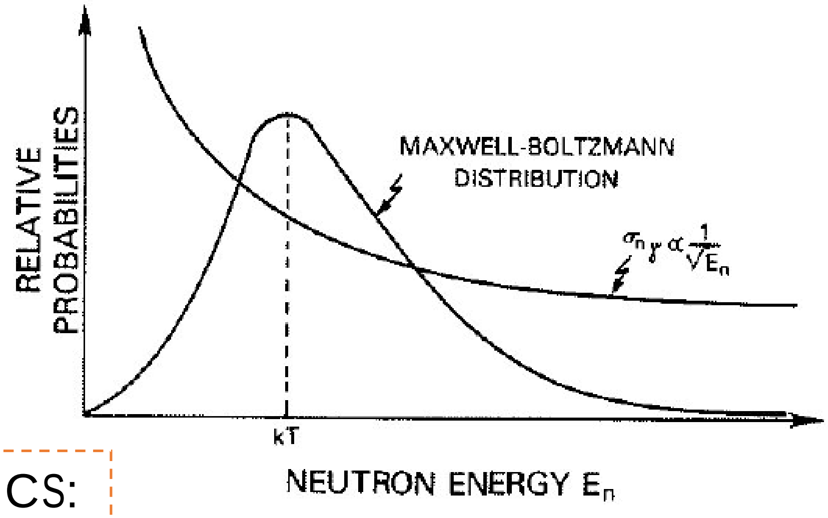
The maxwllian averaged cross sections (MACS)

For Astrophysical applications it is important to determine **Maxwellian Averaged Cross-Sections (MACS)**, for various temperatures (kT depends on stellar site).

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

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

MACS typically needed in a temperature range from 5 to 100 keV



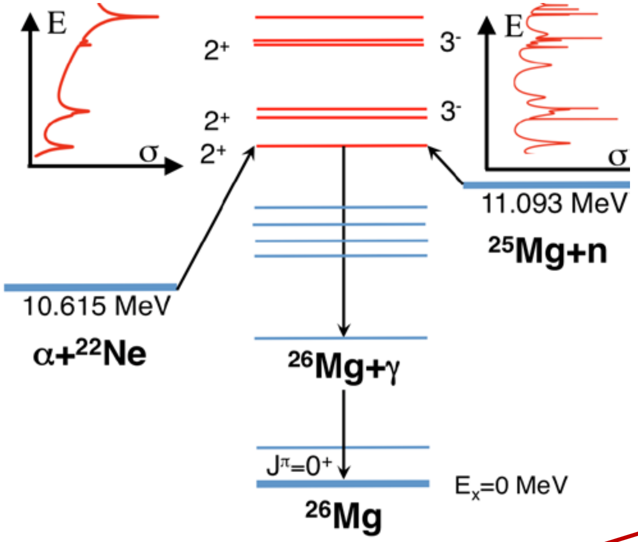
Two methods used to determine MACS:

- **integral measurements** (energy integrated) with neutron beams of Maxwell-like spectrum
- **time-of-flight technique** to measure energy-differential cross-sections.
  - TOF allows to determine MACS at various stellar temperatures and for any isotope.

Large activity currently undergoing at accelerator-based neutron beams:

- TOF facilities
- Quasi-maxwellian beams
- monoenergetic beams

Neutron data for stellar neutron sources



Neutron spectroscopy of **^{26}Mg** levels provide information on the **^{22}Ne(α,n)** neutron source.

Levels not easily accessible in α+^{22}Ne studied via **^{25}Mg capture and total** cross section.

For free: **MACS of ^{25}[illegible]n,γ)** neutron poison.

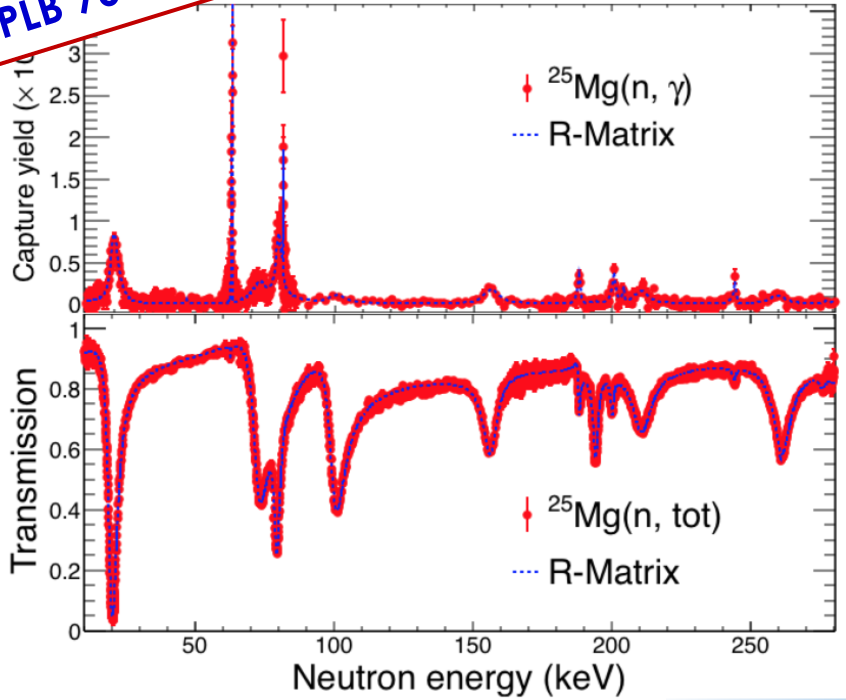
C. Massimi et al., PLB 768, 1 (2016)

High accuracy, [illegible]ution measurements of:

- capture XS at **n_TOF**
- Total XS at **GELINA**
- highly **enriched sample**.

For various levels high accuracy determination of:

- **energy**
- **spin and parity**
- Neutron and gamma widths



Neutron data for applications

Current activity in nuclear energy production by fission:

- **Criticality assesment and safety re-evaluation** of current nuclear reactors (including decay heat generation)
- Evaluation of nuclear waste at decommissioning
- **Design of Generation IV** fast nuclear reactors for recycling of nuclear fuel (closed cycle)
- **Transmutation of minor actinides** in different types of nuclear power reactors and accelerator-driven systems

HPRL The NEA High Priority Request List

OECD

www.nea.fr/html/dbdata/hprl/

Accurate nuclear data needed for advanced fission reactor systems in the **fast energy region** (from a few keV to several MeV)**:**

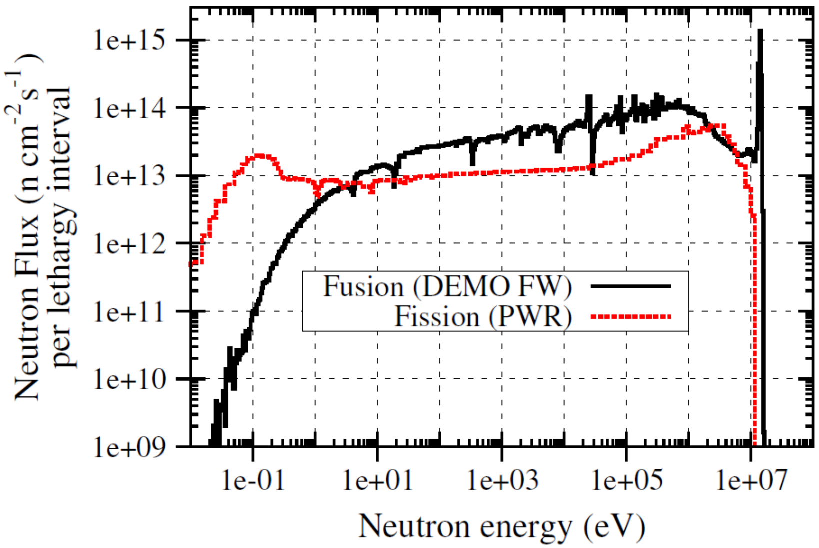
- Capture and inelastic cross section on FP and minor actinides
- fission of major and minor actinides

Reliable data needed for reliable simulations (**GIGO effect**)

Needs related to fusion for energy

Two main needs of **neutron data for Fusion for Energy**:

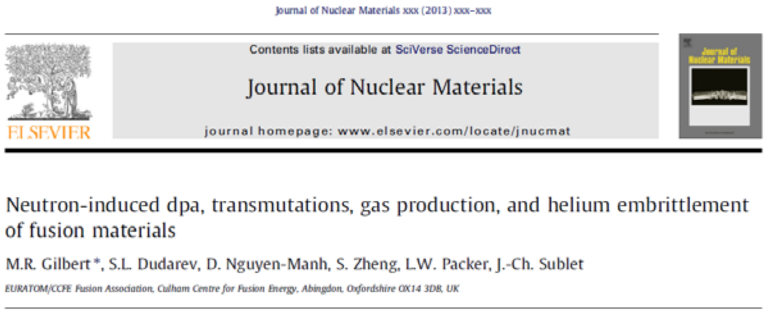
- **Activation** (and **transmutation**) data for structural material;
- **Gas production** (H and He) and He **embrittlment of structural material**



The **neutron spectrum** in future **fusion** reactors extends from 14 MeV down to thermal.

Neutron data are needed in a wide energy range for **ITER** and **DEMO**

Neutron facilities based on low-energy accelerators well suited for studying neutron-induced reactions for **Fusion**



Journal of Nuclear Materials xxx (2013) xxx–xxx

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journal homepage: www.elsevier.com/locate/jnucmat

Neutron-induced dpa, transmutations, gas production, and helium embrittlement of fusion materials

M.R. Gilbert *, S.L. Dudarev, D. Nguyen-Manh, S. Zheng, L.W. Packer, J.-Ch. Sublet

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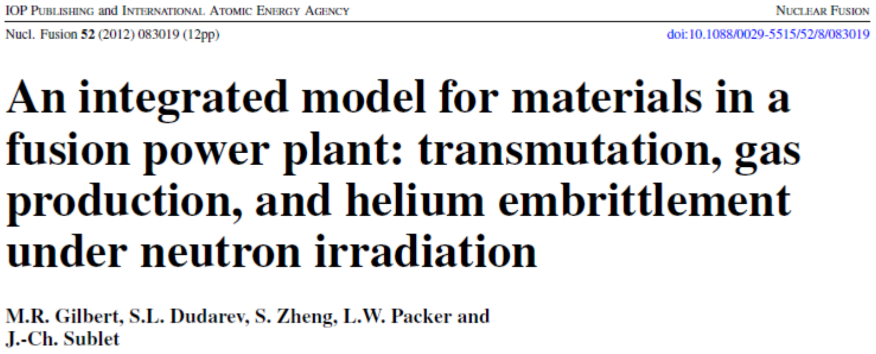


IOP Publishing and International Atomic Energy Agency — Nuclear Fusion

Nucl. Fusion **52** (2012) 083019 (12pp) — doi:10.1088/0029-5515/52/8/083019

An integrated model for materials in a fusion power plant: transmutation, gas production, and helium embrittlement under neutron irradiation

M.R. Gilbert, S.L. Dudarev, S. Zheng, L.W. Packer and J.-Ch. Sublet

Need of activation data for fusion

Cross sections for (n,p) and (n,α) reactions required for **structural elements** for application to Fusion Reactors (embrittlement of structural elements).

For most **stable isotopes**, **the (n,cp) cross section** could be measured at a TANDEM-based neutron source

Nuclide	Abund.	Reaction	Residual	Priority	Comment
Ne-20	90%	(n,p)	F-20	1	No data, judged measurable
Ne-22	9.2%	(n,α)	O-19	1	No data, judged measurable
Ne-22	9.2%	(n,d)	F-21	1	No data, judged measurable
S-34	4.2%	(n,d)	P-33	1	No data, judged measurable
S-34	4.2%	(n,α)	Si-31	1	Discrepant data
Cl-37	24%	(n,p)	S-37	1	Discrepant data
Ni58	68%	(n,t)	Co-56	1, A	Discrepant data
Zn-67	4.1%	(n,p)	Cu-67	1, B	Discrepant data
Ga-71	40%	(n,t)	Zn-69	1	No data, judged measurable
Kr-78	0.3%	(n,α)	Se-75	1	No data, judged measurable
Zr-90	51%	(n,p)	Y-90g	1, B	Discrepant data
Mo-92	15%	(n,d)	Nb-91	1	Discrepant data
Mo-94	9.2%	(n,p)	Nb-94	1	Discrepant data
Xe-132	27%	(n,α)	Te-129	1	No data, judged measurable
Re-187	63%	(n,t)	W-185	1	No data, judged measurable
Pt-195	34%	(n,d)	Ir-194m	1	No data, judged measurable
Pb-208	52%	(n,t)	Tl-206	1	No data, judged measurable

Neutron-induced reactions on the main structural materials (**Fe, V, Cr, Mo, Nb, Ta, W, Be and Zr**) may have a significant impact on their lifetime.

The **^{16}O(n,a)^{13}C** is the time-reversal reaction of the main neutron source in stars (s-process). Big interest in this reaction for **Nuclear Astrophysics**.

For a complete list, see R. Forrest, Fus. Eng. and Design 81 (2006) 2143

Needs related to Nuclear Medicine

There is an ongoing "Coordinated Research Project" of the IAEA on "Nuclear Data for Charged-particle Monitor Reactions and Medical Isotope Production".

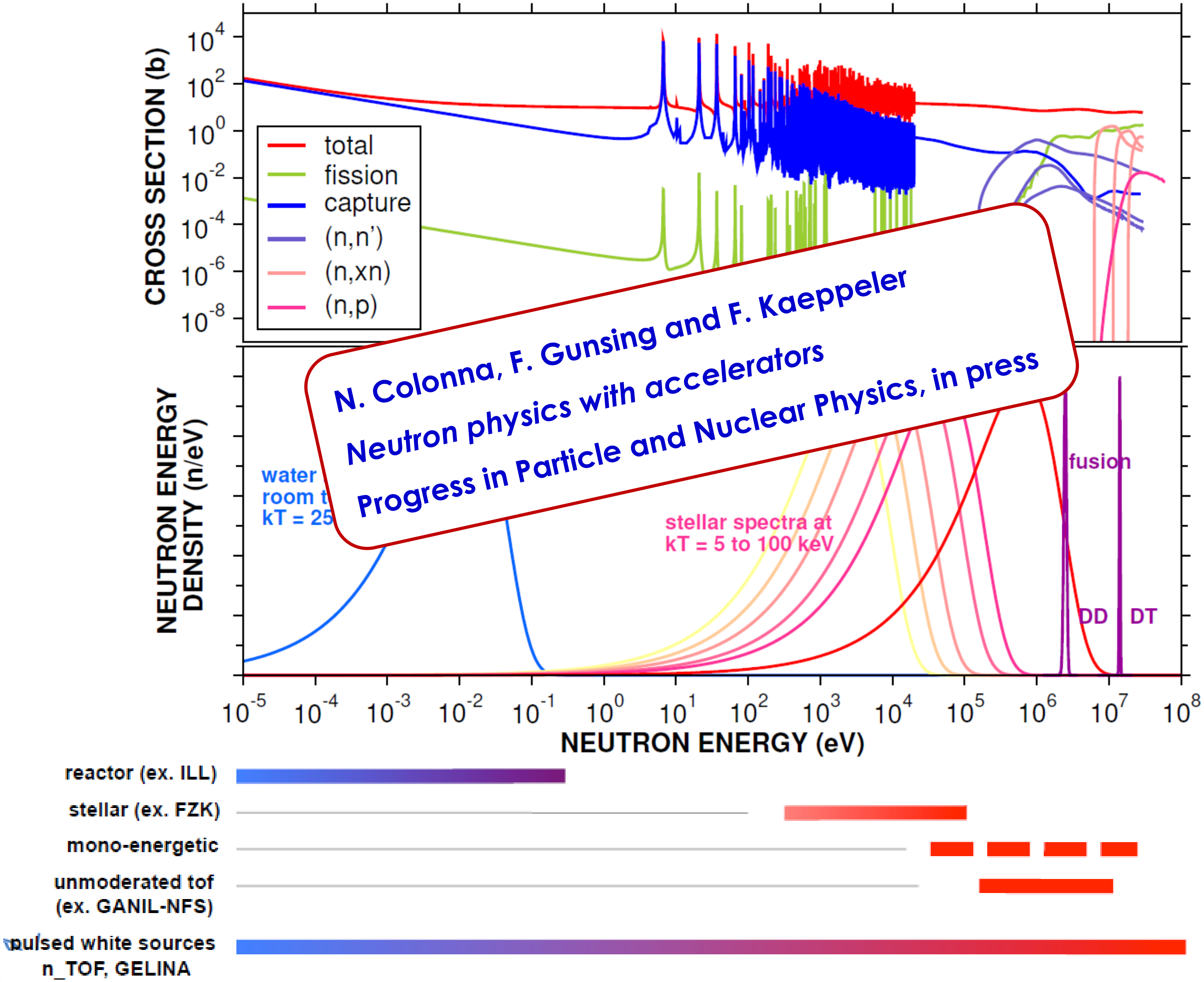
It focuses mostly on charged-particle induced reactions. However, there are a few neutron-induced reactions for medical applications, for which it may be important to measure the cross sections:

- **$^{90}Zr(n,p)^{90}Y^{g+m}$**
- **$^{67}Zn(n,p)^{67}Cu$, $^{68}Zn(n,x)^{67}Cu$, $^{64}Zn(n,p)^{64}Cu$**
- **New isotopes for theranostic (a new frontier in oncology)**
- **Elements involved in BNCT (like Sulphur)**

Other applications:

- Detector test (response to neutrons of new scintillators)
- Dosimetry
- In vivo neutron activation analysis

Neutron beams



N. Colonna, F. Gunsing and F. Kaeppeler

Neutron physics with accelerators

Progress in Particle and Nuclear Physics, in press

Neutrons beams

Neutron studies related to **Nuclear Astrophysics** and Nuclear **Technology** are mainly done at **a few large-scale facilities** in the world (n_TOF, LANSCE, JRC-IRMM, etc…).

However, many measurements cannot be performed at these facilities, because of technical difficulties or beam-time limitations.

Several small scale neutron facilities currently operating in the world and producing a wealth of data on basic and applied neutron physics. **Complementary to large-scale facilities**.

Neutrons time-of-flight facitlies

(p,n) and (d,n) reactions:

- Low and medium energy accelerator (pulsed)
- thick targets (for higher flux)
- moderated spectrum

Many facilities, often at Universities
Tandem, VdG, cyclotron
NFS, Ganil

High-intensity **electron beams**:

- neutron production though **(γ,n) reactions**
- target made of high-Z material (and U, in some cases)
- moderated spectra

GELINA (JRC-Geel, Belgium)
~~ORELA (Oak Ridge, USA)~~
nELBE (Dresden, Germany)

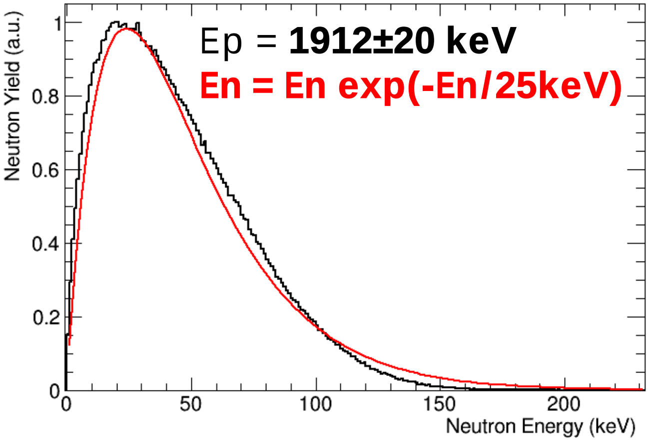
Spallation neutron sources:

- based on high-energy (GeV) protons beams
- Large blocks of heavy material
- Moderated spectrum

LANSCE (Los Alamos, USA)
n_TOF (CERN)
J-PARC (Japan)
CSNS (China)

Quasi-maxwellian neutron beams

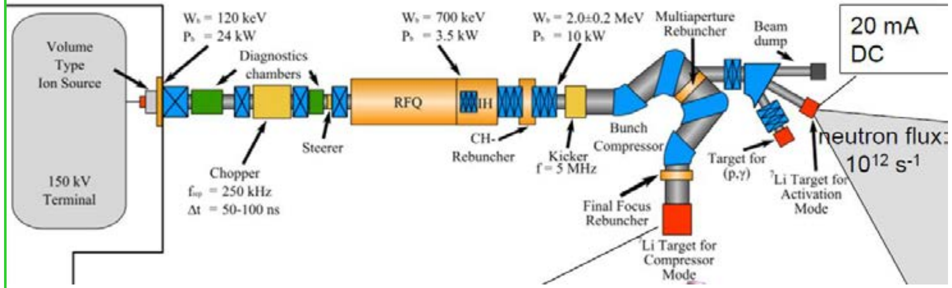
Practically all based on near-threshold ^{7}Li(p,n) reaction



Current frontier: high-intensity proton beams

Soreq Applied Research Accelerator Facility - SARAF (Israel)

- Superconducting Linac
- Liquid Lithium Target



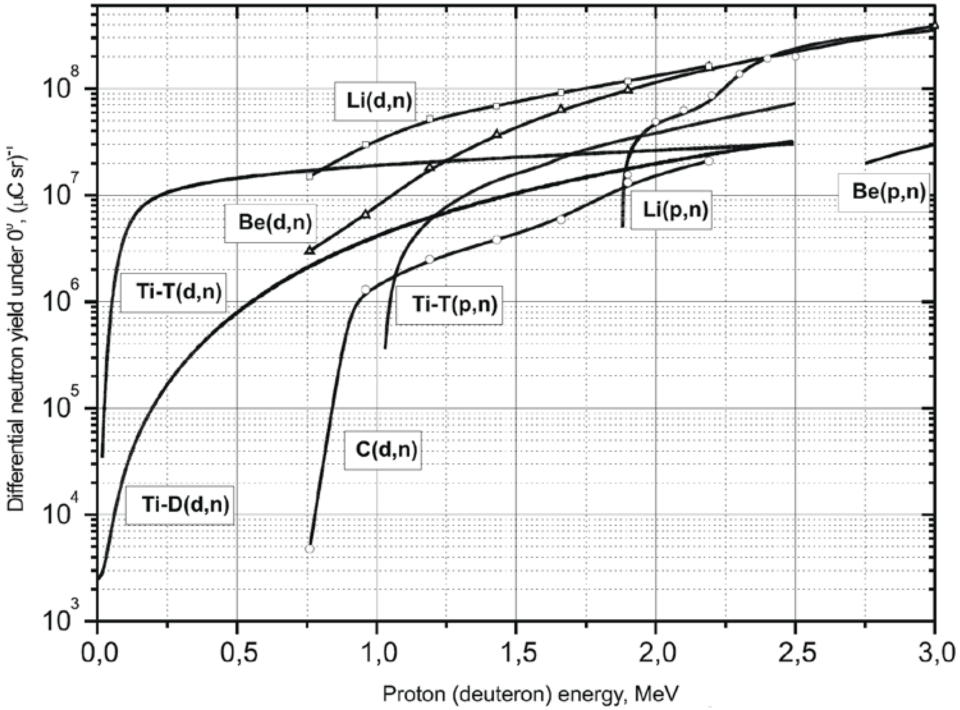
FRANZ (Germany)

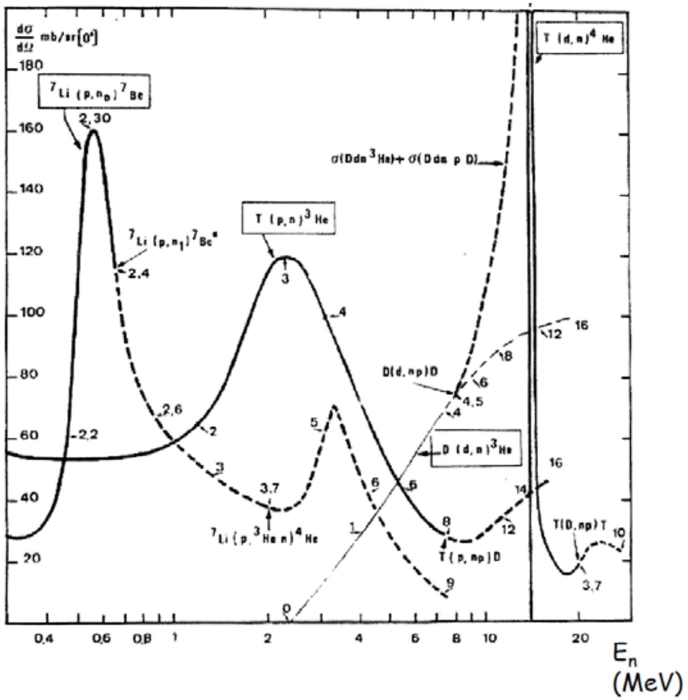
Delay in construction, possible to use a TANDEM at Un. of Frankfurt.

Monoenergetic neutrons beams

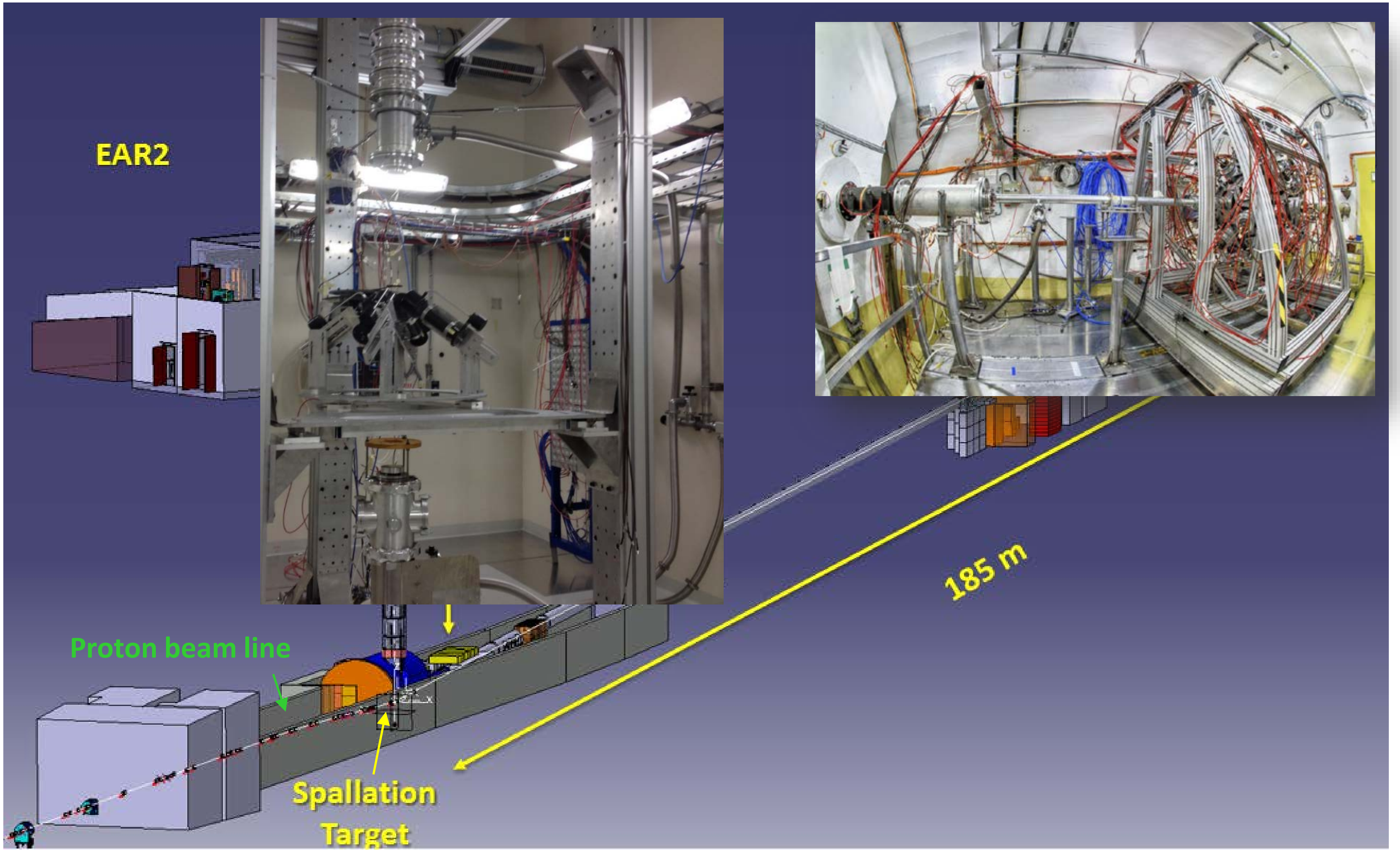
Monoenergetic neutron sources:

- typically based on **p- or d-induced** reaction produced with **low- and medium-energy** accelerators (VdG, Pelletron, cyclotrons, etc …)
- The **fabulous four**: D(d,n), T(d,n), ^{7}Li(p,n), ^{9}Be(p,n)
- Other neutron-producing reactions: T(p.n), ^{15}N(p,n)
- **accordable** neutron energy (by changing energy of the primary beam)
- neutron energies up to **20 MeV**



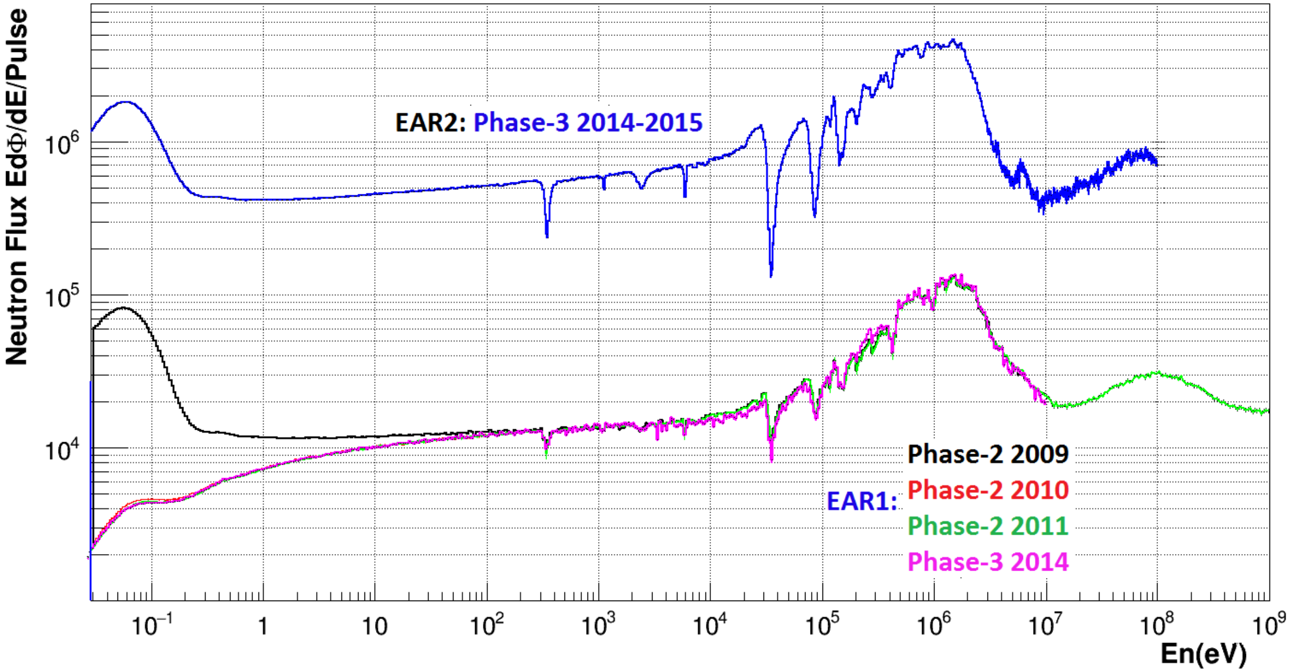


The n_TOF facility at CERN



The main advantage over other facilities is the **high neutron intensity**, allowing to measure reactions on **radioactive isotopes** (such as **branching points**).

The n_TOF neutron beams



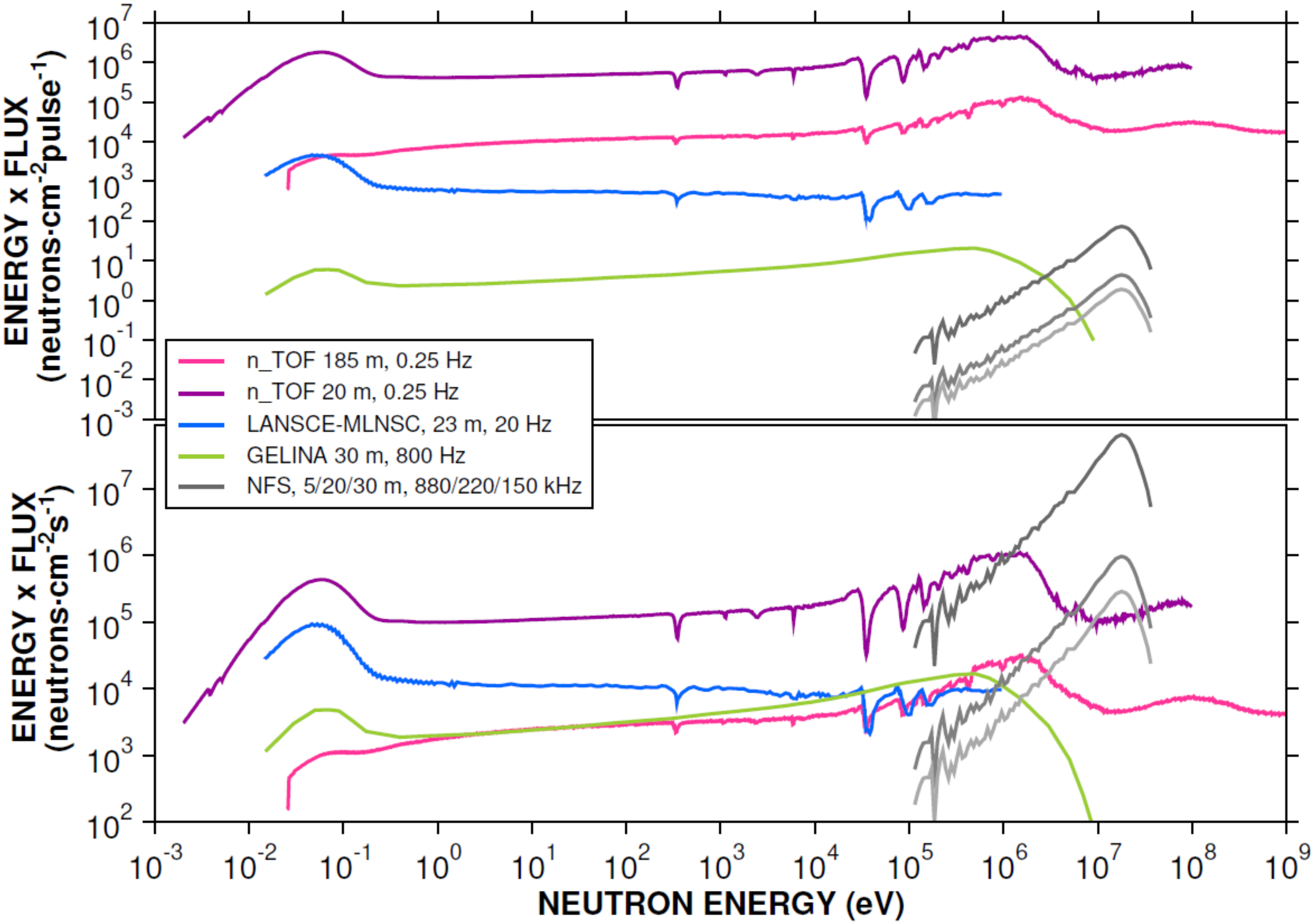
EAR1 (185 m)

- In operation since 2001.
- Measure radionuclides with half-life down to a **few hundred years**
- **High resolution** in energy allows to study **resolved resonances** up to several keV.

EAR2 (19 m)

- In operation since 2014.
- Neutron intensity increased by a **factor 40**, relative to EAR1.
- Possible to measure **sub-mg samples**, and radionuclides with **half-life** of a **few years**.

Neutrons time-of-flight facitlies



The n_TOF Astrophysics program

The combination of **excellent resolution**, **unique brightness** and **low background** has allowed to collect **high-accuracy data**, in some cases for the **first time ever.**

n_TOF measurements relevant for Nuclear Astrophysics

Capture cross sections (s-process)

- branching point isotopes
  - ^{151}Sm, ^{63}Ni, ^{147}Pm, ^{171}Tm, ^{204}Tl
- abundancies in presolar grains
  - ^{91,92,93,94,96}Zr
- magic nuclei and end-point
  - ^{139}La, ^{90}Zr, ^{204,206,207,208}Pb,^{209}Bi
- seeds isotopes
  - ^{54,56,57}Fe, ^{58,60,62}Ni
- Cosmocronometer, neutron poison, etc.
  - ^{186,187,188}Os, ^{24,25,26}Mg

(n,cp) reactions

- Big Bang Nucleosynthesis
  - ^{7}Be(n,a) and ^{7}Be(n,p)
- Various
  - ^{59}Ni(n,a), ^{26}Al(n,α), ^{33}S(n,α)

The PTB neutron sources

PTB Ion Accelerator Facility (**PIAF**) based on 3.5 MV VdG (plus cyclotron for higher energy neutrons):

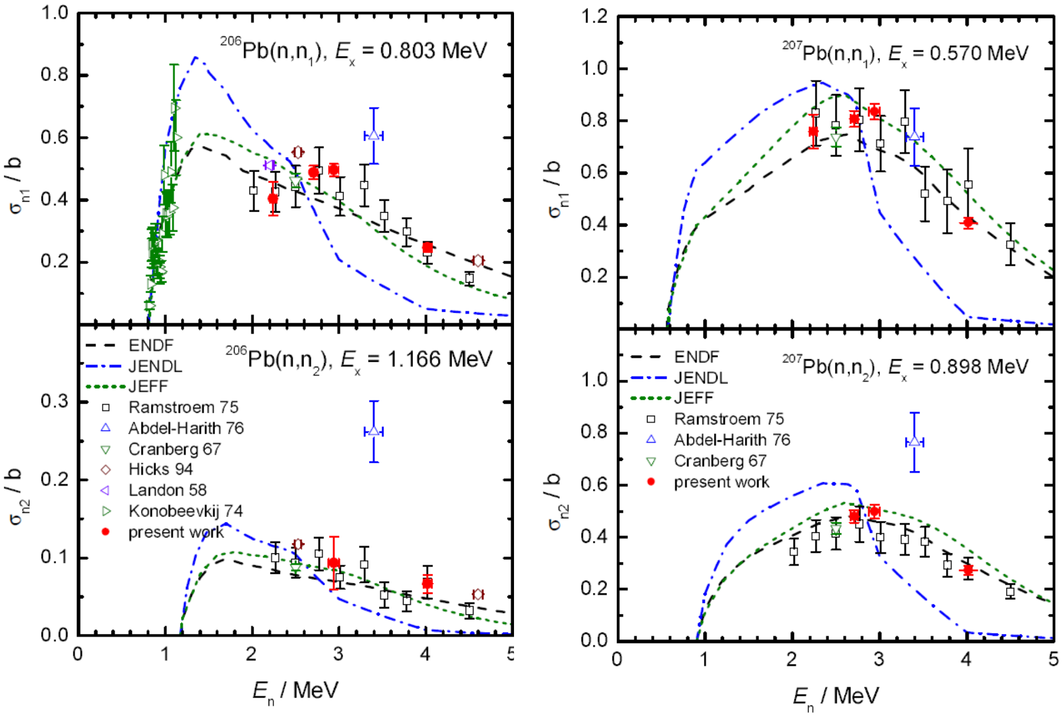
- **Fusion- and fission**-related studies
  - Inelastic scattering on ^{206,207}Pb, ^{209}Bi
  - β-delayed neutrons from ^{232}Th and ^{237}Np
- **Metrology**
- Study of the **$^{15}N(p,n)^{15}O$ neutron source**
- **Detector testing** (for example, the Proton Recoil Telescope for n_TOF)

Monoenergetic fields:

^{7}Li(p,n): En= 144keV - 1MeV
T(p,n) : En = 1MeV - 4 MeV
D(d,n):En=5 MeV - 8MeV
T(d,n) : En =14,8 MeV-17MeV

Quasi-monokinetic fields:

D(d,n): En =8MeV - 15 MeV
T(d,n): En =17MeV - 23 MeV



E. Poenitz et al., JKPS 59 (2011) 1876

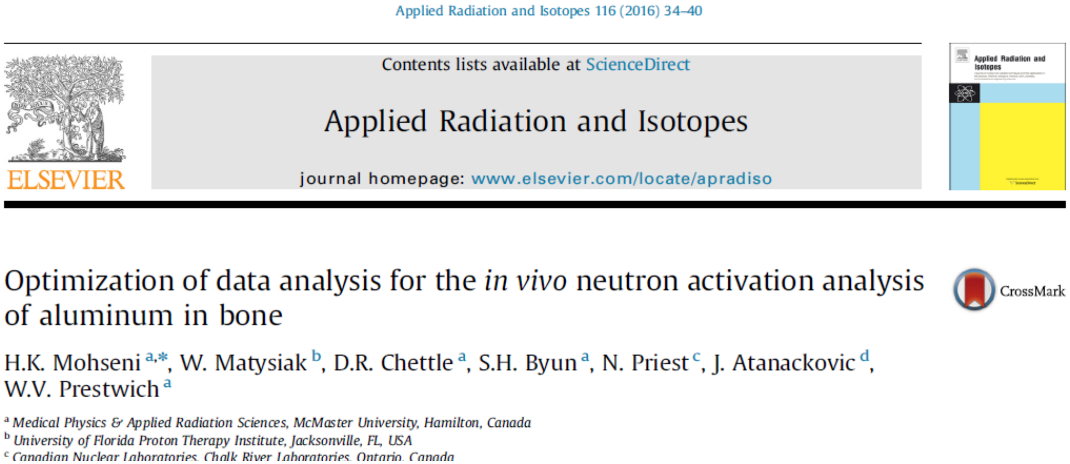
The Tandem at McMaster University

In Vivo Neutron Activation Analysis performed on hand bone with thermal neutrons produced with a TANDEM at the **McMaster University, Canada**

Allows to determine the **concentration of some isotopes** in human tissues (Ca, Na, Cl, Al), due to **environmental, medical, and occupational exposures**.

Neutrons produced with the near-threshold $^{7}Li(p,n)$ reaction, and moderated down to thermal energy.

Fig. 1. Irradiation cavity of the Tandetron accelerator at McMaster University.



Applied Radiation and Isotopes 116 (2016) 34–40

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Optimization of data analysis for the *in vivo* neutron activation analysis of aluminum in bone

H.K. Mohseni [a,*], W. Matysiak [b], D.R. Chettle [a], S.H. Byun [a], N. Priest [c], J. Atanackovic [d], W.V. Prestwich [a]

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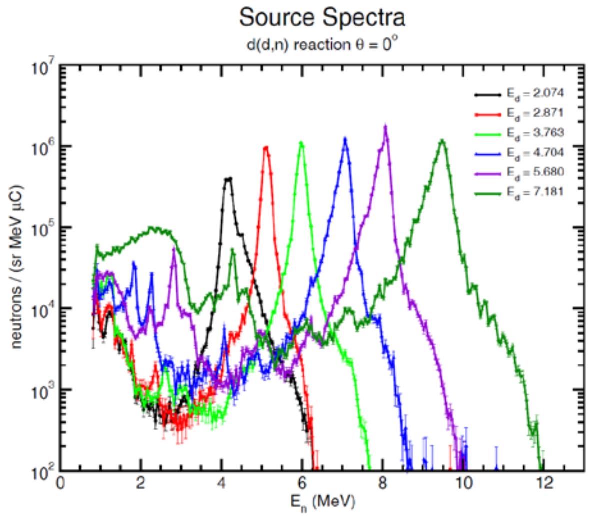
[b] *University of Florida Proton Therapy Institute, Jacksonville, FL, USA*
[c] *Canadian Nuclear Laboratories, Chalk River Laboratories, Ontario, Canada*

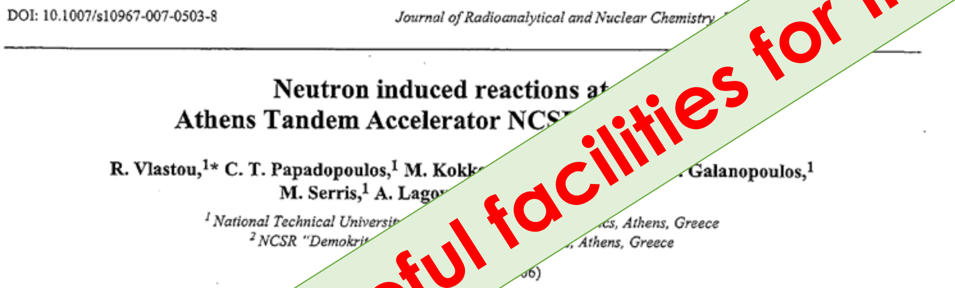
Other Tandem-based neutron sources



At the 4.5 MV Tandem of Ohio Uni ity **white-spectrum and monoenergeti n** beams are produced with en o 20 MeV for various purposes.

C. Brune et al., Edward Laboratory at Ohio Un.

Very useful facilities for training and education



DOI: 10.1007/s10967-007-0503-8 *Journal of Radioanalytical and Nuclear Chemistry*

Neutron induced reactions at
Athens Tandem Accelerator NCS

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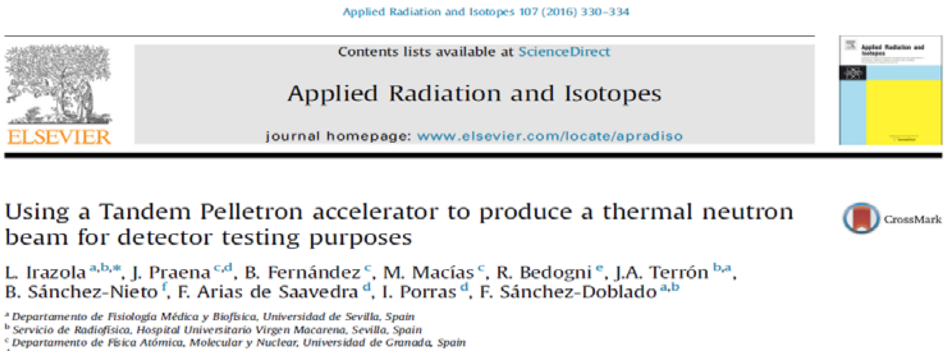
06)

veral **inelastic reactions** measured at the Tandem Laboratory at **Demokritos**, Athens.

Fission measurements have complemented n_TOF data.

3 MV Tandem Pelletron in **Sevilla used for measurements** in Nuclear Astrophysics, **detector testing**, imaging, etc…



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ELSEVIER

Using a Tandem Pelletron accelerator to produce a thermal neutron beam for detector testing purposes

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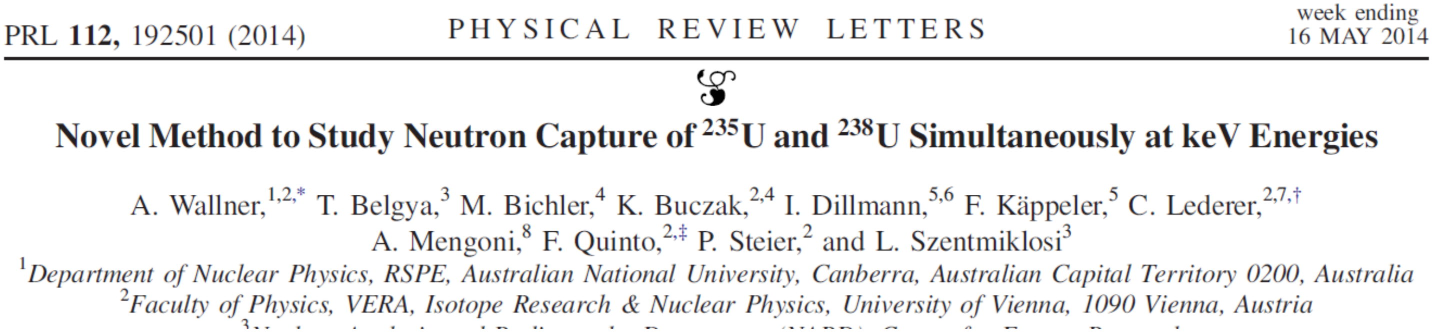
Combined activation and atom counting

Last but not least, **a new technique** can be exploited for challenging measurements: **irradiation with neutron beams** from low-energy accelerators **followed by atom counting** at AMS facilities.

Very sensitive technique, virtually background free, allows **high precision** measurements (neutron capture and (n,cp) reactions).



PRL **112,** 192501 (2014) PHYSICAL REVIEW LETTERS week ending 16 MAY 2014

Novel Method to Study Neutron Capture of ^{235}U and ^{238}U Simultaneously at keV Energies

A. Wallner,[1,2,*] T. Belgya,[3] M. Bichler,[4] K. Buczak,[2,4] I. Dillmann,[5,6] F. Käppeler,[5] C. Lederer,[2,7,†]
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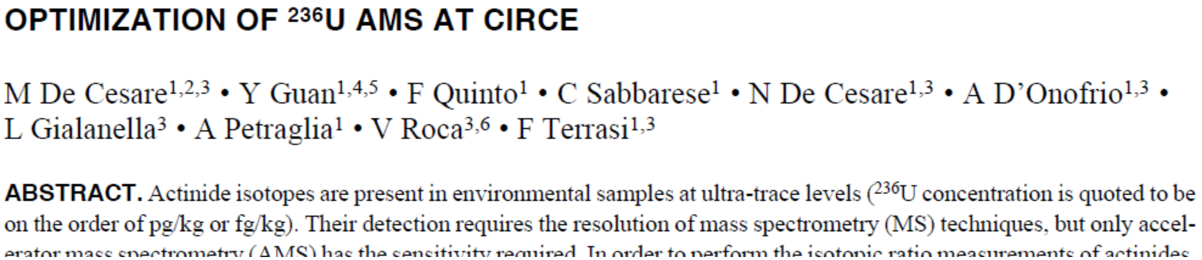


OPTIMIZATION OF ^{236}U AMS AT CIRCE

M De Cesare[1,2,3] • Y Guan[1,4,5] • F Quinto[1] • C Sabbarese[1] • N De Cesare[1,3] • A D'Onofrio[1,3] •
L Gialanella[3] • A Petraglia[1] • V Roca[3,6] • F Terrasi[1,3]

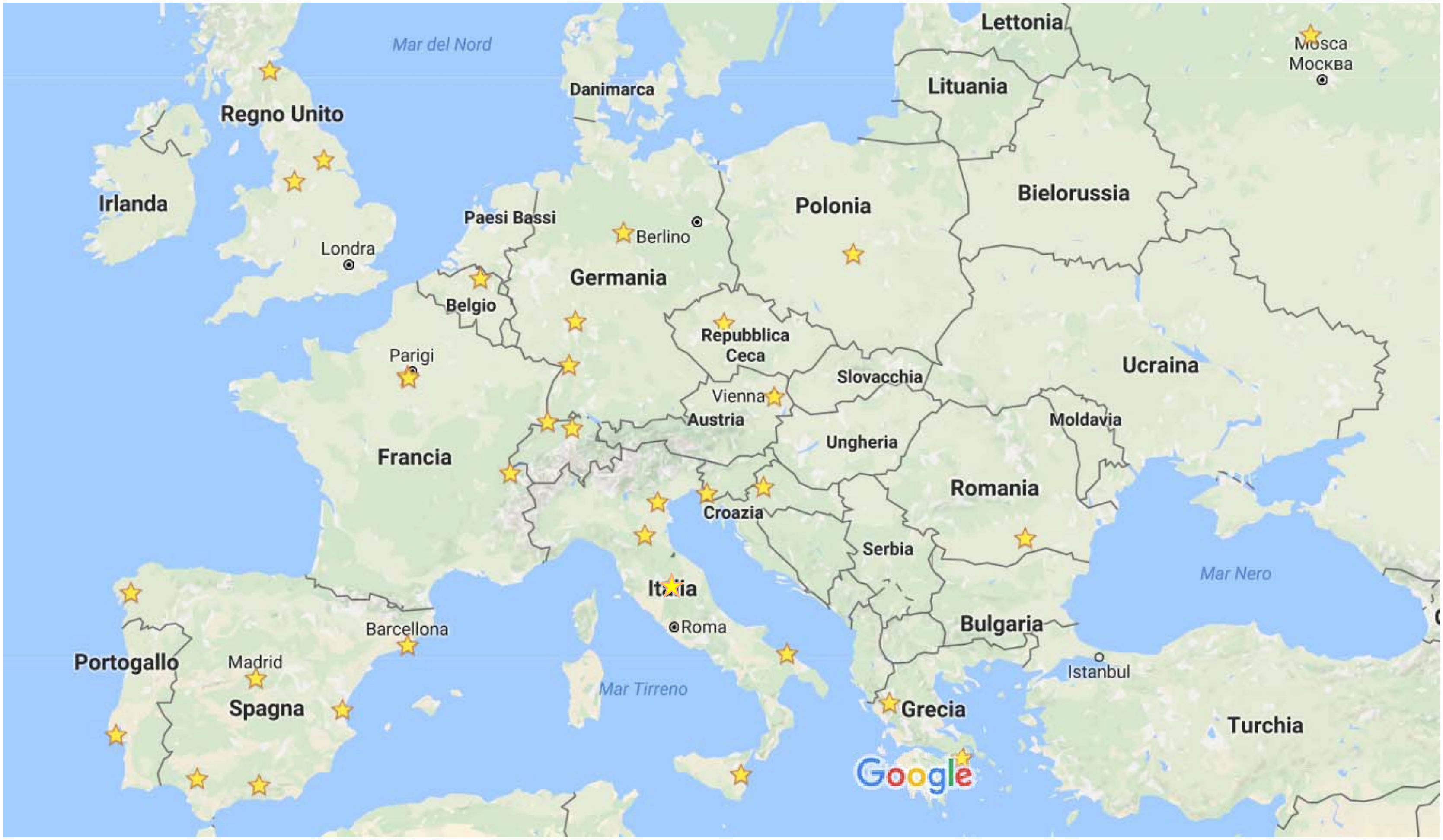
ABSTRACT. Actinide isotopes are present in environmental samples at ultra-trace levels (^{236}U concentration is quoted to be on the order of pg/kg or fg/kg). Their detection requires the resolution of mass spectrometry (MS) techniques, but only accelerator mass spectrometry (AMS) has the sensitivity required. In order to perform the isotopic ratio measurements of actinides

Conclusions

- ❑ There is need of **accurate new data** on neutron reactions for **Nuclear Astrophysics, Nuclear Technology, Nuclear Medicine, etc….**
- ❑ **Large-scale facilities** mostly dedicated to challenging new measurements, **small-scale** neutron beams very important for high-precision measurements, detector testing, various applications. **Complementarity.**
- ❑ **University-based facilities** extremely important (I would say essential) for **education and training** (many PhD students and Post-docs in n_TOF come from small-scale facilities such as Demokritos, Sevilla, FRANZ, etc…).
- ❑ One interesting possibility is the **combination of the Tandem** lab in Naples with the **Circe** AMS facility.

Thank you

The n_TOF Collaboration



38 Participating Institues: EU (34), Japan (2), India (1), Australia (1)

120 Participating researchers