Direct Measurements in Nuclear Astrophysics

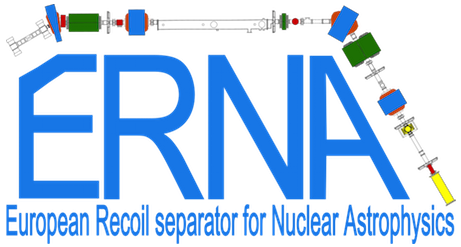
D.Piatti for LUNA (denise.piatti@pd.infn.it)

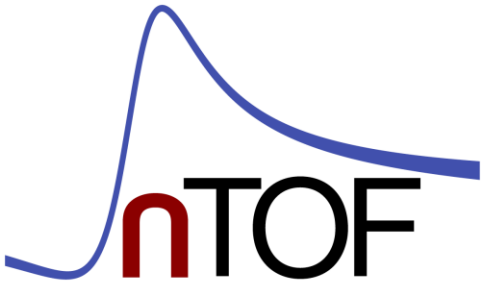
S. Amaducci for n_TOF

(simone.amaducci@lns.infn.it)

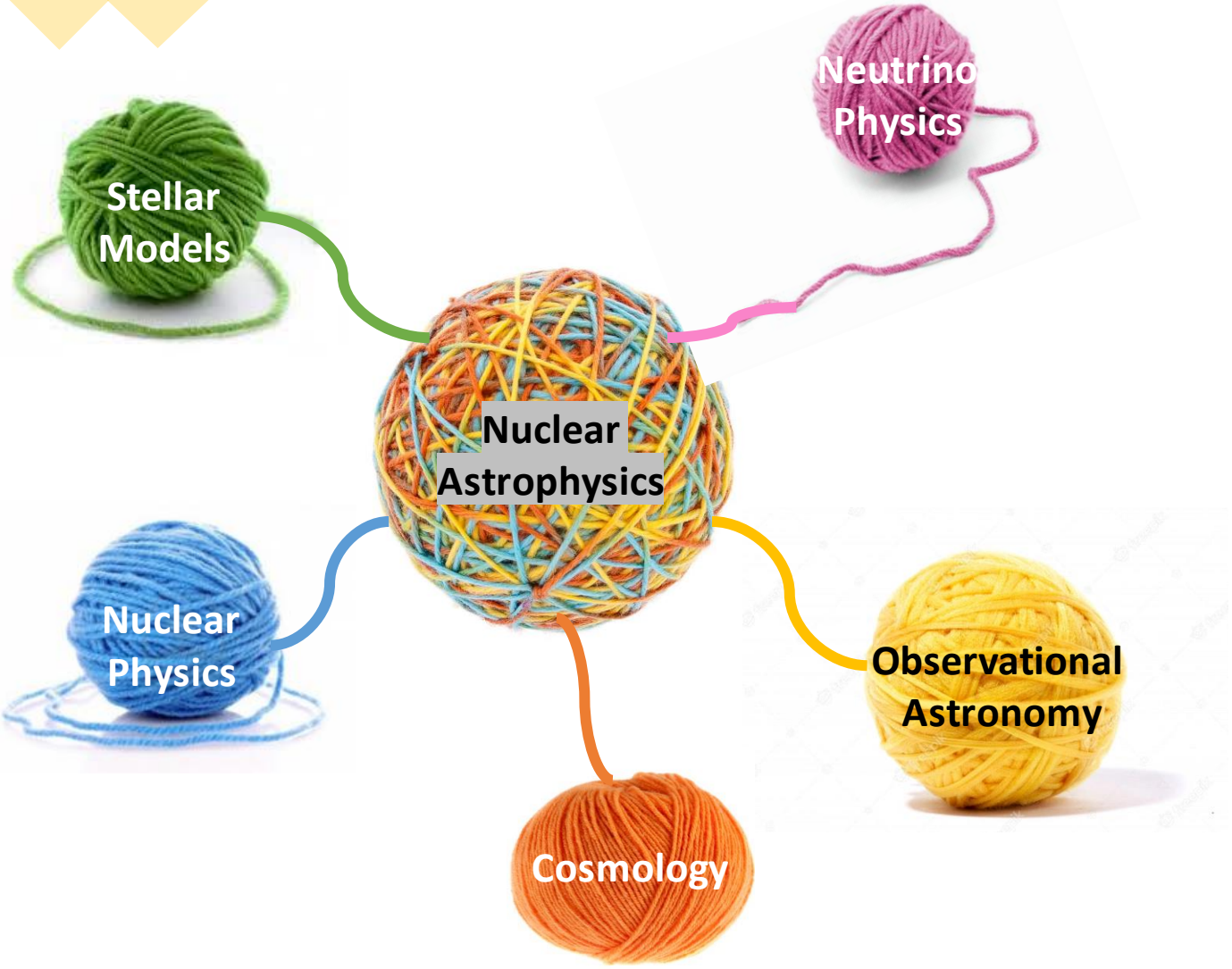
R. Buompane for ERNA

(raffaele.buompane@na.infn.it)





Nuclear Astrophysics



- Nuclear Astrophysics is a transversal science
- *Three* souls:
  - Theoretical
  - Experimental
- The experimental can be divide:
  - **Direct Measurements**
  - Indirect Measurements

Italian Facilities for Direct Measurements for Nuclear Astrophysics

n_TOF @ CERN

LUNA400kV at LNGS

ERNA at CIRCE Laboratory

Direct Measurement in Nuclear Astrophysics

Reaction Rate = reactions per unit of volume and time

$= N_b \times N_t \times \sigma(E) \times \text{efficiency}(E)$

10^{12} pps (with typical beam current ~ μA q= 1+)

10^{18} atoms/cm^2 (solid target)

~ 10^{-12} barn (~ 10^{-36} cm^2) at energies of interest

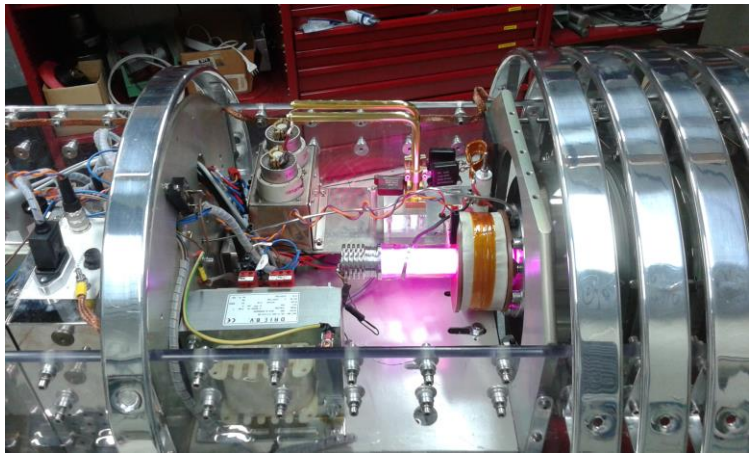
from ≤ 1% up to 10% in case of HPGe detector(s)
up to ~60% with scintillators

Observed Count Rate = 1-10 counts/day -> **S/N** ≤ 1

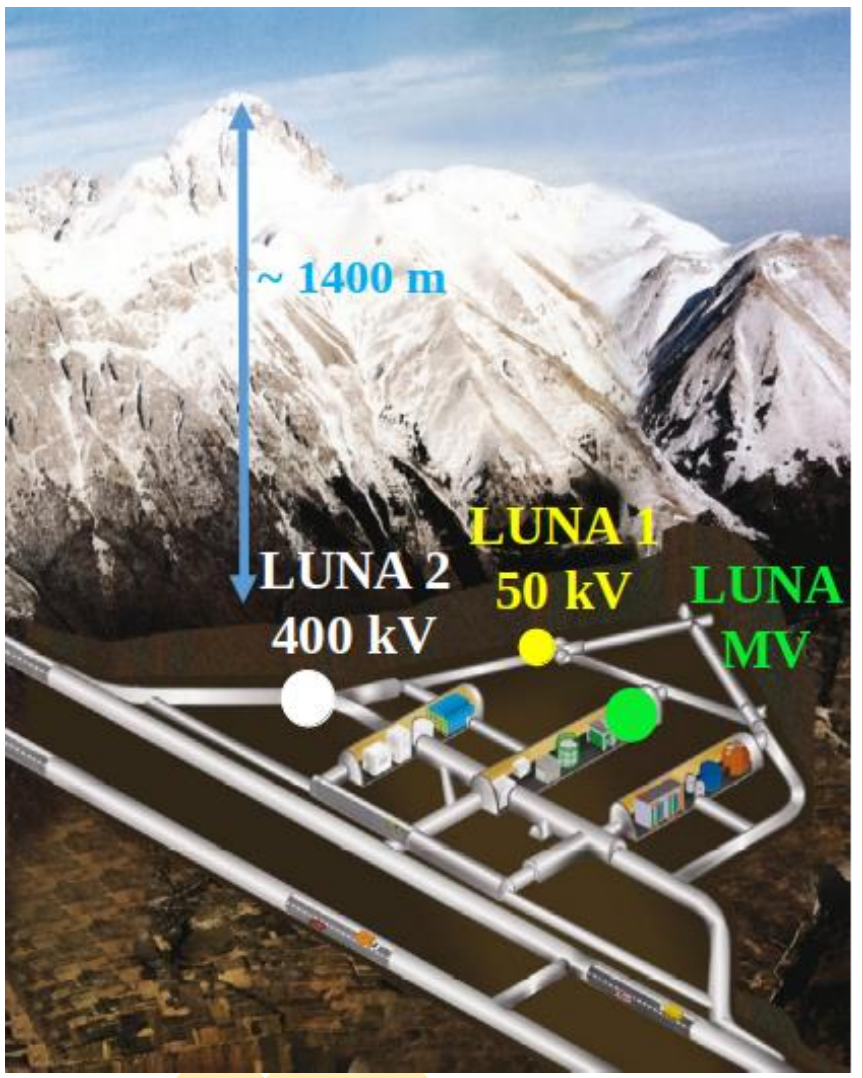
Laboratory for Underground Nuclear ∩strophysics

- LUNA is located at Laboratori Nazionali del Gran Sasso
- Shielded by 1400 m of rock (4000 m w.e.)
- Background reduction:
  - Muon 10^{-6}
  - Neutron 10^{-3} -> γ-spectrum
  - by factor 15 -> particle spectra
- 30 years long story -> 3 accelerators:
  - LUNA50kV(1991-2001)
  - LUNA400kV (2001-…)
  - LUNAMV (2022-…)

TV =50 - 400 kV
H^+ = 1000 µA
He^+ = 500 µA
High stability and collimated beam
2 Beamlines: solid and gas target

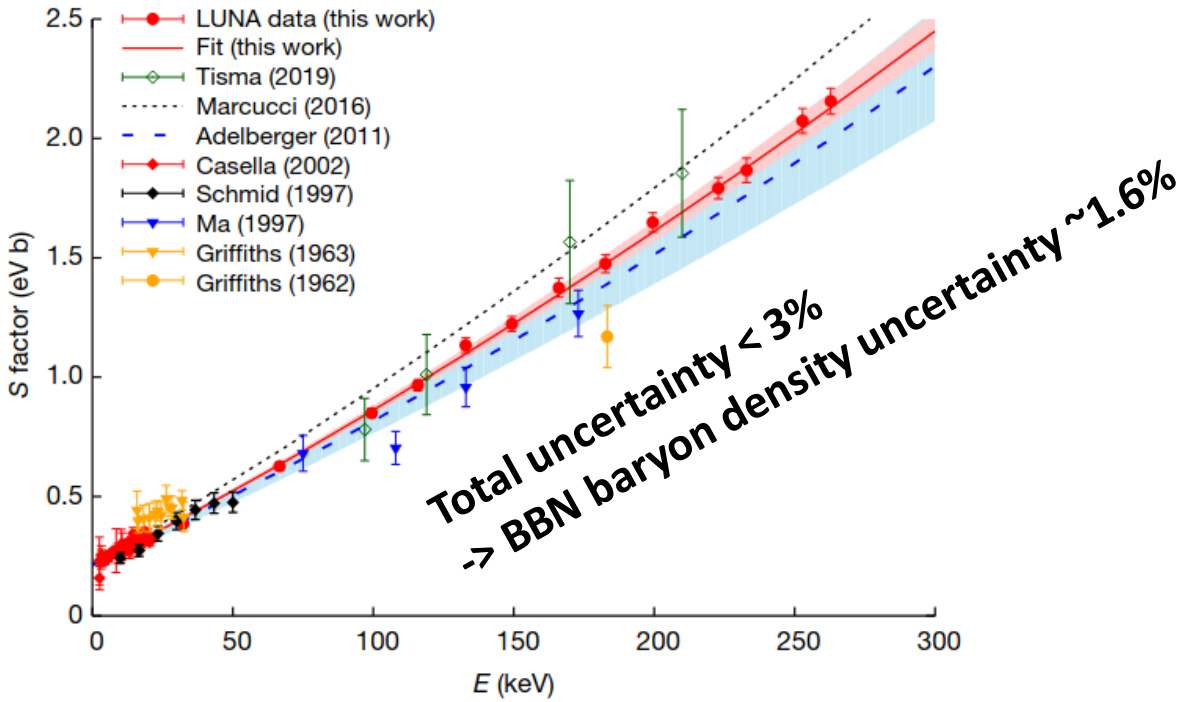


TV = 0.3 - 3.5 MV
H^+ = 1000 µA
He^+ = 500 µA
$^{12}C^+/^{12}C^{++}$ = 150/100 µA
2 beamlines: solid and gas target



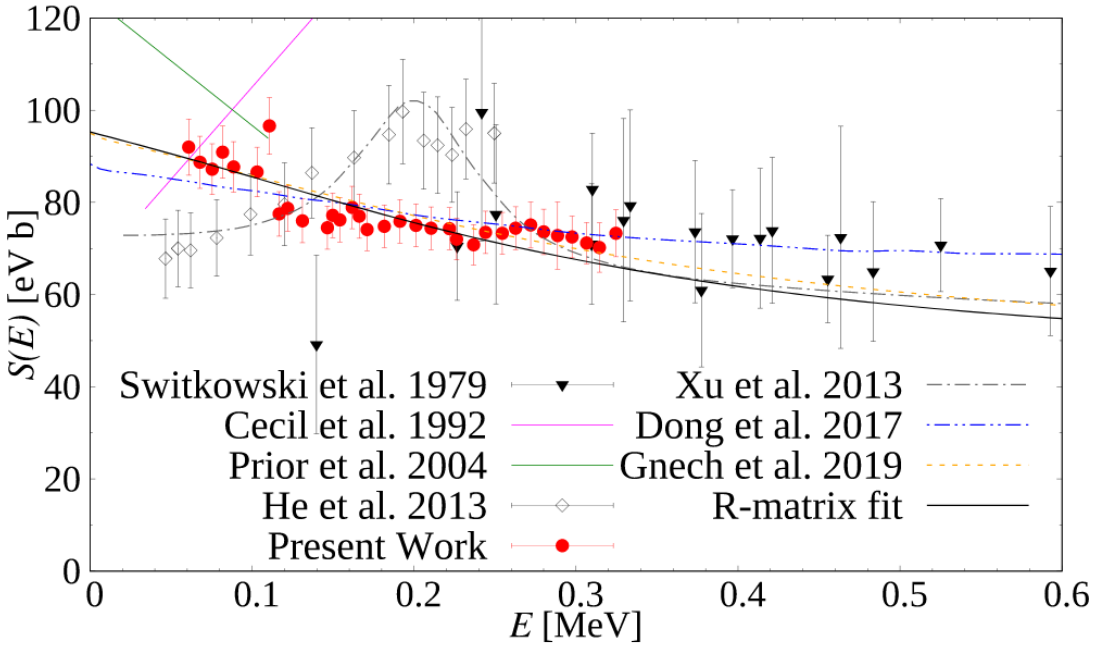
Latest News from/about LUNA

High precision study of the $^{2}H(p,\gamma)^{3}He$ reaction



[V. Mossa et al., Nature (2020)]

Underground study of the $^{6}Li(p,\gamma)^{7}Be$ reaction



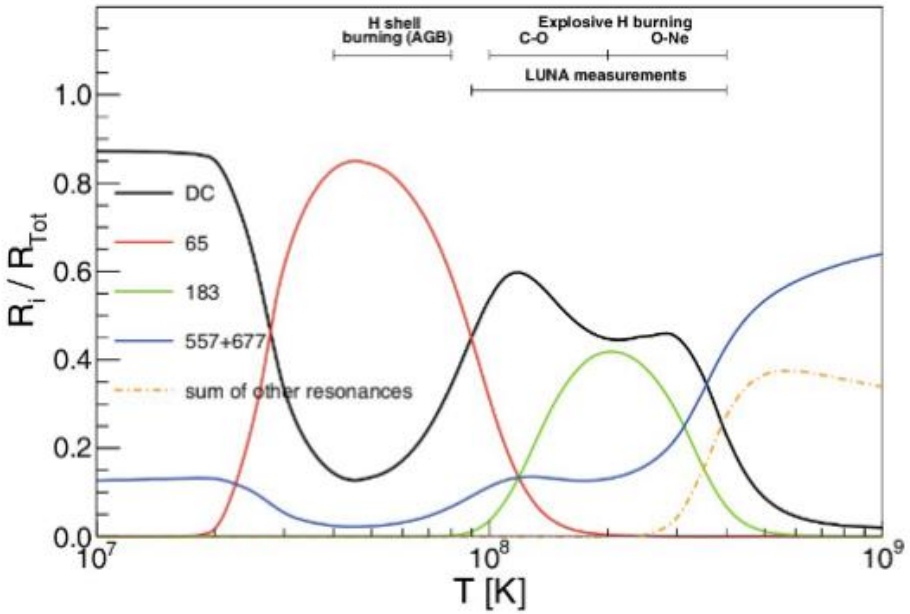
[D. Piatti et al., PRC Rapid Communication (2020)]
Recently confirmed by G. G. Kiss et al., PRC (2021)

Other Recent Results:

- G.Ciani et al., accepted PRL -> $^{13}C(\alpha,n)^{16}O$ cross section measurement into the *s*-process Gamow peak
- F.R.Pantaleo et al., PRC (2021) -> Low-energy resonances in the $^{18}O(p,\gamma)^{19}F$ reaction-> H-shell burning in AGB
- Piatti et al., submitted to A&A -> New upper limit of $^{22}Ne(\alpha,g)^{26}Mg$ resonance at 334 keV->*s*-process and AGB

In progress at LUNA : $^{17}O(p,\gamma)^{18}F$

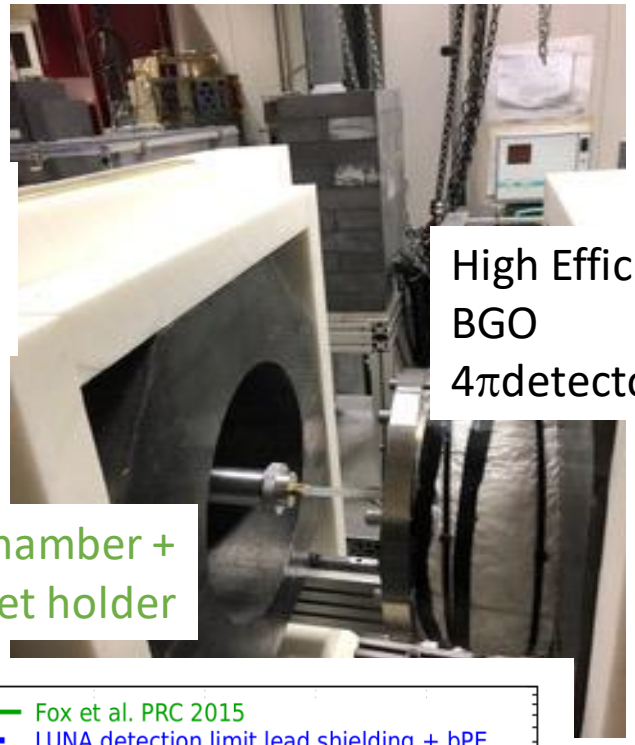
- Motivation:



- SoA: Only indirect measurements
  -> $\omega\gamma = 1.6 \times 10^{-11}$ eV [C.Fox et al., PRC (2005)]
  -> estimated count rate << 1 c/C!!!

- Setup:

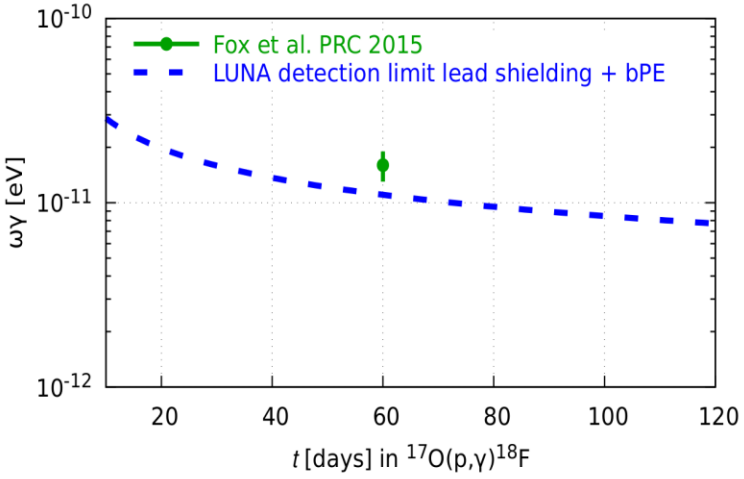
Double shielding: bPe+Pb

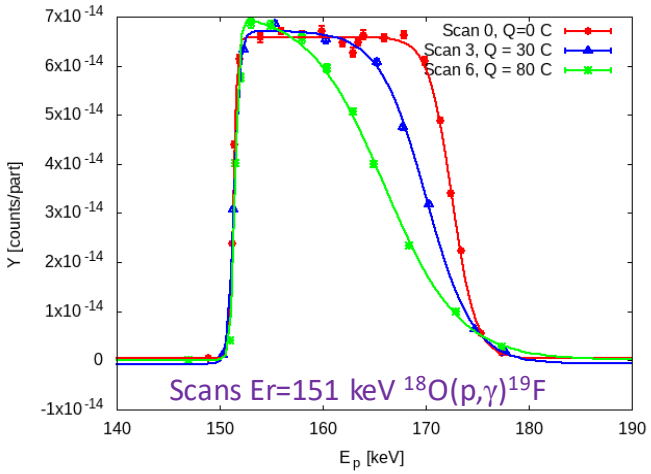


High Efficiency BGO 4πdetector

Al chamber + target holder

Solid target by anodic oxidation





$^{20}Ne(p,\gamma)^{21}Na$ -> HAVE A LOOK AT ELIANA MASHA TALK

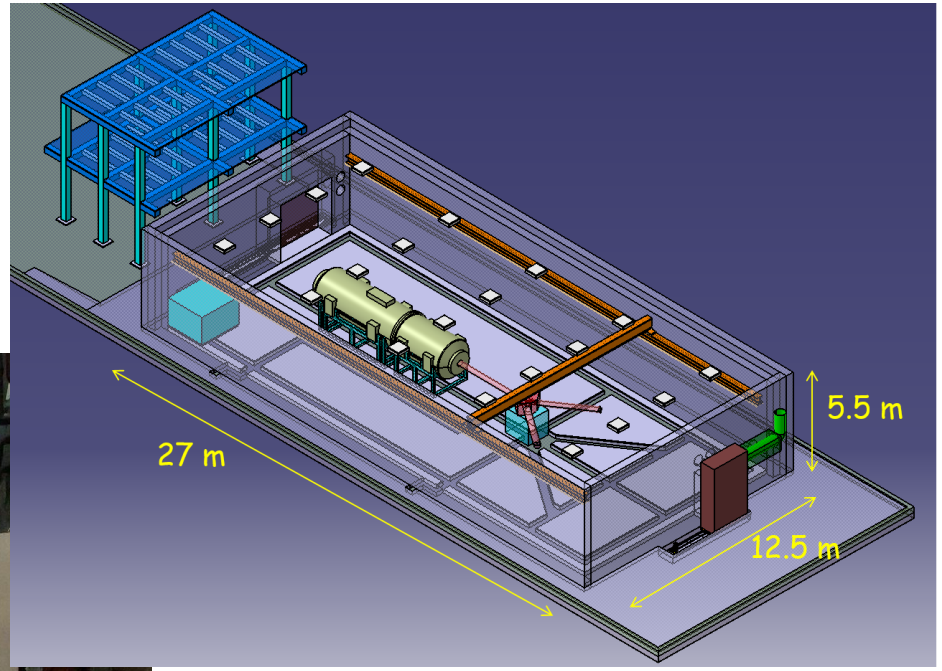
$^{12/13}C(p,\gamma)^{13/14}N$ -> HAVE A LOOK AT JAKUB SKOWRONSI

Next at LUNA

New LUNA400kV proposal (2022-2025) :

- $^{16}O(p,\gamma)^{17}F$
- $^{21}Ne(p,\gamma)^{22}Na$
- $^{23}Na(p,\alpha)^{20}Ne$
- $^{27}Al(p,\alpha)^{24}Mg$

} H-shell burning in AGB



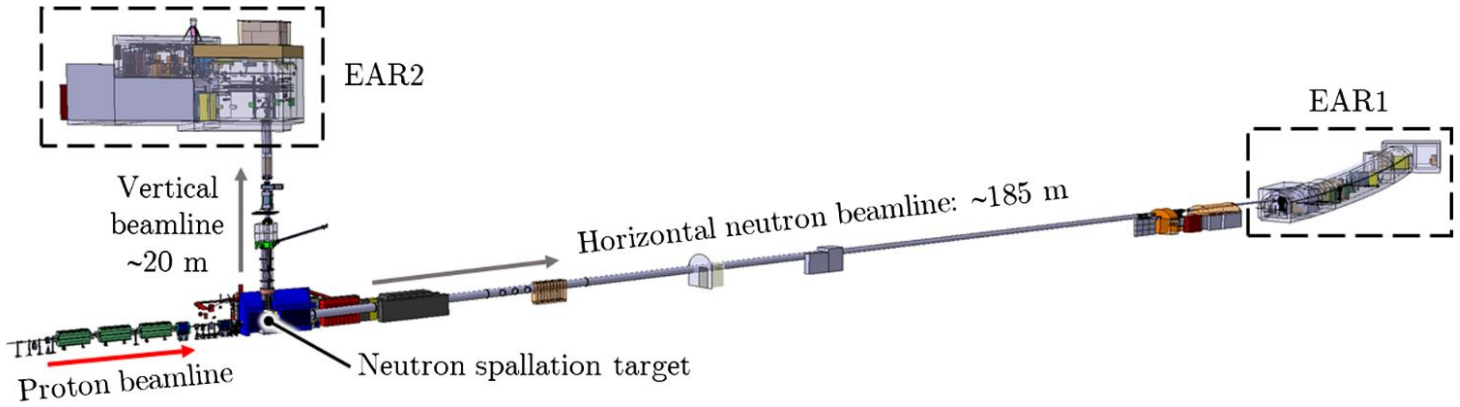
HERE IS LUNAMV!

- Installation will start in October 2021
- Scientific Proposal:
  - $^{14}N(p,\gamma)^{15}O$ CNO cycle
  - $^{12}C + ^{12}C$ Carbon burning
  - $^{13}C(\alpha,n)^{16}O$
  - $^{22}Ne(\alpha,n)^{25}Mg$

} s-process

neutron _ Time Of Flight

Pulsed spallation **neutron source** located at **CERN**, n_TOF is a unique environment to perform high accurate measurements of neutron induced reactions cross sections.
Two experimental areas with different flight path (hence flux and resolution) are available.



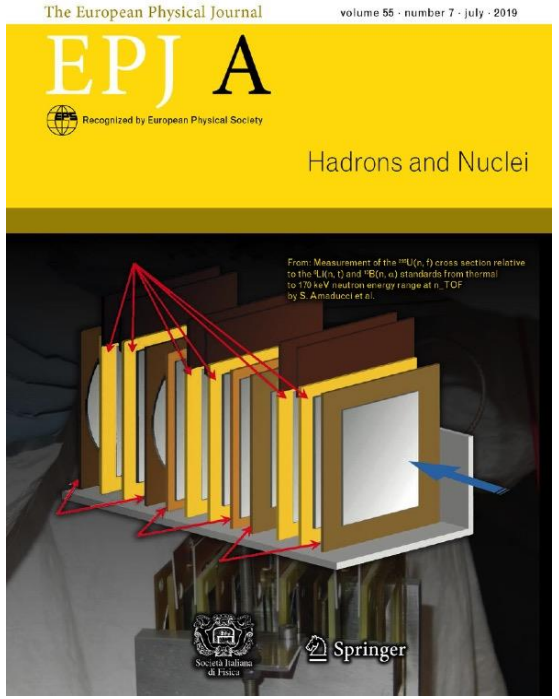
Quantity		EAR1	EAR2
Neutron flux(n/bunch)		10^6	10^8
Energy range	Minimum	Subthermal	Subthermal
	Maximum	1 GeV	100 MeV
Best resolution ($\Delta E/E$)		10^{-4}	10^{-3}

EAR2 is especially suited to measure **high active samples**, the destruction reactions of the ^{7}Be [**^{7}Be(n,α) and ^{7}Be(n,p)**] have been investigated because of their interest for the **Big Bang Nucleosynthesis and the Cosmological Lithium Problem**
M. Barbagallo et al. (The n_TOF Collaboration), Phys. Rev. Lett. 117 (2016) 152701
L. A. Damone et al. (The n_TOF Collaboration), Phys. Rev. Lett. 121 (2018) 042701

Latest results from n_TOF

Measurement of the $^{235}U(n,f)$ cross section relative to the $^{6}Li(n,t)$ and $^{10}B(n,\alpha)$ standards from thermal to 170 keV neutron energy range at n_TOF

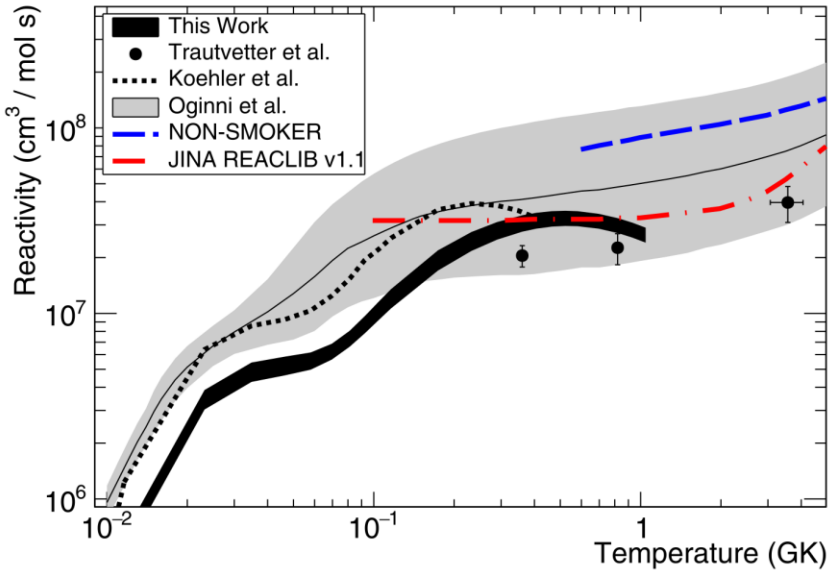
S. Amaducci et al. (The n_TOF Collaboration),



Most used reference reaction for neutron induced fission cross section measurements, fundamental for fission recycling during r-process

https://doi.org/10.1140/epja/i2019-12802-7

Study of the **^{26}Al (signature of nucleosynthesis in AGB) destruction** reactions:
^{26}Al(n,p) published by C. Lederer-Woods et al. (The n_TOF Collaboration)
https://doi.org/10.1103/PhysRevC.104.L022803



^{26}Al(n,α) accepted for pubblication, C. Lederer-Woods et al. (The n_TOF Collaboration)

Heavy elements nucleosynthesis via s-process

n_TOF allow to perform **high accuracy neutron capture cross section** measurement, which are foundamental for the s-process models. Nuclei recently studied are **^{171}Tm, ^{154}Gd and ^{140}Ce**

PHYSICAL REVIEW LETTERS **125,** 142701 (2020)

Neutron Capture on the *s*-Process Branching Point ^{171}Tm via Time-of-Flight and Activation

C. Guerrero et al. (The n_TOF Collaboration)

https://doi.org/10.1103/PhysRevLett.125.142701

Physics Letters B 804 (2020) 135405

Contents lists available at ScienceDirect

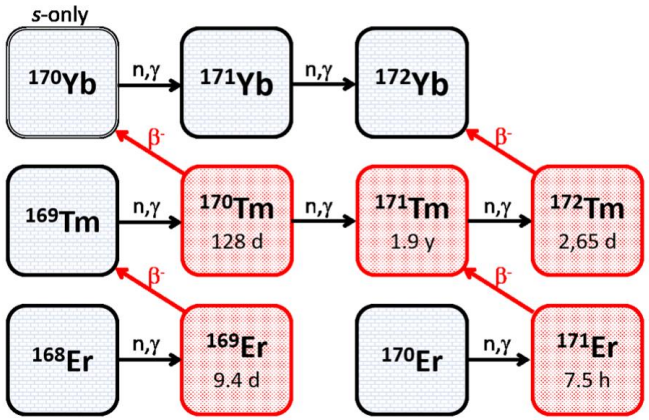
Physics Letters B

www.elsevier.com/locate/physletb

Measurement of the ^{154}Gd(n,γ) cross section and its astrophysical implications

A. Mazzone et al. (The n_TOF Collaboration)

https://doi.org/10.1016/j.physletb.2020.135405



universe

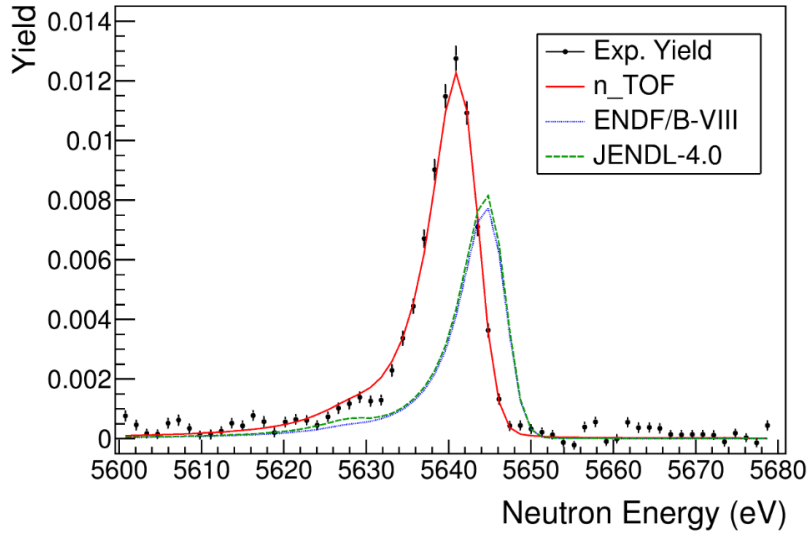
MDPI

Communication

First Results of the ^{140}Ce(n,γ)^{141}Ce Cross-Section Measurement at n_TOF

S. Amaducci et al. (The n_TOF Collaboration),

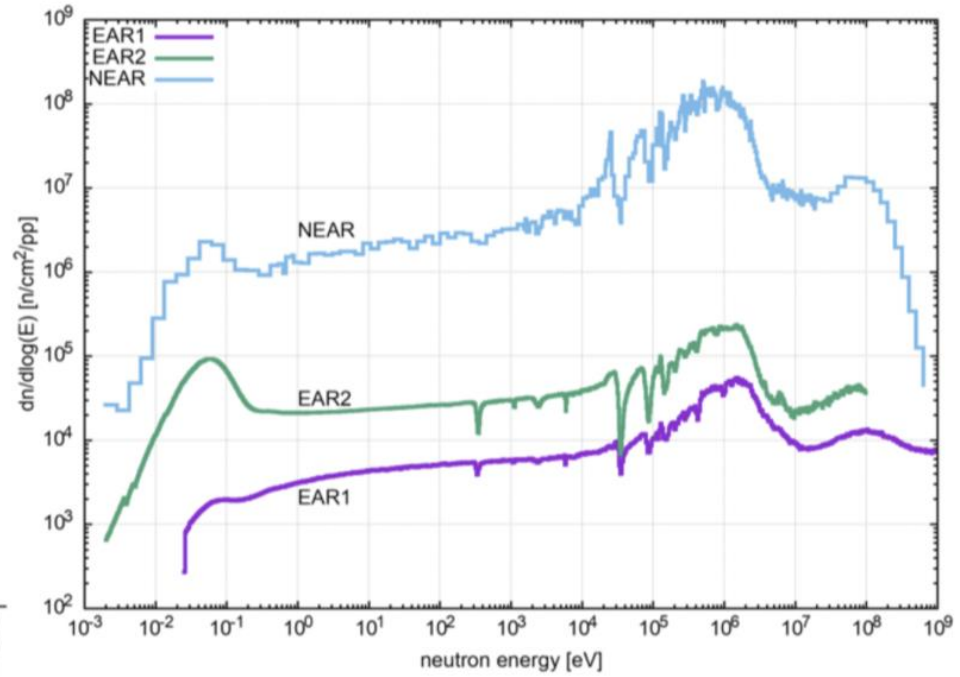
https://doi.org/10.3390/universe7060200



n_TOF Upgrade and future measurements

New spallation target and new experimental station NEAR

- 2-3 m from the target assembly
- a factor ~100 higher than EAR2 neutron fluence expected
- possibility to perform irradiation and activation measurements

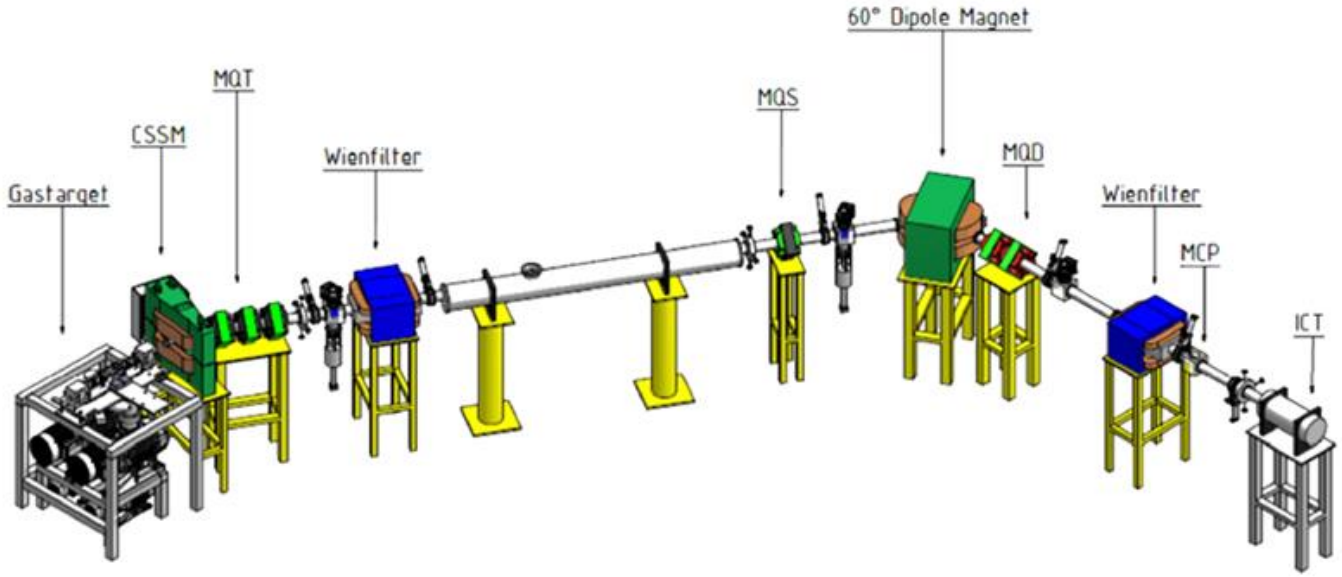


Forthcoming measurements:

- **^{94,95,96}Mo(n,γ)** for s-process
- **^{94}Nb(n,γ)** for anomalies in solar grains
- **^{79}Se(n,γ)** s-process thermometer
- **^{40}K(n,p) and ^{40}K(n,α)** radiogenic heating in earth-like exoplanets

The European Recoil Separator for Nuclear Astrophysics (**ERNA**) is coupled with the Tandem Accelerator Laboratory at CIRCE, University of Campania, Caserta, Italy.

ERNA is one of few recoil separator in the world dedicated to the radiative capture reaction cross section measurements.



The γ array detector **GASTLY** has been developed and installed at CIRCE since 2018 to study nuclear reaction with charged particle in exit channel.

The program of the collaboration includes **mass spectrometry** measurements of extraterrestrial and terrestrial samples to search events of astrophysical interest.


Radiocarbon, Vol 62, Nr 5, 2020, p 1403–1418 DOI:10.1017/RDC.2020.58
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CAN THE ^{14}C PRODUCTION IN 1055 CE BE AFFECTED BY SN1054?

F Terrasi[1,2*] • F Marzaioli[1,2] • R Buompane[1,2] • I Passariello[2] • G Porzio[1,2] • M Capano[3] • S Helama[4] • M Oinonen[5] • P Nöjd[6] • J Uusitalo[5,7] • A J T Jull[8,9,10] • I P Panyushkina[11] • C Baisan[11] • M Molnar[10] • T Varga[10] • G Kovaltsov[12] • S Poluianov[13] • I Usoskin[13]

F. Terrasi et al. CAN THE 14C PRODUCTION IN 1055 CE BE AFFECTED BY SN1054? *Radiocarbon, 62*(5), 1403-1418.

A. Zucchini et al. Chemical and mineralogical characterization of the Mineo (Sicily, Italy) pallasite: A unique sample. Meteorit Planet Sci, 53: 268-283.

PHYSICAL REVIEW C 97, 065806 (2018)

Measurement of the $^{12}C(^{12}C, p)^{23}Na$ cross section near the Gamow energy

J. Zichefoose et al.

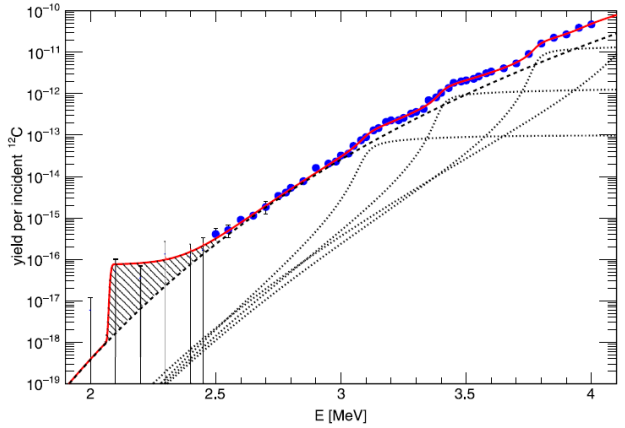


FIG. 4. Thick-target yields (blue circles) of the $^{12}C(^{12}C, p)^{23}Na$

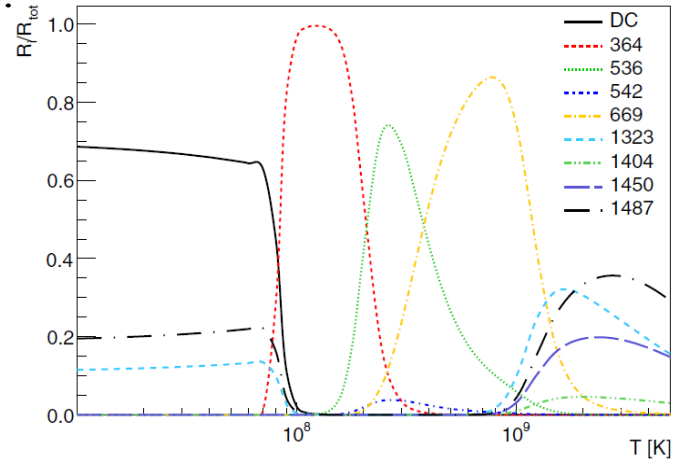
- Energy range of direct measurements extended up to Ecm = 2 MeV.
- The results are in fair agreement with previous results.
- New measurement campaign with GASTLY detector array. Data analysis in progress.

PHYSICAL REVIEW C 95, 045803 (2017)

Measurement of 1323 and 1487 keV resonances in $^{15}N(\alpha, \gamma)^{19}F$ with the recoil separator ERNA

A. Di Leva et al.

- Direct measurement of the cross section successfully obtained with the recoil separator ERNA@CIRCE.
- A significant difference is found for the 1323 keV resonance Γ_α.



Eur. Phys. J. A (2018) 54: 92
DOI 10.1140/epja/i2018-12522-6

THE EUROPEAN PHYSICAL JOURNAL A

Regular Article – Experimental Physics

Test measurement of $^{7}Be(p, \gamma)^{8}B$ with the recoil mass separator ERNA

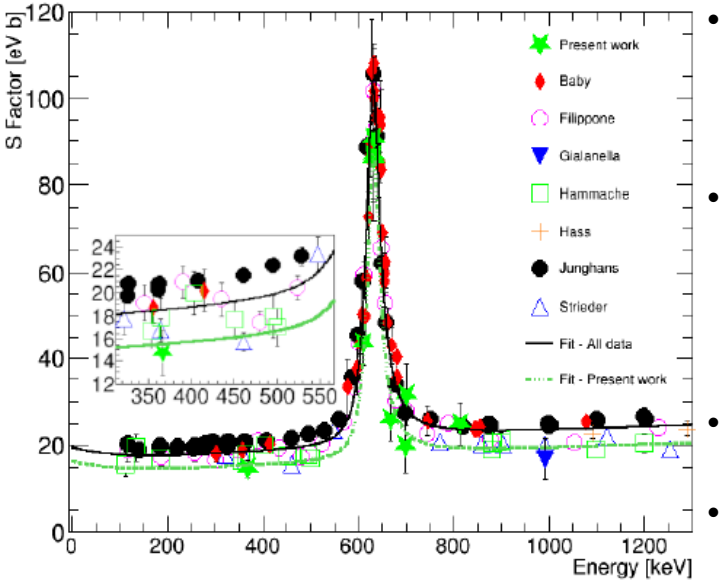
R. Buompane et al.

- ^{7}Be Radioactive beam intensity up to 10^{9}pps.
- Windowless Gas Target.
- Invers kinematics.
- Direct recoils detection.

Submitted

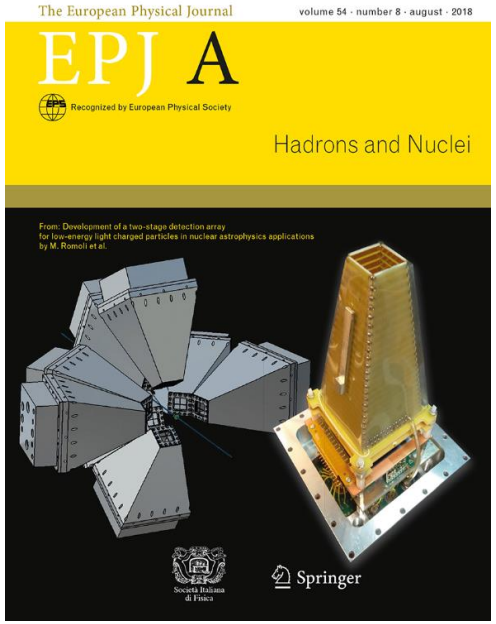
Determination of the $^{7}Be(p, \gamma)^{8}B$ cross section at astrophysical energies using a radioactive ^{7}Be ion beam

R. Buompane et al.



- Energy range of measurements in the range 367 e 812 keV.
- First measurements with significant statistics in inverse kinematics.
- S17(0)=16.1±2.0 eV b.
- New measurements ongoing at Ecm >1MeV.

From $^{12}C + ^{12}C$ to $^{16}O + ^{12}C$ reaction



Eur. Phys. J. A (2018) 54: 142
DOI 10.1140/epja/i2018-12575-5
THE EUROPEAN PHYSICAL JOURNAL A
Special Article – New Tools and Techniques

Development of a two-stage detection array for low-energy light charged particles in nuclear astrophysics applications

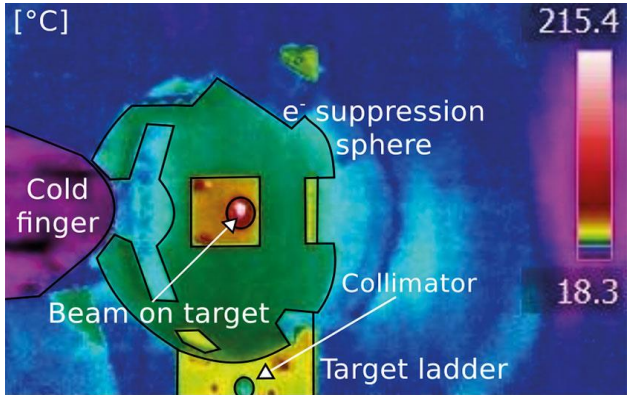
M. Romoli et al.

- Carbon burning study still in progress, new measurements of reaction $^{16}O+^{12}C$.
- $^{12}C+^{12}C$ developed setup, detector array and target, used for the $^{16}O+^{12}C$ reaction measurements.
- Charged particle detectors array GAs-Silicon Two-Layer sYstem (GASTLY).
- Target di (Hy Ordered Pyrolytic Graphite) HOPG.

Eur. Phys. J. A (2018) 54: 132
DOI 10.1140/epja/i2018-12564-8
THE EUROPEAN PHYSICAL JOURNAL A
Regular Article – Experimental Physics

Reduction of deuterium content in carbon targets for $^{12}C + ^{12}C$ reaction studies of astrophysical interest

L. Morale-Gallegos et al.



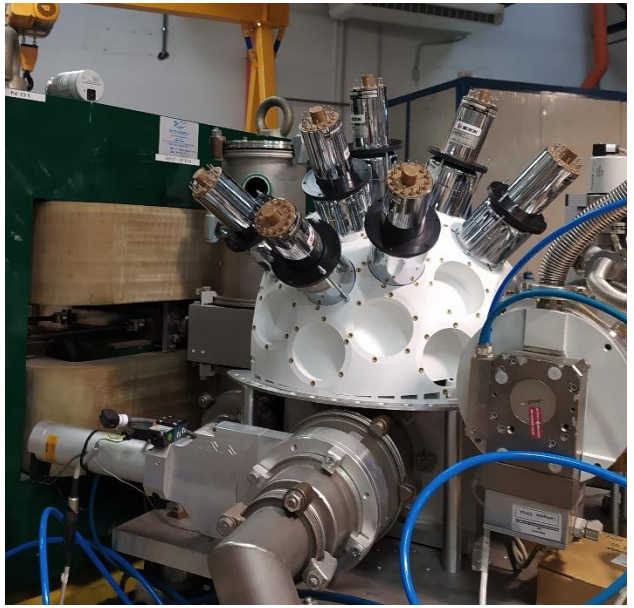
Infrared picture of HOPG target during measurement.

$^{12}C(\alpha,\gamma)^{16}O$ reaction

Details in section I contribution:

Verso la misura della sezione durto della $^{12}C(\alpha,\gamma)^{16}O$ a basse energie.

SANTONASTASO C. (1)(2), BUOMPANE R. (1)(2), DE CESARE M. (1)(2)(4), DI LEVA A. (2)(3), GARCIA DUARTE J. (5), GIALANELLA L. (1)(2), FORMICOLA A. (6), MORALES-GALLEGOS L. (2), PORZIO G. (1)(2), RAPAGNANI D. (2)(3), ROMOLI M. (1)(2)



- The $^{12}C(\alpha,\gamma)^{16}O$ is the reaction that was the main motivation behind the ERNA recoil mass separator construction.
- The direct measurements of total cross section in invers kinematics will be extended up to Ecm=1MeV.
- Angular distribution measurements, with new γ-detector array, up to 25 NaI detectors.

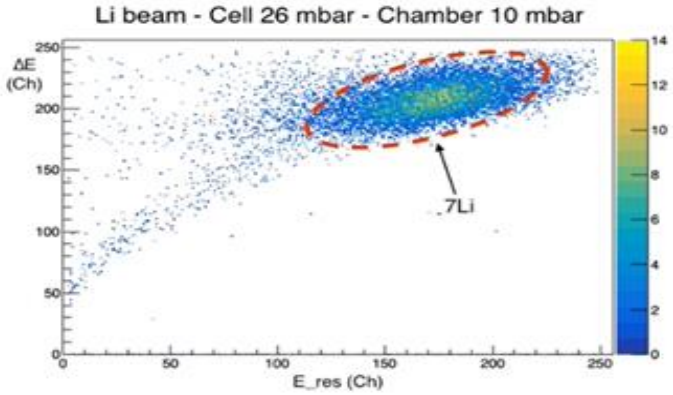
Nuclear Instruments and Methods in Physics Research B 407 (2017) 217–221
Contents lists available at ScienceDirect
Nuclear Instruments and Methods in Physics Research B
journal homepage: www.elsevier.com/locate/nimb
ELSEVIER
BEAM INTERACTIONS WITH MATERIALS AND ATOMS

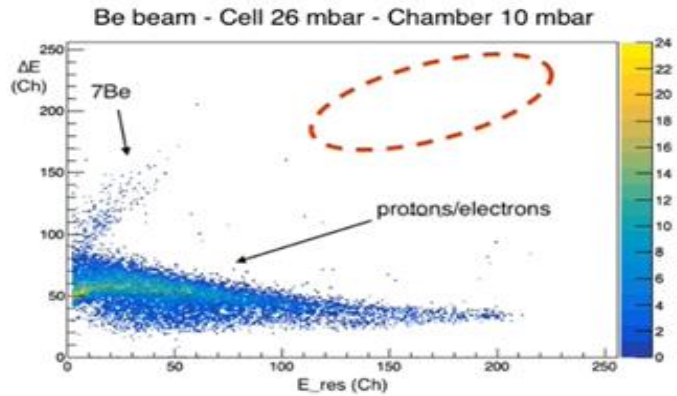
A supersonic jet target for the cross section measurement of the $^{12}C(\alpha, \gamma)^{16}O$ reaction with the recoil mass separator ERNA

CrossMark

D. Rapagnani et al.

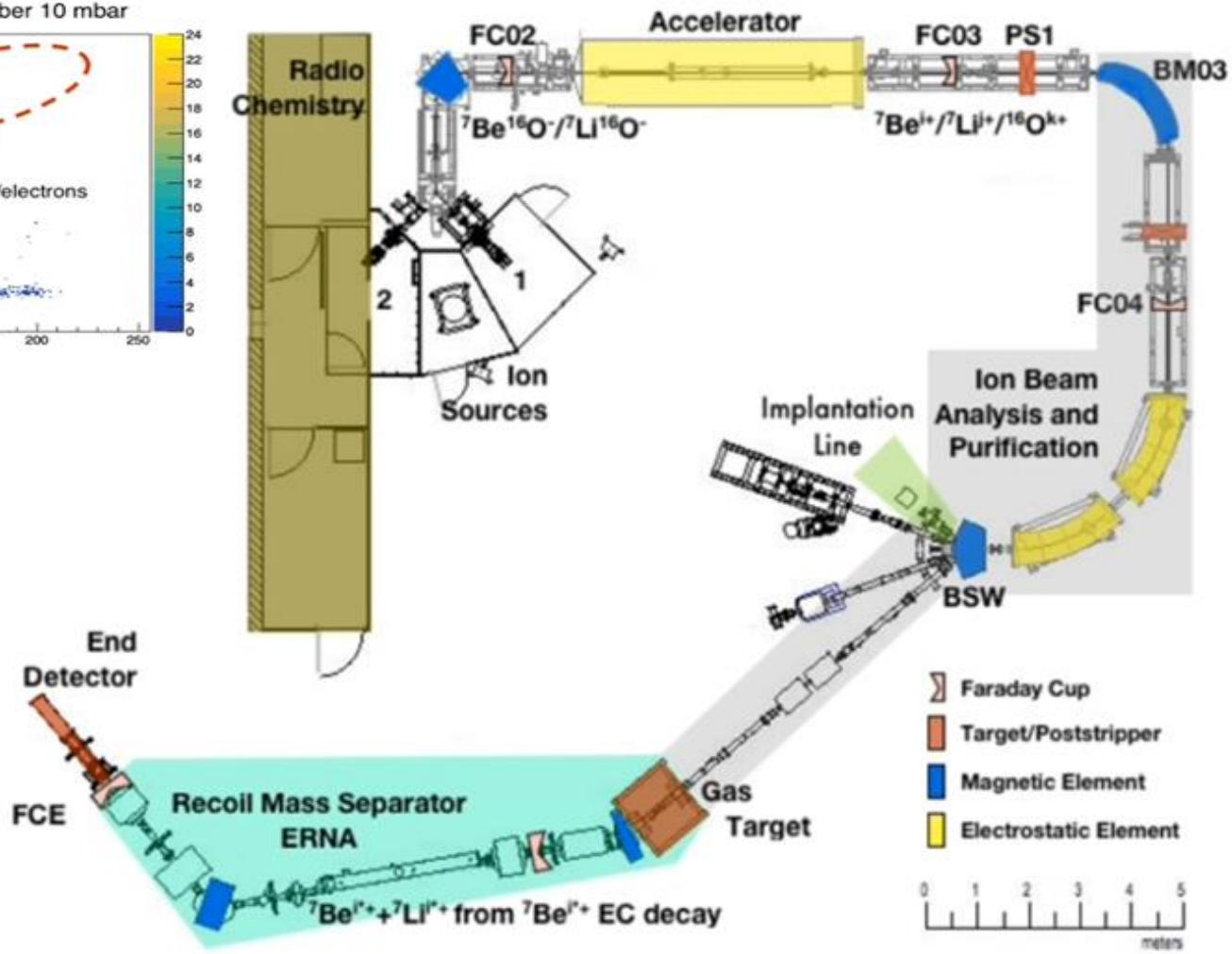
Ionized ^{7}Be half life measurement





- Eventi attesi:~1event/day(70pA di 7Be3+)

- The influence of environmental conditions on the decay of ^{7}Be is of interest in nuclear physics and astrophysics.
- A pure ^{7}Be beam fully stripped is produced at CIRCE facility.
- The beam interaction with a stripper in the gas target produce different charge of 7Be.
- The ^{7}Li produced by the in-flight decay of accelerated ^{7}Be ions in different charge states are detected in the end detector.



- Layout of the Pelletron Tandem Accelerator facility at CIRCE.

843. Influenza dell'ambiente sulla vita media del \chem{^{7}Be}.
Claudio Santonastaso
14/09/2020, 00:00

Details in the SIF2020 contribution:

Conclusion

- The efforts and the great results of the italian groups working on direct measurements for nuclear astrophysics were described
- Gruppi Italiani di Astrofisica Nucleare Teorica e Sperimentale = GIANTS gathered n_TOF, ERNA, LUNA, ASFIN and PANDORA

- Newsletter for updates: https://pandora.infn.it/public/giantsnews