"Nuclear Physics Mid Term Plan in Italy"

LNGS Session

WG: Direct measurement for nuclear astrophysics

Topic

Measurements with recoil separators and other astrophysical relevant studies at CIRCE

Raffaele Buompane University of Campania L. Vanvitelli & INFN Napoli

Contributors:

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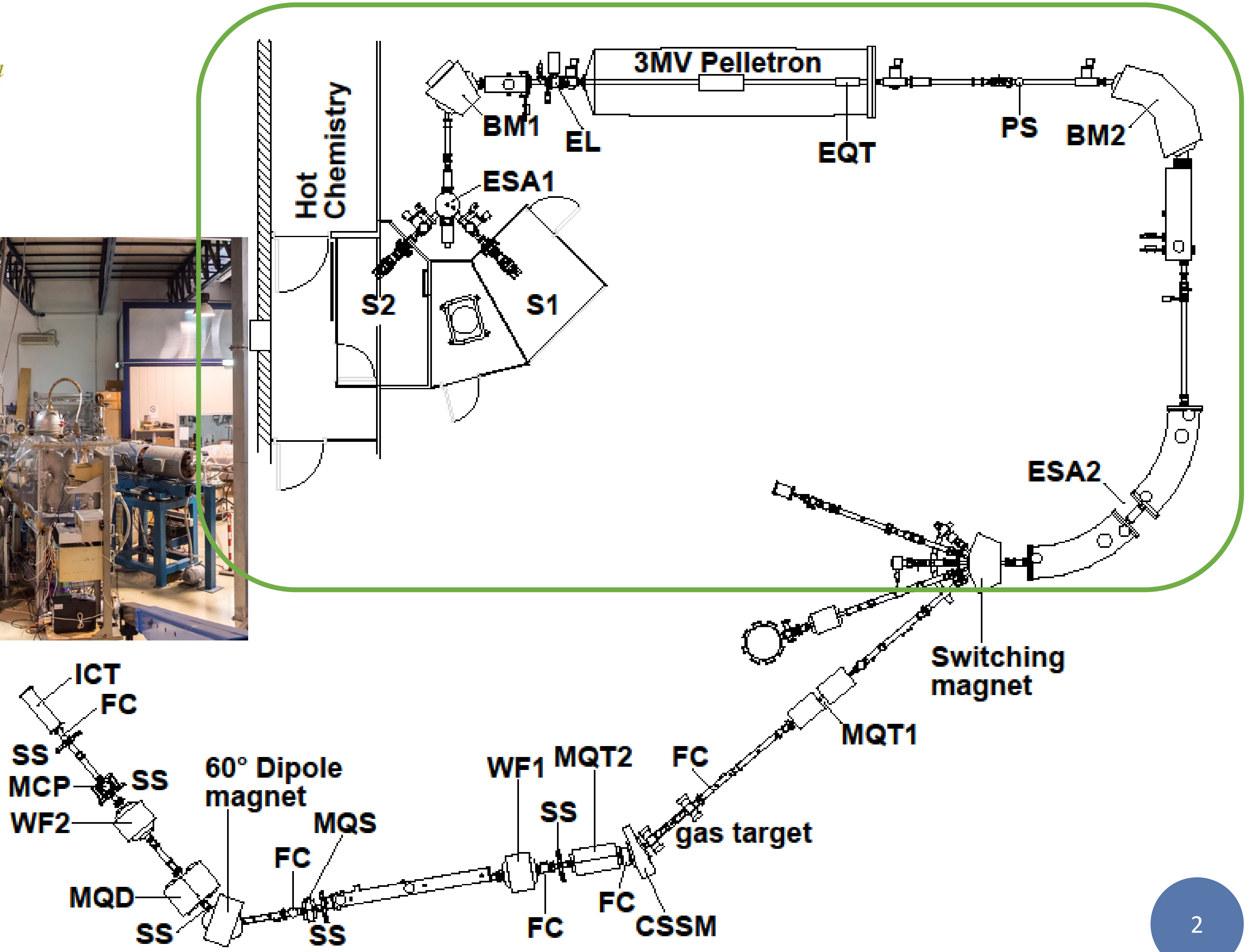
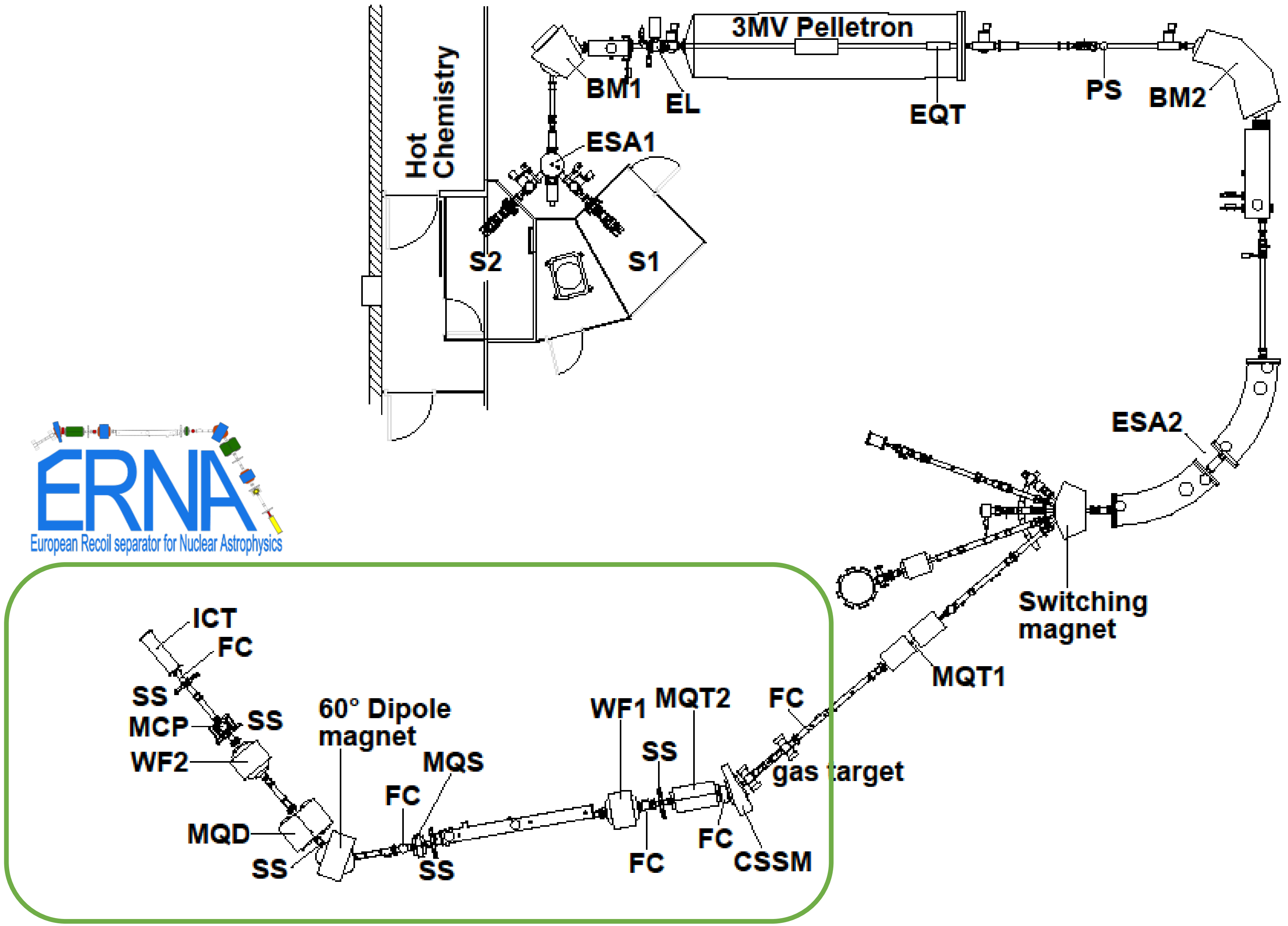
CIRCE-DMF laboratory

Università
degli Studi
della Campania
Luigi Vanvitelli

Dipartimento di Matematica e Fisica



CIRCE-DMF laboratory



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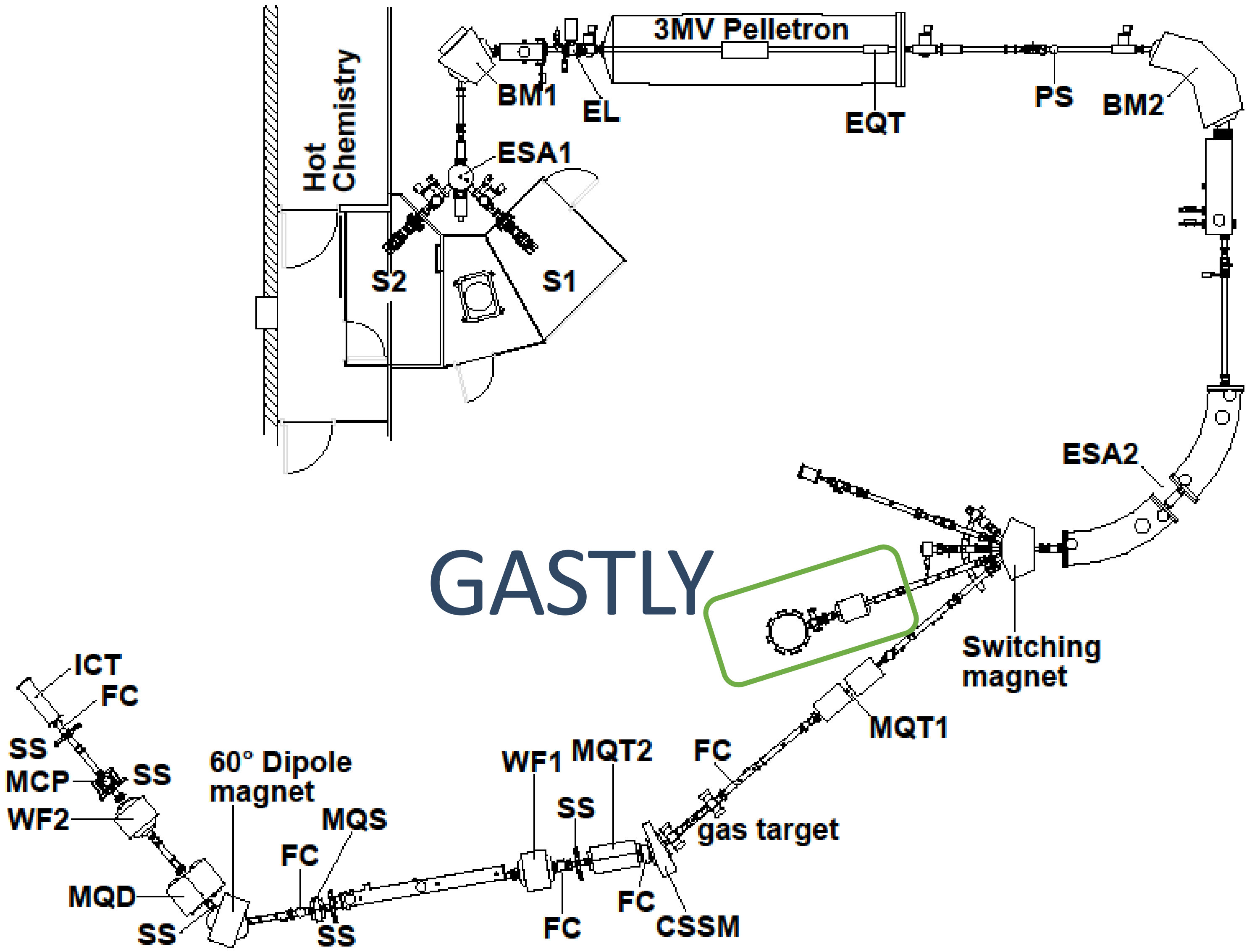
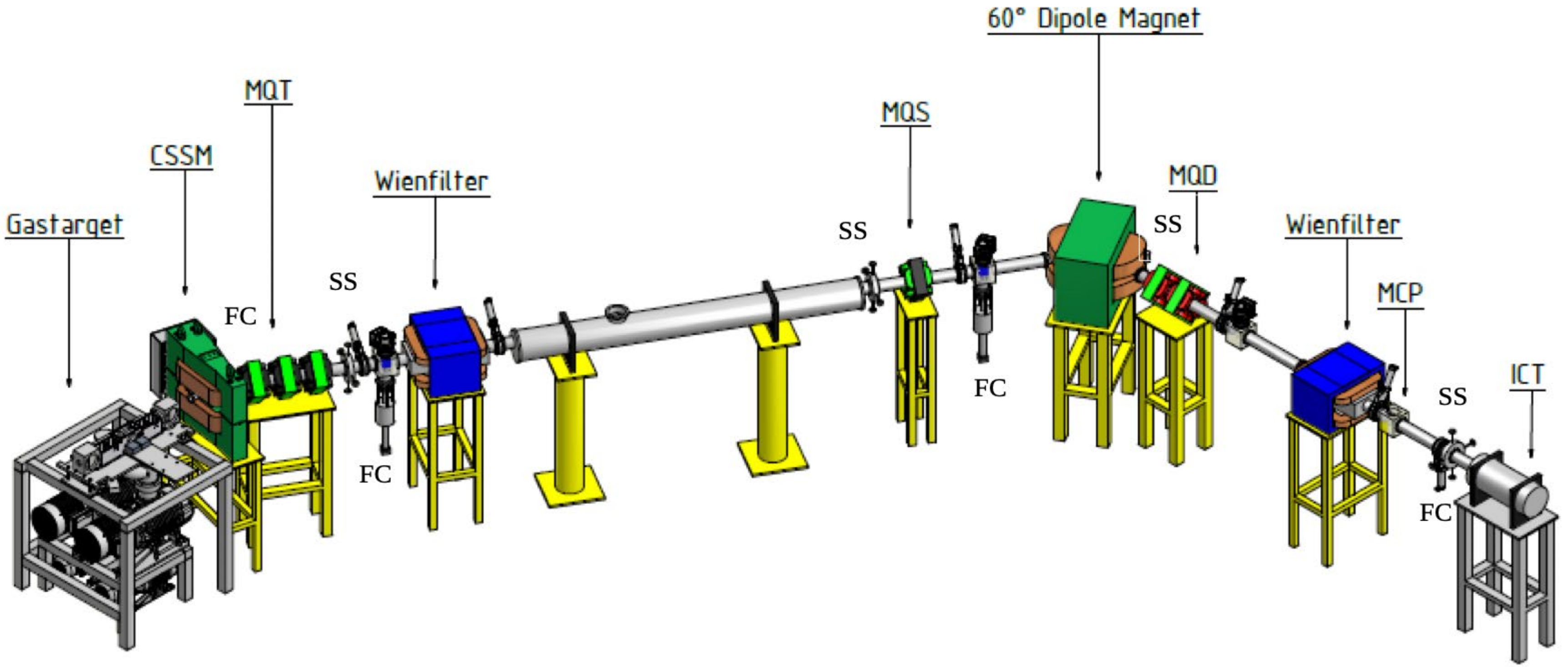
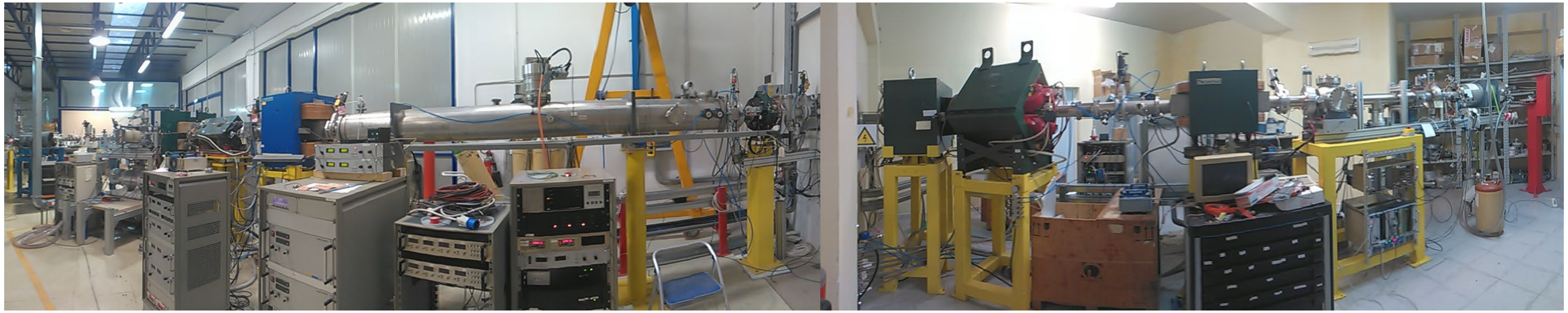


European Recoil separator for Nuclear Astrophysics - ERNA

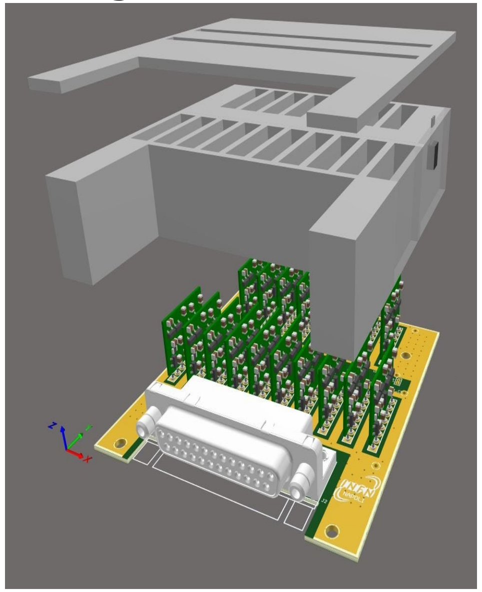


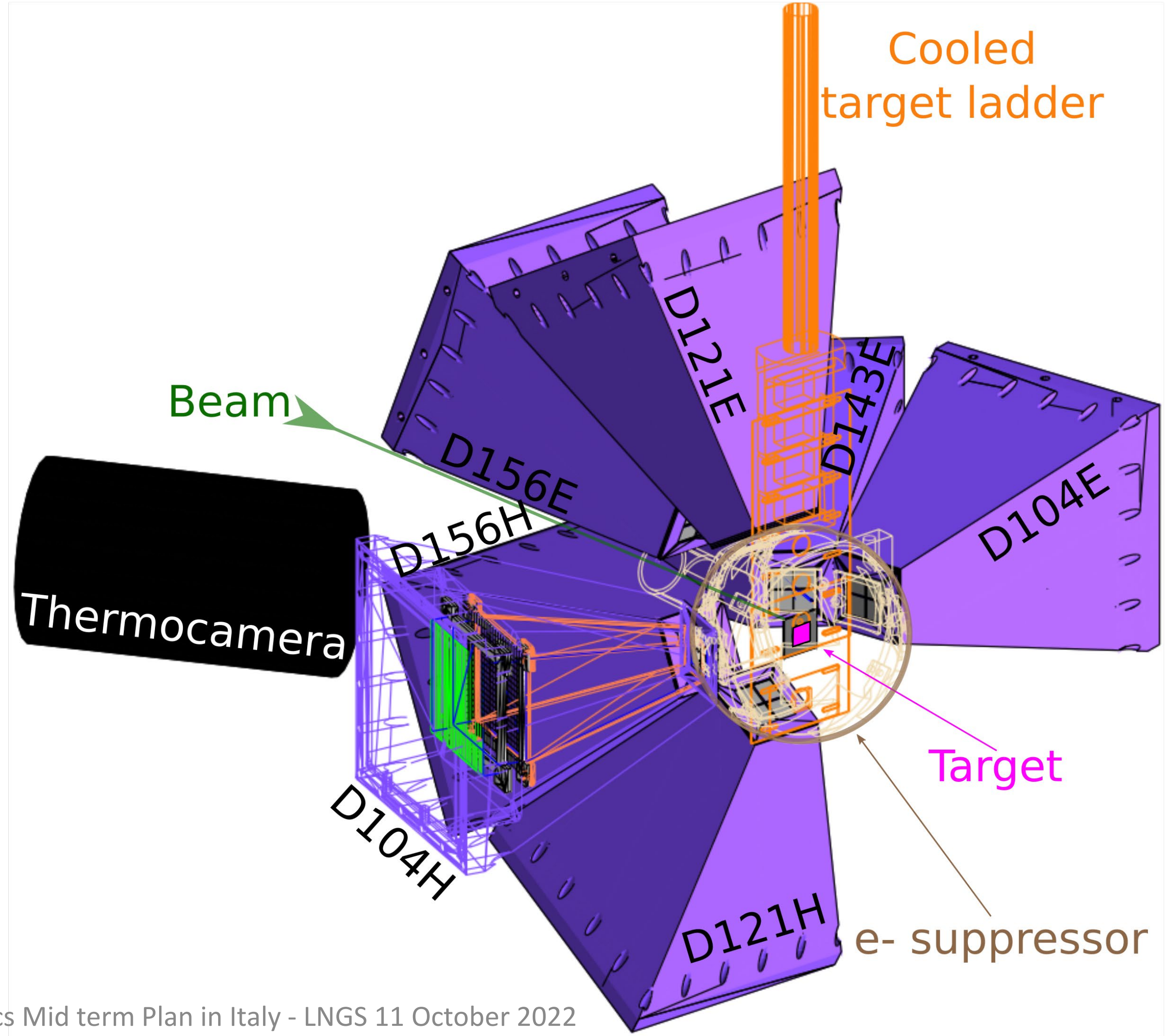


GASTLY (GAs-Silicon Two-Layer sYstem)

7 GASTLY detectors with 16 functioning strips each

< 1.3° step
Range = 95° -163°





Recent results

- H and He burning:
  - $^{7}Be(p,\gamma)^{8}B$

Physics Letters B 824 (2022) 136819

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

R. Buompane [a,b,*], A. Di Leva [c,b], L. Gialanella [a,b,*], A. D'Onofrio [a,b], M. De Cesare [d,b], J.G. Duarte [a,b,1], Z. Fülöp [e], L.R. Gasques [f,a,b], Gy. Gyürky [e], L. Morales-Gallegos [b,a], F. Marzaioli [a,b], G. Palumbo [g,b], G. Porzio [a,b], D. Rapagnani [c,b], V. Roca [a,b], D. Rogalla [h], M. Romoli [b], C. Santonastaso [a,b], D. Schürmann [a,b]

  - $^{15}N(\alpha,\gamma)^{19}F$

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,[1,2,*] G. Imbriani,[1,2] R. Buompane,[2,3] L. Gialanella,[2,3] A. Best,[1,2] S. Cristallo,[4,5] M. De Cesare,[2,3,6] A. D'Onofrio,[2,3] J. G. Duarte,[2,3] L. R. Gasques,[2,3,7] L. Morales-Gallegos,[2,8] A. Pezzella,[2,9] G. Porzio,[2,3] D. Rapagnani,[5,10] V. Roca,[1,2] M. Romoli,[2] D. Schürmann,[1,2] O. Straniero,[2,4] and F. Terrasi[2,3]
(ERNA Collaboration)

- Advanced burnings
  - $^{12}C(^{12}C,p)^{23}Na$ and $^{12}C(^{12}C,\alpha)^{20}Ne$

Eur. Phys. J. A (2022) 58:65
https://doi.org/10.1140/epja/s10050-022-00717-7

THE EUROPEAN PHYSICAL JOURNAL A

Regular Article - Experimental Physics

Direct measurements of the $^{12}C+^{12}C$ reactions cross-sections towards astrophysical energies

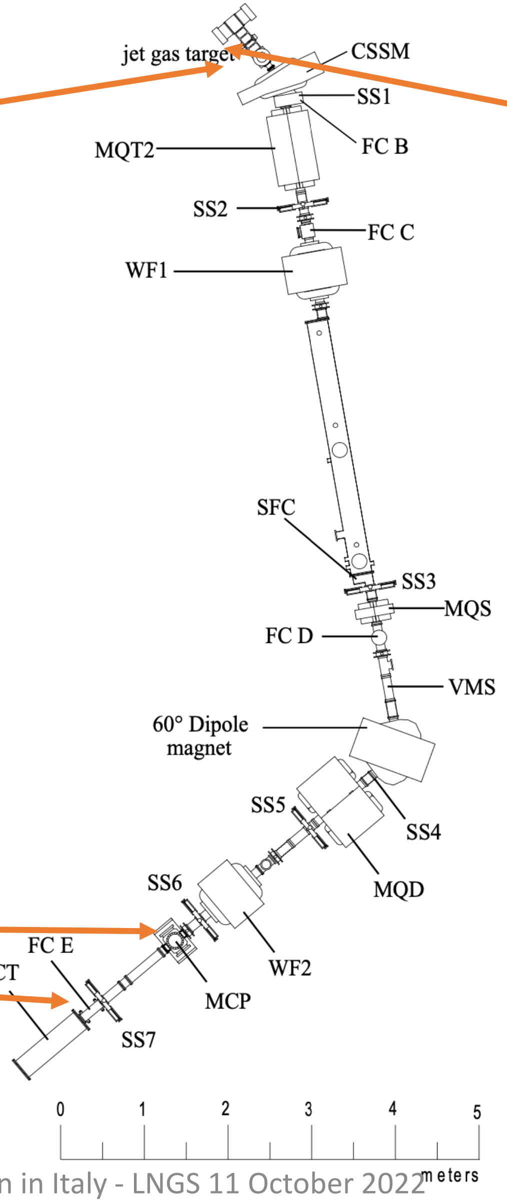
L. Morales-Gallegos[1,2,3,a], M. Aliotta[1,2], L. Gialanella[1,3], A. Best[3,5], C. G. Bruno[2], R. Buompane[1,3], T. Davinson[2], M. De Cesare[3,4], A. Di Leva[3,5], A. D'Onofrio[1,3], J. G. Duarte[1,3,6], L. R. Gasques[1,3,7], G. Imbriani[3,5], G. Porzio[1], D. Rapagnani[1,3], M. Romoli[3], F. Terrasi[1,3]

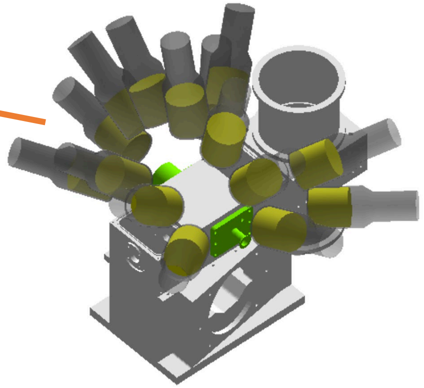
- AMS - search for the supernova signal in the tree (WG3 - Fabio Marzaioli)

Experimental Setup – Recent Upgrade

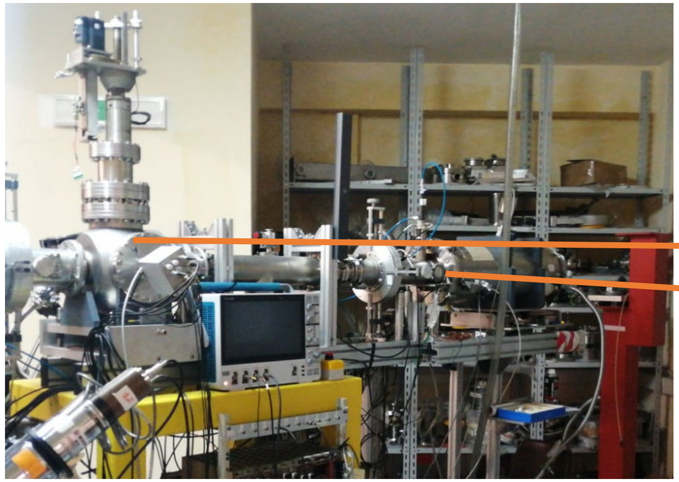
Jet He target

European Recoil Separator for Nuclear Astrophysics





TOF-E position sensitive



Ongoing research program

Separator

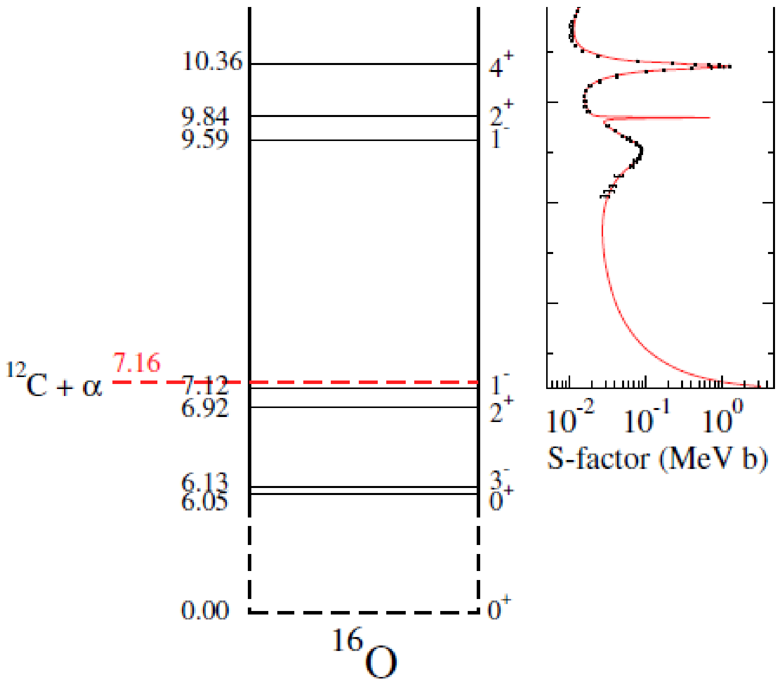
- H and He burning:
  - $^{7}Be(p,\gamma)^{8}B$ at Ecm > 1 MeV
  - ^{7}Be Ionized Half Life (ASBeST)
    - ^{7}Be RIB production optimization
  - $^{12}C(\alpha,\gamma)^{16}O$
    - Total Cross section
    - Angular distribution (through gamma detection)

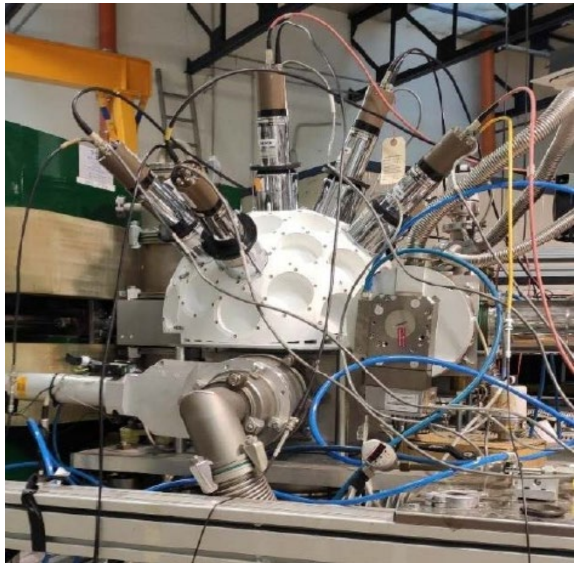
Particle spectroscopy

- Advanced burnings
  - $^{12}C(^{16}O,p)^{27}Al$ and $^{12}C(^{16}O,\alpha)^{24}Mg$

$^{12}C(\alpha,\gamma)^{16}O$ (Q=7.162 MeV)

- Low energy cross section is dominated by
  - The ground state transition
  - E1 and E2 multipolarities
  - A 1- and 2+ subthreshold state, a broad 1- resonance at 2.3 MeV
  - Interference effects are strong
  - Weak E2 direct capture can interfere with strong E2 subthreshold state to produce a sizable effect, for example





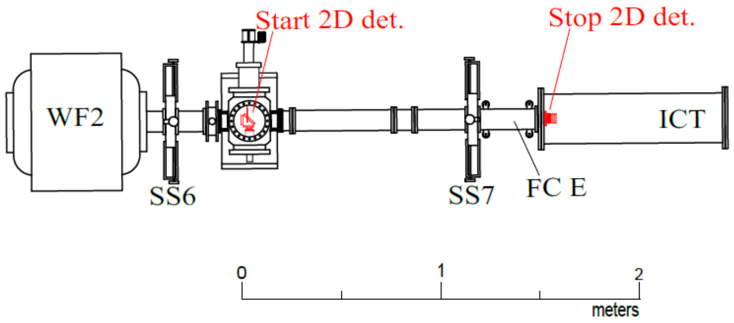
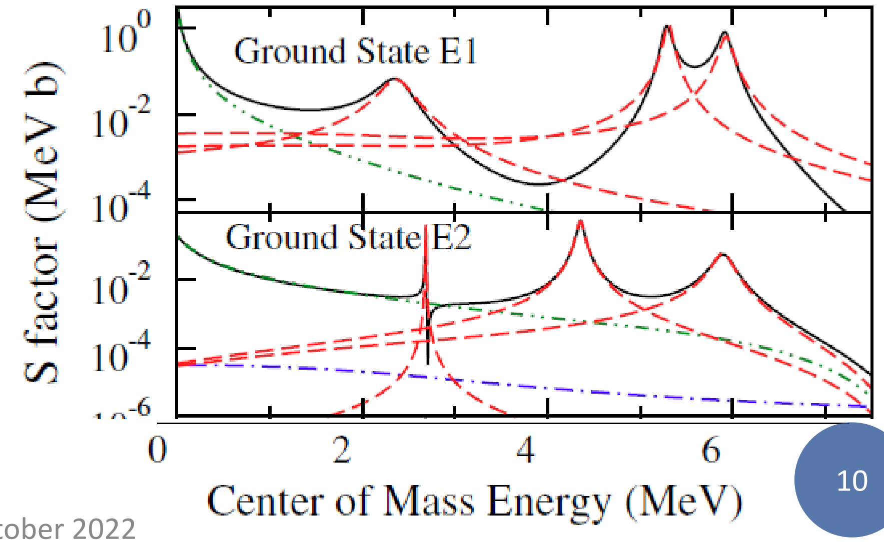


Figure 2: *Schematic drawing of the ToF-tracking detector.*



Next at CIRCE-DMF

- BBN:
  - $^{7}Be(d,p)^{8}Be$ with THM
- H and He burning:
  - Triple-α process ($^{13}C(^{3}He,\alpha_2)^{12}C^*$)
  - $^{16}O(\alpha,\gamma)^{20}Ne$
    - Total Cross section
    - Angular distribution
- AGB ^{19}F nucleosynthesis
  - $^{15}N(\alpha,\gamma)^{19}F$
  - $^{14}N(\alpha,\gamma)^{18}F$
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- Other applications:
  - THM applications $^{13}C(\alpha,n)^{16}O$; $^{22}Ne(\alpha,n)^{25}Mg$; $^{23}Na(p,\alpha)^{20}Ne$.
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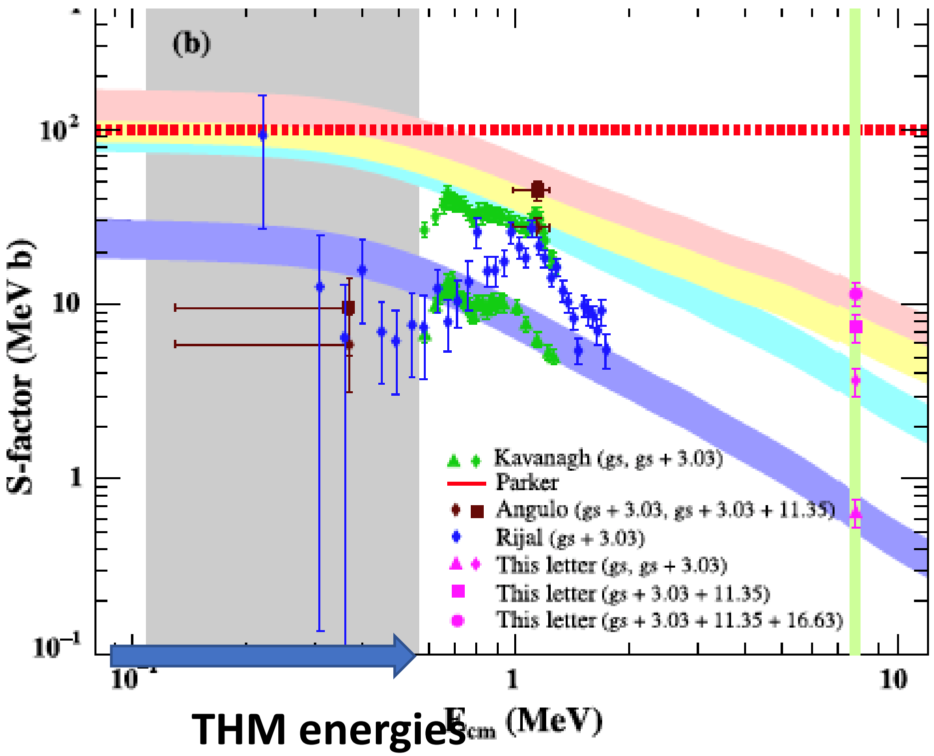
Experimental study of the ^{7}Be(d,p)^{8}Be rection via THM at BBN energies

L. Lamia (for the ASFIN group)

PHYSICAL REVIEW LETTERS 128, 252701 (2022)

Resonance Excitations in ^{7}Be$(d,p)^{8}$Be* to Address the Cosmological Lithium Problem

Sk M. Ali,[1,*] D. Gupta,[1,†] K. Kundalia,[1] Swapan K. Saha,[1,‡] O. Tengblad,[2]



The Astrophysical Journal, 879:23 (8pp), 2019 July 1
https://doi.org/10.3847/1538-4357/ab2234
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CrossMark

Cross-section Measurement of the Cosmologically Relevant ^{7}Be(n, α)^{4}He Reaction over a Broad Energy Range in a Single Experiment

L. Lamia[1,2], M. Mazzocco[3,4], R. G. Pizzone[2], S. Hayakawa[5], M. La Cognata[2], C. Spitaleri[1,2], C. A. Bertulani[6], A. Boiano[7],

The Astrophysical Journal Letters, 915:L13 (14pp), 2021 July 1
https://doi.org/10.3847/2041-8213/ac061f
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CrossMark

Constraining the Primordial Lithium Abundance: New Cross Section Measurement of the ^{7}Be + n Reactions Updates the Total ^{7}Be Destruction Rate

S. Hayakawa[1], M. La Cognata[2], L. Lamia[2,3,4], H. Yamaguchi[1,5], D. Kahl[6,19], K. Abe[1], H. Shimizu[1], L. Yang[1,20],

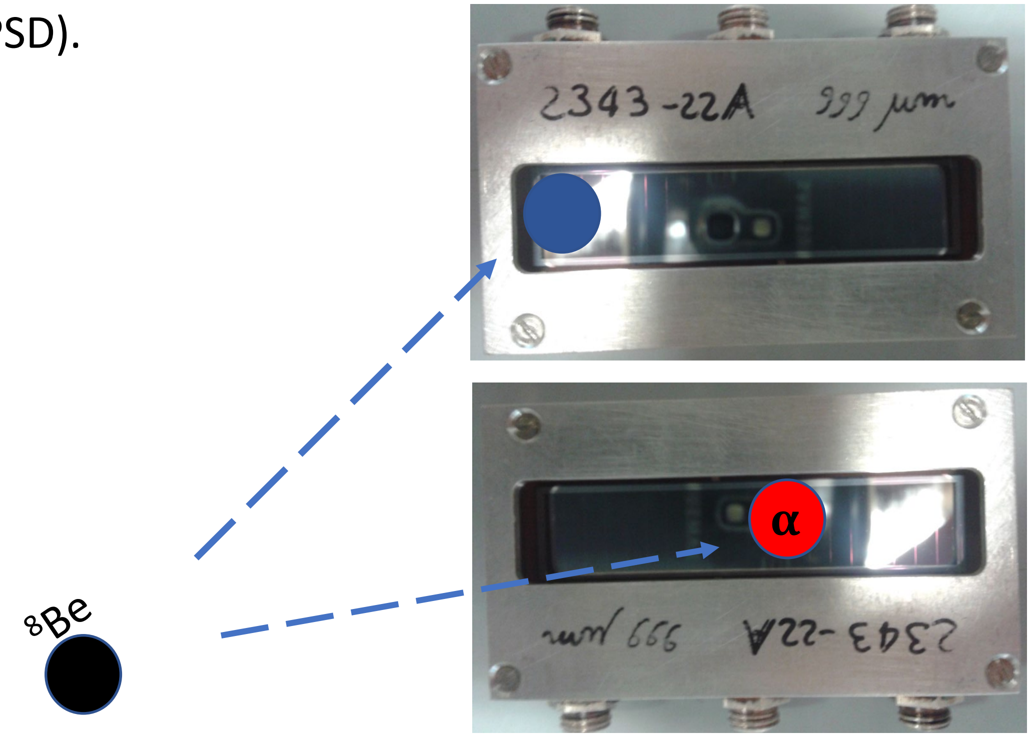
Direct data partially cover BBN energies: THM measurements will cover the present «unexplored» energy region

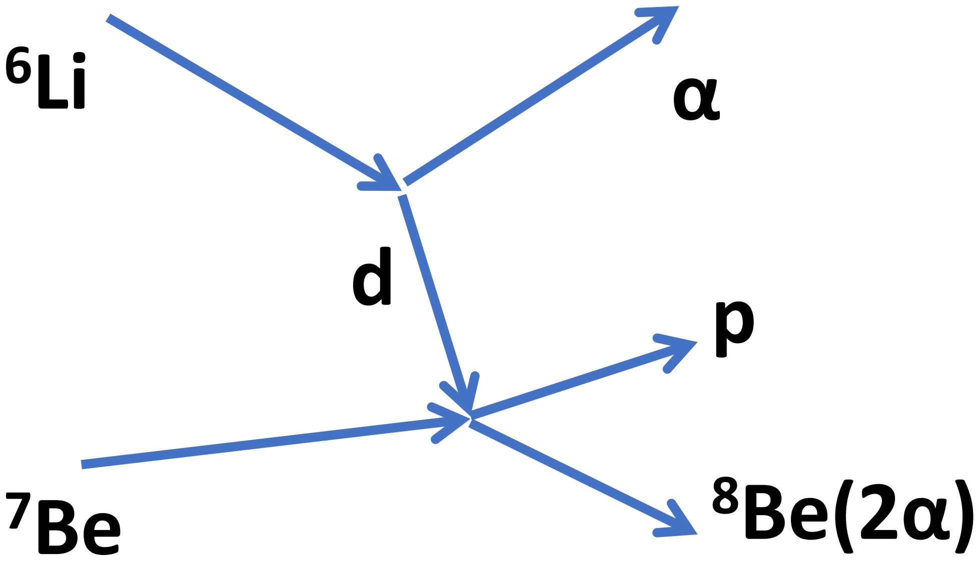
THE THM investigation at CIRCE

J. Phys. G: Nucl. Part. Phys. **39** (2012) 015106 L Lamia *et al*

New measurement of the $^{11}B(p,\alpha_0)^{8}Be$ bare-nucleus $S(E)$ factor via the Trojan horse method

8Be identification as coincidence detection of 2 alpha-particles hitting the Dual Position Sensitive Silicon Detectors (DPSD).





1) ^{7}Be beam energy: **7 MeV**
2) ^{6}LiF target: **200-400 ug/cm^2**
3) Detection of 2-out-of-3 emitted particles, i.e. protons and ^{8}Be
4) ^{8}Be «reconstruction» as performed in previous THM measurements (see Lamia L. et al. JpG 2012);
5) THM measurement at 7 MeV will span the BBN energy region

Next at CIRCE-DMF

- BBN:
  - $^{7}Be(d,p)^{8}Be$ with THM
- H and He burning:
  - **Triple-α process ($^{13}C(^{3}He,\alpha_2)^{12}C^*$)**
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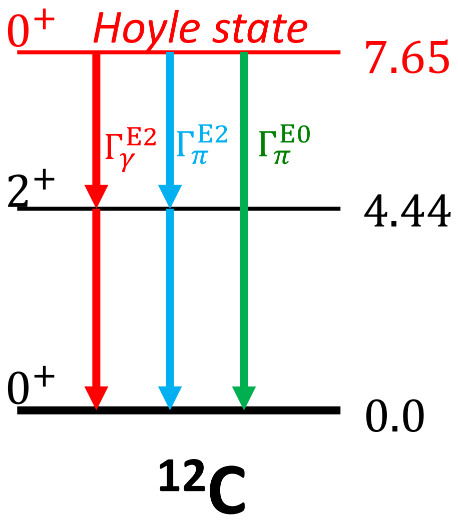
Triple-α



→ <u>**new experiments are required**</u>!
Recently approved experiment MORALIS @ INFN-LNL (2023) aims to measure Γ_{rad}/Γ using *particle-particle coincidence techniques*.

Using **fragment separators** might help to perform an experiment with *enhanced sensitivity*, a possible reaction: $^{13}C(^3He,\alpha_2)^{12}C^*$, Γ_{rad}/Γ can be extracted measuring α_2-^{12}C coincidence with ^{12}C close to 0-degrees→ **ERNA @ CIRCE**.

A complementary alternative, underground γ-spectroscopy experiments using ^3He beams at 3 MeV on ^{13}C targets to populate the Hoyle state → γ-cascade reconstruction with *zero-background* → **Underground.**

For $T > 2$ GK → higher excitation energy states in ^{12}C play a role → present spectroscopic ambiguities call for <u>**high-sensitivity *particle or γ-spectroscopy* experiments**</u>.

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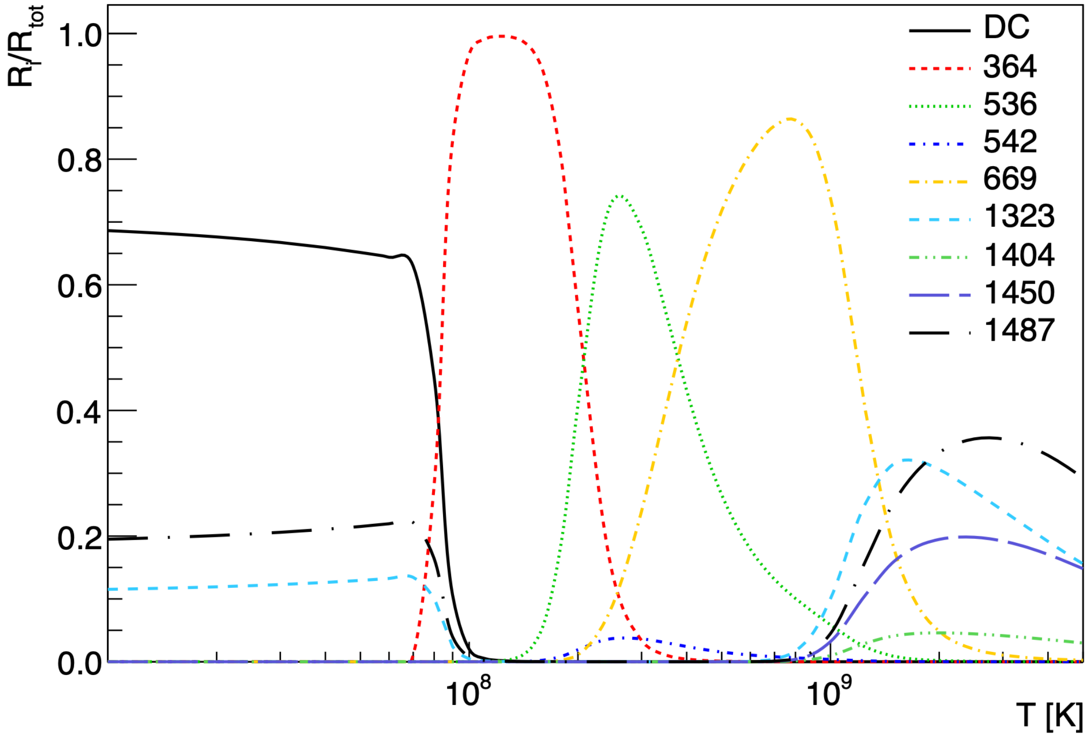
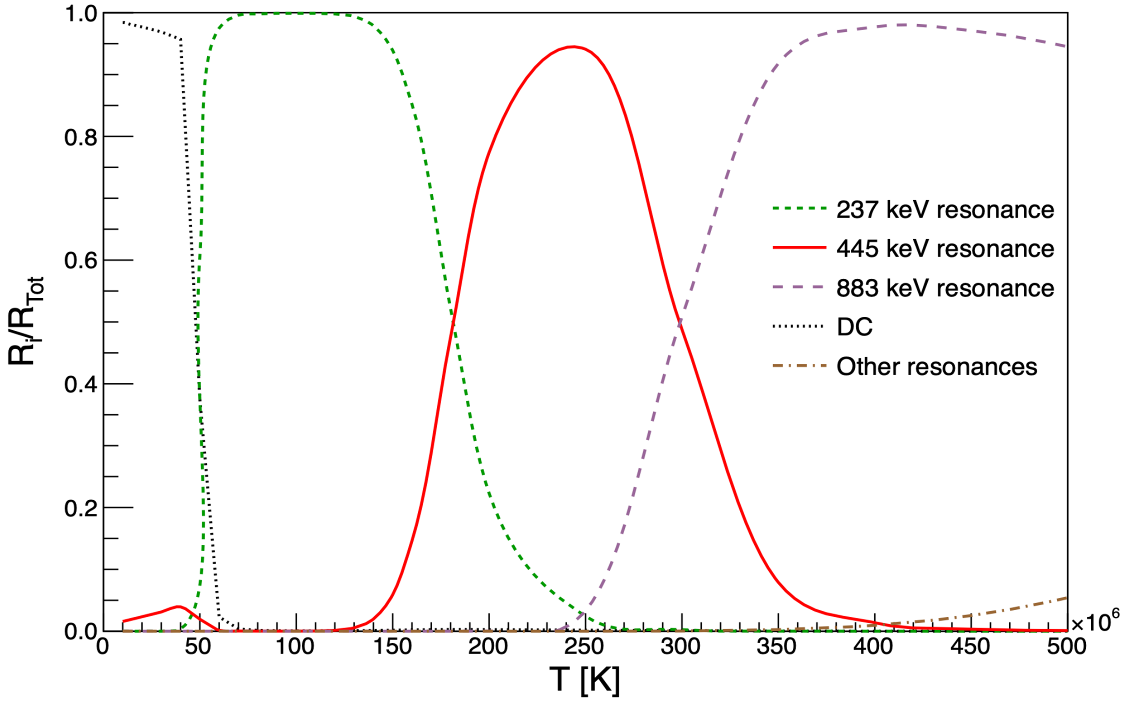
$^{15}N(\alpha,\gamma)^{19}F$ (Q=4013.8 keV) $^{14}N(\alpha,\gamma)^{18}F$ (Q=4414.6 keV)





E_{cm} [keV]	363.9	536.1	542.3	668	1091.2	1323	1487
ωγ [keV]	6.0 10^{-12} u.l.	(9.5±1.2) $\times10^{-8}$	(6.4±2.5) $\times10^{-9}$	(5.6±0.6) $\times10^{-6}$	(9.7±1.6) $\times10^{-6}$	(1.69±0.14) $\times10^{-3}$	(3.56±0.28) $\times10^{-3}$
Reactions/day/μA	1	8.5 10^{3}	5.5 10^{2}	3.8 10^{5}	3.9 10^{5}	6 10^{8}	1 10^{9}

E_{cm} [keV]	237	445	535	883	1088	1189	1258
ωγ [keV]	1.48E-18	(4.6±0.3) $\times10^{-8}$	1×10^{-9} u.l.	(2.11±0.03) $\times10^{-5}$	(7.0±1.0) $\times10^{-6}$	(1.30±0.10) $\times10^{-3}$	(4.4±0.2) $\times10^{-4}$
Reactions/day/μA	1.03E-08	1.13E+02	1.80E+00	1.59E+04	3.78E+03	6.12E+05	1.90E+05

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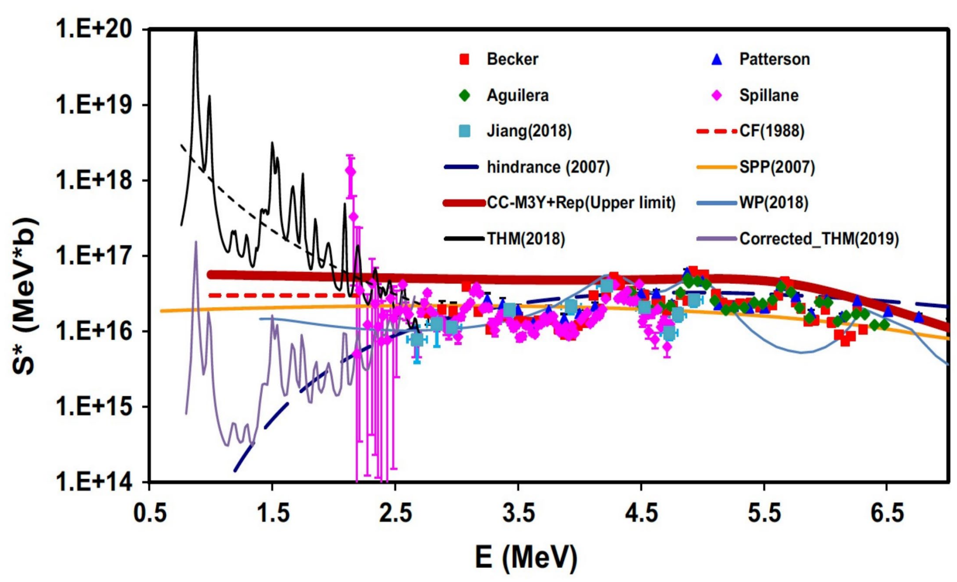
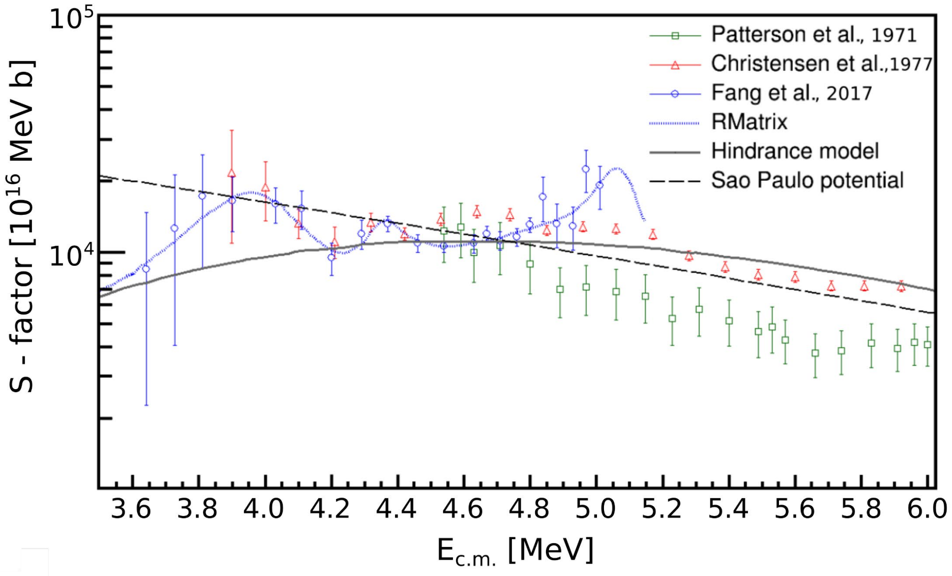
12C+12C

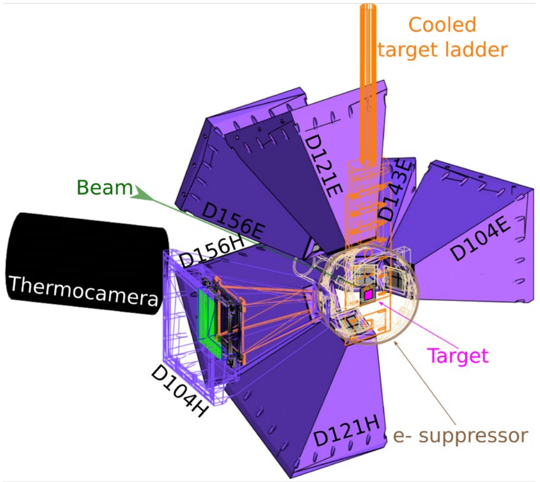


12C+16O



50 years of measurements still carry huge uncertainties, discrepancies between data sets and inaccurate extrapolations → Direct measurements are required!

Both reactions can be measured at low energies with charged particles (protons and alphas) at CIRCE-DM.



Estimated beam on target:

- 4 months for **12C+12C (up to Ecm= 2 MeV)**
- 1 months for **12C+16O (up to Ecm= 3MeV)**

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  - Ionized Gas Jet Target (CIRA collaboration)

$^{7}Be(\alpha,\gamma)^{11}C$ (Q=7.544 MeV)

PHYSICAL REVIEW C VOLUME 29, NUMBER 4

Resonant alpha capture by ^{7}Be and ^{7}Li

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Physics Division, Argonne National Laboratory, Argonne, Illinois 60439

M. Wiescher
Physics Department, The Ohio State University, Columbus, Ohio 43210

R. E. Segel
Physics Department, Northwestern University, Evanston, Illinois 60201
(Received 2 December 1983)

- A single measurement of the resonance strengths.
- Actually, measurements on going at DRAGON separator.

- Large acceptance necessary, due to large Q_{value}, update necessary.

- There are a lot more ^{10}B+p data
- Multichannel R-matrix calculations
- Obtaining a simultaneous fit to all data has proved to be very challenging.

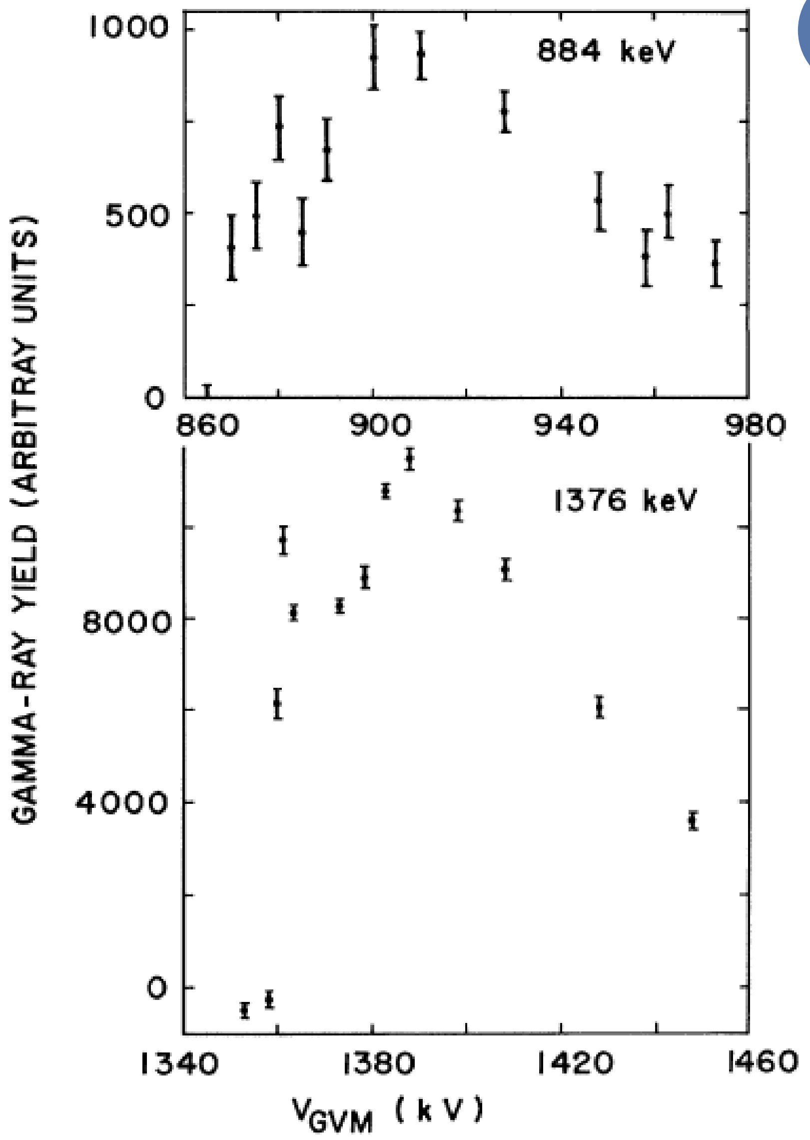

FIG. 4. Resonance curves for the $^{7}Be(\alpha,\gamma)$ reaction. For both resonances the yield of γ rays to the ground-state transition is plotted.

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THM and ERNA

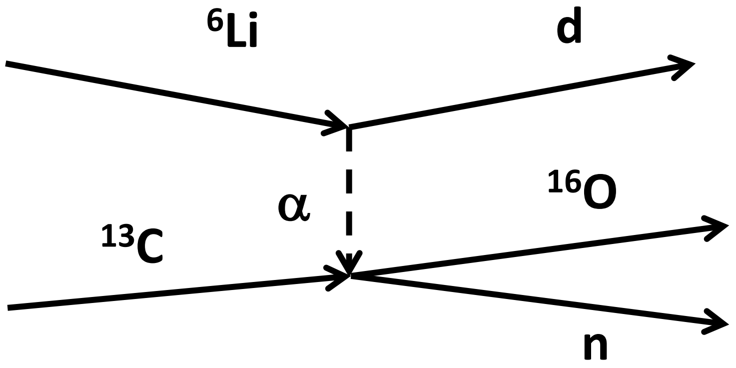
Possible advantages of the coupling of THM and recoil separator:
- measurements where the TH nucleus *a* is used as projectile and one of the two ejectiles (*c* or *C)* is a neutron as for the $^{13}C(\alpha,n)^{16}O$ or $^{22}Ne(\alpha,n)^{25}Mg$ reactions → *leading to different and complementary way to apply the THM*

- when one of the two ejectiles are emitted at very forward angles (for instance case of the $^{23}Na(d, \alpha\ ^{20}Ne)n$ THM reaction measured to study the $^{23}Na(p,\alpha)^{20}Ne$

To investigate the possible experimental advantages of the THM recoil separator coupling →

test measurement: study of the $\mathbf{^{13}C(\alpha,n)^{16}O}$ the neutron source for the main component of the s-process applying the THM to the $\mathbf{^{13}C(^{6}Li,n\ ^{16}O)d}$ where $^{6}Li = (\alpha+d)$ is the TH nucleus

reactions already studied with THM Trippella O. & La Cognata M., ApJ, 837, 41 (2017)



^{6}Li beam delivered on a **^{13}C target**

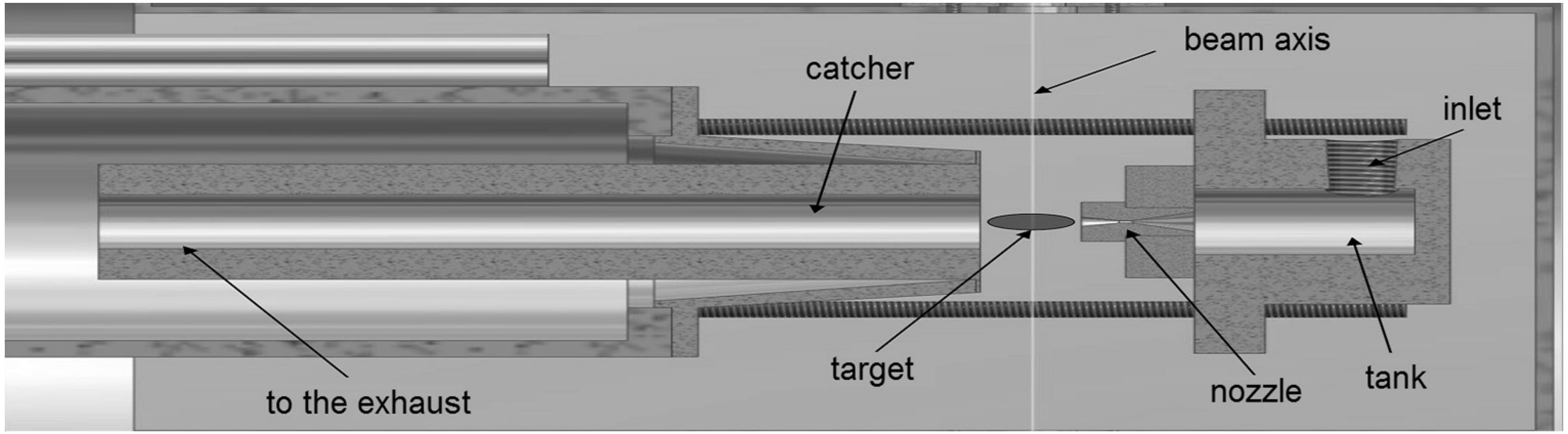
Deuteron (spectator) detected with ERNA in coincidence with ^{16}O detected with a silicon position sensitive detector.

→ scattering chamber to place a solid target and an array of DSSSD

Next at CIRCE-DMF

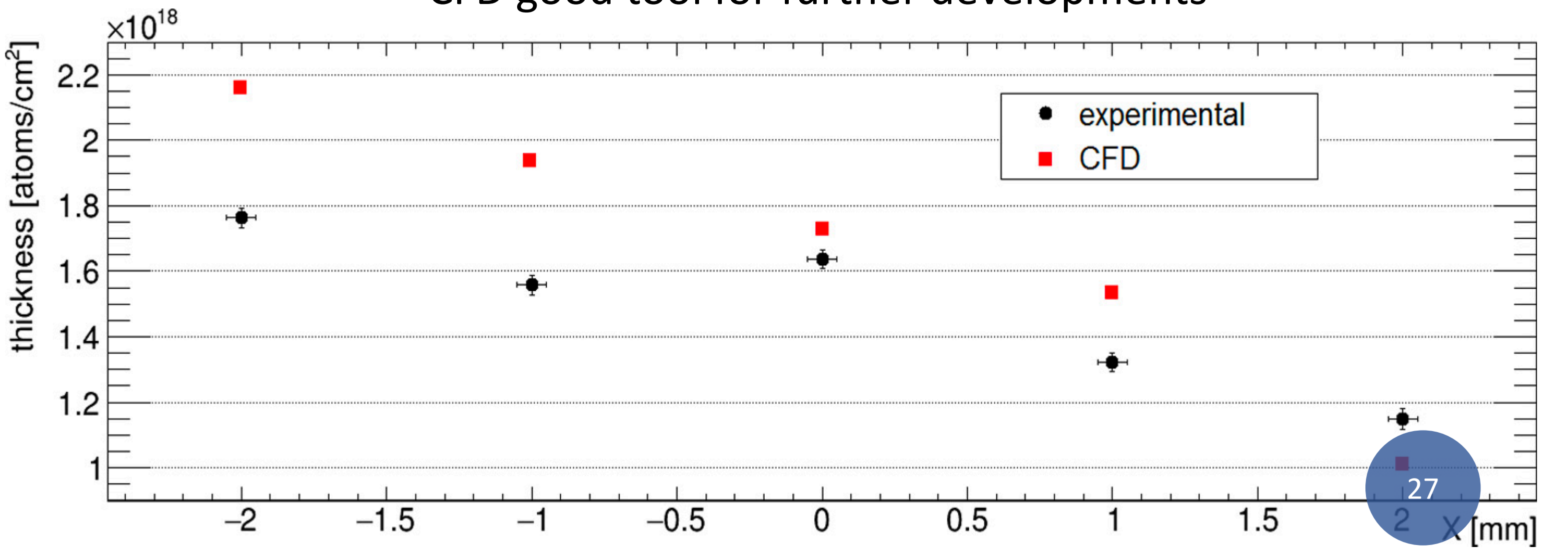
- BBN:
  - $^{7}Be(d,p)^{8}Be$ with THM
- H and He burning:
  - Triple-α process ($^{13}C(^{3}He,\alpha_2)^{12}C^*$)
  - $^{16}O(\alpha,\gamma)^{20}Ne$
    - Total Cross section
    - Angular distribution
- AGB ^{19}F nucleosynthesis
  - $^{15}N(\alpha,\gamma)^{19}F$
  - $^{14}N(\alpha,\gamma)^{18}F$
- Advanced burnings
  - $^{12}C(^{12}C,p)^{23}Na$ and $^{12}C(^{12}C,\alpha)^{20}Ne$ (chiedere energia LIZ)
- P-process
  - $^{7}Be(\alpha,\gamma)^{11}C$
- Other applications:
  - THM applications $^{13}C(\alpha,n)^{16}O$; $^{22}Ne(\alpha,n)^{25}Mg$; $^{23}Na(p, \alpha)^{20}Ne$.
  - **Ionized Gas Jet Target (CIRA collaboration)**

Electron screening-
Ionized Supersonic Gas Jet Target



- short (less than 1 cm)
- dense ~10^{18} nuclei / cm^2
- auto-confinement, i.e. no gas diffusion in the reaction chamber
- ionizable

CFD good tool for further developments



OUTLOOKS

- heat conditions for ionization must be calculated in advance (CEA2, NExT codes)
- a possible market available technology should be found

Thanks