Activities with the EXOTIC facility at LNL

Dimitra Pierroutsakou

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Overview

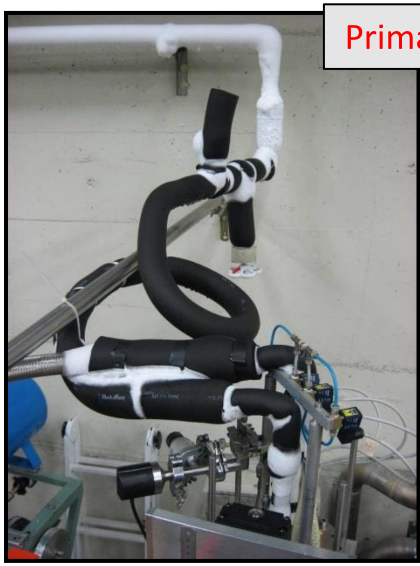
1) EXOTIC facility

2) Activity 2015-2017

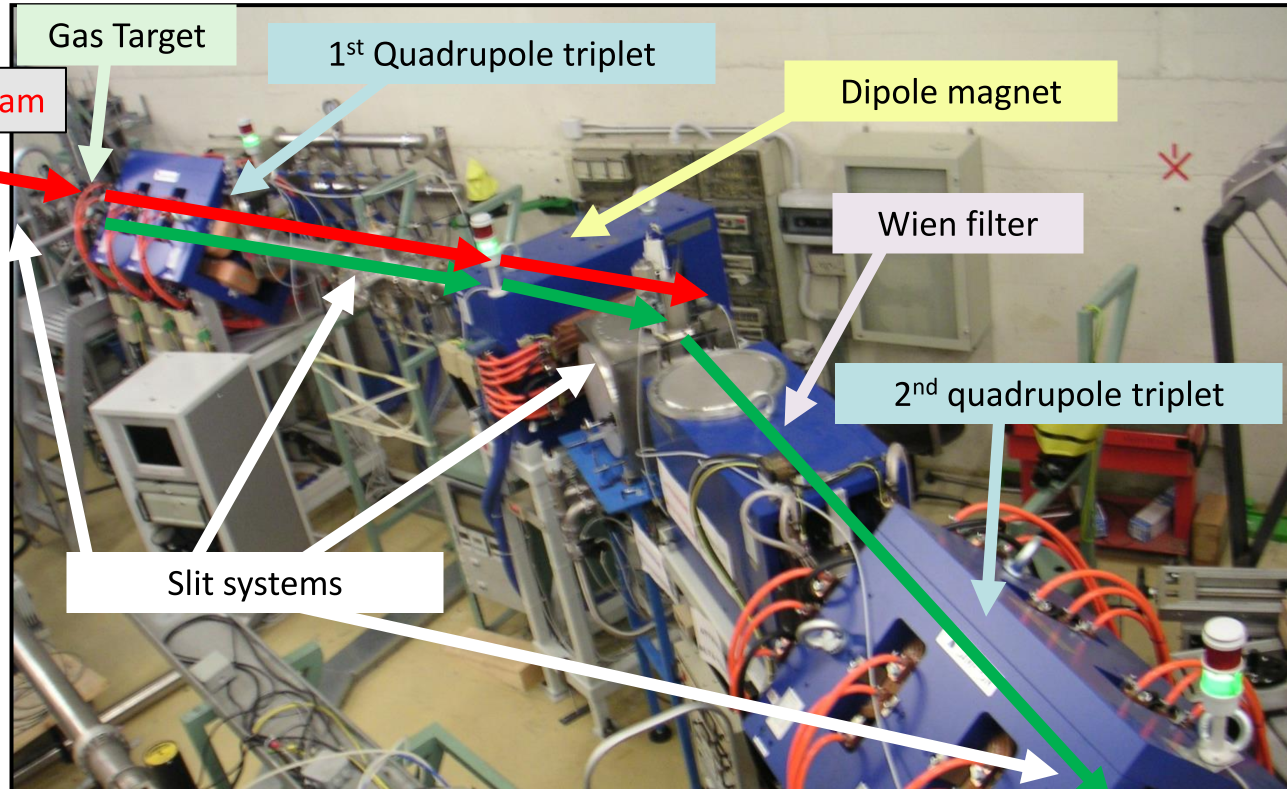
- Data taking
- Highlights on results of previously performed runs

3)Future activity

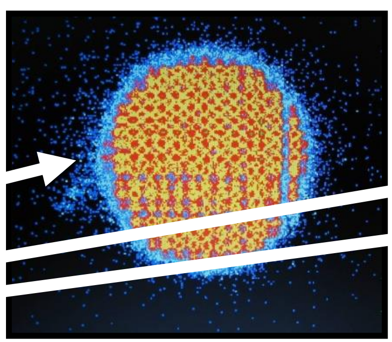
The EXOTIC facility @ LNL



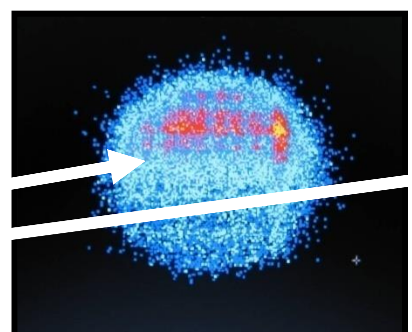
Cryogenic Gas Target



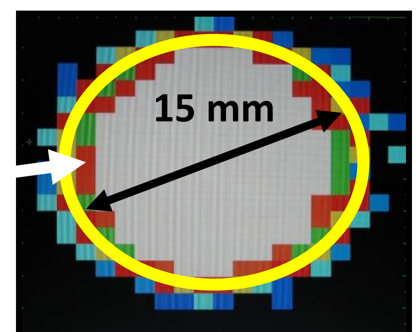
RIB Tracking



PPAC A
910 mm



PPACB
365 mm



Reconstruction
on the target

RIBs and experimental program @ EXOTIC

Delivered RIBs

^{17}F, ^{8}B, ^{7}Be, ^{15}O, ^{8}Li, ^{10}C, ^{11}C

E_{lab}= 2-5 MeV/nucleon, I= 10^{3}-10^{6} pps,

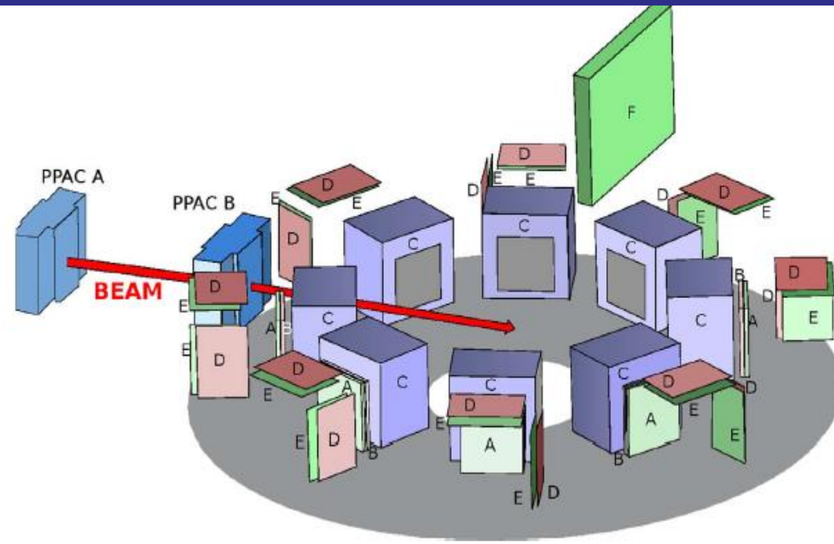
Purity: 98-99% (a part from ^{8}B RIB that has a lower purity)

- ***Study of reaction dynamics with light RIBs on various mass targets at Coulomb barrier energies***
- ***Study of α clustering phenomena in light exotic nuclei***
- ***Direct and indirect measurements of astrophysical interest***
- ***EXOTIC facility as a velocity filter for fusion-evaporation measurements***

The experimental set-up of the EXOTIC facility

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 EXPADES Telescopes

ΔE1 – IC
ΔE2 (40/60 μm) + E $_{res}$ (300 μm) - DSSSDs

DSSSDs: 64 x 64 mm^2 active area
(32 x 32 strips)

→

Z and A identification
TOF information
Good energy, time and angular resolution
High granularity
($\Delta\theta$=1° at d=10.5 cm)
Flexibility
Coverage: 22% of 4π sr at 10.5 cm

Nuclear Instruments and Methods in Physics Research A 834 (2016) 46–70

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

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

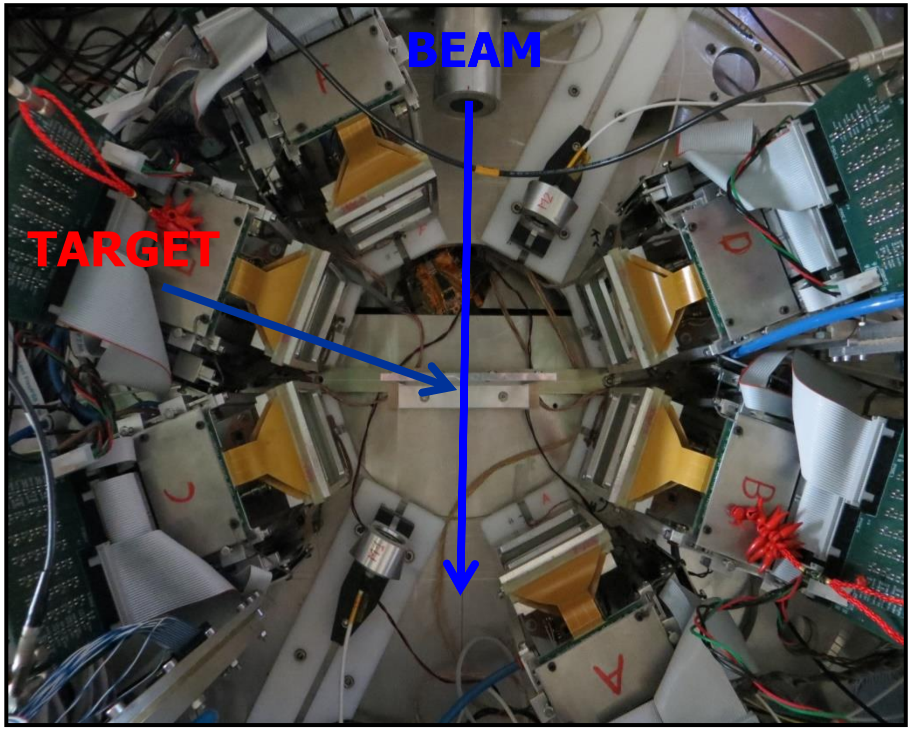
ELSEVIER

The experimental set-up of the RIB in-flight facility EXOTIC

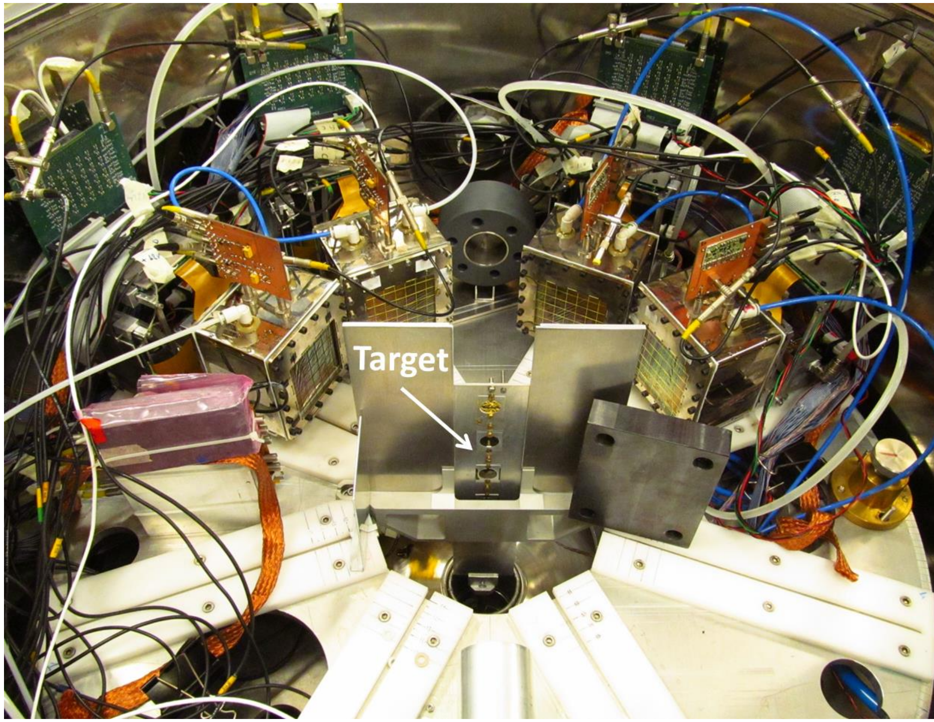
D. Pierroutsakou [a,*], A. Boiano [a], C. Boiano [b], P. Di Meo [a], M. La Commara [c,a], C. Manea [d], M. Mazzocco [e,d], M. Nicoletto [d], C. Parascandolo [a], C. Signorini [e,d], F. Soramel [e,d], E. Strano [e,d], N. Toniolo [f], D. Torresi [e,d], G. Tortone [a], A. Anastasio [a], M. Bettini [d], C. Cassese [a], L. Castellani [d], D. Corti [d], L. Costa [f], B. De Fazio [c], G. Galet [e,d], T. Glodariu [g], J. Grebosz [h], A. Guglielmetti [i,b], P. Molini [e,d], G. Pontoriere [a], R. Rocco [a], M. Romoli [a], L. Roscilli [a], M. Sandoli [c,a], L. Stroe [g], M. Tessaro [d], P.G. Zatti [d]

(some) 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 configurations for experimentation.

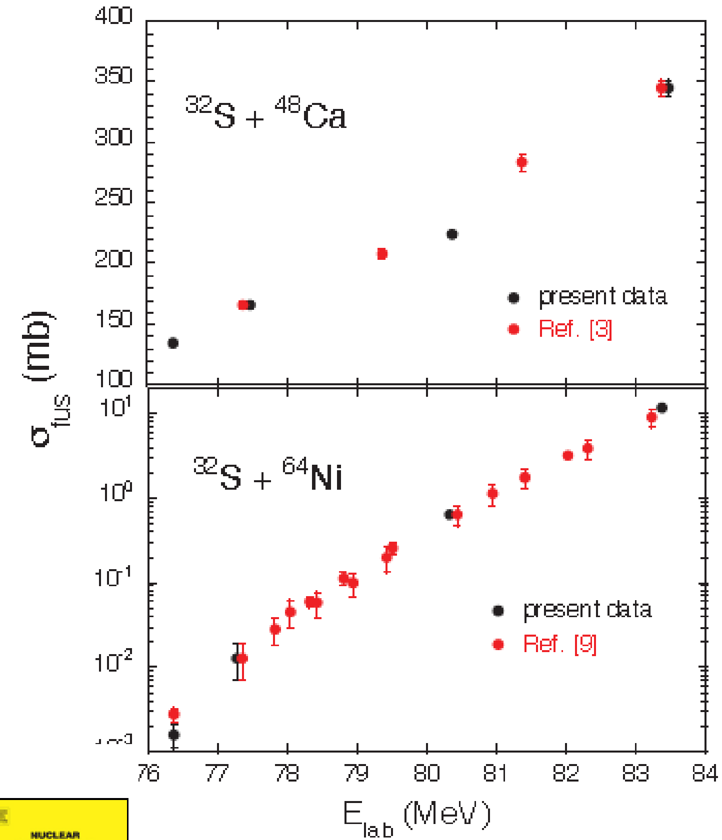
Upgrade 1: 1 mm-thick DSSSDs for the detection of more energetic particles in addition or in alternative to the 300 μm-thick E_{res} DSSSDs.
Upgrade 2: add the annular detectors QQQ2 (300 μm-thick)
Upgrade 3: fast DAQ system for more intense beams

Data taking 2015-2017

EXOTIC facility for fusion-evaporation studies (3 days, July/2015)

The fusion excitation function of $^{32}S+^{48}Ca,^{64}Ni$ has been previously studied at LNL (*G. Montagnoli, et al., Phys. Rev. C 87 (2013) 014611, A. Stefanini et al., Nucl. Phys. A 456 (1986) 509*) 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 allows us to compare 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**.



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Nuclear Inst. and Methods in Physics Research, A

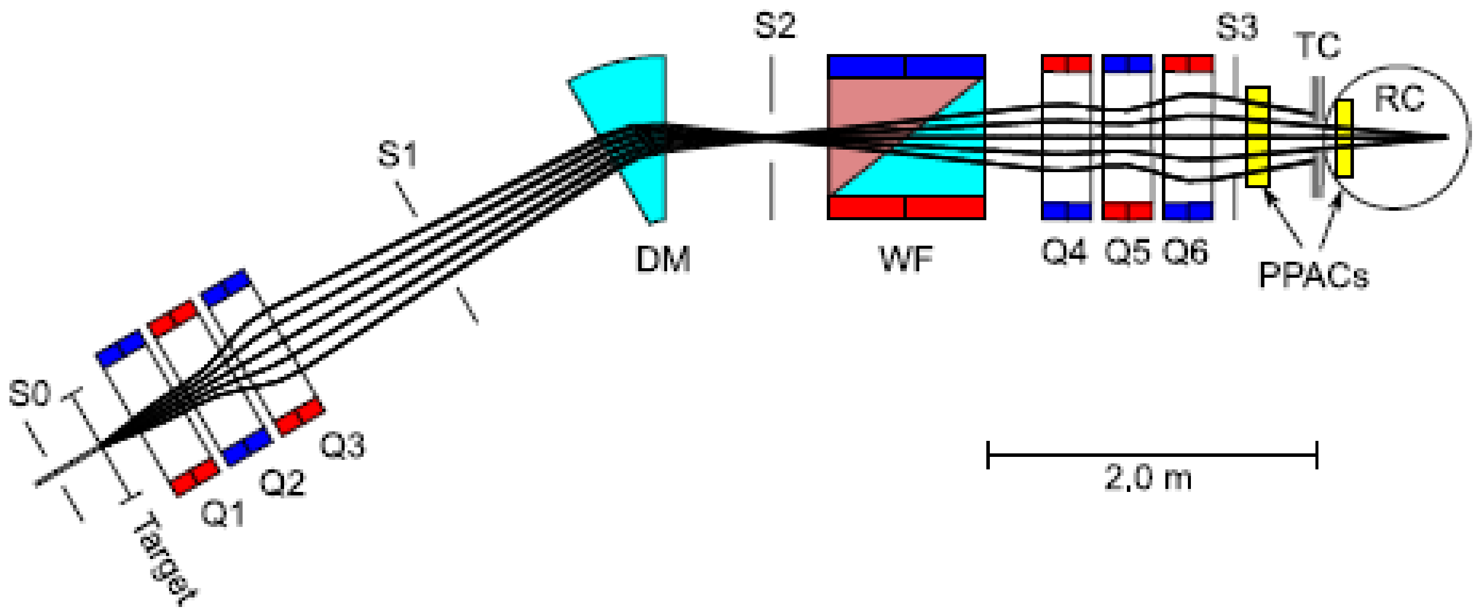
journal homepage: www.elsevier.com/locate/nima

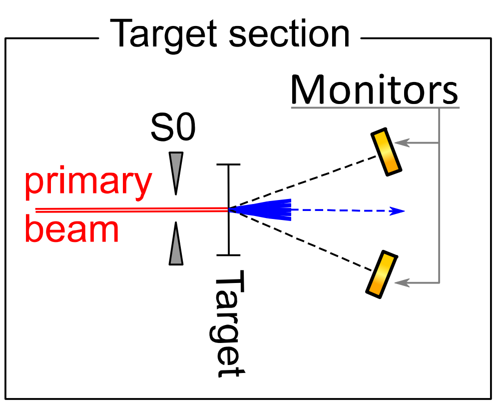
Use of the facility EXOTIC for fusion–evaporation studies

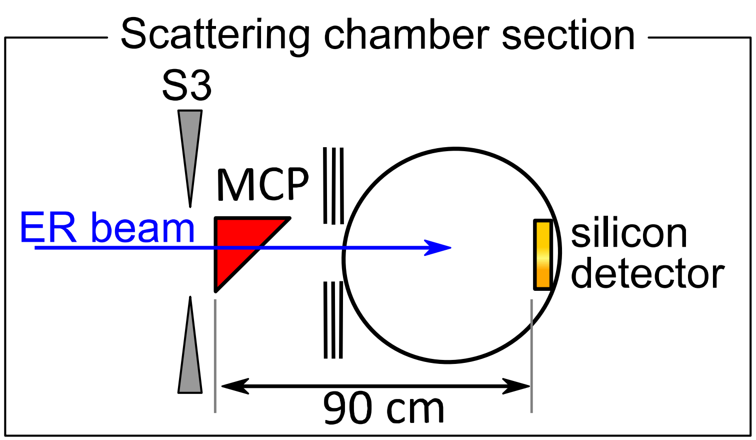
CrossMark

E. Strano [a,b,*], G. Montagnoli [a,b], A.M. Stefanini [c], M. Mazzocco [a,b], G.L. Zhang [c,d], I. Zanon [a,b], G. Colucci [a,b], D. Ackermann [e], A. Boiano [h], L. Corradi [c], E. Fioretto [c], F. Galtarossa [c,f], M. La Commara [g,h], G. La Rana [g,h], C. Parascandolo [h], D. Pierroutsakou [h], F. Scarlassara [a,b], F. Soramel [a,b], D. Torresi [i]

EXOTIC facility for fusion-evaporation studies





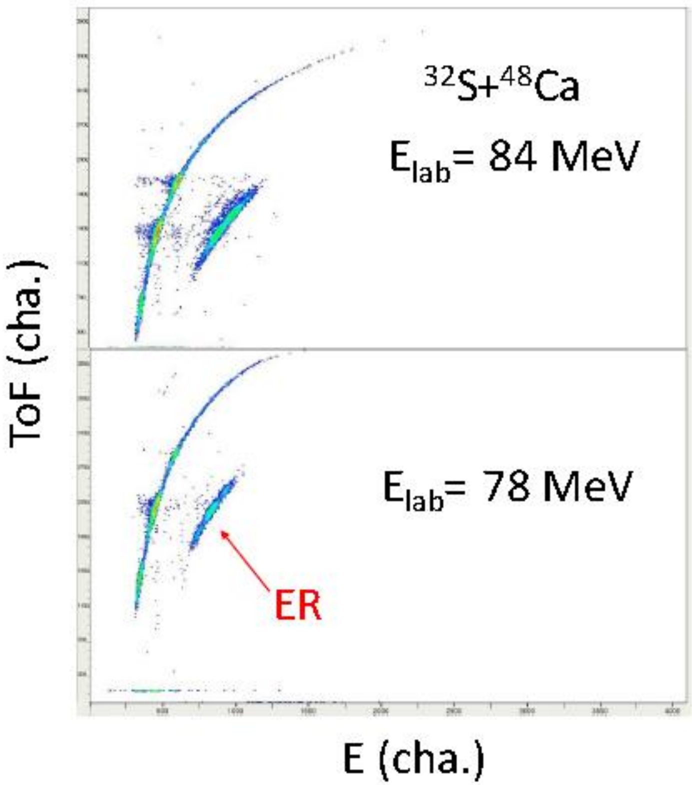


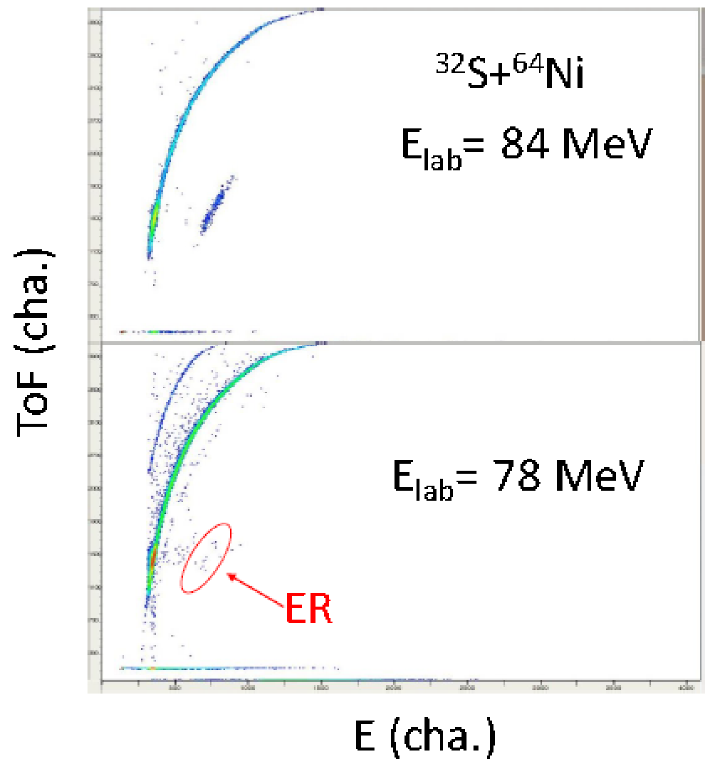
EXOTIC facility for fusion-evaporation studies

- **Higher Rejection factor** at 0° (10^8 and $2\text{-}6 \cdot 10^9$ for $^{32}S + ^{48}Ca$ and $^{32}S + ^{64}Ni$, respectively) with respect to PISOLO

- The **Evaporation detection rate** was found to be 3 times larger than that obtained with PISOLO and this can be improved in the next future by using a lower voltage Wien filter and a larger solid angle detector

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





New RIBs : ^{10,11}C (2 days, Oct/2015)

Spokespersons: D. Torresi, C. Parascandolo

^{10}C radioactive beam production: p(^{10}B,**^{10}C**)n ---- Q = -4.43 MeV

I=45 enA E_{lab}=65 MeV.

P=1 bar at cryogenic temperature (90 K), which corresponds to a Hydrogen target thickness of about 1.35 mg/cm^2.

I(**^{10}C)=**0.8 kHz at E_{lab} =43 MeV and a purity of almost 99%.

Low intensity due to the natural boron target for the tandem source (20% of ^{10}B). With a 100% enriched target source estimated I= 4 KHz

^{11}C radioactive beam production: p(^{11}B,**^{11}C**)n ----- Q = -2.764 MeV

I=40 enA E_{lab}=65 MeV.

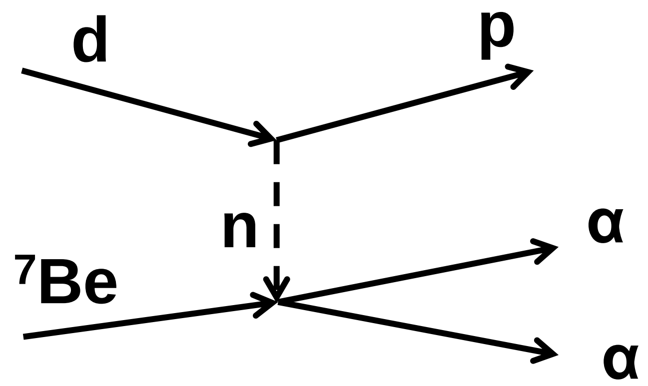
P=1 bar at cryogenic temperature (90 K), which corresponds to a Hydrogen target thickness of about 1.35 mg/cm^2.

I(**^{11}C)=1-2x**10^5 kHz at E_{lab} =44 MeV and a purity of almost 99%.

$^7Be(n,\alpha)^4He$ (13 days, november 2015)

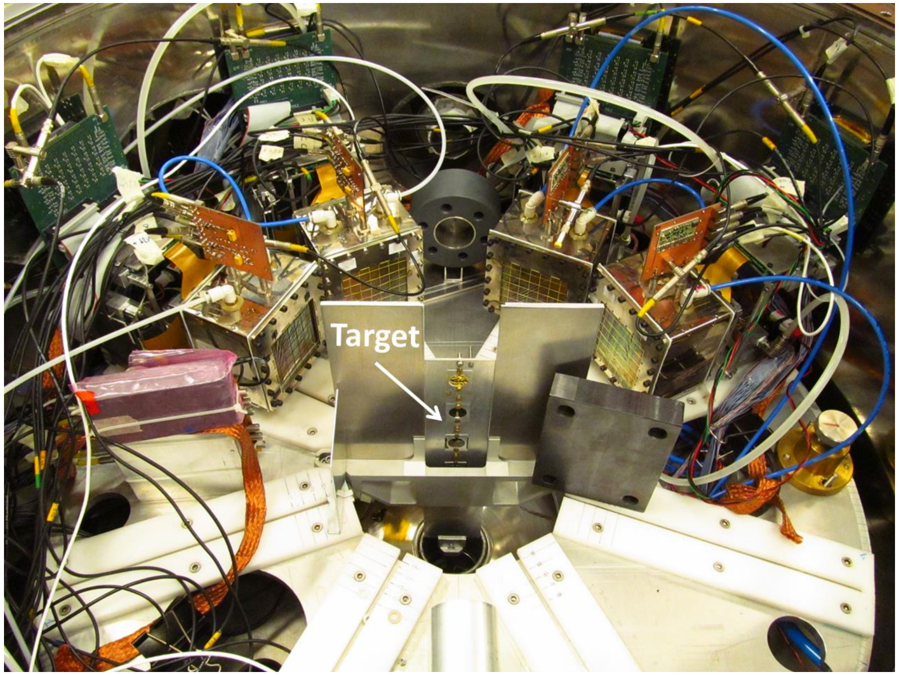
Spokespersons: L. Lamia, M. Mazzocco

Study of the **$^7Be(n,\alpha)^4He$ (Q_{value} =18.99 MeV)** reaction by applying the Trojan Horse Method (THM) that allows us to span the energy region of interest for Bing Bang Nucleosynthesis E_{cm}= 0-1.5 MeV, at which the reaction rate is still assumed with an order of magnitude of uncertainty.



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

EXPADES (IC+ 300 μm DSSD)



^7Be secondary beam

E_{lab} =(20.4 ± 0.5) MeV

Intensity (average): $5*10^5$ pps

- 400 μg/cm^2 CD_2 target;
- Calibration with lithium beam on ^{12}C, ^{197}Au and CH_2

Study of α clustering in ^{15}O @ EXOTIC (8 days, nov/dec 2016) with the Thick Target Inverse Kinematics method

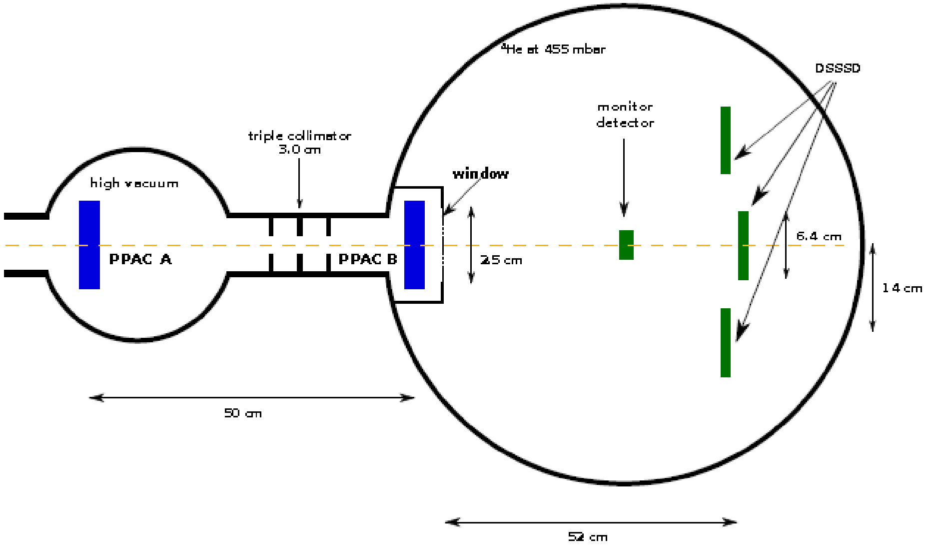
Spokespersons: D. Torresi, C. Parascandolo

Elastic Scattering Excitation Function of ^{11}C+ ^{4}He employing the **^{11}C RIB** to obtain the energy, width, spin of the states with E* up to 8 MeV above the α-decay threshold (10.22 MeV)

Experimental setup: EXPADES 300 μm DSSSDs

I(^{11}C)=5 x 10^5 kHz at E_{lab}=30 MeV and a purity of almost 99%.

Scattering chamber filled with 570 mbar ^{4}He gas to stop the beam and separated with a 2.2 μm Havar foil from the beam line.



Proposals and runs pending @ EXOTIC

1) ^{8}**B** beam production run $^{3}He(^{6}Li,^{8}B)n$ (Q_{val} = -1.97 MeV)
Spokesperson: C. Parascandolo
Approved by the July 2016 LNL PAC: scheduled in march and june 2017, problems with tandem

2) **^{8}B +^{208}Pb @ E_{lab}= 43 MeV** : study of the coupling mechanisms at sub-barrier energies by investigating elastic scattering and ^{8}B breakup.
Experimental set up: 6 EXPADES telescopes (DSSSD 40+300 μm)

Spokespersons: A. Pakou, D. Pierroutsakou
Presented at the LNL PAC in February 2017
Not approved because the ^{8}B test production (needed for this experiment) was still not performed at that moment (see previous point)

3) ^{18}**Ne** beam production run : $^{3}He(^{16}O,^{18}Ne)n$ (Q_{val} =-3.19 MeV)
Spokesperson: C. Parascandolo
Presented at the LNL PAC in February 2017, approved with priority B due to the large backlog of experiments with the LNL tandem

Highlights on results of previously performed runs

^{7}Be (S_α = 1.586 MeV, $T_{1/2}$ = 53.22 d g.s. $J^p=3/2^-$)

Nucleus	Breakup Threshold (MeV)
^{7}Be	1.6
^{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.

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

Interesting to:

- investigate the similarity between ^{7}Be and ^{7}Li or ^{6}Li;
- study the direct reaction mechanisms involved;
- determine the fusion cross section;
- identify the extent of the competition between direct reactions and compound-nucleus formation as a function of energy.

^{7}Be+^{28}Si at Coulomb barrier energies

Study of **elastic scattering** and **relevant reaction mechanisms** for the system **^{7}Be+^{28}Si** at near barrier energies, namely 13 MeV, 20 MeV and 22 MeV corresponding to (0.78-1.64)$E_{C.b}$ ($E_{C.b}$ = 11.5 MeV)

Experimental set up: EXPADES

PHYSICAL REVIEW C **94**, 044623 (2016)

α and ^{3}He production in the ^{7}Be + ^{28}Si reaction at near-barrier energies: Direct versus compound-nucleus mechanisms

O. Sgouros,[1] A. Pakou,[1,*] D. Pierroutsakou,[2] M. Mazzocco,[3,4] L. Acosta,[5,6] X. Aslanoglou,[1] Ch. Betsou,[1] A. Boiano,[2] C. Boiano,[7] D. Carbone,[8] M. Cavallaro,[8] J. Grebosz,[9] N. Keeley,[10] M. La Commara,[11,2] C. Manea,[4] G. Marquinez-Duran,[12] I. Martel,[12] N. G. Nicolis,[1] C. Parascandolo,[2] K. Rusek,[13] A. M. Sánchez-Benítez,[14,12] C. Signorini,[15] F. Soramel,[3,4] V. Soukeras,[1] C. Stefanini,[3] E. Stiliaris,[16] E. Strano,[3,4] I. Strojek,[10] and D. Torresi[3,4]

O. Sgouros PhD Thesis

PHYSICAL REVIEW C **95**, 054609 (2017)

Elastic scattering of ^{7}Be + ^{28}Si at near-barrier energies

O. Sgouros,[1] A. Pakou,[1,*] D. Pierroutsakou,[2] M. Mazzocco,[3,4] L. Acosta,[5,6] X. Aslanoglou,[1] Ch. Betsou,[1] A. Boiano,[2] C. Boiano,[7] D. Carbone,[8] M. Cavallaro,[8] J. Grebosz,[9] N. Keeley,[10] M. La Commara,[2,11] C. Manea,[4] G. Marquínez-Durán,[12] I. Martel,[12] N. G. Nicolis,[1] C. Parascandolo,[2] K. Rusek,[13] A. M. Sánchez-Benítez,[12,14] C. Signorini,[15] F. Soramel,[3,4] V. Soukeras,[1] C. Stefanini,[3] E. Stiliaris,[16] E. Strano,[3,4] I. Strojek,[10] and D. Torresi[3,4]

$^{7}Be + ^{58}Ni$ at Coulomb barrier energies

Experimental set up: DINEX (Univ. Huelva)

Elastic Scattering: agreement with an earlier measurement by E.F. Aguilera and collaborators [Phys. Rev. C. 79, 021601(R) (2009)].
Reaction channels studied for the first time: No coincidences detected

PHYSICAL REVIEW C **92**, 024615 (2015)

Direct and compound-nucleus reaction mechanisms in the $^{7}Be + ^{58}Ni$ system at near-barrier energies

M. Mazzocco,[1,2,*] D. Torresi,[1,2,†] D. Pierroutsakou,[3] N. Keeley,[4] L. Acosta,[5,6,‡] A. Boiano,[3] C. Boiano,[7] T. Glodariu,[8] A. Guglielmetti,[9,7] M. La Commara,[10,3] J. A. Lay,[1,2] I. Martel,[5] C. Mazzocchi,[9,7,§] P. Molini,[1,2,∥] C. Parascandolo,[3] A. Pakou,[11] V. V. Parkar,[5,¶] M. Romoli,[3] K. Rusek,[12] A. M. Sánchez-Benítez,[5,#] M. Sandoli,[10,3] O. Sgouros,[11] C. Signorini,[1,2,**] R. Silvestri,[10,3] F. Soramel,[1,2] V. Soukeras,[11] E. Stiliaris,[13] E. Strano,[1,2] L. Stroe,[8] and K. Zerva[11]

$^{7}Be + ^{208}Pb$ at Coulomb energies

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

Experimental set up: EXPADES
Goal: Study of the elastic scattering and reaction mechanisms
Detection of charged particles in **coincidence** allows to determine the triggering process

C. Stefanini
Master Thesis

^{8}Li (S_n = 2.03 MeV, $T_{1/2}$ = 0.84 s g.s. J^p=2^+)

Neutron rich β decaying nucleus, attracting a strong interest due to its role in astrophysical problems as ^{8}Li-induced reactions can have important consequences for the abundances of $^{6,7}Li$ and other nuclei

For the OM potential and coupling channel effects, interesting test case in comparison with its stable but weakly bound neighbors $^{6,7}Li$.

Breakup threshold:

2.03 MeV for $^{8}Li \rightarrow {}^{7}Li + n$ breakup

1.47 MeV for $^{7}Li \rightarrow a + d$

2.47 MeV for $^{7}Li \rightarrow a + t$ breakup;

One neutron separation threshold:

S_n=2.03 MeV, 7.25 MeV and 5.66 MeV for ^{8}Li, ^{7}Li and ^{6}Li, respectively

Interesting to compare the interplay of breakup and transfer couplings effects over a range of *Q* values without the complication of significant differences in Coulomb barriers.

^{8}Li + ^{90}Zr QE scattering at Coulomb barrier energies

Eur. Phys. J. A (2015) 51: 90
DOI 10.1140/epja/i2015-15090-3

THE EUROPEAN PHYSICAL JOURNAL A

Letter

Important influence of single neutron stripping coupling on near-barrier ^{8}Li + ^{90}Zr quasi-elastic scattering

A. Pakou[1,a], N. Keeley[2,b], D. Pierroutsakou[3], M. Mazzocco[4,5], L. Acosta[6,7], X. Aslanoglou[1], A. Boiano[3], C. Boiano[8], D. Carbone[9], M. Cavallaro[9], J. Grebosz[10], M. La Commara[11,3], C. Manea[5], G. Marquinez-Duran[12], I. Martel[12], C. Parascandolo[3], K. Rusek[13], A.M. Sánchez-Benítez[14], O. Sgouros[1], C. Signorini[15], F. Soramel[4,5], V. Soukeras[1], E. Stiliaris[16], E. Strano[4,5], D. Torresi[4,5], A. Trzcińska[13], Y.X. Watanabe[17], and H. Yamaguchi[18]

Eur. Phys. J. A (2015) 51: 55
DOI 10.1140/epja/i2015-15055-6

THE EUROPEAN PHYSICAL JOURNAL A

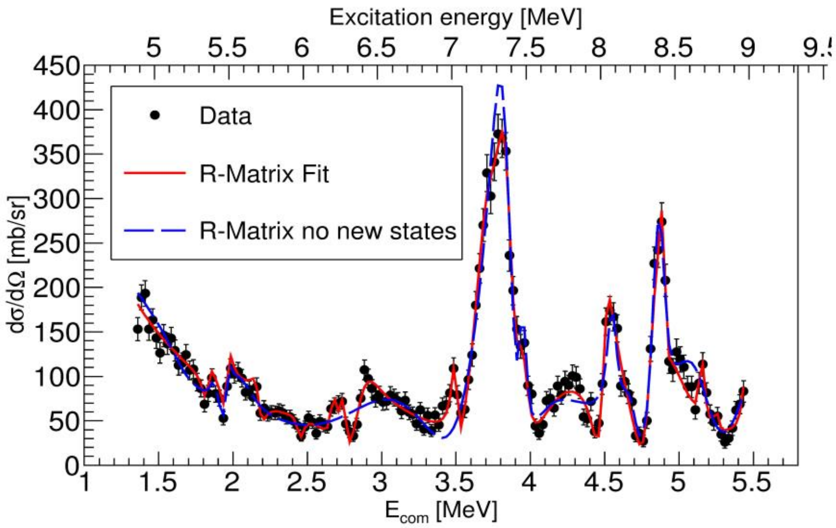
Regular Article – Experimental Physics

Total reaction cross sections for ^{8}Li + ^{90}Zr at near-barrier energies

A. Pakou[1,a], D. Pierroutsakou[2], M. Mazzocco[3,4], L. Acosta[5], X. Aslanoglou[1], A. Boiano[2], C. Boiano[6], D. Carbone[7], M. Cavallaro[7], J. Grebosz[8], N. Keeley[9], M. La Commara[10,2], C. Manea[4], G. Marquinez-Duran[5], I. Martel[5], C. Parascandolo[2], K. Rusek[11], A. M. Sánchez-Benítez[12], O. Sgouros[1], C. Signorini[13], F. Soramel[3,4], V. Soukeras[1], E. Stiliaris[14], E. Strano[3,4], D. Torresi[3,4], A. Trzcinska[11], Y. X. Watanabe[15], and H. Yamaguchi[16]

$^{15}O+^{4}He$ elastic scattering excitation function for studying α clustering in ^{19}Ne with the Thick Target Inverse Kinematics method

1. A number of Ne isotopes manifest evidences of clustering phenomena (example: $^{20,21}Ne$). This makes the ^{19}Ne a good candidate to manifest cluster structures.
2. The structure of low-lying levels in ^{19}Ne near the $^{15}O+^{4}He$ and p threshold in ^{19}Ne are important: their study can improve our knowledge on the $^{15}O(\alpha,\gamma)$ ^{19}Ne and $^{18}F(p,\alpha)^{15}O$ reaction rate of astrophysical interest.



Significant new results using *R*-Matrix formalism for resonant reactions.
– spins and parities of the states have been established
– large number of partial decay widths
- Clustering below the proton threshold suspected from previous studies confirmed by the present one

PHYSICAL REVIEW C **96**, 044317 (2017)

Evidence for $^{15}O+\alpha$ resonance structures in ^{19}Ne via direct measurement

D. Torresi,[1,2,3] C. Wheldon,[1,*] Tz. Kokalova,[1] S. Bailey,[1] A. Boiano,[4] C. Boiano,[5] M. Fisichella,[2] M. Mazzocco,[6,7] Parascandolo,[4] D. Pierroutsakou,[4] E. Strano,[6,7] M. Zadro,[8] M. Cavallaro,[2] S. Cherubini,[2,3] N. Curtis,[1] A. Di Pietro,[2] J. P. Fernández Garcia,[2] P. Figuera,[2] T. Glodariu,[9] J. Grębosz,[10] M. La Cognata,[2] M. La Commara,[4] M. Lattuada,[2,3] D. Mengoni,[11] R. G. Pizzone,[7,2] C. Signorini,[11] C. Stefanini,[6] L. Stroe,[9] and C. Spitaleri[2,3]

Future activity: Proposals for the next LNL PAC

1)Study of the **$^{8}B+^{28}Si$ total reaction** at Coulomb barrier energies with **the active target technique** combined with a **TOF** measurement for the rejection of pile up and frame scattering

2) **$^{7}Be+^{208}Pb$** reaction at Coulomb barrier energies: to study direct reactions by detecting charged particles in coincidence with good statistics

2) **$^{8}B+^{208}Pb$** reaction mechanisms

Experimental set up: 6 EXPADES telescopes (DSSSD 40+300 μm)

Future activity: Study of the $^{18}Ne(\alpha, p)^{21}Na$ reaction

In case of successful ^{18}Ne RIB production @ EXOTIC

	^{18}Ne
Primary Beam	^{16}O
Energy	86 MeV
Intensity	50-100 pnA
Reaction	$^{3}He(^{16}O,^{18}Ne)n$
Q-value	-3.19 MeV
Cross section	50 mb
Gas target	cryogenic ^{3}He at 1 bar
Secondary Beam	^{18}Ne
Energy	30 MeV
Transmission	1%
Intensity	2.5×10^{5} pps

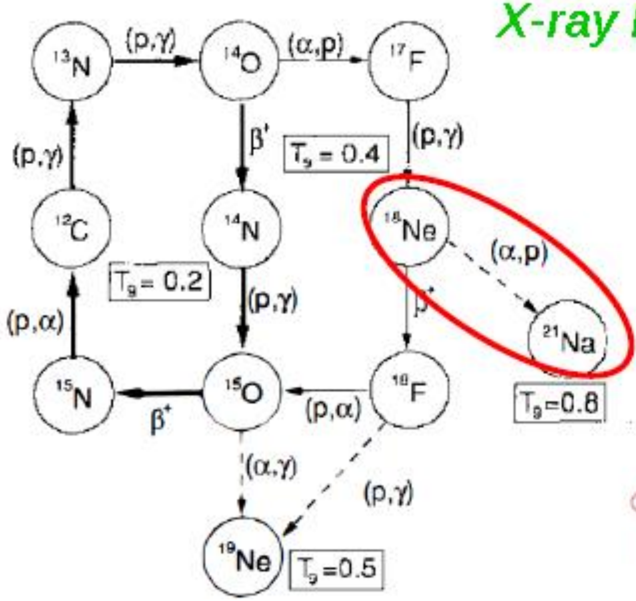
→ Wien Filter transmission ~ 50%

^{18}Ne(α, p)^{21}Na

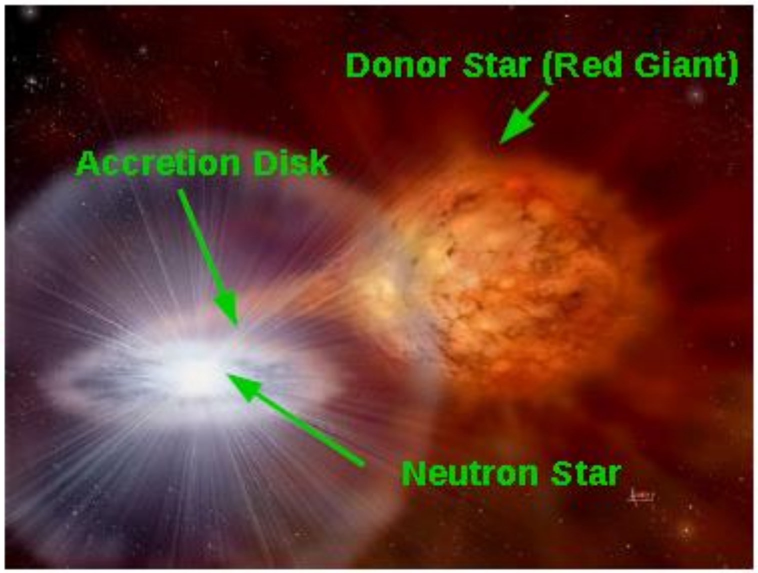
In ambients like novae and x-ray bursts the hydrogen explosive combustion occurs through a series of reactions called **hot cycle CNO (HCNO)** -> with a net result of a large energy production.

At T~0.75 GK a rupture of this cycle could occur, depending on the **β+** decay of **^{18}Ne($T_{1/2}$=1.67 s)** and the capture reaction rate **^{18}Ne(α,p)^{21}Na.** The formed ^{21}Na in this reaction constitutes the initial seed of the **rp process,** which forms elements with maximum mass around A=100.

CM energies of astrophysical interest: 500 keV - 2 MeV (E_{cm}= 1 MeV -> E_{Lab}=5.5 MeV)



X-ray Burst



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

Key parameter: **Rate of ^{18}Ne(α,p)^{21}Na reaction**

Activity related with SPES

The Letter of Intent *"Study of the Dynamical Dipole Resonance mode with the SPES radioactive beams"* was endorsed by the Scentific Advisory Committee (SAC) of SPES:

"The SAC endorses the LOI which is considered to be ready to develop into an extended research proposal."

EXOTIC: Letter Of Intent for SPES

Study of the Dynamical Dipole Resonance mode with the SPES RIBs

D. Pierroutsakou, C. Parascandolo, R. Alba, V. Baran, M. Colonna, A. Del Zoppo, T. Glodariu, A. Guglielmetti, M. La Cognata, G. La Rana, C. Maiolino, M. Mazzocco, A. Pakou, M. Papa, S. Pirrone, C. Rizzo, R. G. Pizzone, S. Romano, D. Santonocito, C. Signorini, O. Sgouros, F. Soramel, V. Soukeras, S. Stiliaris, E. Strano, L. Stroe, D. Torresi, A. Tumino, E. Vardaci

Dynamical Dipole (DD) → excitation of a **pre-equilibrium GDR** in charge-asymmetric heavy-ion collisions: emission of **prompt** dipole γ–rays

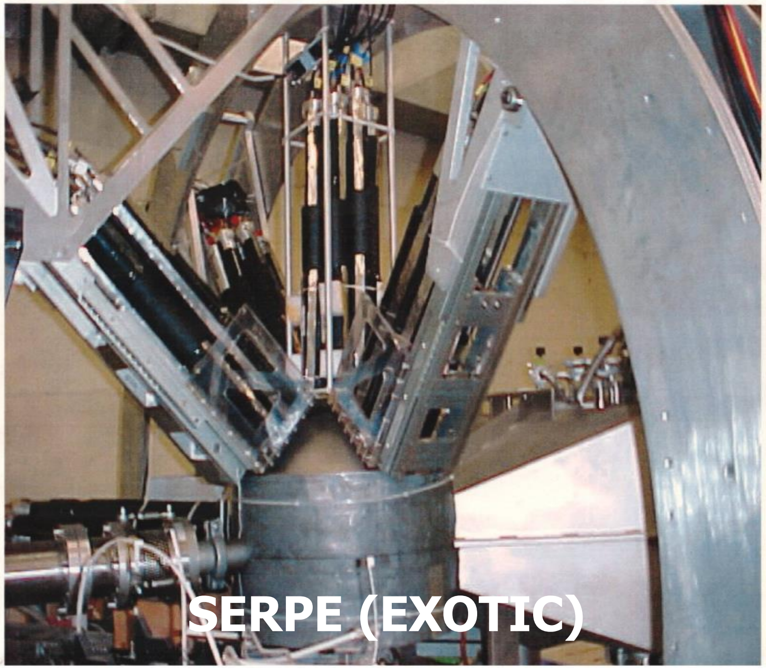
Why to study:
1)insight on the reaction dynamics: charge equilibration
2) informations on the density dependence of the nuclear matter EOS at $\rho < \rho_0$
3) new cooling mechanism in fusion reactions

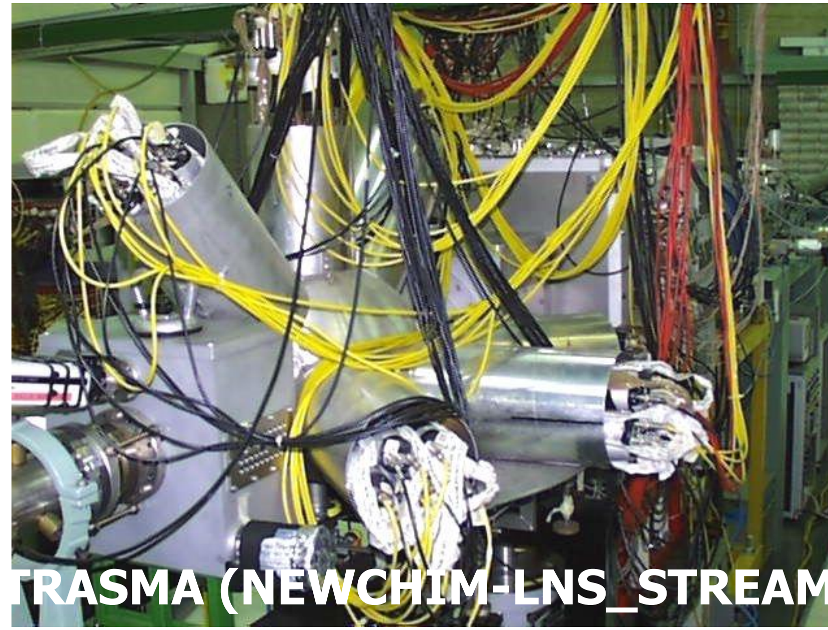
We propose:
A systematic study of the DD with charge asymmetry, incident energy, mass asymmetry and mass by combining stable and RIBs (**Te, I, Kr, Sr, Sn** and **Cs**) produced by SPES.
Request for the RIB: I=10^8-10^9 pps, high purity, pulsed $\Delta t \sim 1$ ns (FWHM)

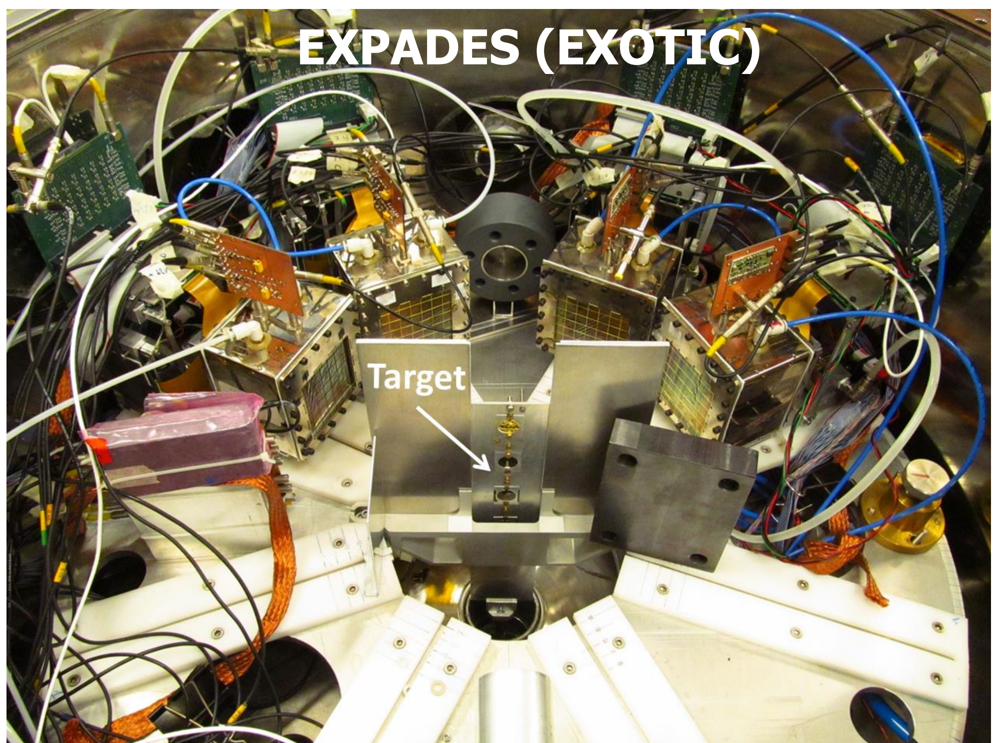
Experimental set up

γ-ray and light particle detection: (SERPE+TRASMA) BaF_2 (48% of 4π at 22 cm from the target)

To tag the reaction: position-sensitive PPACs, IC+silicon telescopes, EXPADES array (presently installed at the EXOTIC facility focal plane)


SERPE (EXOTIC)


TRASMA (NEWCHIM-LNS_STREAM)


EXPADES (EXOTIC)
Target

Letter Of Intent for SPES

The LOI for SPES endorsed by the SAC will be presented in the apropriate LNL PAC (to be decided when it will be held). In case of approval, the preparatory work will start for the first reaccelerated high purity neutron-rich RIBs, foreseen in 2021. Other high purity RIBs will be produced after the HRMS commissioning in 2022.

EXOTIC (from 2015)

12 publications ISI

14 talks

3 posters

1 Master Thesis

1 PhD Thesis

EXOTIC collaboration

A. Boiano, M. La Commara, G. La Rana, M. Mazzocco , C. Parascandolo,

D. Pierroutsakou, F. Soramel, E. Strano

National and International Collaborations

LNS, INFN-Sez. Catania, LNL, Univ. of Ioannina, IASA and Univ. of Athens, Univ. of Thessaloniki, Horia Hulubei-NIPNE, IFJ-PAN(Krakow, Poland), Univ. Of Warsow, Univ. Of Huelva, CEA-Saclay, CNS, coll. KEK/JAEA, Univ. Osaka, Univ. Birmingham