EXOTIC 2013 → 2014 (8 ricercatori, 6 FTE)

PD (4.5 FTE)

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NA (1.5 FTE)

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MI (0.4 FTE)

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The EXOTIC project at LNL

Research Interest: Dynamics induced by light weakly-bound Radioactive Ion Beams at Coulomb barrier energies.

Facility: development of the facility EXOTIC at LNL for the RIB production via the in-flight technique.

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

F. Farinon et al., NIM B 266, (2008) 4097, M. Mazzocco et al., NIM B 266, 4665 (2008)

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

D. P. et al., EPJ ST 150, (2007) 47, C. Signorini et al., EPJ A 44, 63 (2010)

The EXOTIC beamline @ LNL

1 – 1st slit system

2 – production gas target

3 – 1st quadrupole triplet

4 – 2nd slit system

5 – 30° analysing magnet

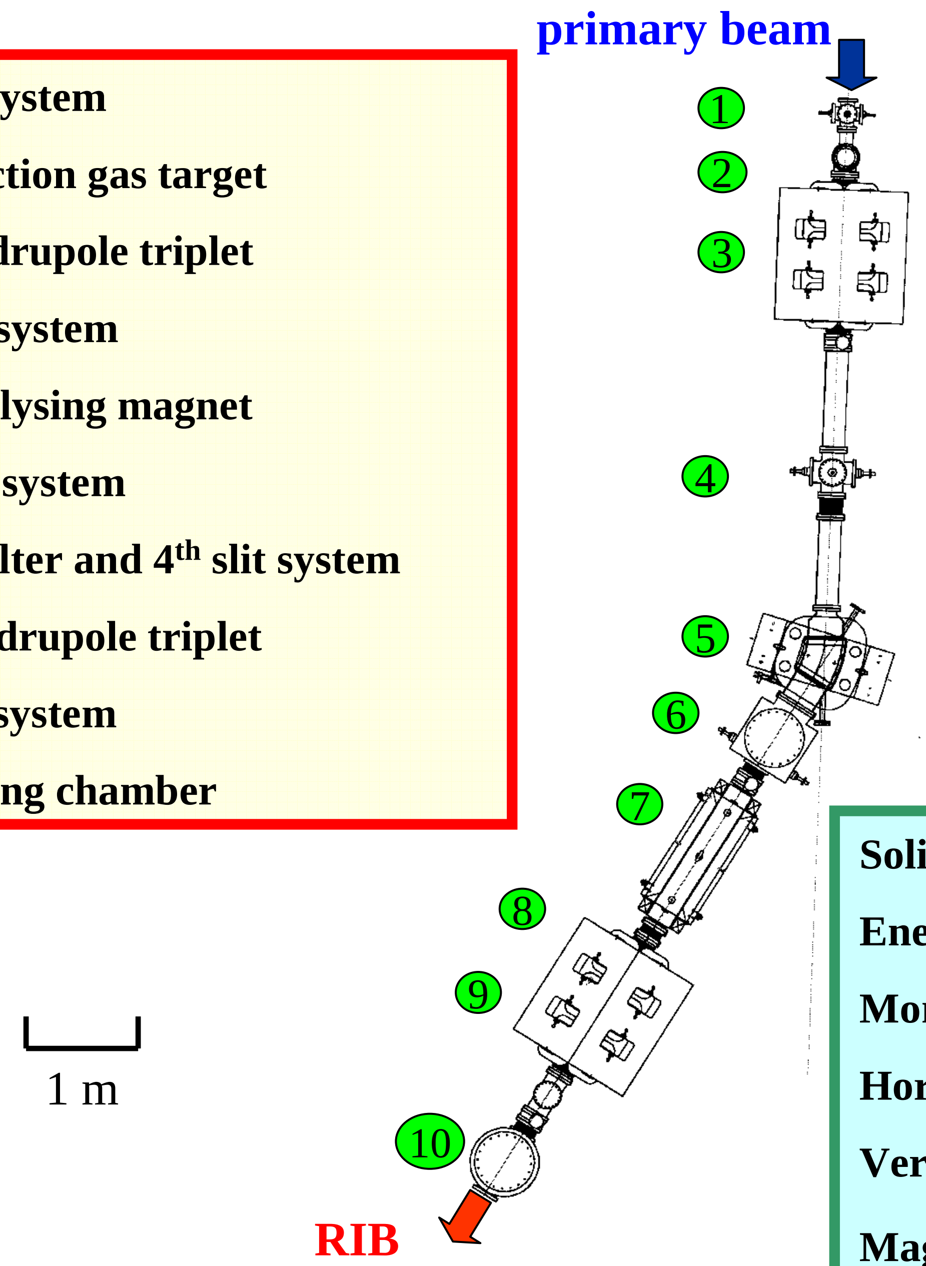
6 – 3rd slit system

7 – Wien filter and 4th slit system

8 – 2nd quadrupole triplet

9 - 4th slit system

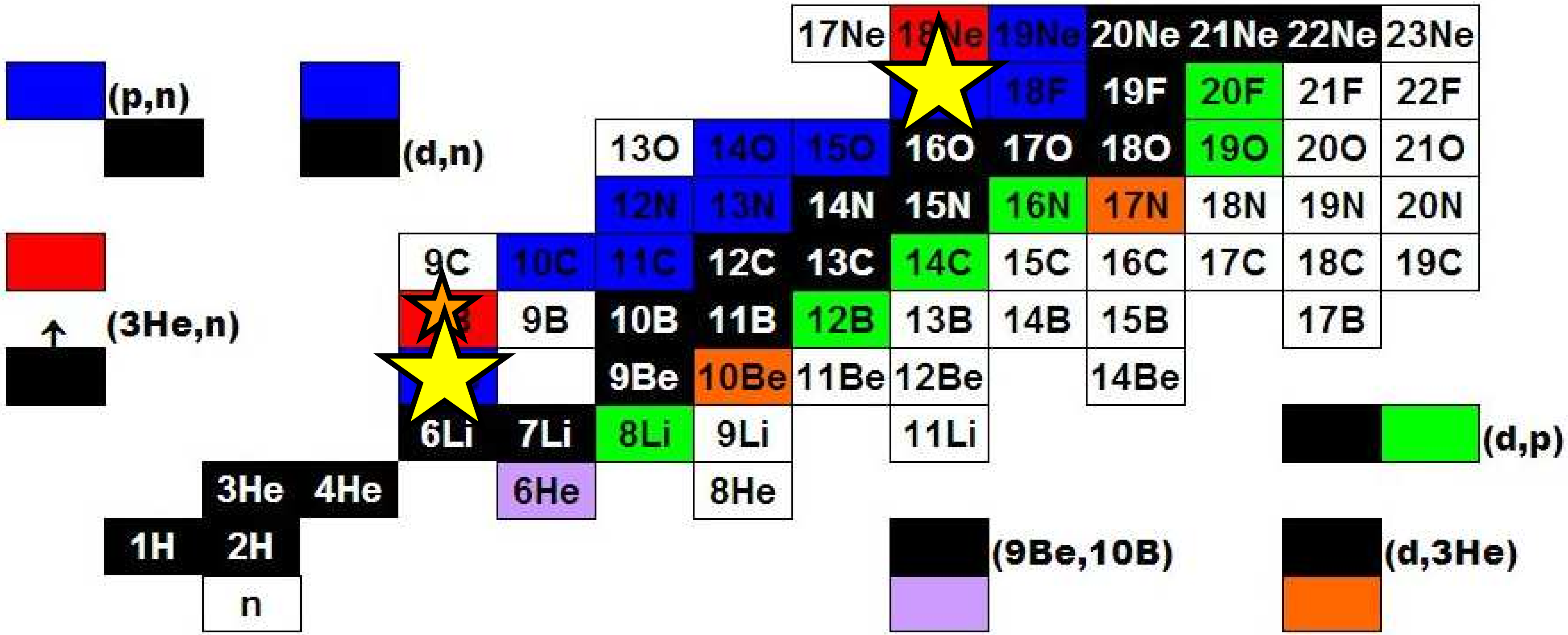
9 – scattering chamber



Cryogenic production gas target: 5-cm long double-walled cylindric cell: H_2,D_2,^3He,^4He
Entrance (exit) windows: 14 (16) mm
2 havar windows: 2.2 μm
Pressure: up to 1.4 bar.

Solide angle Δω	~ 10 msr
Energy acceptance ΔE/E	±10%
Momentum acceptance Δp/p	± 5%
Horizontal acceptance Δθ	± 50 mrad
Vertical acceptance Δϕ	± 65 mrad
Magnetic rigidity Bρ	0.98 Tm

Light RIBs @ EXOTIC

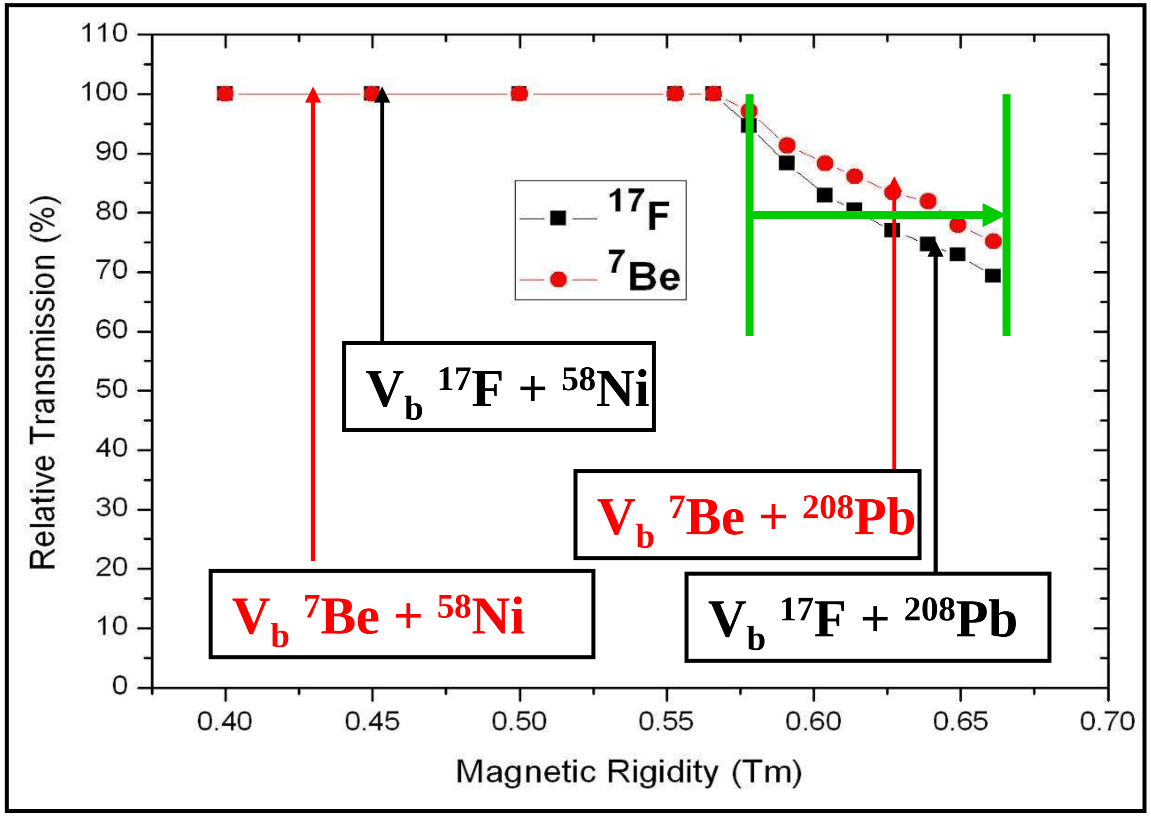


^{17}**F** E = 3–5 MeV/u Purity: **93-96%** Intensity: **10^5 pps** (ANL)

^{8}**B** E = 3 MeV/u Purity: **40-50%** Intensity: **10^3 pps** (ND, CRIB)

^{7}**Be** E = 3 MeV/u Purity: **99%** Intensity: **2-3*10^5 pps** (ND, CRIB)

The EXOTIC Upgrade (FIRB project)



The facility has been recently upgraded (financed within the project **FIRB cod. RBFR08P1W2_001**) of their power supplies will **increase** the RIB maximum magnetic rigidity by **+ 15 %,** thus providing:

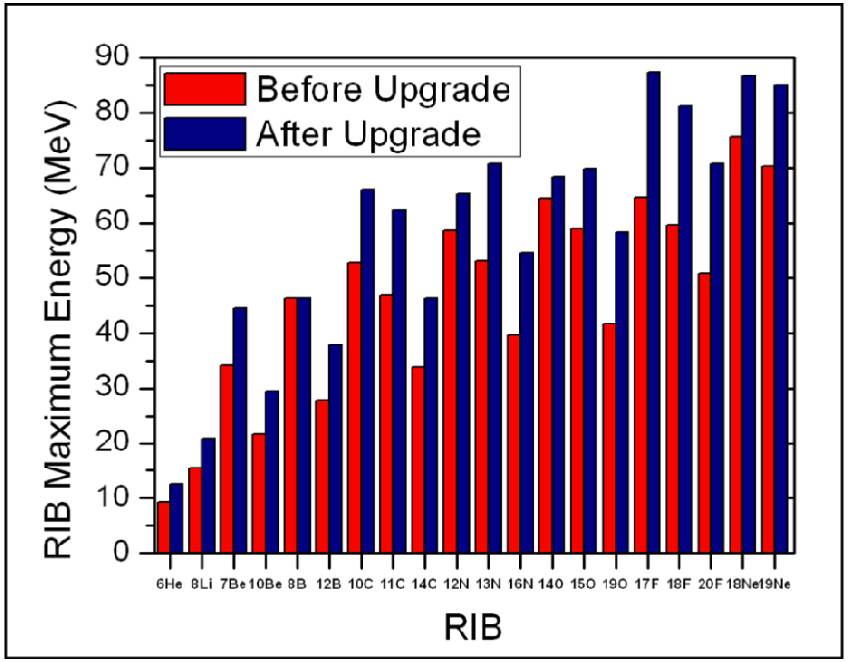
1) 35% increase of the RIB's maximum energy

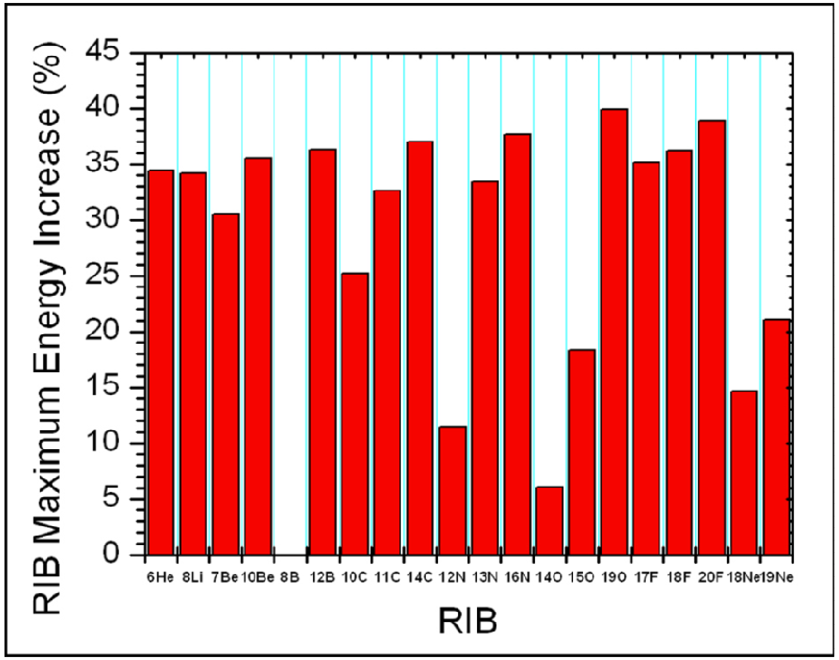
2) Higher Transmission (and secondary beam intensity)

3) B-scaling of all ion-optical elements

The EXOTIC Upgrade (FIRB project)

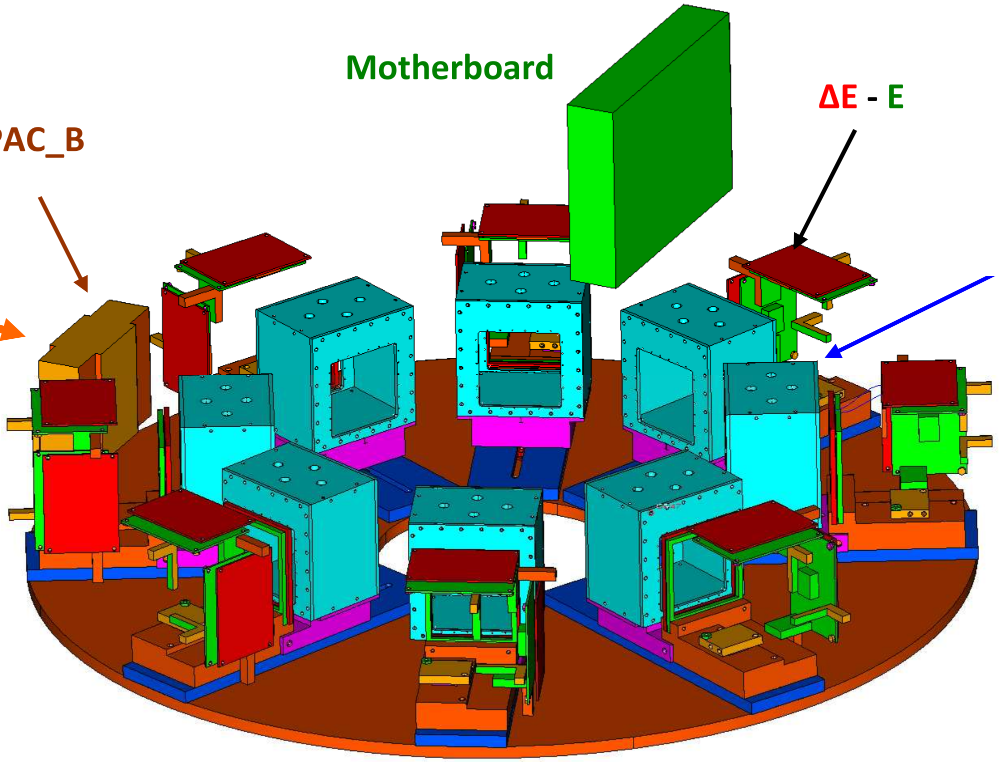
Inrease of the maximum RIB's energy after the upgrade





M. Mazzocco et al., NIM B, Proceeding of the EMIS2012 (to be published)

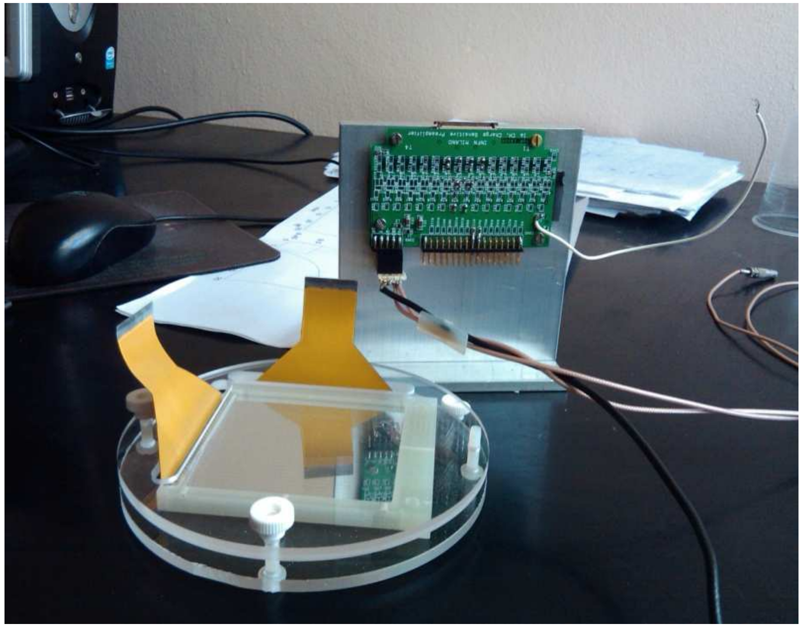
EXOTIC new apparatus for measurements with RIBs



8 Telescopes each one consisting of:
ΔE – Ionization Chamber
ΔE(40 μm) + E (300 μm)
Double Sided Silicon Strip Detectors
62.5 x 62.5 mm^2 active area
32 x 32 strips (2 mm) $\Delta\theta = 1°$ at d=10 cm
last stage: 50 x 50 mm^2 500 μm Silicon (single pad) from the **EXODET set up**

Z identification through ΔE-E
TOF information
Good energy, time and angular resolution
High granularity: coincidence measurements
Coverage: 24% of 4π sr

ΔE stage: DSSD 40 μm



Readout: home made highly integrated low-noise electronics (INFN, Milan)

16 channel low-noise pre–amplifier boards

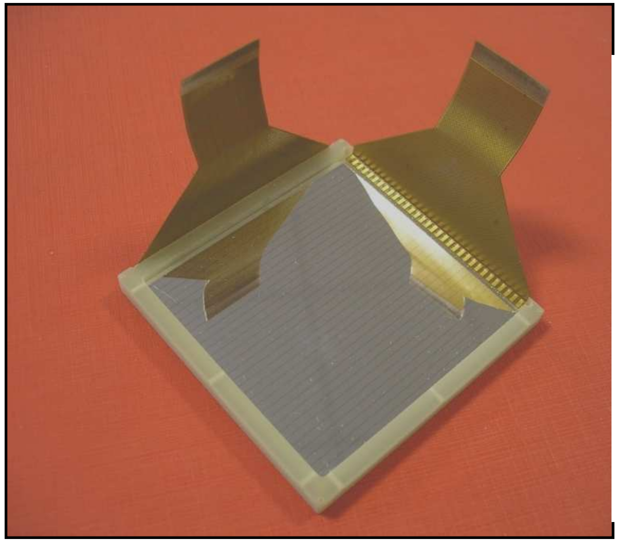
16 channel MEGAMP: (SA+CFD+TAC) modules that allow a sequentially read out of both energy and timing information by means of a fast multiplexer circuit

C. Boiano et al, 2012 IEEE NSS 2012

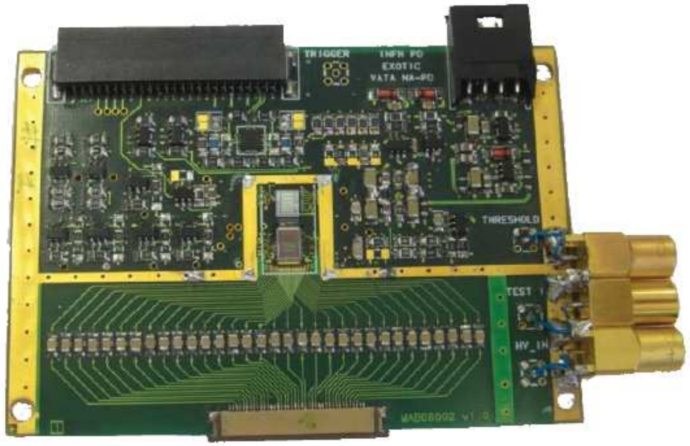
ΔE (FWHM): **34 keV**

Δt (FWHM): **0.5 ns**

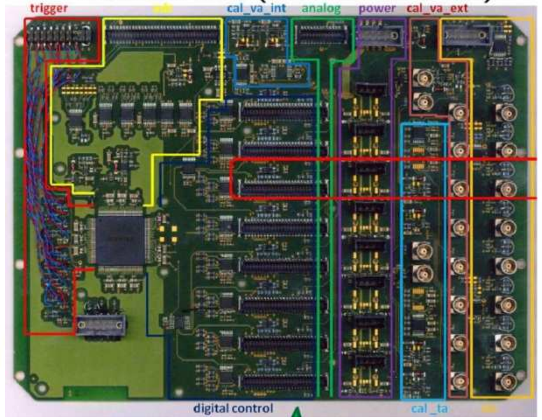
E stage: DSSD 300 μm

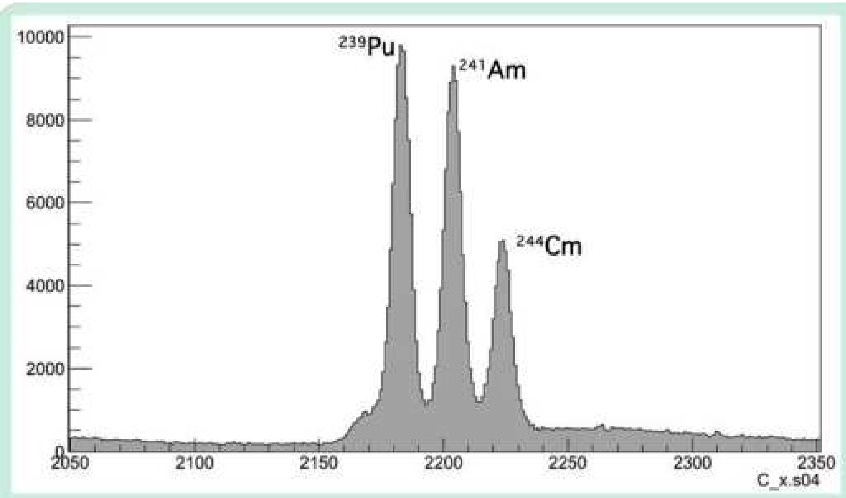


ASIC electronic board VATA



Motherboard (ASIC electronics)





Innovative readout electronics by means of an 32-channel ASIC chip manufactured by IDEAS-GM (Norway) dedicated to the treatment of the linear and the logical part of the electronic signals coming from the detector strips.

Energy Resolution achieved: **80 keV**

M. Romoli et al., NIM B 266, 4637 (2008)

E. Strano et al., NIM B, Proceeding of the EMIS 2012 (to be published)

$^{7}Be+^{58}Ni$ @ EXOTIC (05/2010)

^{7}Be: S_a = 1.587 MeV, $T_{1/2}$ = 53.22 d

Primary Beam: $^{7}Li^{3+}$

E_{lab}= 34.2 MeV

i ~ 100-150 pnA on target

Target: H_2 Gas

p_1 = 1 bar, T_1 = 90 K

(t_1 ~ 1.35 mg/cm^2)

Secondary Beam: $^{7}Be^{4+}$

E_1 = (23.2 ± 0.4) MeV

$Purity_1$ ~ 100 %

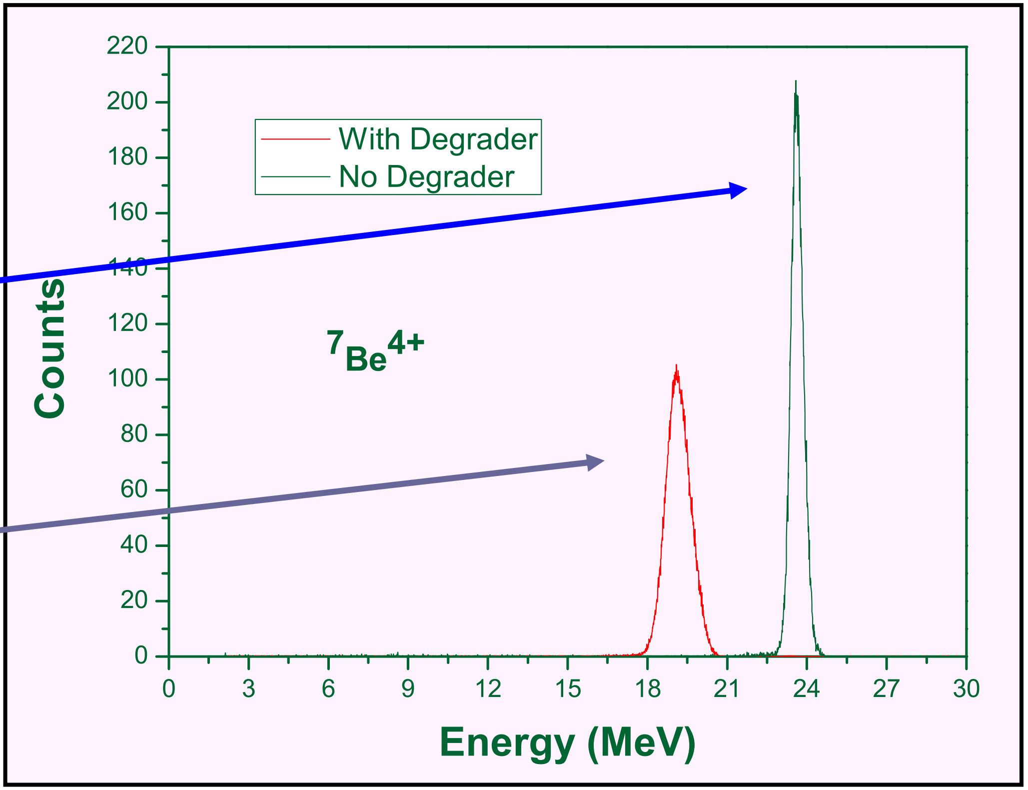
Degrader: 10 μm Al

E_2 = (19.0 ± 0.5) MeV

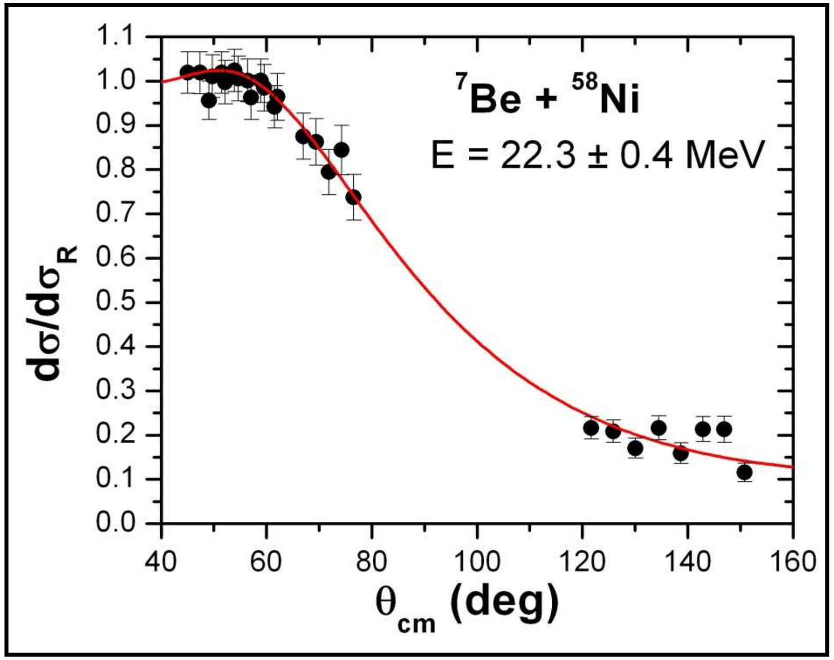
$Purity_2$ ~ 100 %

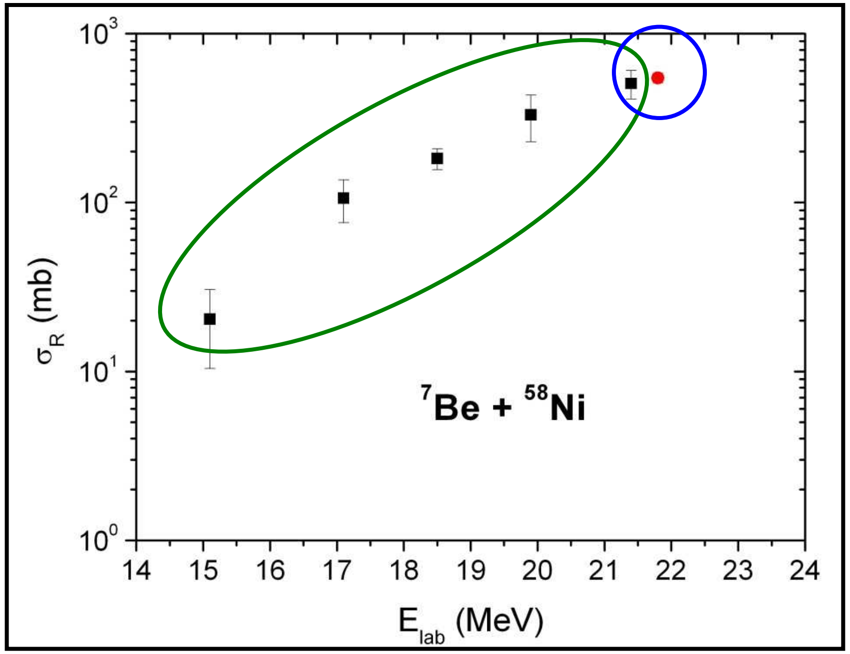
Intensity: 2-3*10^5 pps

Δx ~ Δy (FWHM) ~ 8 mm



$^{7}Be+^{58}Ni$ @ EXOTIC: Reaction cross sections

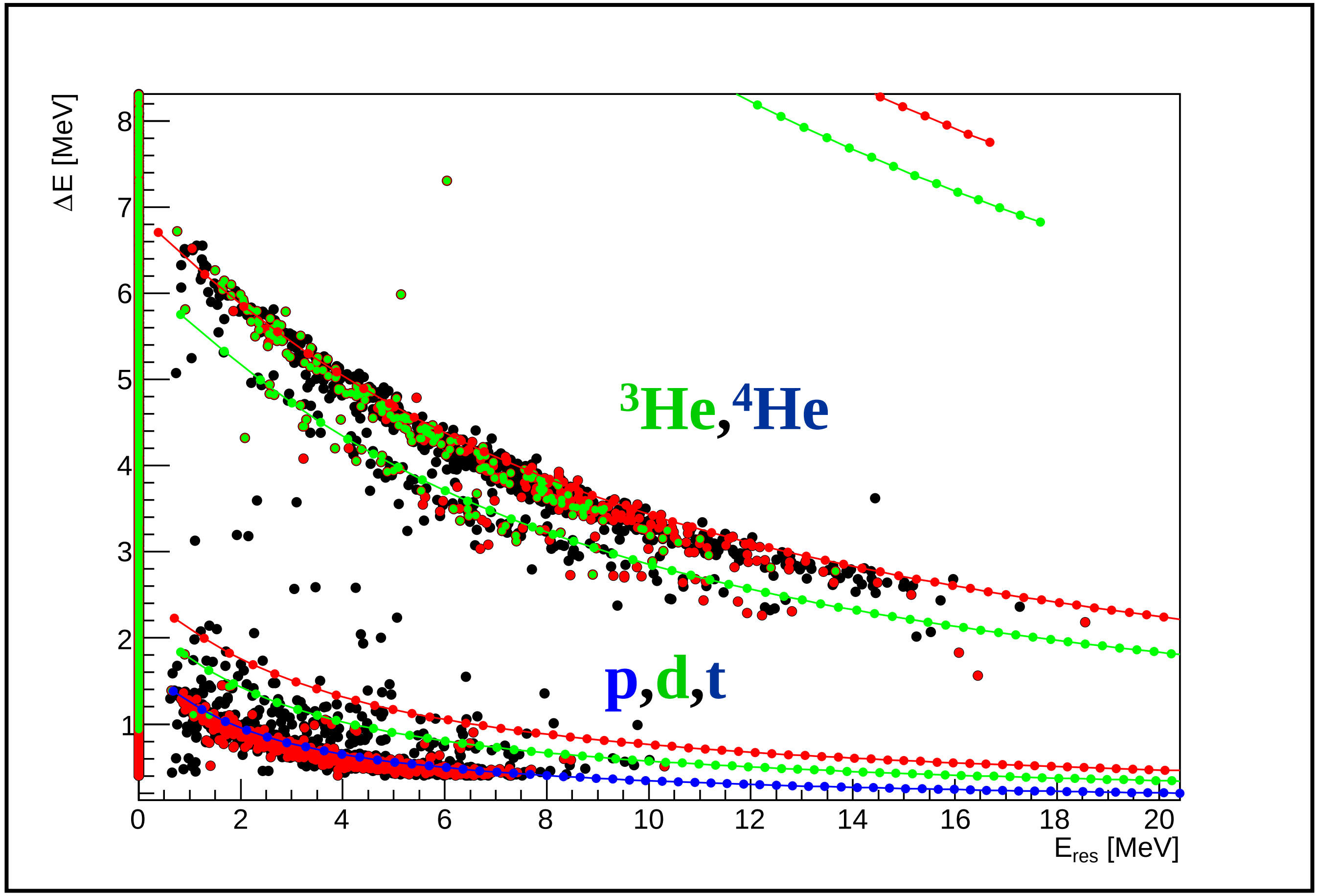




The **elastic scattering angular distribution** was fitted within the optical model framework with the code **FRESCO**.

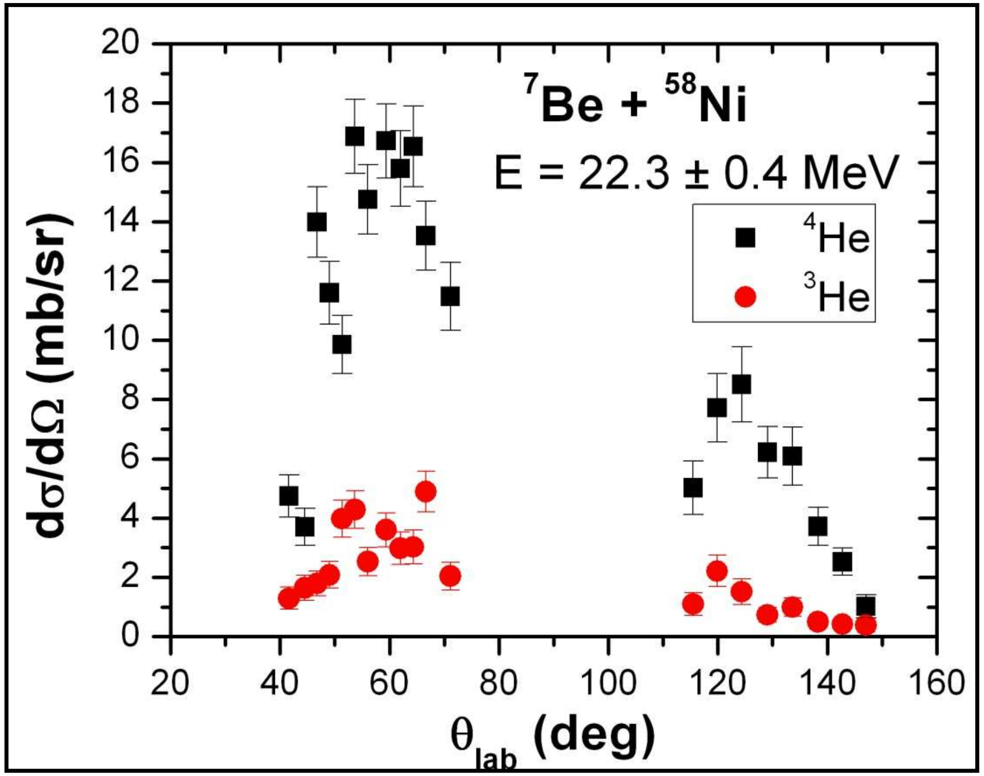
The **reaction cross section** (546 ± 36 mb) is in **fairly good agreement** with the trend individuated by the data at lower energies.

$^{7}Be+^{58}Ni$ @ EXOTIC: ^{3}He and ^{4}He production



A fairly large charged particles production, mainly **^{1}H** and **^{3}He, ^{4}He**, was observed both at forward and backward angles.

$^{7}Be+^{58}Ni$ @ EXOTIC: ^{3}He and ^{4}He angular distributions



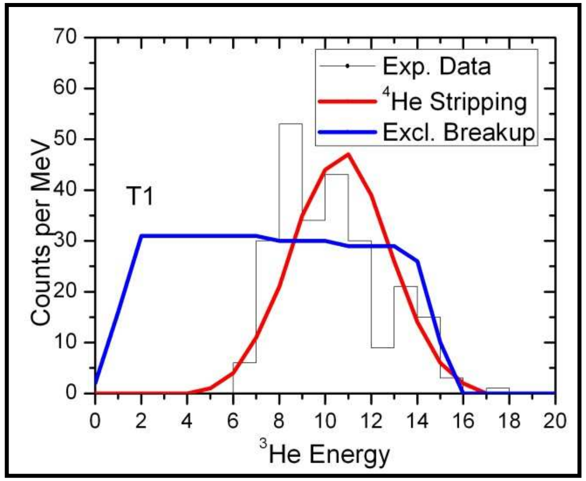
^{4}He ions are about **4-5 times** more abundant than **^{3}He**.

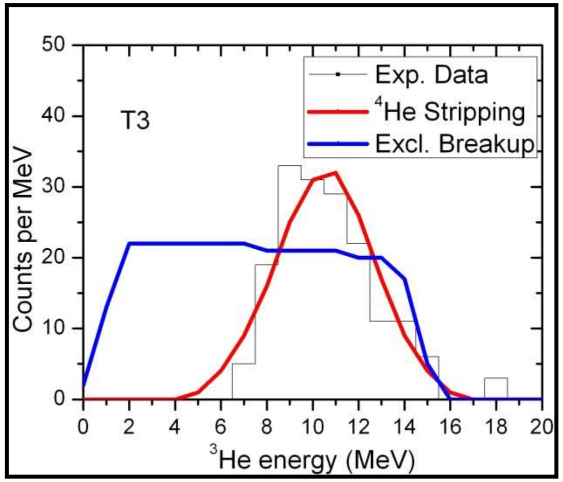
Their angle-integrated cross sections sum up to ~ 20 mb and ~ 100 mb for **^{3}He** and **^{4}He**, respectively.

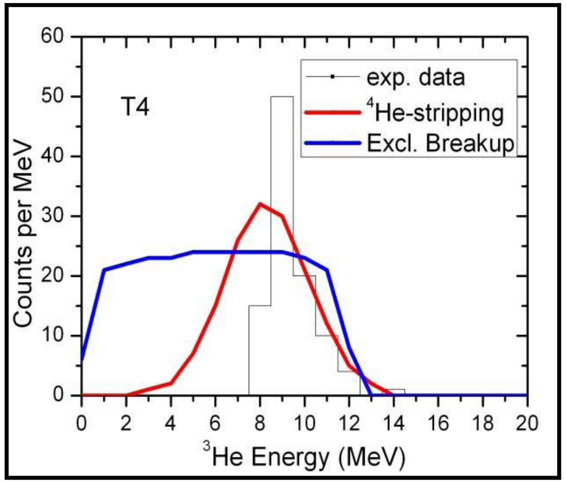
The **breakup channel ^{7}Be → ^{3}He + ^{4}He** is not the only reaction mechanism responsible for the **^{3}He and ^{4}He** production.

What else? **Transfer? Fusion?**

$^7Be+^{58}Ni$ @ EXOTIC: ^3He energy spectra







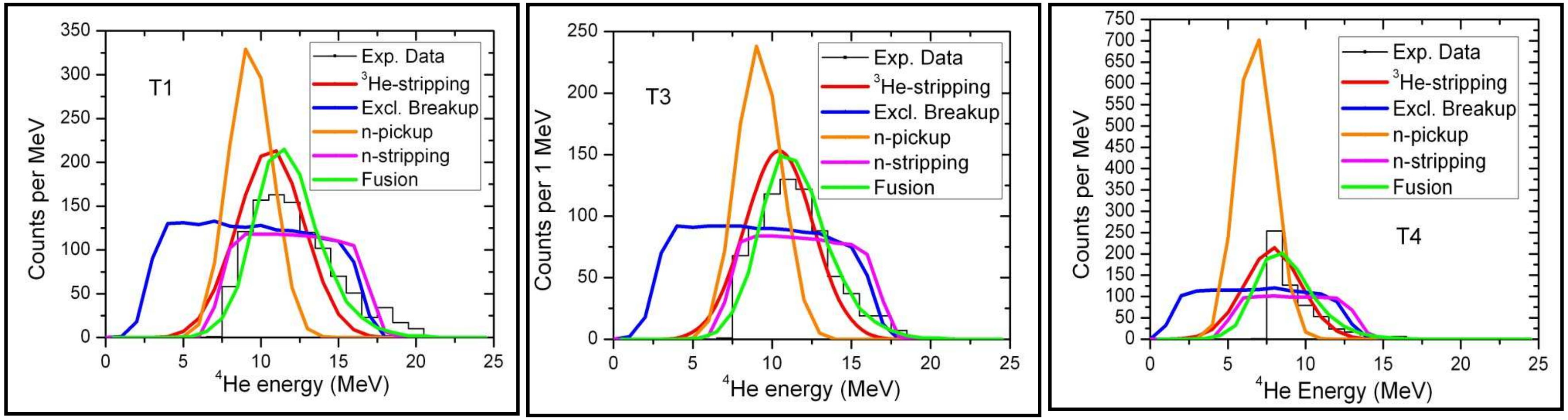
^{3}He can be originated by two main processes:

Exclusive Breakup: $^7Be \rightarrow {}^3He + {}^4He$;

^{4}He-Stripping: $^7Be + {}^{58}Ni \rightarrow {}^3He + {}^{62}Zn$ (Q_{val} = +1.78 MeV, E_x = 10.81 MeV).

^{3}He energy spectra compatible with a **^{4}He-Stripping process**

$^{7}Be+^{58}Ni$ @ EXOTIC: ^{4}He energy spectra



^{4}He can be originated by several processes:

Exclusive Breakup ^{7}Be → ^{3}He + ^{4}He;

^{3}He-Stripping: → ^{4}He + ^{61}Zn (Q_{val} = +9.46 MeV, E_x = 18.49 MeV).

n-Stripping: → ^{6}Be (= ^{4}He+2p) + ^{59}Ni (Q_{val} = –1.68 MeV, E_x = 0 MeV);

n-Pickup: → ^{8}Be (= 2^{4}He) + ^{57}Ni (Q_{val} = +6.68 MeV, E_x = 6.68 MeV);

^{4}He evaporation after compound nucleus formation **(Fusion)**.

Energy spectra are mainly compatible with **^{3}He-Stripping** and **Fusion**

$^{7}Be+^{58}Ni$ @ EXOTIC: ^{4}He coincidences

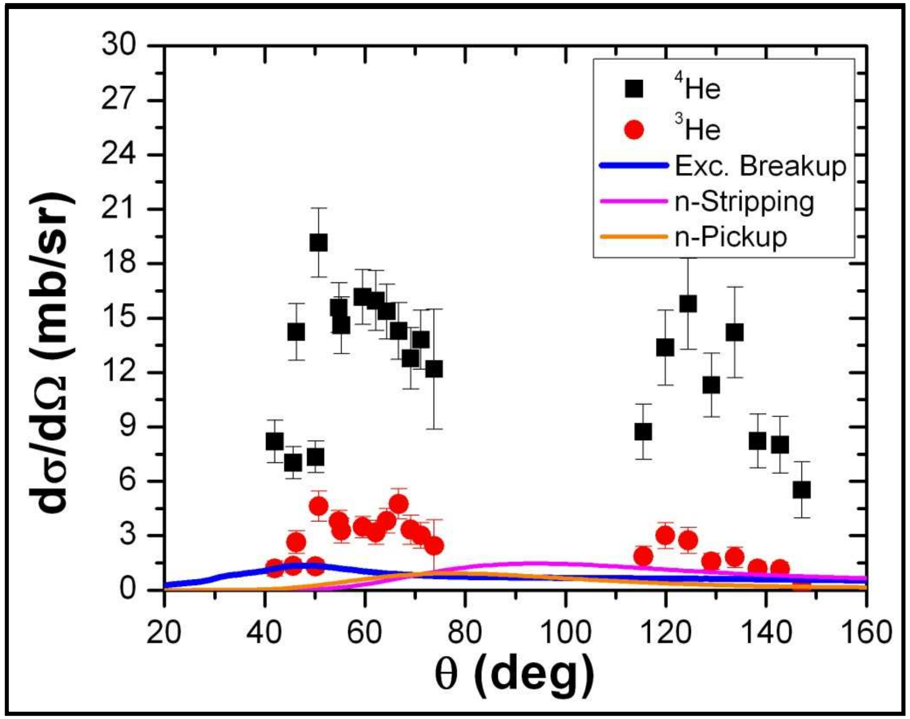
Within the geometrical efficiency of the set-up, no detection of:

- $^{4}He+^{3}He$ **(Exclusive Breakup)** coincidences (σ < 3 mb);
- $^{4}He+^{4}He$ **(n-Pickup)** coincidences (σ < 6 mb);
- $^{4}He+^{1}H$ **(n-Stripping)** coincidences (σ < 7 mb).

Theoretical (**CDCC** and **DWBA**) calculations (by N. Keeley):

- **Exclusive Breakup**: 9.3 mb
- **n-Pickup**: 5.8 mb
- **n-Stripping**: 10.3 mb

Theoretical and **experimental** confirmation that ^{3}He and ^{4}He are mainly produced by other reaction mechanisms, ^{4}He- and ^{3}He-stripping (plus **fusion?**)
Theoretical calculations of the ^{3}He and ^{4}He transfer angular distributions will help to disentagle the question



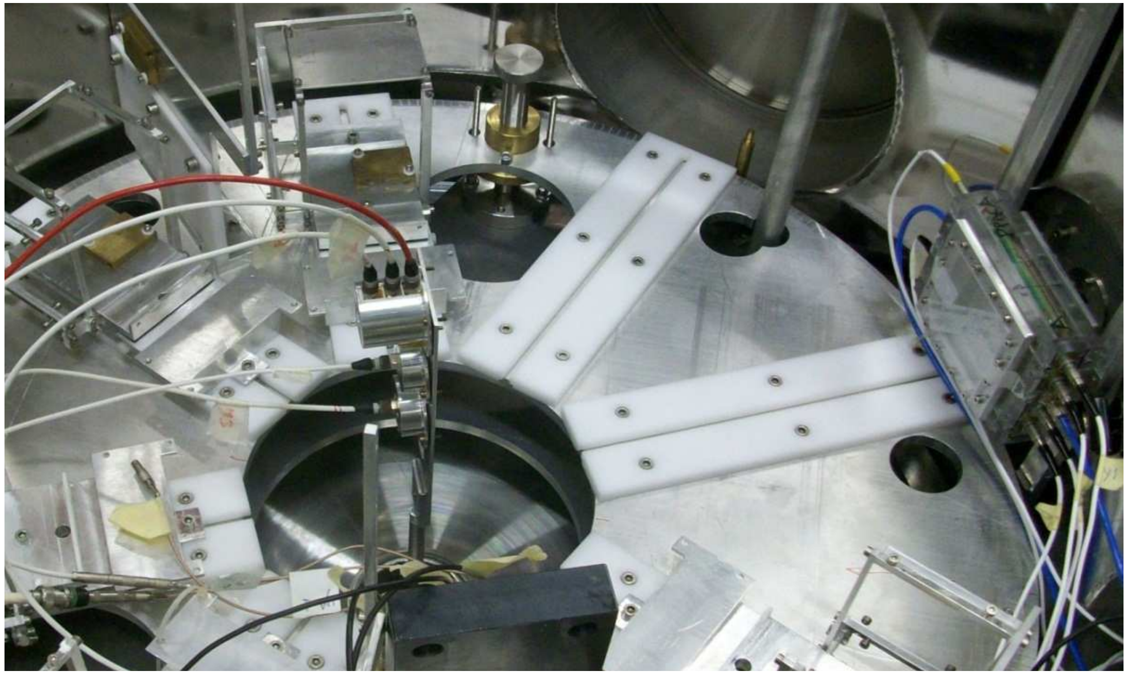
(INPC2013, paper in preparation)

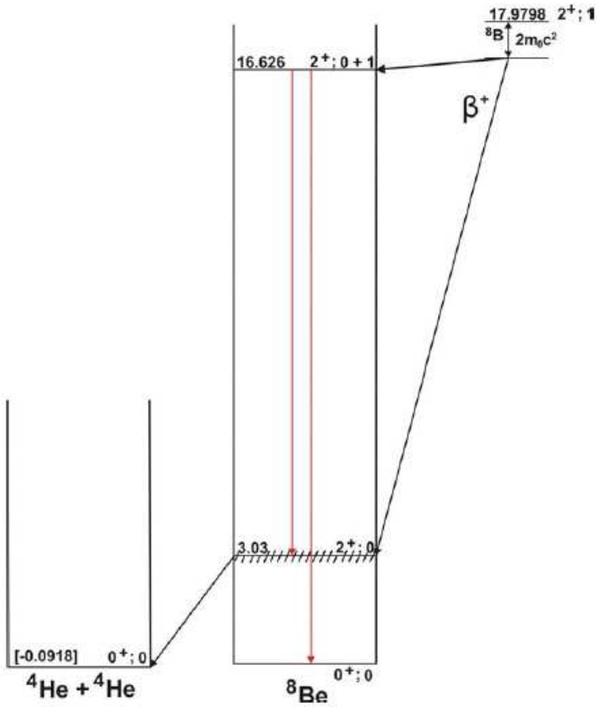
$^{8}B+^{28}Si$ @ EXOTIC

Experimental setup: ΔE 45 μm + ΔE 45 μm + E 2000 μm set at 0° degrees used both as an active target and as a calorimeter.

Reaction events are separated from non reaction events from their energy.
Fusion cross section obtained from the α particle cross section.
ΔE-E technique allows for particle identification and for frame scattering rejection

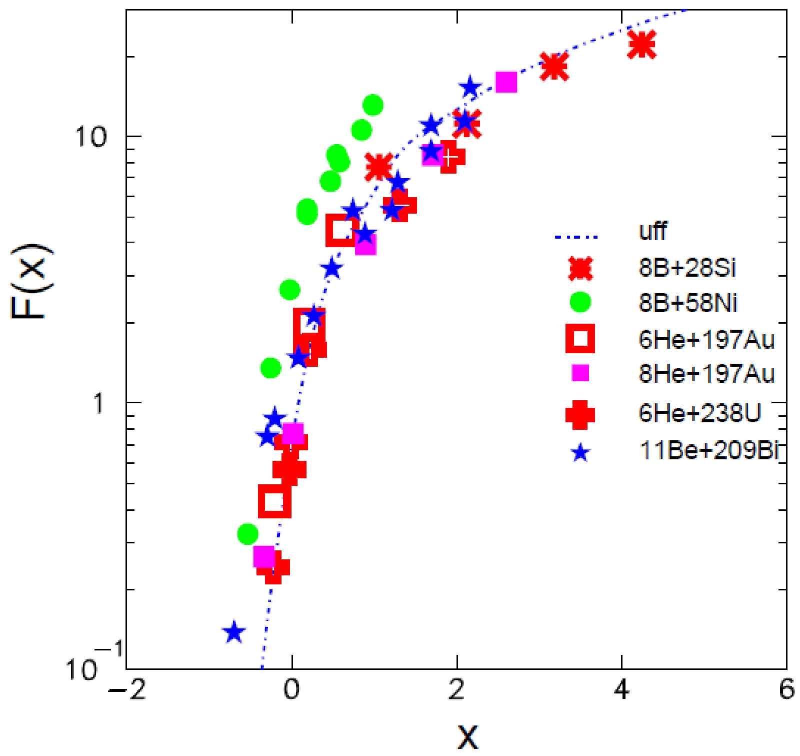
Pile up rejection challenging

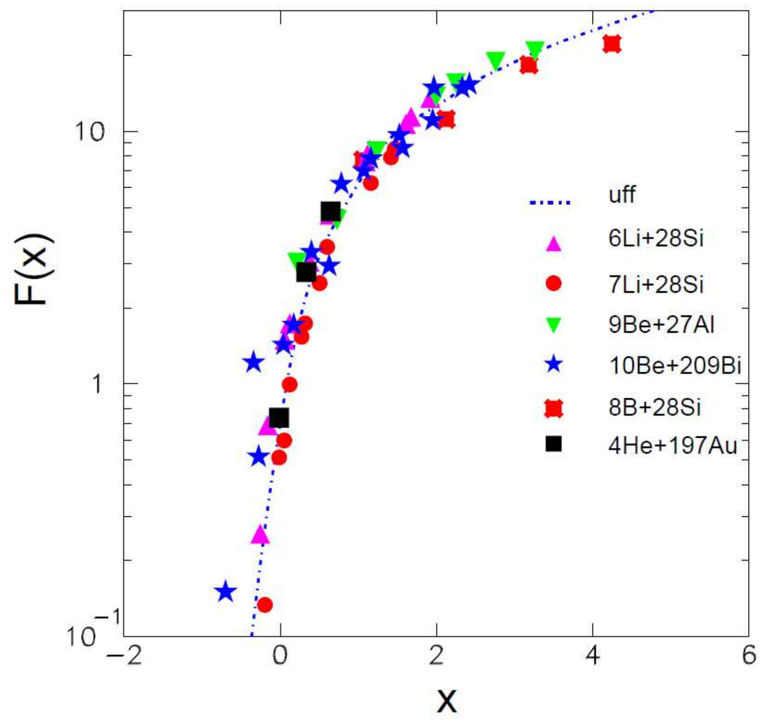




^{8}B Decay Scheme

$^{8}B+^{28}Si$ @ EXOTIC: Reduced Fusion cross section





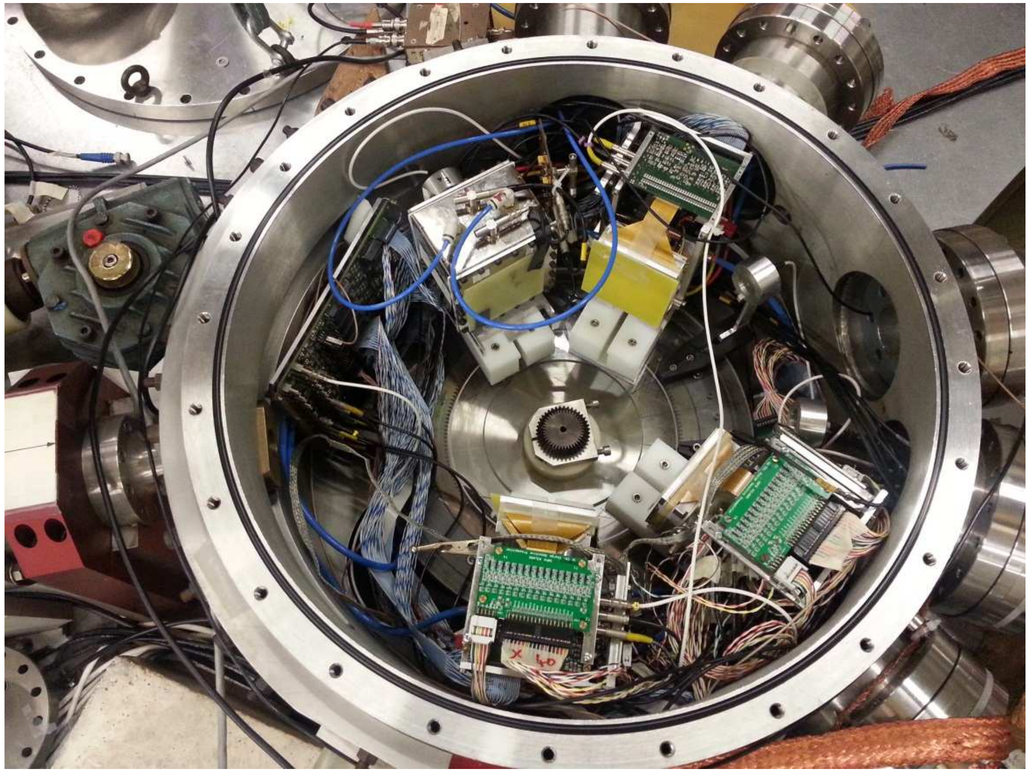
Despite the ^{8}B proton halo nature, the fusion of $^{8}B+^{28}Si$ at near barrier energies is compatible with the results of weakly bound but stable projectiles and with the 2n-halo ^{6}He exotic projectile on the same or similar target and also with the UFF curve.

*A. Pakou et al., PRC **87**, 014619 (2013)*

$^{17}O+^{58}Ni,^{208}Pb$ @ LNL (15-17 november 2012)

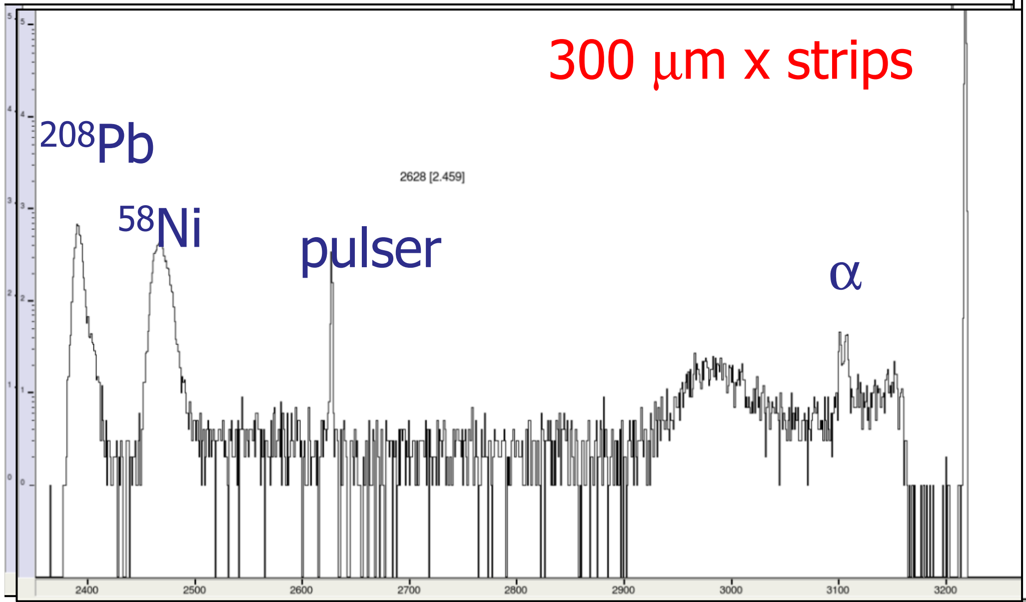
1)**Commissioning of the whole telescope** of the new experimental apparatus and the relative electronics

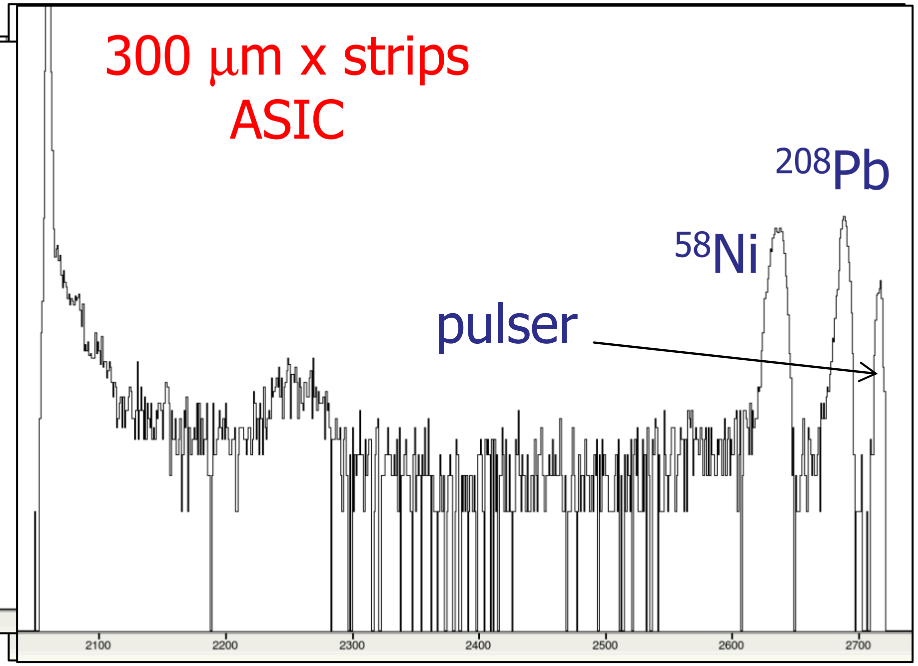
2)Study of the elastic scattering and reaction cross section for the $^{17}O+^{58}Ni,^{208}Pb$ systems at different energies around the Coulomb barrier



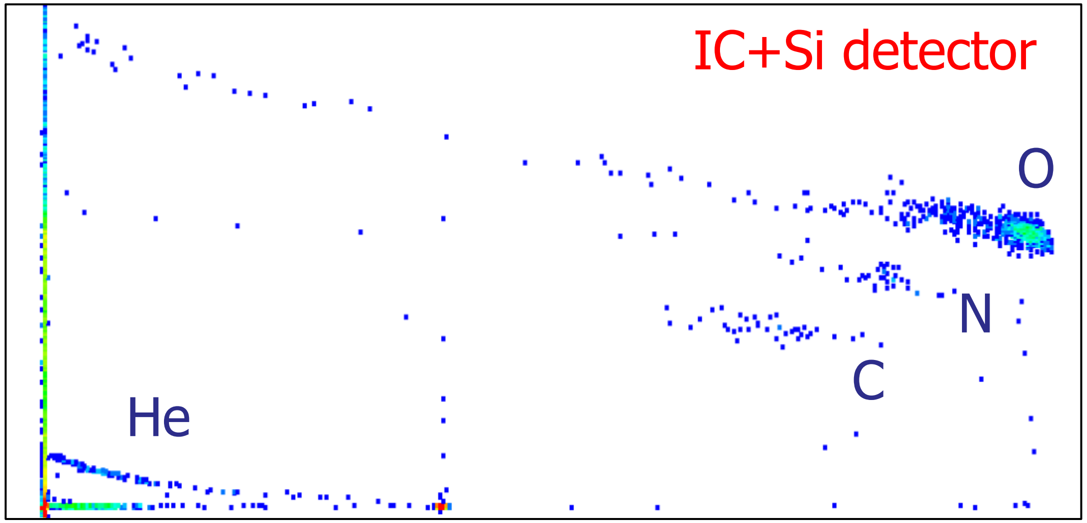
^{17}O+^{58}Ni,^{208}Pb @ LNL: raw data

^{17}O+^{58}Ni,^{208}Pb @ 42.5 MeV

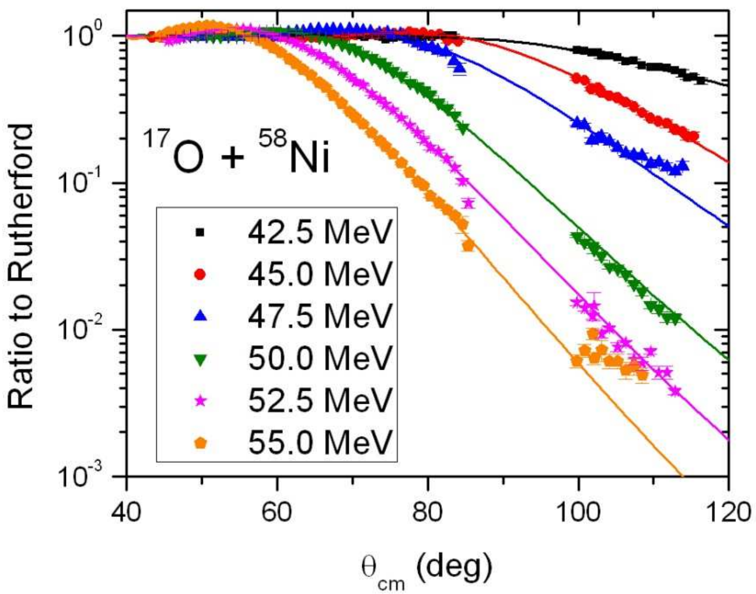


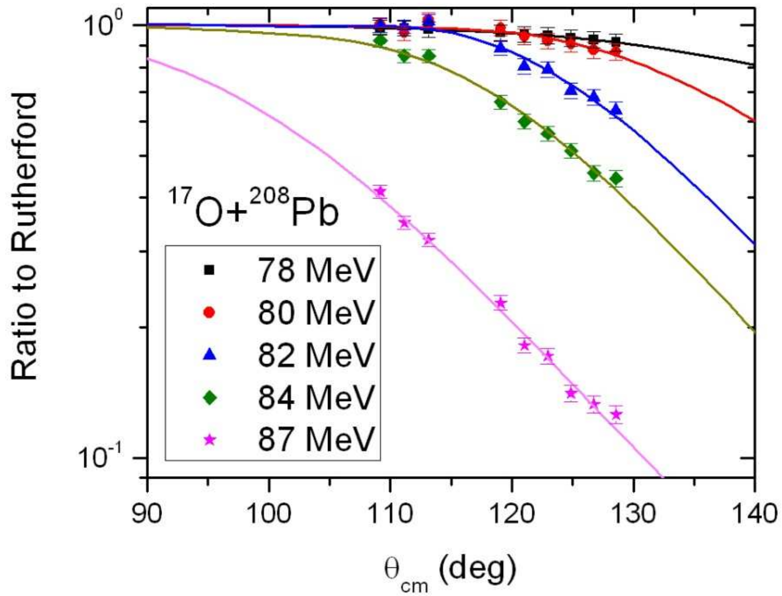


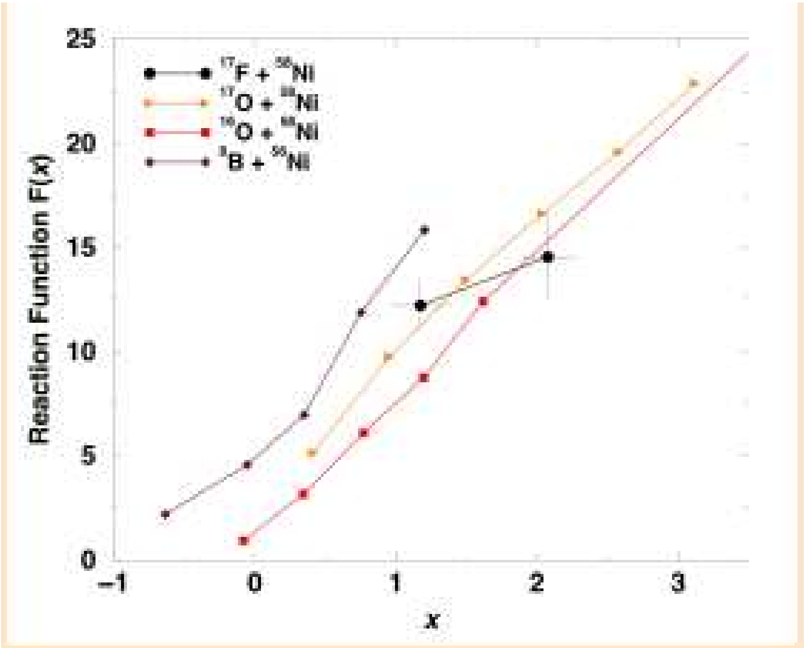
^{17}O+^{208}Pb @ 84 MeV



$^{17}O+^{58}Ni,^{208}Pb$ @ LNL: preliminary results







Similar reduced cross section of the $^{17}F+^{58}Ni$ system studied @ EXOTIC (*Mazzocco et al., PRC 82 (2010)* 054604) with those of the "reference" stable systems $^{16,17}O+^{58}Ni$: small influence of the low binding energy in the reaction dynamics

In agreement with our previous findings on $^{17}F+^{208}Pb$ system at sub barrier energy (*Signorini et al., EPJA 44 (2010) 63*)

Paper in preparation

EXOTIC beamline: velocity filter

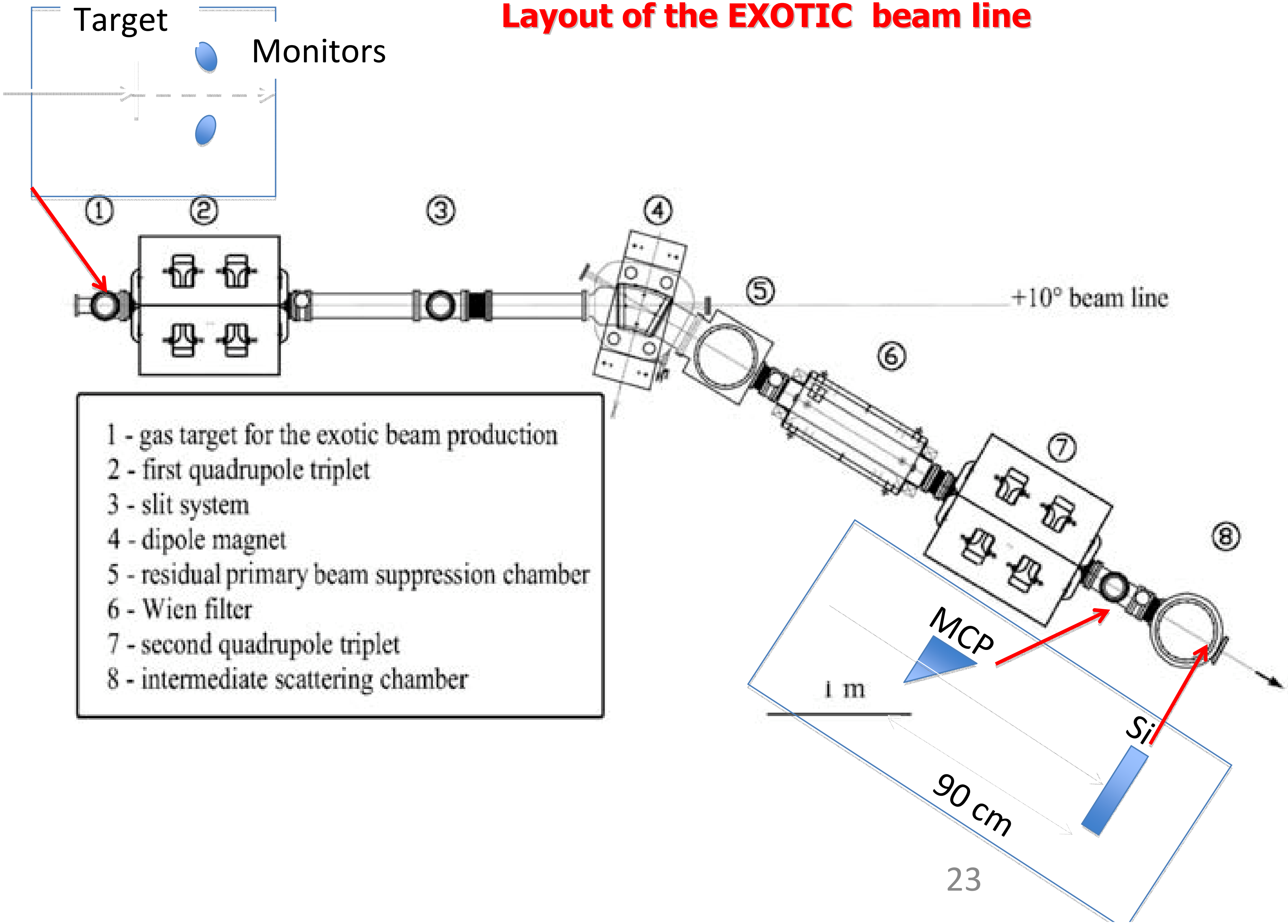
Aim: to use the EXOTIC beamline as a velocity filter for fusion-evaporation experiments with stable beams to study:

- α and p radioactivity
- Fusion at sub-barrier energies (*in coll. with PRISMA-FIDES*) to study the fusion "hindrance" phenomenon: in the deep sub-barrier region experimental fusion cross sections have been observed to systematically fall below the predictions of standard coupled-channels calculations

Configuration: dipole magnet and Wien filter used to select evaporation residues + suppression of the primary beam (taking advantage of the smaller velocity of compound nucleus with respect to that of the projectile)

Detection: implanted residues in EXPADES at 0° and study the respective decay.

Layout of the EXOTIC beam line



PISOLO *vs* EXOTIC

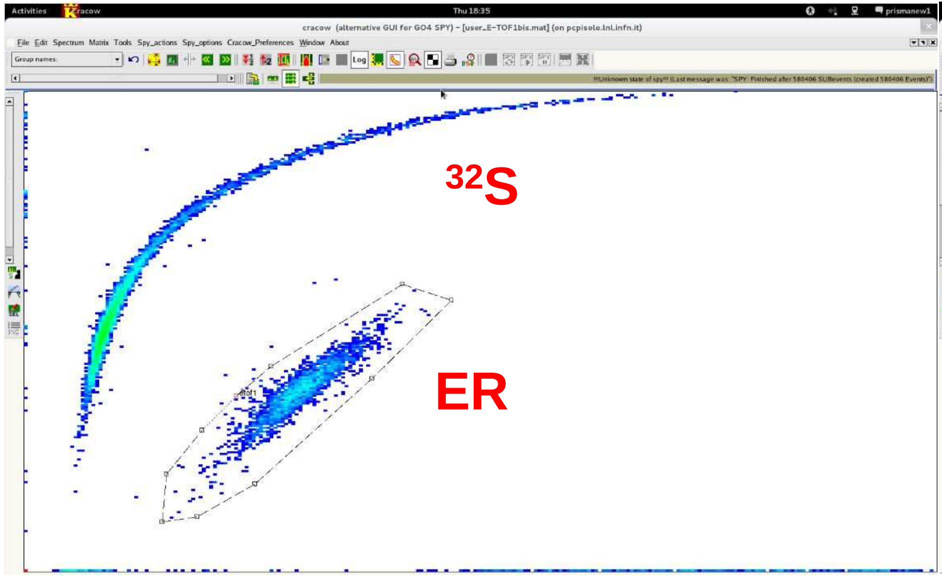
Set-up / Param.	Pisolo	Exotic
Geometrical solid angle	0.04 msr	10 msr
Rejection Factor	10^7-10^8	~10^{10}
Total detection efficiency	~0.5%	~5 %

Test of 05/2013 @ EXOTIC: first results

Rejection factor: 10^{11}, highly reduced experimental background.

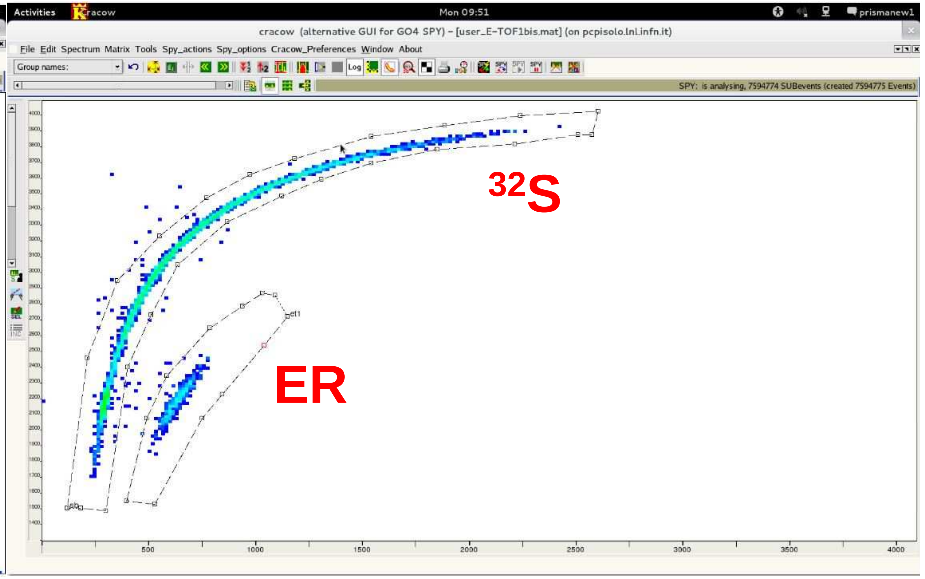
$^{32}S + {}^{48}Ca$ @ E_{lab}= 84 MeV

TOF



E

$^{32}S + {}^{64}Ni$ @ E_{lab}= 84 MeV



E

For technical problems (vacuum problems of the tandem) the test was not completed: we will ask for two more days in autumn to study the **transmission** of the EXOTIC beam line which was lower than that expected (probably because of primary beam alignment problems)

Approved proposals to be done @ EXOTIC by the end of 2013

Fall/2013: ^{7}Be + ^{208}Pb: study of the elastic scattering and exclusive and inclusive breakup of the ^{7}Be RIB in ^{3}He and ^{4}He fragments at Coulomb energies

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

Fall/2013: ^{7}Be + ^{28}Si reaction at EXOTIC at five near-barrier energies. At the highest energy a full study of both elastic scattering and relevant reaction mechanisms (transfer, breakup and fusion) will be performed, while the focus at the lower energies will be on the elastic scattering for probing the energy dependence of the optical potential and therefore the potential threshold anomaly

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

Fall/2013: ^{15}O radioactive beam production at EXOTIC. The ^{15}O can be used in order to search for possible cluster configurations ^{15}O + α in the p-rich nucleus ^{19}Ne by using the Thick Target Inverse Kinematics scattering. The measurements of the α decay width of low energy resonances in the elastic scattering excitation function ^{15}O(α, α) has also an astrophysical interest since ^{15}O is a nucleus involved in the hot CNO cycle. The ^{15}O(α, γ)^{19}Ne radiative capture represents a breakout of the Hot CNO cycle.

Approved proposals (RIKEN)

$^{8}B+^{208}Pb$ @ CRIB (Japan): elastic and inelastic scattering in a first moment and in the future inclusive, exclusive breakup and fusion cross section

experimental setup: 40 μm DSSD + 300 μm DSSD EXPADES (8 telescopes)

To be done in 2014

Next (07/2013 LNL PAC) proposals @ EXOTIC
^{6}He and ^{8}Li production

^{6}He (0.6 s) production via the inverse kinematics reaction
^{7}Li(^{2}H, ^{3}He) ^{6}He at E(^{7}Li) = 20 - 55 MeV (150 pnA) Q_{value}= -4.48 MeV

FIRB cod. RBFR08P1W2_001: *Produzione di un fascio radioattivo di ^{6}He e suo utilizzo per studi di dinamica di reazione su bersagli medio-leggeri (2010, Coordinatore: Marco Mazzocco)*

^{8}Li (830 ms) production via the inverse kinematics reaction
^{7}Li(^{2}H, ^{3}He) ^{6}He at E(^{7}Li) = 20 - 55 MeV (150 pnA) Q_{value}= -0.19 MeV

In case of a successful beam production test, the facility EXOTIC will be able to deliver secondary beams of ^{8}Li and ^{6}He up to about 20 and 12 MeV beam energy, respectively, and with intensities 10^{4} - 10^{5} pps. These value are sufficient for performing reaction dynamics studies induced at Coulomb barrier energies on targets up to Ni(Z=28)-Zn(Z=30) region and, in the case of ^{8}Li, even up to the Sn(Z=50)-Ba(Z=56) region.

Next (07/2013 LNL PAC) proposals @ EXOTIC
$^{8}B+^{208}Pb$ @ 43 MeV

$^{8}B + ^{208}Pb$ @ E_{lab}= 43 MeV: study of the coupling mechanisms at sub-barrier energies by investigating elastic scattering and ^{8}B breakup. In CDCC investigations strong couplings of elastic scattering to direct channels do not seem to be directly connected to the observation of large breakup or transfer reaction cross sections.

Coulomb rainbow suppression or a deviation from Rutherford scattering at energies below barrier was observed in previous elastic scattering experiments like $^{6}He + ^{208}Pb$, $^{11}Be + ^{64}Zn$ and $^{11}Li + ^{208}Pb$ attributed to Coulomb dipole couplings and/or nuclear couplings (A.M. Sánchez-Benítez et al., Nucl. Phys. A803, 30 (2008), M. Cubero et al., Phys. Rev. Lett. 109, 262701 (2012), A. Di Pietro et al., Phys. Rev. Lett. 105, 022701(2010))

According to existing calculations [N. Keeley et al., Nucl. Phys. A834, 729c (2010)], almost **no deviation from Rutherford** is predicted for the **$^{8}B+^{208}Pb$** system and this has to be verified experimentally, while a large ^{7}Be production yield is expected with a cross section for ^{8}B breakup of 360 mb exhausting almost all the total reaction cross section.

Experimental set up: 4-6 EXPADES telescopes (DSSD 40+300 μm)

Richieste finanziarie 2014: Missioni

Richieste totali Missioni: 21.5 k€ Interno - 26 k€ Estero

NA

Interno:

1.5 k€ (2 riunioni di collaborazione per 2 persone * 0.35 k€)

12 k€ (turni di misura e preparazione: 10 gg*0.12 k€ +0.3 k€)*4 pers (2 ric+2 tec) *2 viaggi)

Estero

9 k€ (1 turno di misura a RIKEN+ preparazione per 4 persone per 10 giorni: (0.12*10+1)*4 pers)

2 k€: contatti scientifici

PD (8 k€ Int + 15 k€ Est)

Interno:

5.5 k€ (Missioni a LNL per preparazione turni di misura e mnutenzione della linea di fascio(6 persone per un totale complessivo di 18 mesi/uomo. Costo stimato 300 Euro per mese/uomo)

2.5 k€ (Riunioni di collaborazione per 6 persone)

Estero

13.5 k€ (Turno di misura a RIKEN: 3 persone per 15 giorni e 3 persone per 7 giorni. Circa 100 Euro pro die e 1000 Euro viaggio pro capita)

1.5 k€: Contatti scientifici (1 viaggio (1 k€) di 5 giorni per una persona (0.1 k€ pro die))

Richieste finanziarie 2014: CA, Cons, T, M

Costruzione Apparati (50 k€)
11 k€ : Teslametri e una pompa turbo di riserva per la linea di fascio
34 k€: acquisto di 2 MCP e relativa elettronica per esperimenti in cui la perdita di energia nei PPAC è critica
5 k€: Flash ADC (pile up rejection)

Consumo (21 k€)
15 k€ : 2 DSSD di 1 mm (necessari per esperimenti di scattering elastico risonante)
6 k€ (elettronica e materiale di laboratorio)

Manutenzione (2 k€)
2 k€

Trasporti (5 k€)
5 k€ (trasporto di materiale fragile)

Simile richiesta finanziaria nel 2015

EXOTIC: Richieste di supporto Servizi Tecnici

Officina Meccanica: (ca. 6 mesi/uomo)
Realizzazione del secondo target criogenico
Produzione e test di tenuta delle finestre di Havar del Gas Target

Laboratorio di Elettronica: (ca. 3 mesi/uomo)
Completamento dell'assemblaggio degli 8 rivelatori di EXPADES.
Completamento dell'elettronica e degli spare parts.
Assistenza e supporto per turni di misura a LNL
Assistenza e supporto per l'esperimento a CRIB (Giappone)

Progettazione: (Nessuna richiesta)

Servizio di Calcolo: (Nessuna richiesta)