Nuclear Physics in Astrophysics VIII

18-23 June 2017, Catania, ITALY

The RIB in-flight facility EXOTIC

CONCETTA PARASCANDOLO

INFN – NAPOLI, ITALY

Exotic @ INFN-LNL

Production of in-flight low-energy light radioactive ion beams (RIBs) through two-body inverse kinematics reactions induced by high intensity heavy-ion beams from the XTU Tandem accelerator impinging on light gas targets (**p, d, ^{3}He, ^{4}He**)

- **Commissioning** of the EXOTIC facility in 2004

V.Z. Maidikov et al., Nucl. Phys. A 746 (2004) 389c, D. Pierroutsakou et al., EPJ SP 150 (2007) 47, F.. Farinon et al., NIM B 266 (2008) 4097, M. Mazzocco et al., NIM B 266 (2008) 4665

- First **"beam for experiment"** ^{17}**F** in 2006

D. Pierroutsakou et al., EPJ SP150 (2007) 47, C. Signorini et al., EPJA44 (2010) 63

- A **substantial upgrade process** was subsequently held in 2012

M. Mazzocco et al., NIM B 317, 223 (2013)

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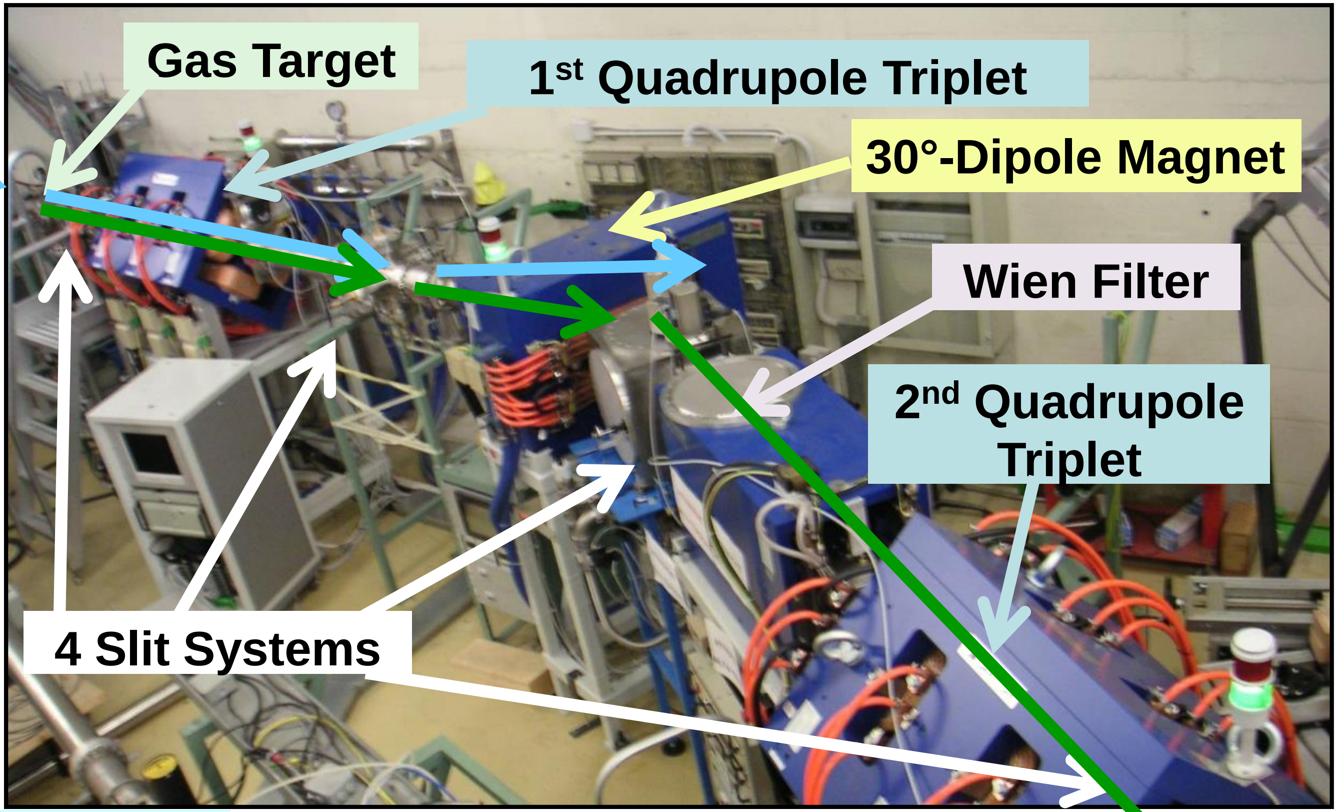
PRIMARY BEAM



SECONDARY BEAM

Solide angle $\Delta\omega$	~ 10 msr
Energy acceptance $\Delta E/E$	$\pm 10\%$
Momentum acceptance $\Delta p/p$	$\pm 5\%$
Horizontal acceptance $\Delta\theta$	± 50 mrad
Vertical acceptance $\Delta\phi$	± 65 mrad
Magnetic rigidity $B\rho$	0.98 Tm

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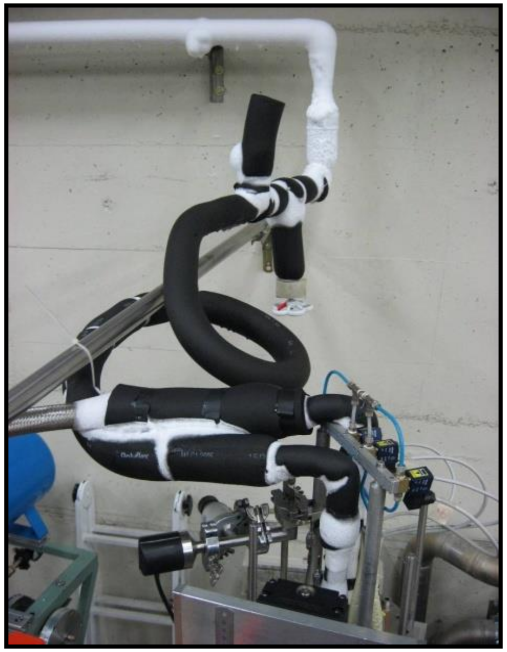
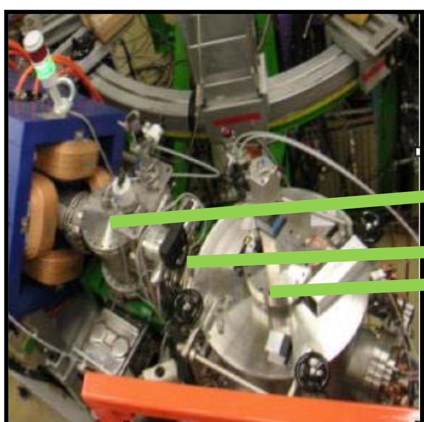


Cryogenic production gas target: 5-cm long double-walled cylindric cell
Entrance (exit) windows: 14 (16) mm made with 2.2 μm **havar**
Pressure: up to 1.2 bar

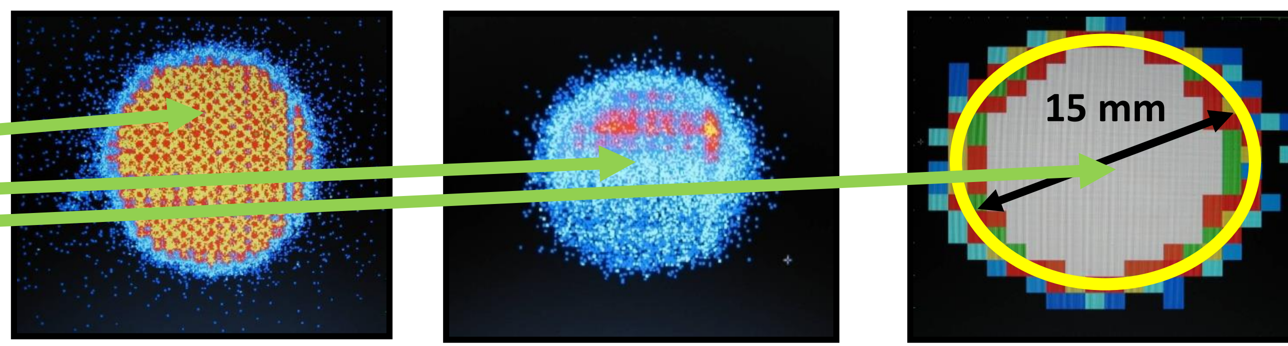
RIB Tracking performed with **position-sensitive PPACs (Parallel Plate Avalanche Counter)**



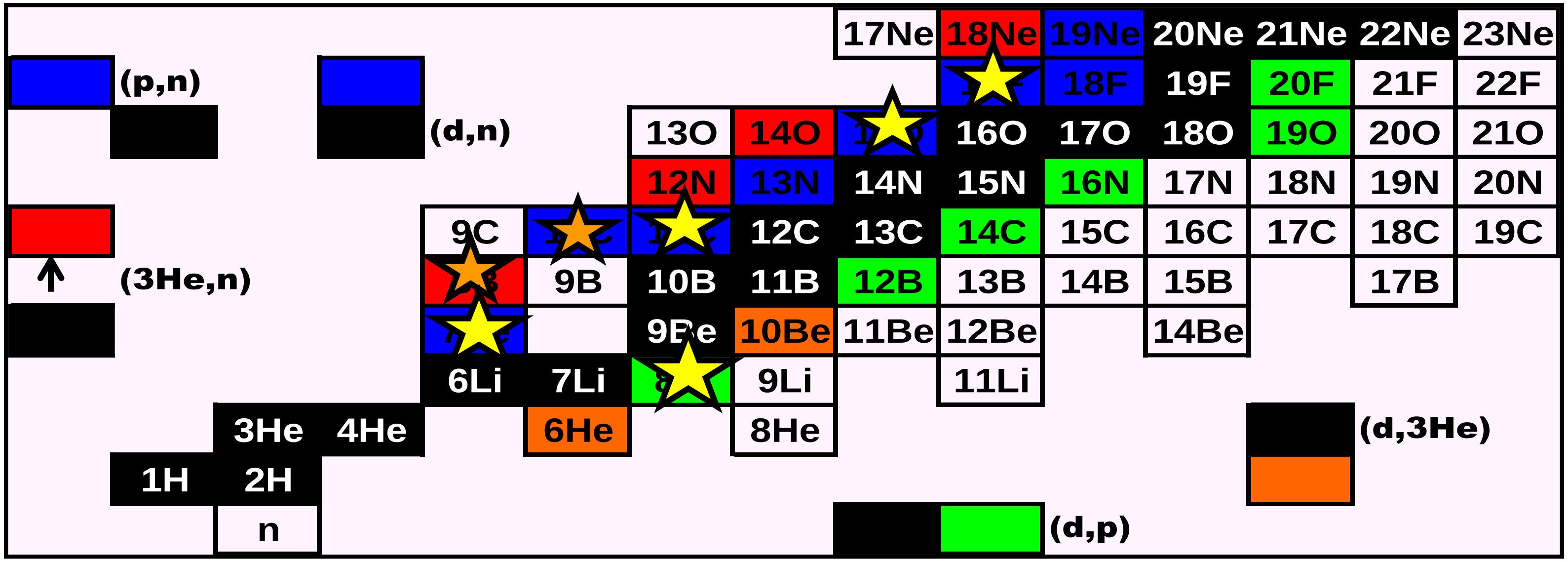
PPAC A
909 mm

PPAC B
365 mm

Reconstruction on the target



Light RIBs @ Exotic



^{17}F (S_p= 600 keV)	*p(^{17}O,^{17}F)n*	Q=–3.54 MeV	E=3–5 MeV/u	P:93-96%	**I:10^5 pps**
^{8}B (S_p= 137.5 keV)	***^{3}He(^{6}Li,^{8}B)n***	Q=–1.97 MeV	E=3–5 MeV/u	P:30-43%	**I:10^3 pps**
^{7}Be (S_α= 1.586 MeV)	***p(^{7}Li,^{7}Be)n***	Q=–1.64 MeV	E=2.5–6 MeV/u	P:99%	**I:10^6 pps**
^{15}O (S_p= 7.297 MeV)	***p(^{15}N,^{15}O)n***	Q=–3.54 MeV	E=1.3 MeV/u	P:98%	**I:4*10^4 pps**
^{8}Li (S_n= 2.033 MeV)	***d(^{7}Li,^{8}Li)p***	Q=–0.19 MeV	E=2–2.5 MeV/u	P:99 %	**I:10^5 pps**
^{10}C (S_p= 4.007 MeV)	***p(^{10}B,^{10}C)n***	Q=–4.43 MeV	E=4 MeV/u	P:99 %	**I:5*10^3 pps**
^{11}C (S_p= 8.689 MeV)	***p(^{11}B,^{11}C)n***	Q=–2.76 MeV	E=4 MeV/u	P:99 %	**I:2*10^5 pps**

Exotic: Experimental Program

- Study of reaction dynamics with light RIBs

- Study of a clustering phenomena in light exotic nuclei

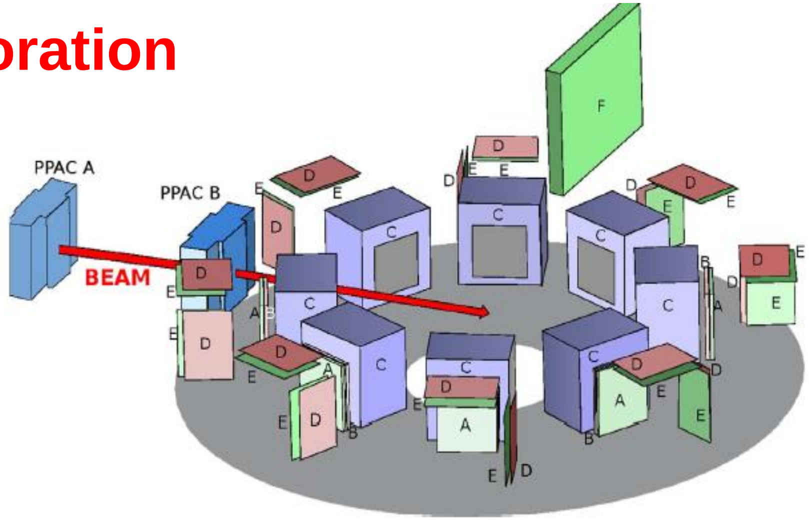
- Direct and indirect measurements of astrophysical interest

- The use of the facility EXOTIC as a separator for Heavy-Ion Fusion Evaporation Residues from stable beams for measurements at sub-barrier energies is under investigation: recent tests performed with encouraging results

Exotic: the experimental set-up

Entirely developed by our collaboration

- 2 **position-sensitive Parallel Plate Avalanche Counters** (PPACs) for beam tracking and ToF measurements
- **EXPADES:** a high-granularity, compact, flexible, portable charged-particle detection array



8 (Tri)Telescopes

ΔE1 – IC, 10 cm x 10cm x 6.8 cm

ΔE2 (40/60 μm) + E $_{res}$ (300 μm) - DSSSDs
64 x 64 mm^2 active area
32 x 32 strips (2 mm pitch size - 40 μm interstrip separation)
2 x 2 mm^2 pixel
$\Delta\theta$ = 1° at d=10.5 cm

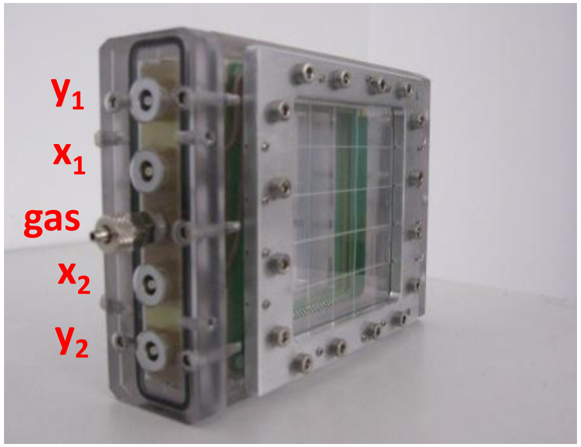
→

Z and A identification through ΔE-E
TOF information
Good energy, time and angular resolution
High granularity
Distance from target varies from 10.5 to 22.5 cm
Coverage: 22% of 4π sr at 10.5 cm

D. Pierroutsakou et al, NIM A 834 (2016) 46

Exotic: the experimental set-up

Parallel Plate Avalanche Counter

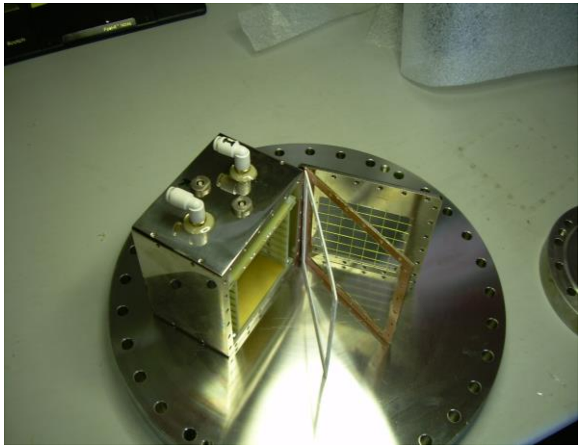


1.5 μm-thick mylar windows
Active area: 62x62 mm^2
Central cathode and two anodes (60 gold-plated tungsten wires in the x and y directions)
(d_{AC} = 2.4 mm)

Gas: C_4H_{10} at 10-20 mbar

1 mm position resolution
High tracking efficiency
Counting up to 10^6 Hz

ΔE1: Transverse Field Ionization Chamber

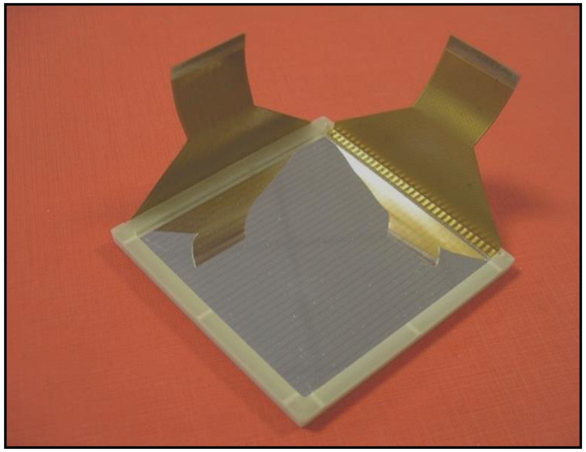


1.5 μm-thick mylar windows

Frisch grid
Gas: CF_4 at 50-100 mbar

FWHM 73 keV for ΔE=1 MeV

DSSSD, ΔE2: 40/60 μm and E_r: 300 μm



Readout: home-made highly integrated low-noise electronics

And/Or

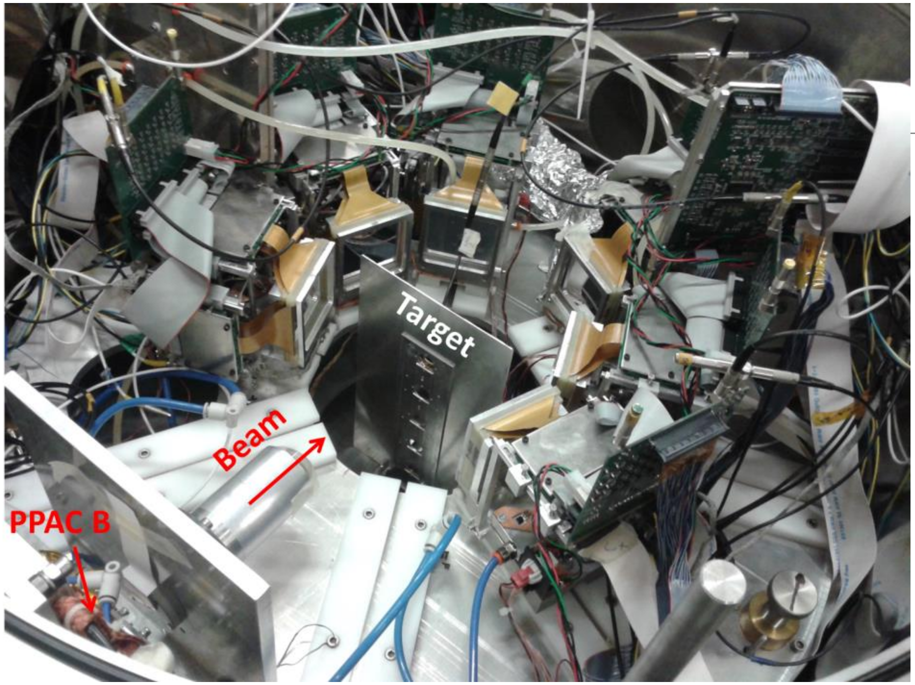
ASIC chip (IDEAS-GM)

ΔE2
FWHM ΔE=38 (34 intrinsic) keV for E=5.805 MeV
FWHM Δt = 1 ns

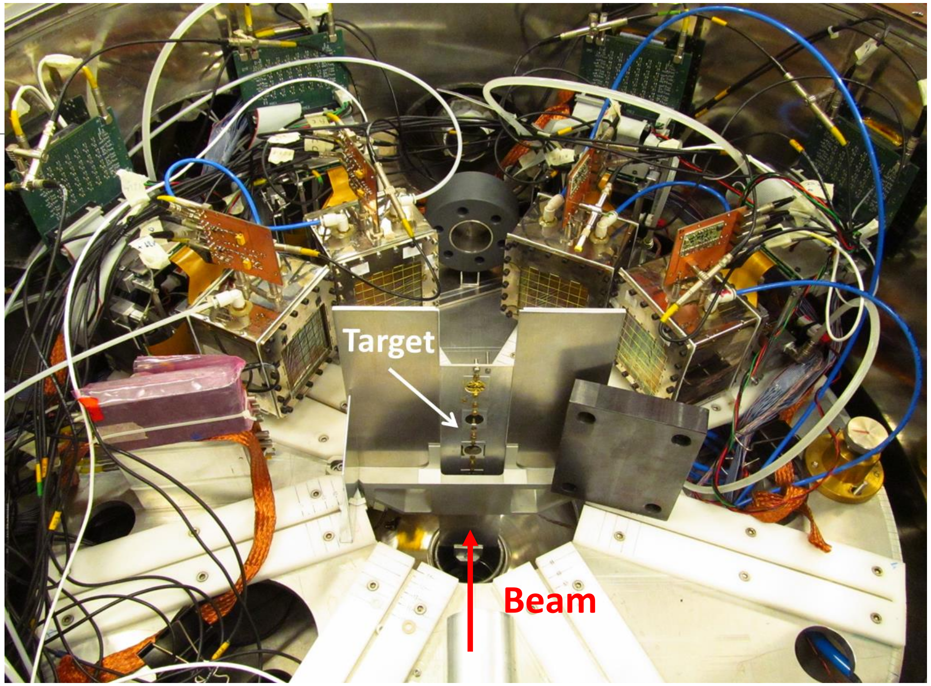
E_r
FWHM ΔE=66 (33 intrinsic) keV for E=5.805 MeV

Expades Configurations

6 two-stage DSSSD telescopes



4 three-stage IC-DSSSD telescopes



EXPADES was installed at the focal plane of the EXOTIC facility in June 2013 and has been used in various experimental configuration, due to its high flexibility.

Upgrade : 1.5 mm-thick DSSSD for the detection of more energetic particles in addition or in alternative to the 300 μm-thick E_{res} DSSSDs.

Exotic nuclei reaction dynamics at near and sub-barrier energies

Characteristics of exotic nuclei: Excess of neutrons or protons, short half-life, low binding energy, halo structure, neutron or proton dominated surface

Coupling to **strong reaction channels (breakup, transfer)** due to the low binding energy and the halo structure → Influence on elastic scattering and fusion → New phenomena at the Coulomb barrier.

Elastic scattering → probe the tail of the wave function, and then surface properties, such as size of nuclei and surface diffuseness -> **peculiar nuclear structure**

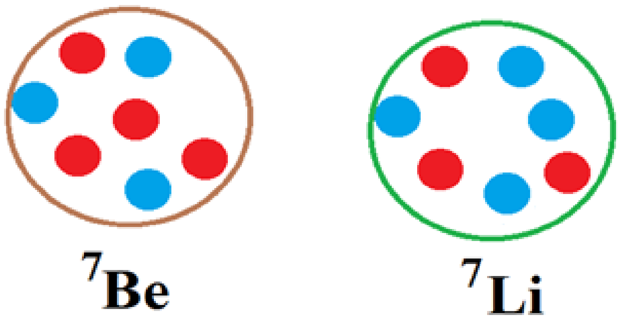
1) Large reaction cross section with respect to stable encounters
2) Disappearance of the conventional “threshold anomaly”
3) Elastic scattering AD shapes that markedly differ from the expected classical Fresnel scattering pattern

Complete fusion cross section → probe the potential from the inner side of the nucleus - insight into a number of static and dynamic effects -> **channel coupling effects**

Enhancement if the breakup is considered as a normal coupling channel, the halo structure causes strong force to begin acting at large distances -> appearance of dipole strength at low E*

Decrease if it prevents complete capture of the projectile by the target

^{7}Be case



S_{α} = 1.586 MeV, $T_{1/2}$ = 53.22 d, g.s. $J^{p}=3/2^{-}$

Nucleus	Breakup Threshold (MeV)
^{7}Be	1.60
^{6}Li	1.48
^{7}Li	2.45

^{7}Be is the mirror weakly bound radioactive nucleus of **^{7}Li** with a well-pronounced **^{3}He+^{4}He** cluster structure and it is the core of **^{8}B**.

^{7}Be breakup threshold in **^{3}He+^{4}He** is similar to that of the weakly bound **^{6}Li**.

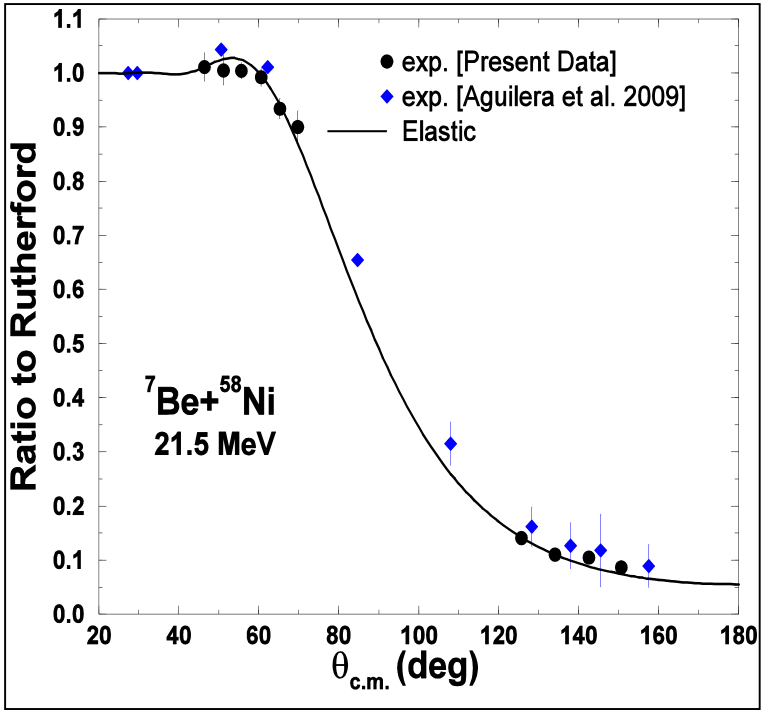
Interesting to study:

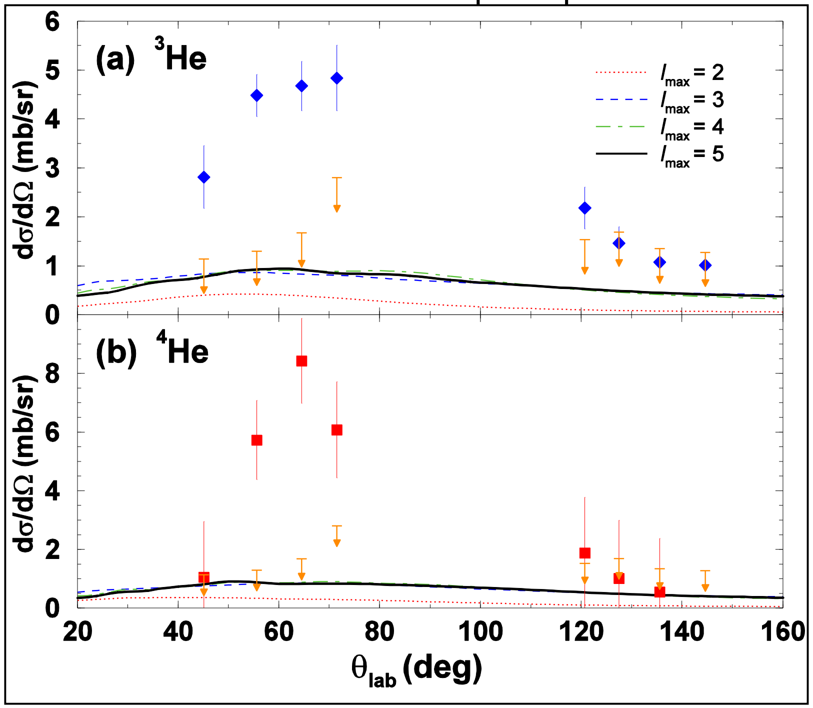
- **Elastic scattering** of ^{7}Be: does it behave like the **^{7}Li** or **^{6}Li** one?
- **Reaction mechanisms: ideal case** (among all light ions) where the **interplay** between **different reaction mechanisms** at Coulomb barrier energies can be easily addressed quite in detail.

^{7}Be + ^{58}Ni

Performed with Dinex Array, see G. Marquınez-Duran et al., NIM A **755**, 69 (2014)

Spokesperson: M. Mazzocco





Elastic Scattering: agreement with an **earlier measurement** by
E.F. Aguilera et al.,
Phys. Rev. C. 79, 021601(R) (2009)

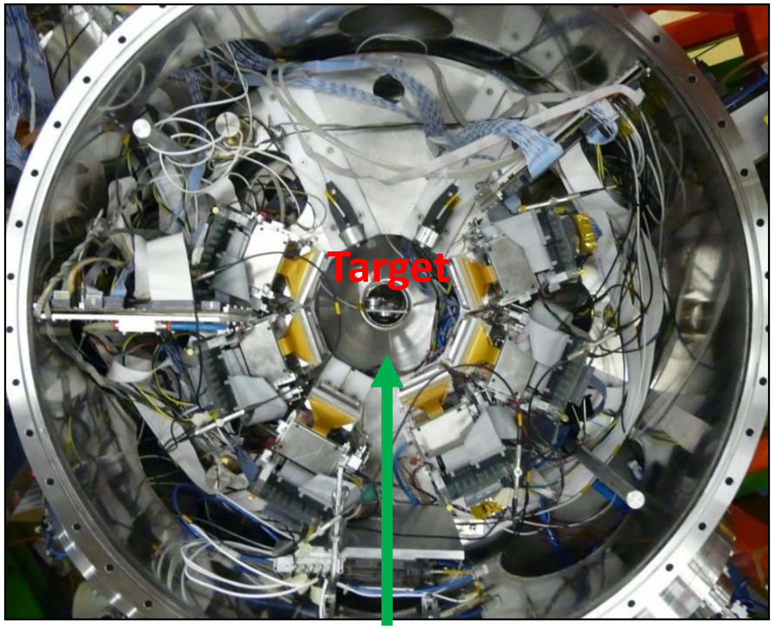
Direct Processes: larger production of ^{4}He than ^{3}He. **No coincidences detected**
M. Mazzocco et al.,
Phys. Rev. C. 92, 024615 (2015)

^{7}Be + ^{208}Pb **Never Measured Before!** **Goal**: to Detect Coincidences

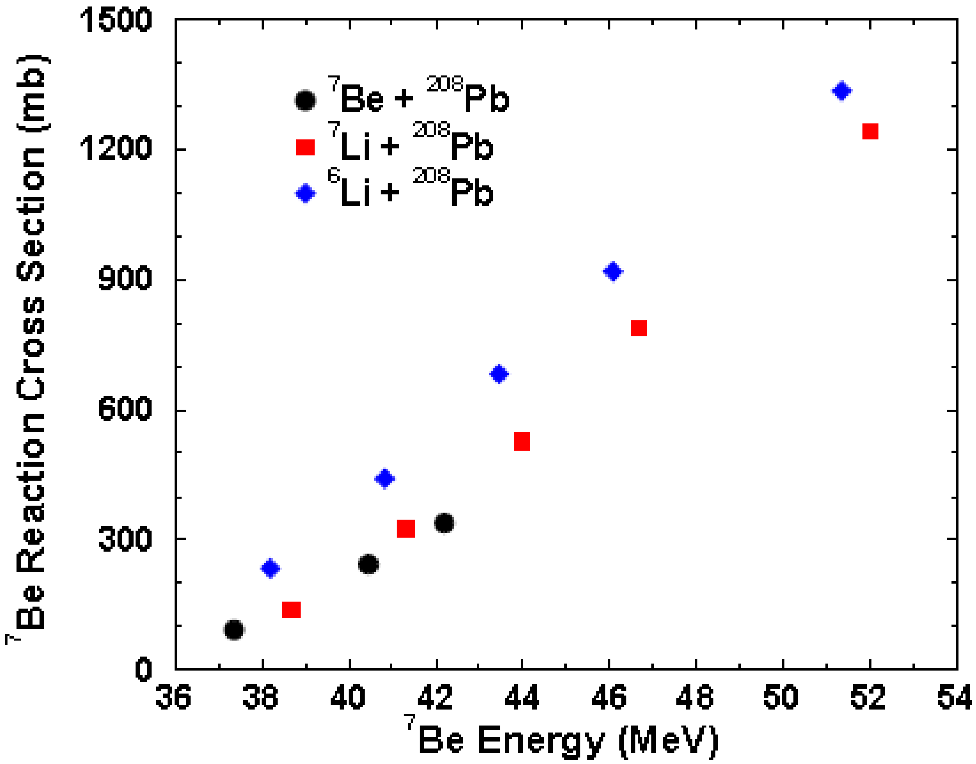
$^{7}Be + ^{208}Pb$

Spokespersons: M. La Commara, L. Stroe, M. Mazzocco

EXPADES



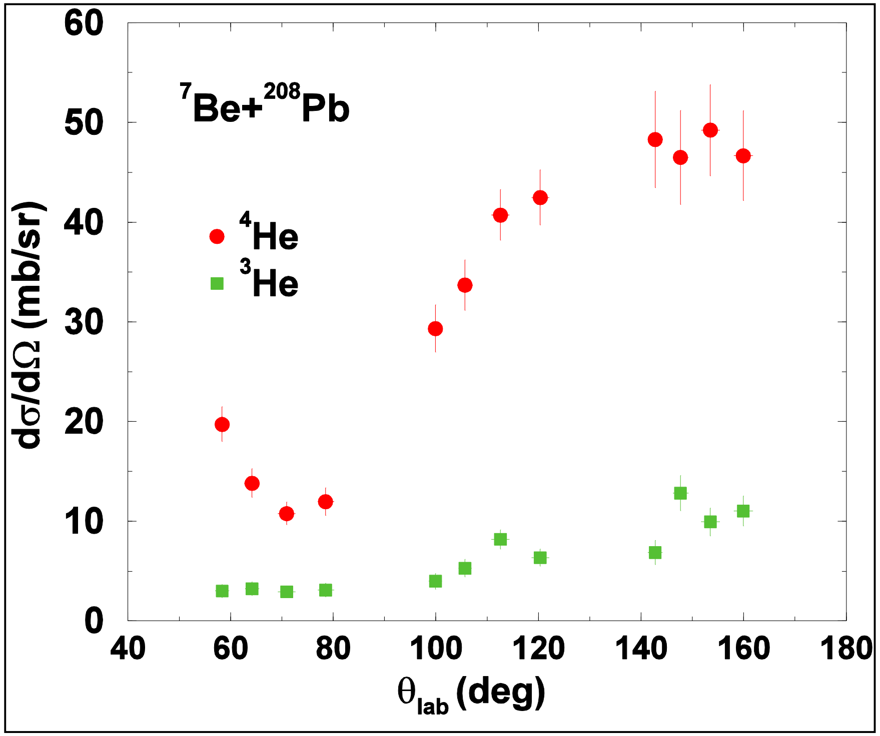
^{7}Be RIB (2.5 * 10^{5} pps)



A preliminary **optical model best-fit analysis** of the quasi-elastic scattering angular distributions suggests for **^{7}Be (S_α = 1.586 MeV)** a **behaviour** more similar to **^{7}Li (S_α = 2.468 MeV)** than to **^{6}Li (S_α = 1.475 MeV)**.

$^{7}Be + ^{208}Pb$

$^{3,4}He$ Production



^{3}He and ^{4}He have significantly different yields, thus the **breakup** process **does not dominate the reaction dynamics**.

The ^{4}He production yield is much larger than the ^{3}He one, **qualitatively confirming** our previous result for the system **$^{7}Be + ^{58}Ni$,** PRC 92, 024615 (2015)

We detected a few !!!

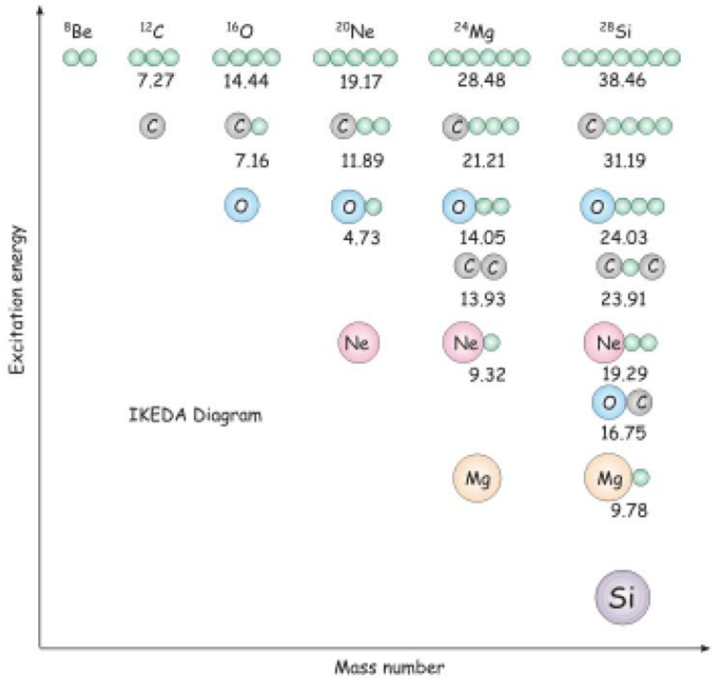
What About Coincidences?

A **detailed kinematical analysis** is on going to investigate the nature of the **detected coincidences→ Q_{value}** and **E_{rel}**

Clustering in nuclei

α clustering manifests itself in α-conjugate nuclei through the existence of twin quasi-rotational bands of states of alternating parities and large α-particle width.

Also non α-conjugate nuclei manifest cluster configurations like ^{6}Li and ^{7}Li or ^{9}Be



And what is expected out of the stability valley?

Light exotic nuclei may show cluster configurations where at least one of the clusters is unbound or weakly bound → **Exotic clustering regime** → More favoured for nuclei approaching the drip-lines

Search for ^{15}O-α configurations associated to ^{19}Ne states

Spokespersons: D. Torresi, C. Wheldon

Elastic scattering of the system ^{15}O+^{4}He, never measured before, performed with the Thick Target Inverse Kinematics method (TTIK).

K. P. Artemov et al., Sov. J. Nucl. Phys. 52, 408(1990)
G. Rogachev PhD thesis

✓ Measurements of the elastic scattering excitation function in a wide range of energies using a single beam energy with the TTIK method

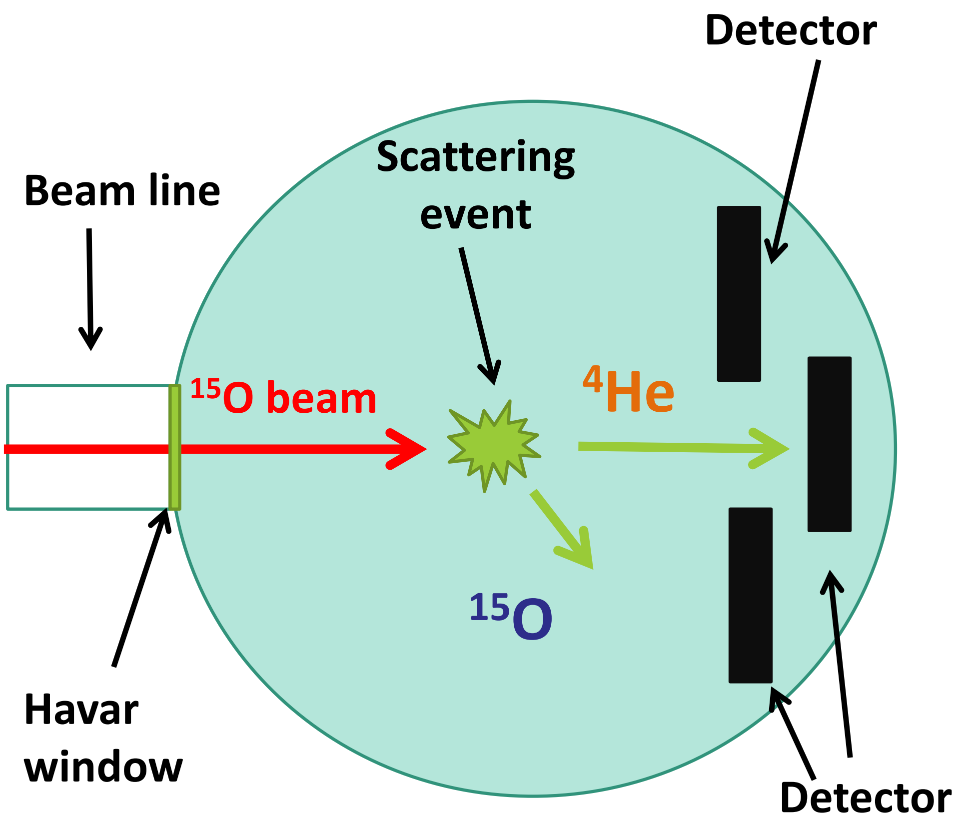
✓ R-matrix analysis for the extraction of

- Energy and width of the resonances
- Reduced α-width

Why ^{19}Ne?

1. A number of Ne isotopes manifest evidences of clustering phenomena. This makes the ^{19}Ne a good candidate to manifest cluster structures.
2. Improvement of our knowledge on the ^{15}O(α,γ) ^{19}Ne and ^{18}F(p,α)^{15}O reaction rate of astrophysical interest.

$^{15}O + \alpha$ experiment

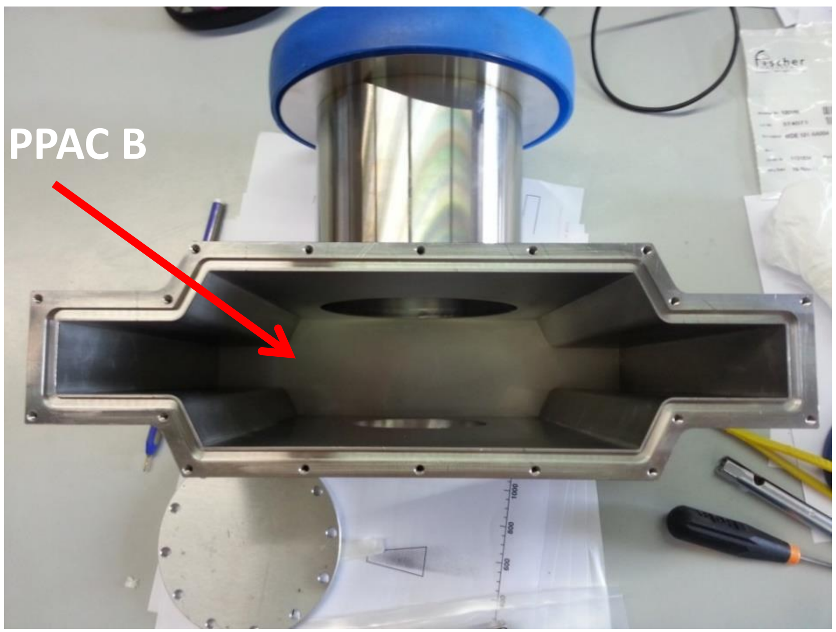


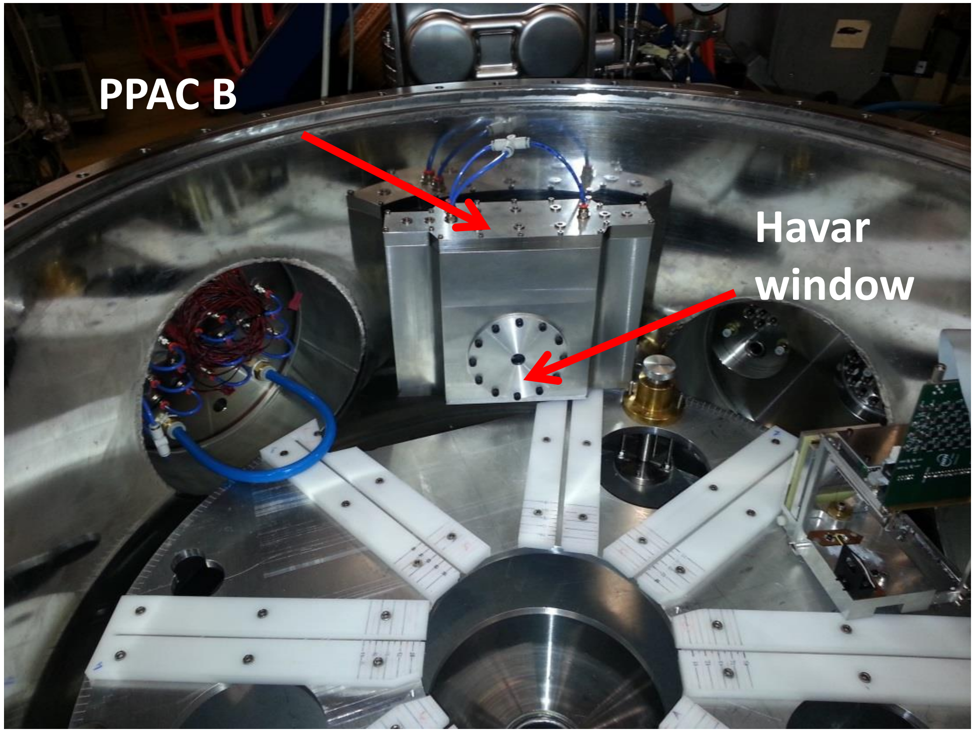
- The chamber is filled with gas at such a pressure to stop the beam
- The beam slows down into the gas
- Elastic scattering occurs at different positions in the chamber
- Detectors placed at 0° and around detect the recoiling a particles
- Energy and position where the reaction occurs can be reconstructed from the energy and position of the detected α
- Stopping power of the beam and α particle should be known

Exotic upgrade for experiments with reaction gas targets

Modifications of the EXOTIC beam line were performed in early 2015, to allow the realization of experiments by employing **RIBs** impinging on reaction **gas targets (thick targets)**.

A new small chamber was built hosting the PPAC B that separates, through a havar window, the scattering chamber (filled with ^{4}He gas) from the beam line (at high vacuum).





Exotic nuclei reactions of astrophysical interest

Stable beams and targets → data on Big Bang nucleosynthesis and quiescent burning scenarios (10^9 years)

Need: High beam intensities, thick targets that can tolerate the beams, low backgrounds, long runs

Stellar nucleosynthesis paths involve **UNSTABLE** species. In astrophysical sites such as novae, x-ray busters and type Ia supernovae, energy source → Explosive Hydrogen and Helium burning.

RIBs provide data for these fast (few seconds to hours) explosive burning scenarios

Need: beams of unstable nuclei (low intensities, contaminants), thick targets (to compensate for the intensity), long runs

What we can study ?

(p, γ) (novae, rp-process)
(α,p) (rp-process)

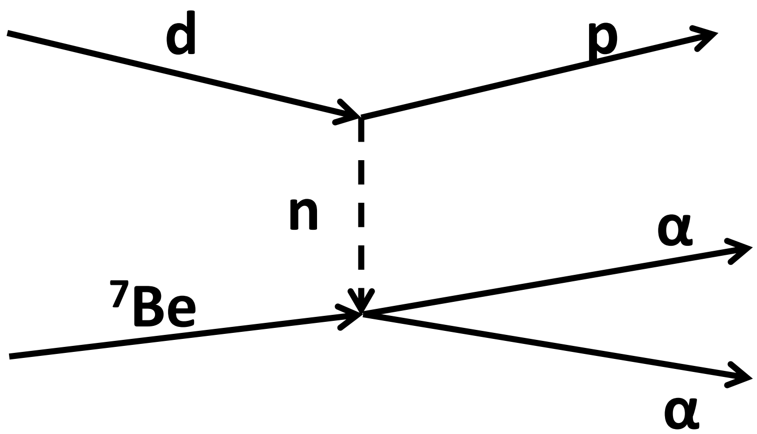
Needs for β-decay rates, masses, (p,γ) and (α,p) reaction rates –> **p-rich RIBs** of first and second generation facilities

(n, γ) (r-process)

Unknown site (supernovae ?) and properties of nuclei in the r-process path (half-lives, masses, n-capture cross sections,….) → **n-rich RIBs** produced by second generation ISOL facilities: SPES, SPIRAL2,…

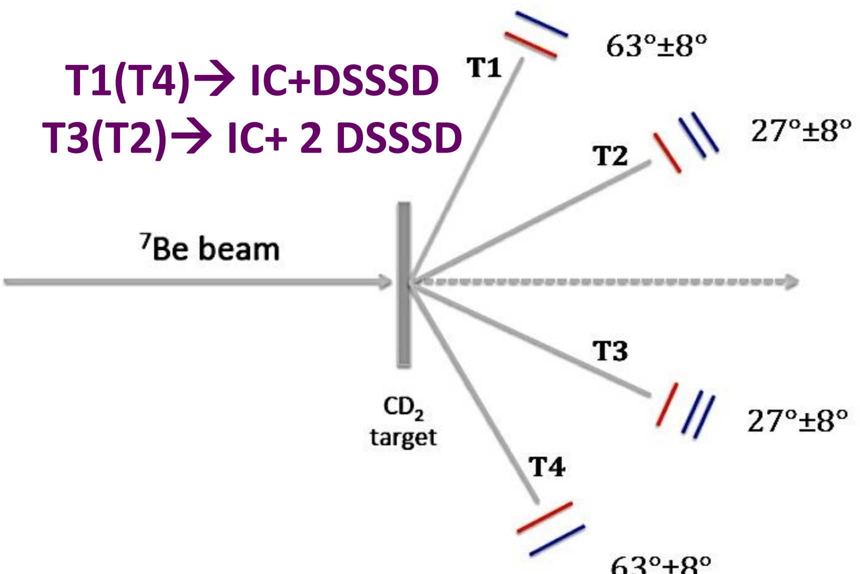
$^7Be(n,\alpha)^4He$: THM @EXOTIC

Spokespersons: L. Lamia, M. Mazzocco



1) **^{7}Be(n,α)α (Q-value=18.99 MeV)** was studied by applying the THM to the reaction **^{2}H(^{7}Be, α ^{4}He)p (Q-value=16.765 MeV)** by properly selecting the corresponding quasi-free contribution (QF) to the total reaction yield;
2) Deuteron "d" is used as **TH-nucleus**
3) Use of large area 6x6 cm^2 **IC & DSSSD**

T1(T4)→ IC+DSSSD
T3(T2)→ IC+ 2 DSSSD



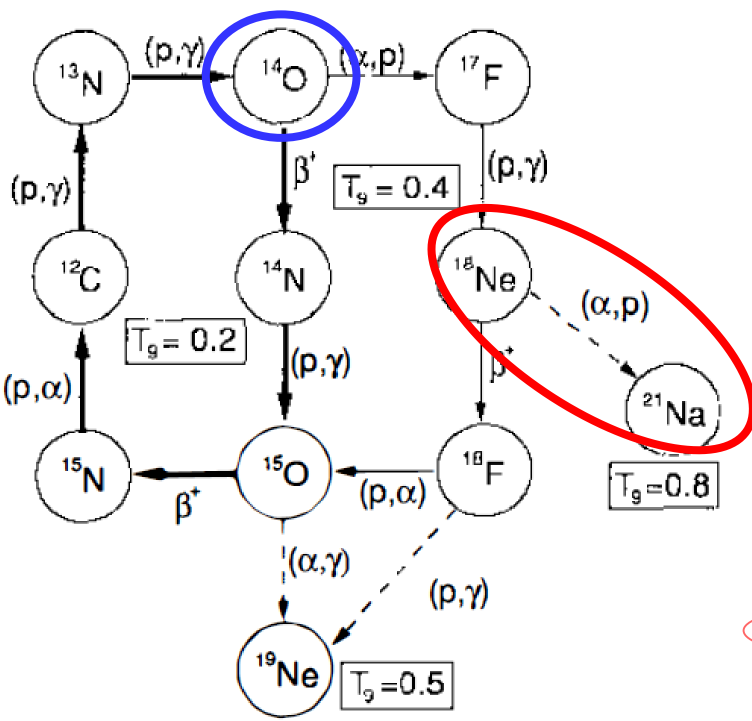
Investigating the energy region of interest for BBN E_{cm}= 0-1.5 MeV, where the reaction rate is still assumed with an order of magnitude of uncertainty.

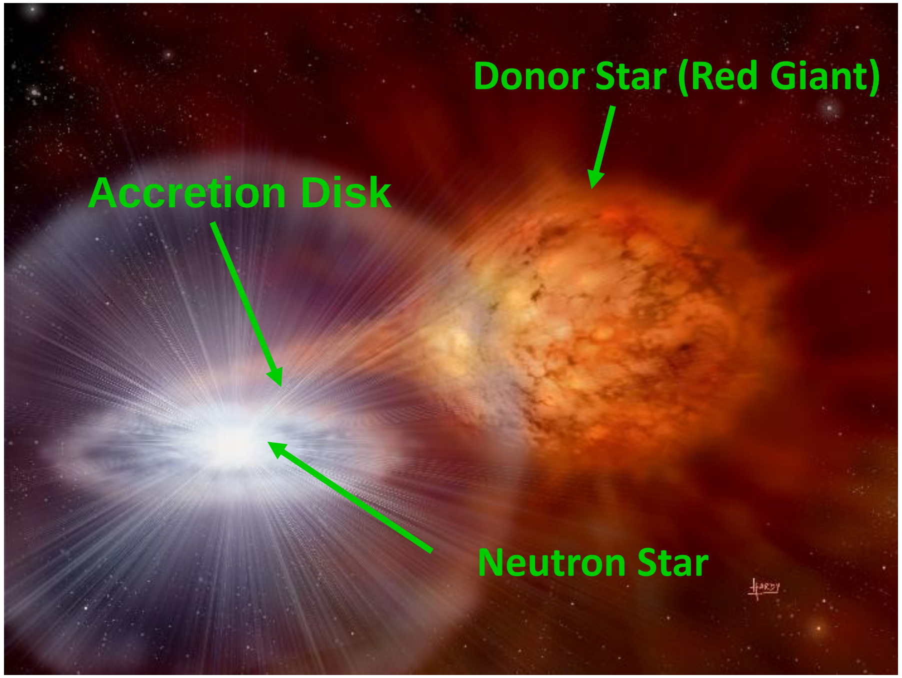
Large discrepancy (about a factor 3) between predicted and observed primordial ^{7}Li abundance, essentially determined by the production and destruction of ^{7}Be nucleus.

See L. Lamia talk

$^{18}Ne(\alpha,p)^{21}Na$ @ EXOTIC: future experiment

Stellar Nucleosynthesis in explosive processes





X-ray Burst

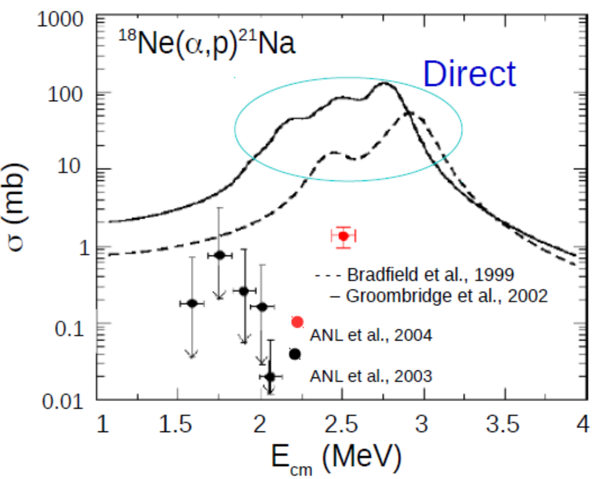
From Hot CNO cycle → *rp* process to synthesize heavier masses

Key parameter: Rate of $^{18}Ne(\alpha,p)^{21}Na$ reaction

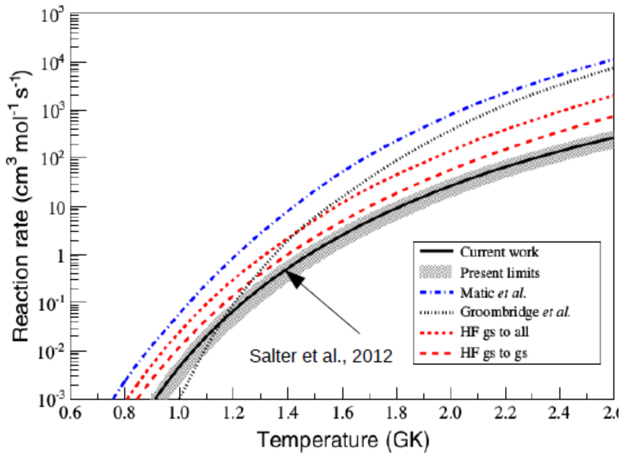
$^{18}Ne(\alpha,p)^{21}Na$ @ EXOTIC: future experiment

Direct Measurements: Only two performed at Louvain-la-Neuve at E_{cm}= 1.7-3.01 MeV. Still **too high energies** to be relevant for astrophysics

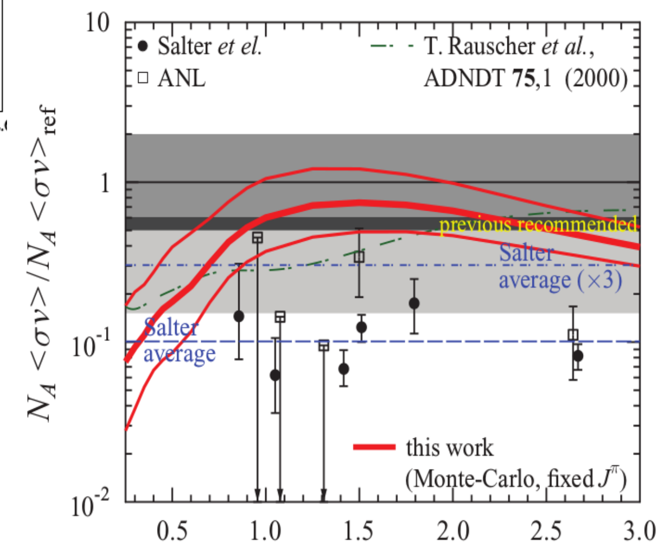
Indirect Measurements: Different techniques (time-reversal, resonant scattering, ...) performed at ISAC II (Triumf, Canada), ANL (Argonne, USA), CRIB (Riken, Japan),...



Sinha et al., ANL Report 2014, unpublished



Salter et al., Phys. Rev. Lett. 108, 242701,2012



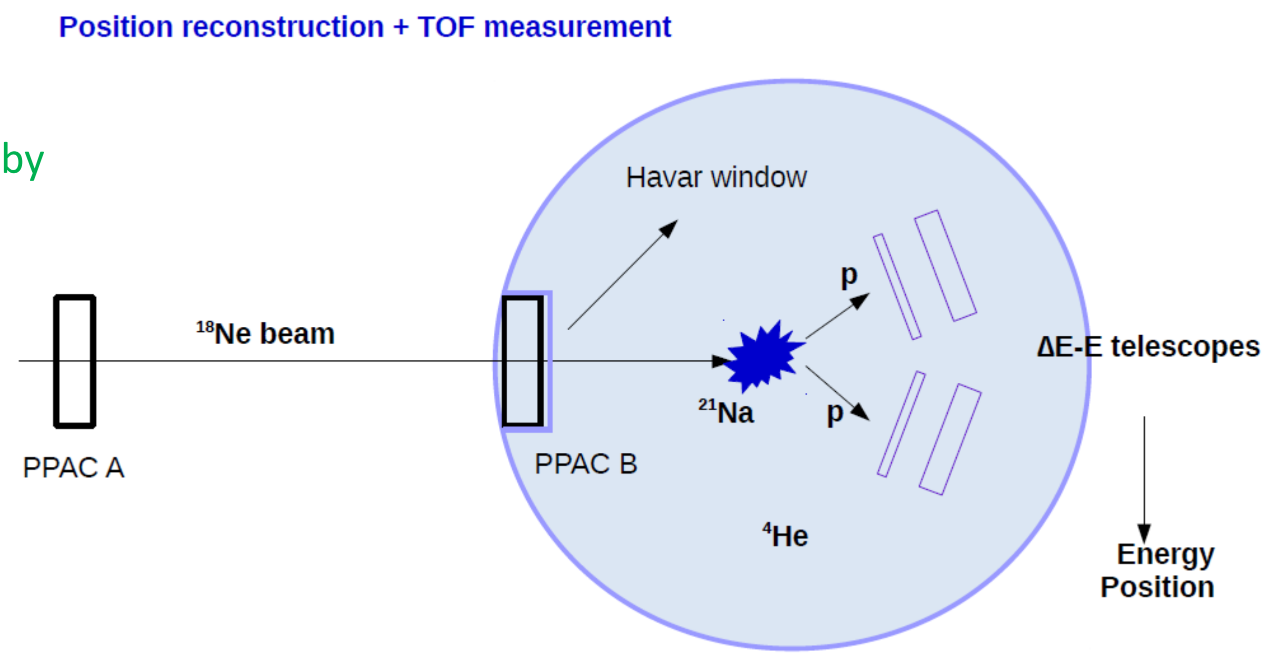
Mohr et al., Phys. Rev. C90, 065806,2014 T_9

$^{18}Ne(\alpha,p)^{21}Na$ @ EXOTIC: future experiment

- Discrepancies between measurements
- Need to lower the energies for astrophysics

→ Perform a new direct measurement at Exotic

By using a ^{18}Ne beam produced by EXOTIC and a ^{4}He extended gas target, in inverse kinematics.



^{18}Ne (1.7 s) production via the reaction $^{3}He(^{16}O, \mathbf{^{18}Ne})n$ at

$E(^{16}O)$ = 86 MeV (50-100 pnA) and P=1 bar

$I(^{18}Ne)=2.5*10^{5}$pps @ EXOTIC, with Wien Filter transmission ≈ 50%

$^{30}P(p,\gamma)^{31}S$ @ EXOTIC: future experiment

(Astro)physical motivation

- This reaction influences the production of elements between Si and Ca in the explosion of O-Ne novae
- The isotopic ratio $^{30}Si/^{28}Si$ depends on this reaction (destroys the ^{30}P before decaying to a ^{30}Si)
- Anomalously high isotopic ratios $^{30}Si/^{28}Si$ measured in pre-solar grains of possible O-Ne novae origin

Existing measurements:

-Yale -> somes resonances were measured through the indirect measurement
-($^{31}P(^{3}He, t)^{31}S$) but the derived cross section has a large uncertainty

-There is also a large uncertainty in the calculation of the reaction rate

$\Rightarrow$ **direct measurements with a RIB are necessary**

$^{27}Al(^{4}He, n)^{30}P$ or $^{29}Si(d, n)^{30}P$ at 50 pnA of primary beam I(^{30}P) ~10^4-10^5 pps @ EXOTIC
Experimental set up: IC+DSSSD 300 μm + γ scintillators

EXOTIC facility as velocity filter

We performed a test of the facility EXOTIC used as a **beam separator** for detecting **Fusion Evaporation Residues** by studying the $^{32}S+^{48}Ca,^{64}Ni$ reactions.

The fusion excitation function of $^{32}S+^{48}Ca,^{64}Ni$ has been recently studied at LNL (by the PRISMA-FIDES collaboration) in a wide energy range, from above the Coulomb barrier down to cross sections in the sub-barrier region with the PISOLO set up.

Re-measuring this fusion excitation function with EXOTIC at selected energies can provide a useful comparison of the performance of the two set-ups (PISOLO and EXOTIC) to determine whether the larger acceptance of EXOTIC allows us to measure cross sections at the level of a few tens of nanobarn.

Higher Rejection factor at 0°

The **ER detection rate** was found to be 3 times larger and this can be improved in the next future by using a lower voltage Wien filter and a larger solid angle silicon detector

Possible use of the EXOTIC facility with the SPES RIBs for sub-barrier fusion measurements

EXOTIC: future and perspectives

EXOTIC is a facility for the in-flight production of low-energy light RIBs, fully operational at INFN-LNL. The **experimental set-up** installed at EXOTIC consists of: two PPACs for the RIB tracking and for ToF measurements and the compact, high-granularity, flexible, portable charged-particle detection array EXPADES.

Stimulating nuclear physics and nuclear astrophysics measurements can be performed employing the produced RIBs, in the framework of international collaborations.

Possibility to use the facility as a velocity filter to perform **fusion-evaporation** experiments at **sub-barrier energies** with **stable** beams and also with the **RIBs** of the next generation ISOL-type facility **SPES**, that is being constructed at INFN-LNL.

EXOTIC Collaboration

A. Boiano, C. Boiano, M. La Commara, G. La Rana, M. Mazzocco
C. Parascandolo, D. Pierroutsakou, C. Signorini, F. Soramel, E. Strano

In collaboration with …

Milano (Italy): A.Guglielmetti

Ioannina (Greece): A.Pakou, O.Sgouros, V.Soukeras, X.Aslanouglou

Athens (Greece): E.Stiliaris

Warsaw (Poland): N.Keeley, C.Mazzocchi, K.Rusek, I.Strojek, A.Trzcinska

Birmingham (UK): T.Kokalova, C.Wheldon

NIPNE (Romania): D.Filipescu, T.Glodariu, A.I.Gheorghe, T.Sava, L.Stroe

Huelva (Spain): I.Martel, L.Acosta, G.Marquinez-Duran, A.M.Sanchez-Benitez, H.Silva

CNS + RIKEN (Japan): H.Yamaguchi, S. Hayakawa, D.Kahl, Y.Sakaguchi, S.Kubono (RIKEN), N.Iwasa (Sendai), T.Teranishi (Kyushu), Y.Wakabayashi (RIKEN)

KEK (Japan): H.Miyatake, S.Jeong, Y.Watanabe, H.Ishiyama, N.Imai (CNS), Y.Hirayama, Y.H.Kim, S.Kimura, I.Mukai, I.Sugai

CIAE (China): H.Q.Zhang, C.J.Lin, H.Jia, Y.Yang, L.Yang, G.L.Zhang

LNL-Padova (Italy): C.Broggini, A.Caciolli, L.Corradi, R.Depalo, E. Fioretto, F.Galtarossa, J.A. Lay, R.Menegazzo, D. Mengoni, G. Montagnoli, D.Piatti, F. Scarlassara, A.M. Stefanini

LNS-Catania (Italy): D.Carbone, M.Cavallaro, S.Cherubini, A.Di Pietro, J.P.Fernandez-Garcia, P.Figuera, M.Fisichella, M.Gulino, M.La Cognata, L.Lamia, M.Lattuada, R.G.Pizzone, S.Puglia, G.G.Rapisarda, S.Romano, C.Spitaleri, D.Torresi, O.Trippella (PG), A.Tumino