Reaction Dynamics for the Systems ^{7}Be,^{8}B + ^{208}Pb at Energies Around the Coulomb Barrier

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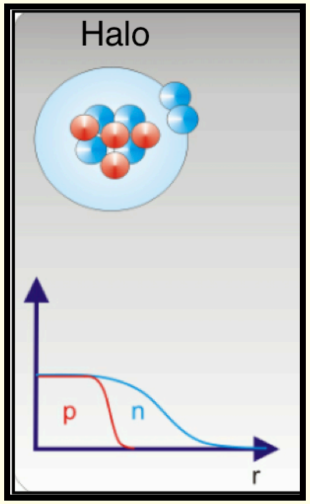
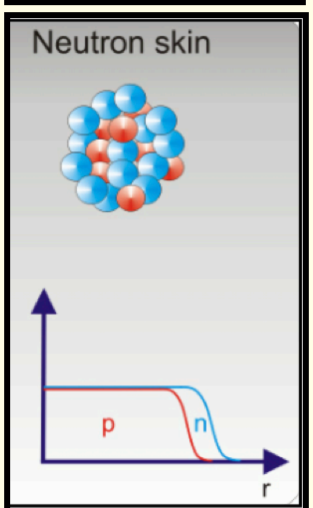
26th International Nuclear Physics Conference (INPC)
Adelaide Convention Centre, Australia
11-16 September 2016

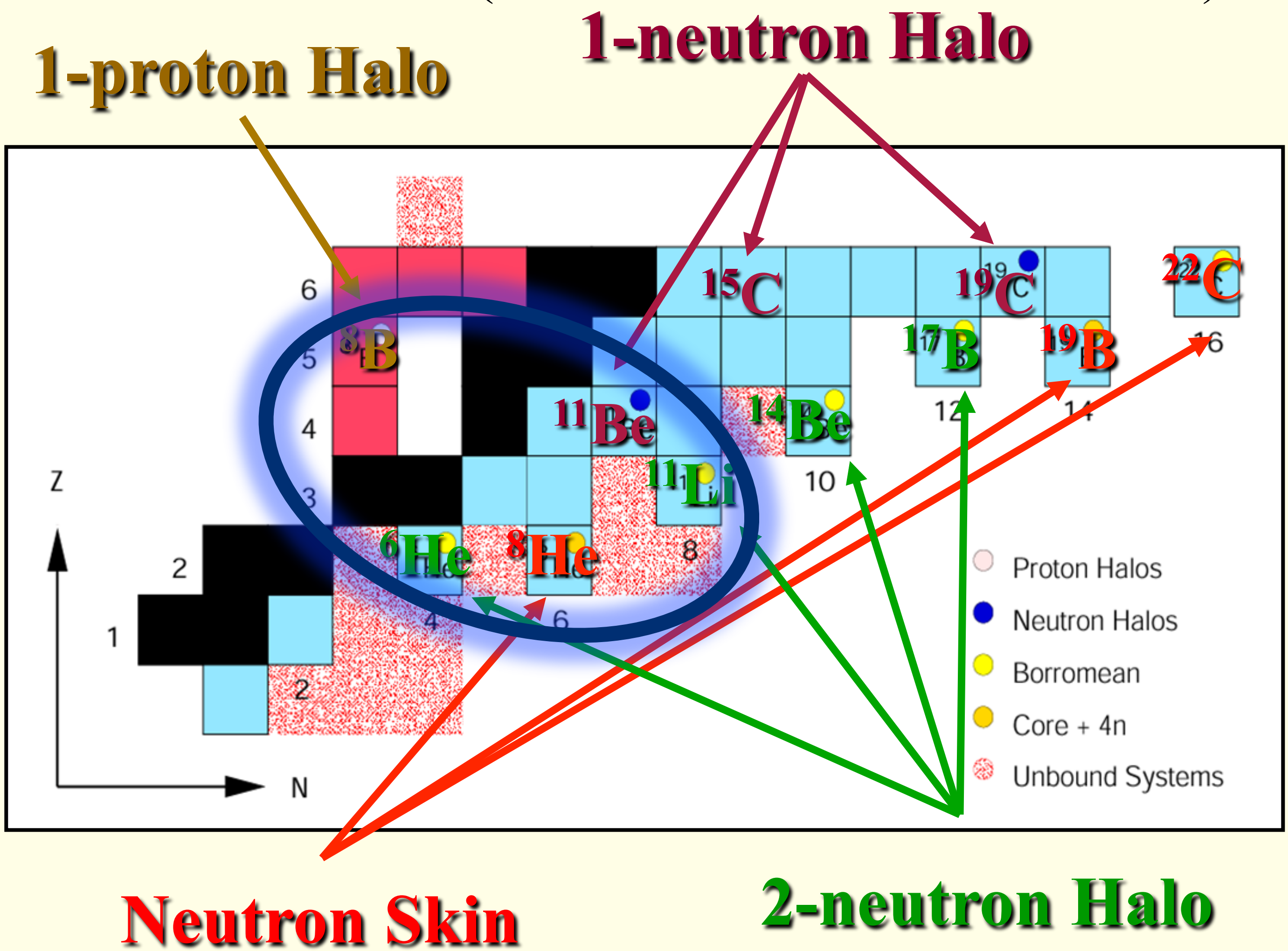
I. Introduction

Light Exotic Nuclei

The light portion of the nuclide chart is full of **weakly-bound nuclei** with **unusual** matter distributions (**halo** and **neutron skin** nuclei).





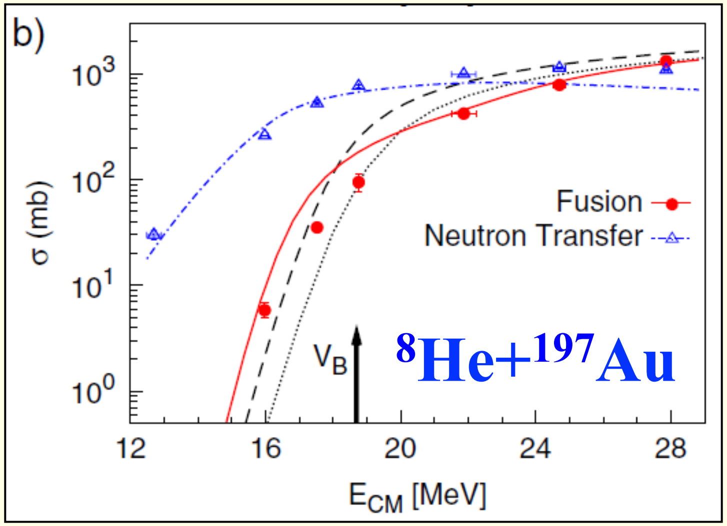


Near-Barrier Studies

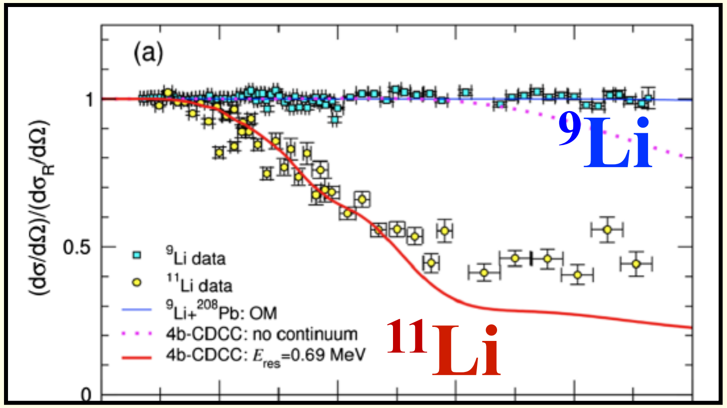
What is the influence of the **nuclear halo** on the **reaction dynamics**?

Depending on the treatment of the **projectile breakup process**, theoretical models predicted either the **enhancement** or the **hindrance** of the **sub-barrier fusion** cross section.

Breakup related effects largely increased the **sub-barrier total reaction** cross section, mainly because of **direct processes**.



A. Lemasson et al., PRL 103, 232701 (2009)



Elastic Scattering: **strong deviations** from the Rutherford differential cross section already at **small angles**.

M. Cubero et al., PRL 109, 262701 (2012)

II. Facility EXOTIC at INFN-LNL (Italy)

The In-Flight Facility EXOTIC

Facility at the **Laboratori Nazionali di Legnaro (LNL)** of the **INFN** for the in-flight production of light weakly-bound **RIBs**, employing **inverse kinematics reactions** with heavy projectiles impinging on **gas targets** (**p**,**d**,**^{3}He**).

The **commissioning** of the facility was performed in 2004.

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

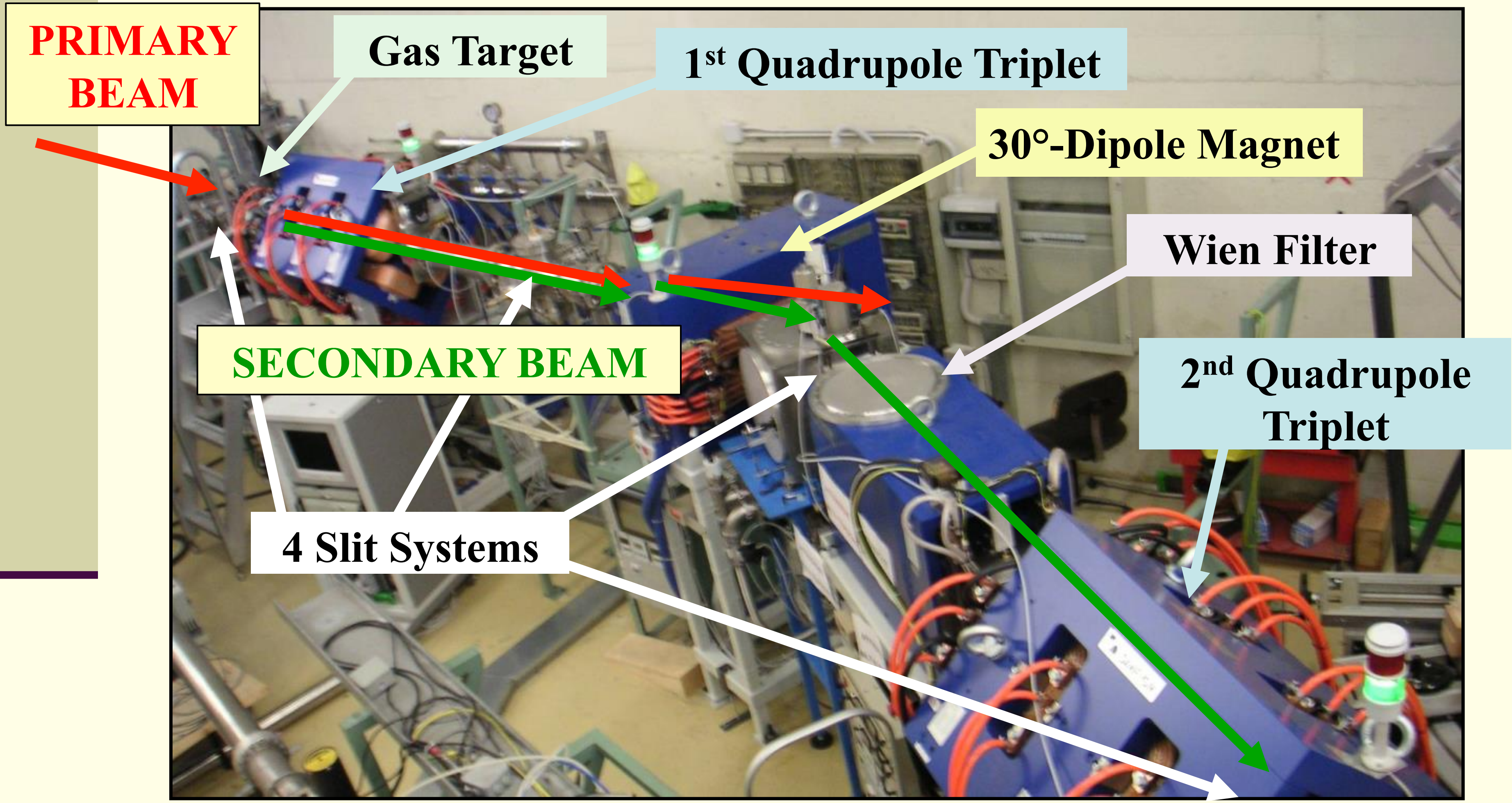
A **substantial upgrade process** was subsequently held in 2012.

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

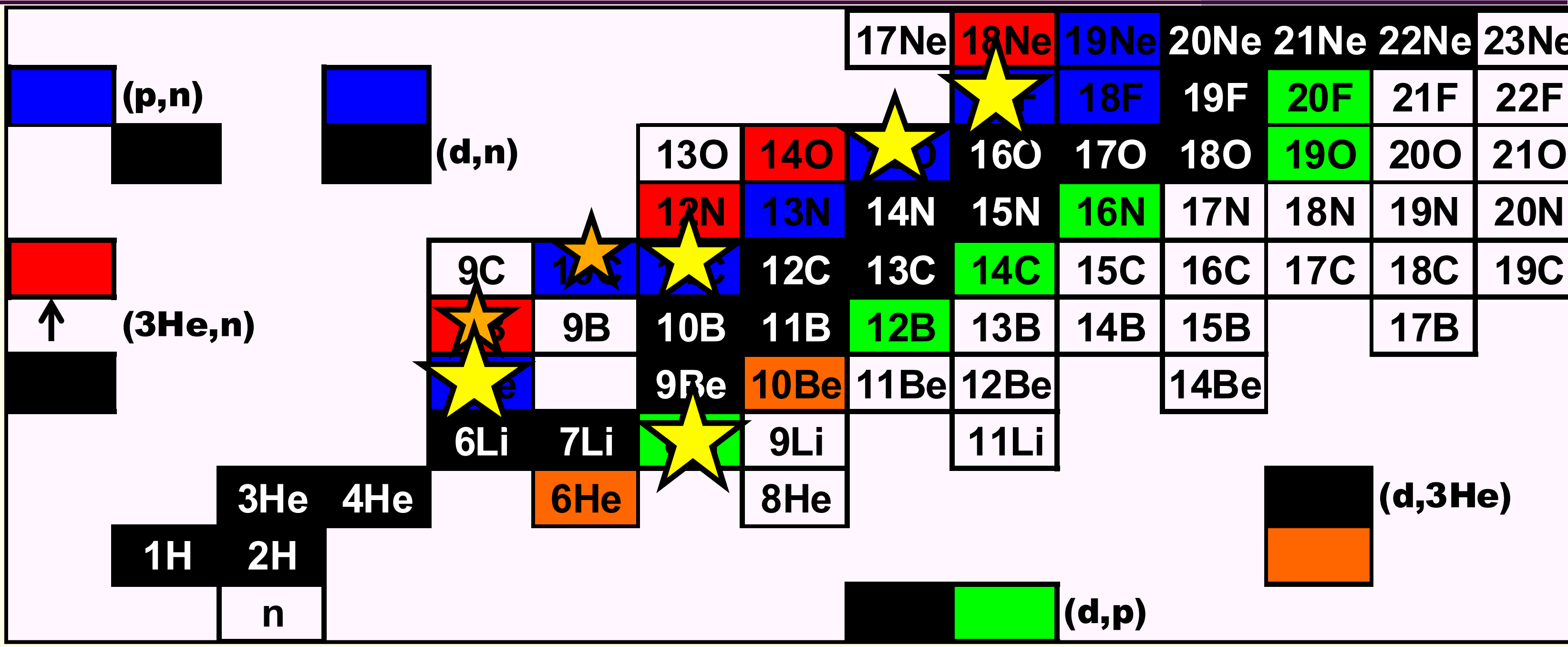
7 Radioactive Ion Beams have been delivered so far:

1.	**^{17}F (S_p = 600 keV):**	**p(^{17}O,^{17}F)n**	Q_{value} = – 3.54 MeV;
2.	**^{8}B (S_p = 137.5 keV):**	**^{3}He(^{6}Li,^{8}B)n**	Q_{value} = – 1.97 MeV;
3.	**^{7}Be (S_α = 1.586 MeV):**	**p(^{7}Li,^{7}Be)n**	Q_{value} = – 1.64 MeV;
4.	**^{15}O (S_p = 7.297 MeV):**	**p(^{15}N,^{15}O)n**	Q_{value} = – 3.54 MeV;
5.	**^{8}Li (S_n = 2.033 MeV):**	**d(^{7}Li,^{8}Li)p**	Q_{value} = – 0.19 MeV;
6.	**^{10}C (S_p = 4.007 MeV):**	**p(^{10}B,^{10}C)n**	Q_{value} = – 4.43 MeV;
7.	**^{11}C (S_p = 8.689 MeV):**	**p(^{11}B,^{11}C)n**	Q_{value} = – 2.76 MeV;

Facility EXOTIC at INFN-LNL



Light RIBs at EXOTIC



^{17}F	E = 3–5 MeV/u	Purity: **93-96 %**	Intensity: **10^5 pps**
^{8}B	E = 3–5 MeV/u	Purity: **30-43 %**	Intensity: **~ 10^3 pps**
^{7}Be	E = 2.5–6 MeV/u	Purity: **99 %**	Intensity: **10^6 pps**
^{15}O	E = 1.3 MeV/u	Purity: **97-98 %**	Intensity: **$4*10^4$ pps**
^{8}Li	E = 2–2.5 MeV/u	Purity: **99 %**	Intensity: **10^5 pps**
^{10}C	E = 4 MeV/u	Purity: **99 %**	Intensity: **$5*10^3$ pps**
^{11}C	E = 4 MeV/u	Purity: **99 %**	Intensity: **$2*10^5$ pps**

Experiments (2006 - 2012)

$^{17}F + ^{208}Pb$ [Quasi-Elastic Scattering and Breakup]

C. Signorini et al., Eur. Phys. J. A 44, 63 (2010)

$^{17}F + ^{58}Ni$ [Quasi-Elastic Scattering]

M. Mazzocco et al., Phys. Rev. C 82, 054604 (2010)

$^{17}F + ^{1}H$ [Elastic Scattering]

N. Patronis et al., Phys. Rev. C 85, 024609 (2012)

$^{8}B + ^{28}Si$ [Fusion]

A. Pakou et al., Phys. Rev. C 87, 014619 (2013)

$^{7}Be + ^{58}Ni$ [Elastic Scattering, Direct Processes]

M. Mazzocco et al., Phys. Rev. C 92, 024615 (2015)

Experiments (2013 - 2016)

^{32}S+ ^{48}Ca, ^{64}Ni [Recoil Separation (PRISMA)]

Spokesperson: G. Montagnoli, A.M. Stefanini, M. Mazzocco

^{7}Be + ^{208}Pb [Elastic Scattering, Direct Processes]

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

^{7}Be + ^{28}Si [Breakup Threshold Anomaly]

A. Pakou et al., PRC (submitted)

^{8}Li + ^{58}Ni [Elastic Scattering]

Spokespersons: D. Torresi, M. Mazzocco

^{8}Li + ^{90}Zr [Total Reaction Cross Section]

A. Pakou at al., Eur. Phys. J. A 51, 55 (2015)

^{15}O + ^{4}He [Resonant Scattering]

D. Torresi, C. Wheldon, Tz. Kokalova et al., PRL (submitted)

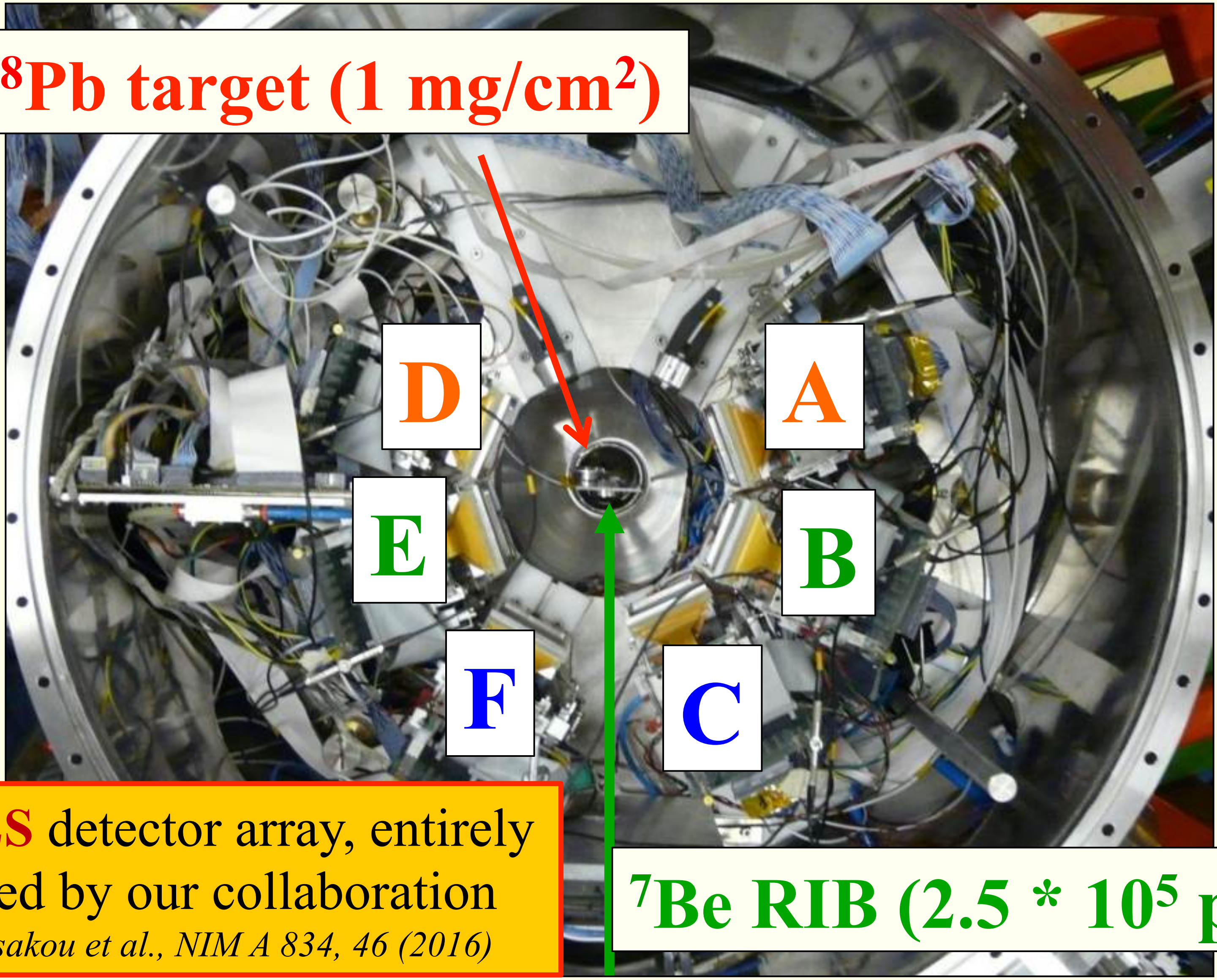
^{7}Be + ^{2}H [Surrogate Trojan Horse Reaction for ^{7}Be+n]

Spokesperons: L. Lamia, C. Spitaleri, M. Mazzocco

III. $^{7}Be + ^{208}Pb$ @ EXOTIC

^{7}Be + ^{208}Pb at LNL

^{208}Pb target (1 mg/cm^{2})

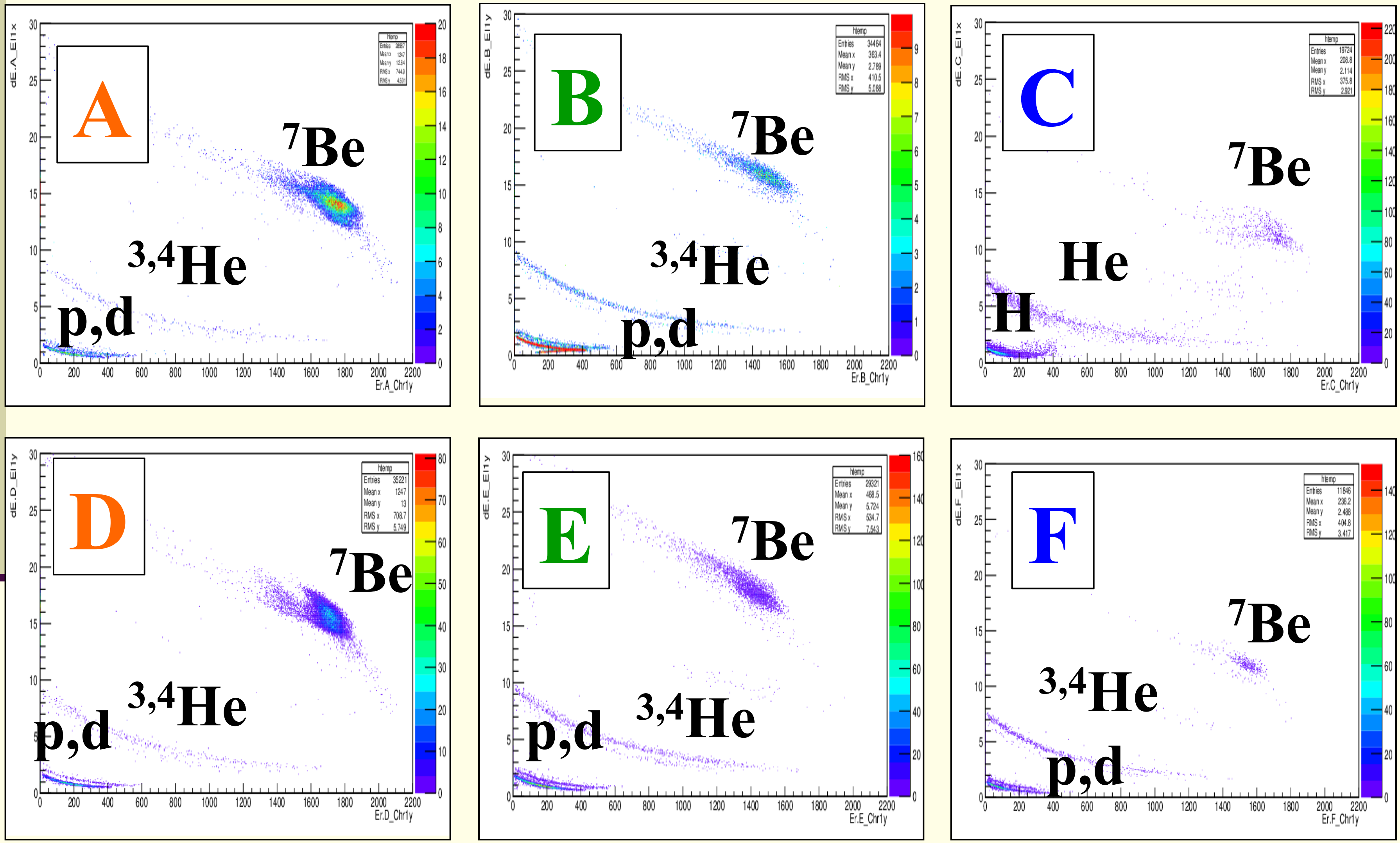


EXPADES detector array, entirely developed by our collaboration

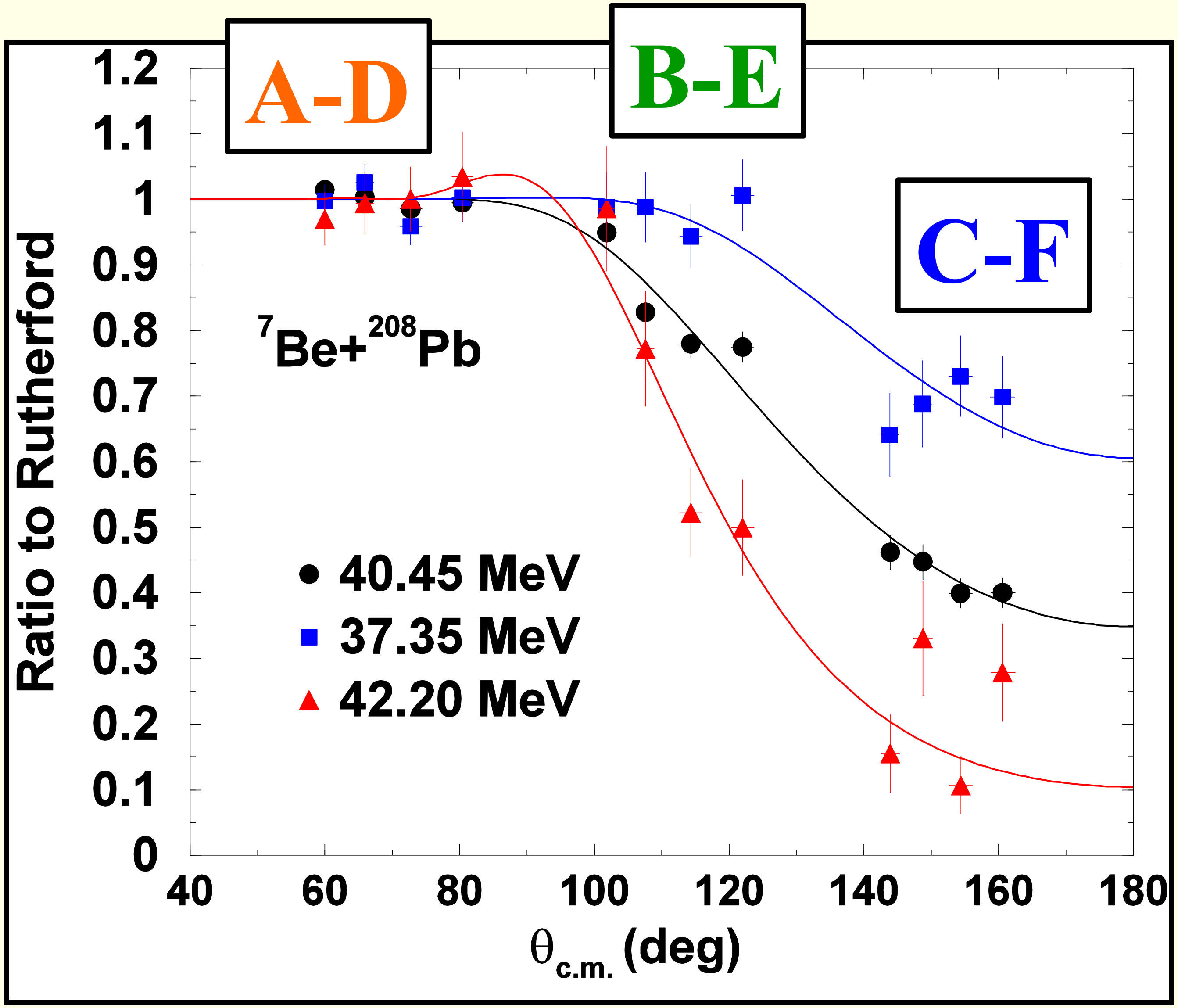
D. Pierroutsakou et al., NIM A 834, 46 (2016)

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

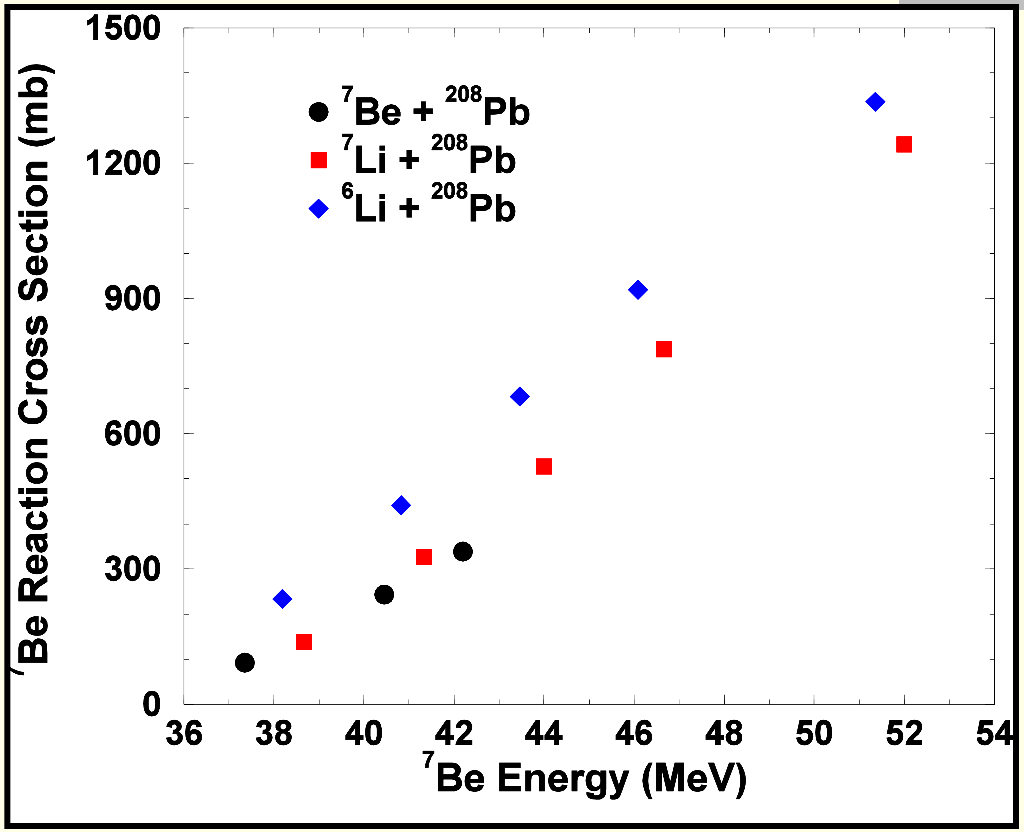
ΔE-E_{res} Plots



(Quasi-) Elastic Scattering

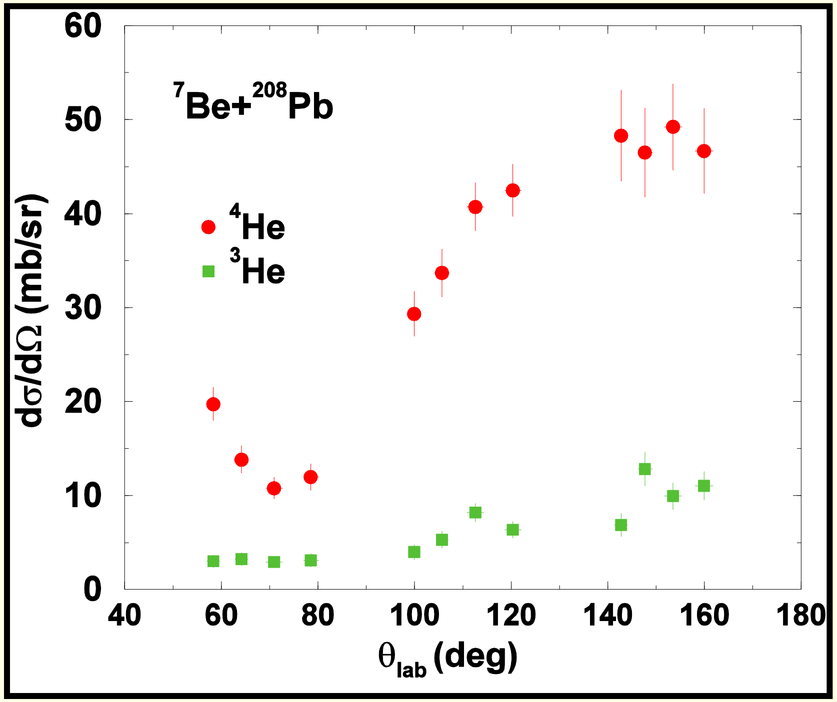


Total Reaction Cross Section



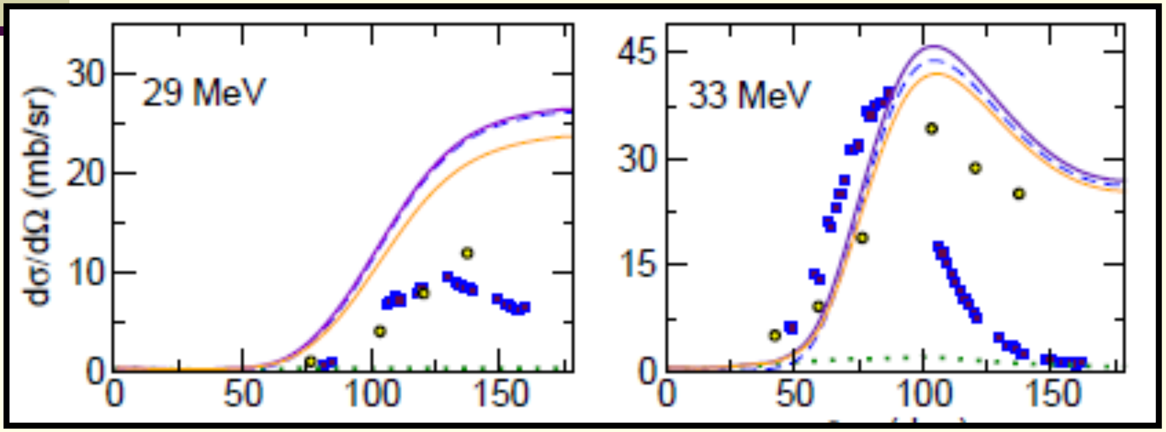
A preliminary **optical model best-fit analysis** of the quasi-elastic scattering angular distributions suggests for **^{7}Be (S_α = 1.586 MeV)** a **behaviour** more similar to **^{7}Li (S_α = 2.468 MeV)** than to **^{6}Li (S_α = 1.475 MeV)**.

^{3,4}He Production



The ^{4}He production yield is much larger than the ^{3}He production yield, **qualitatively confirming** our previous result for the system ^{7}Be + ^{58}Ni.

M. Mazzocco et al., Phys. Rev. C 92, 024615 (2015)



^{7}Li + ^{208}Pb

Theoretical calculations by A.M. Moro and J.Lei (University of Seville, Spain) [unpublished]

What is the Origin of ^{3,4}He?

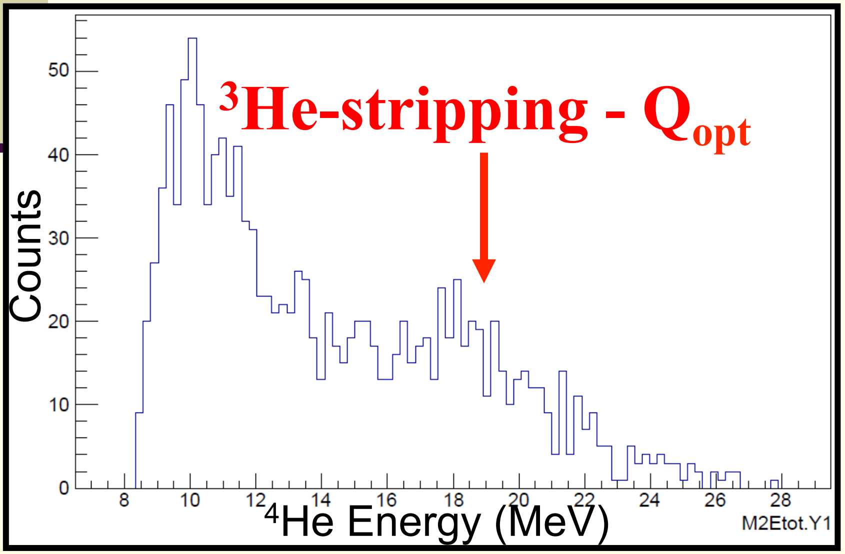
^{3}He and ^{4}He have significantly different yields, thus the **reaction dynamics** is **not dominited** by the **breakup** process.

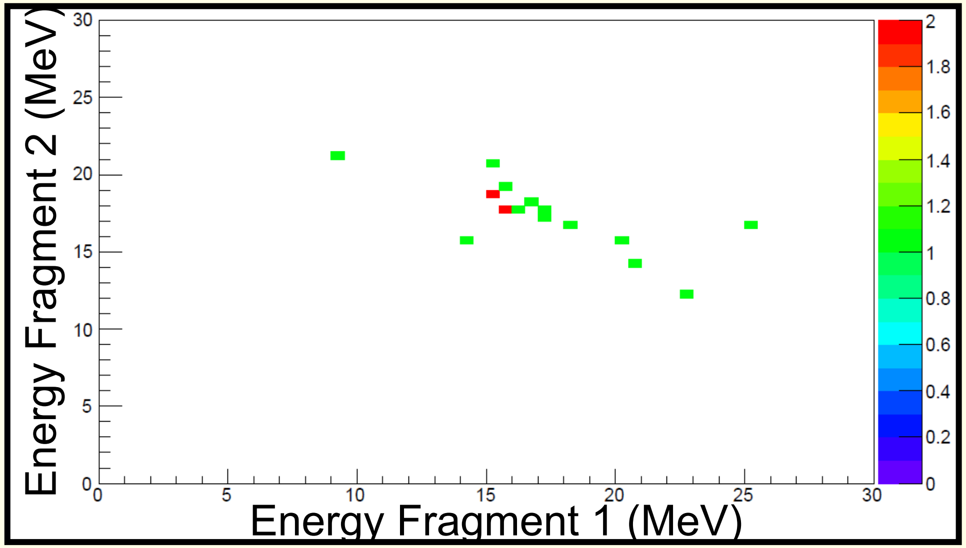
^{3}He (97.5%) and ^{4}He (99.5%) mostly come as **single events**, however we detected a **few coincidences**:

19 ^{3}He+^{4}He (Exclusive Breakup)

15 ^{4}He+^{4}He (n-pickup)

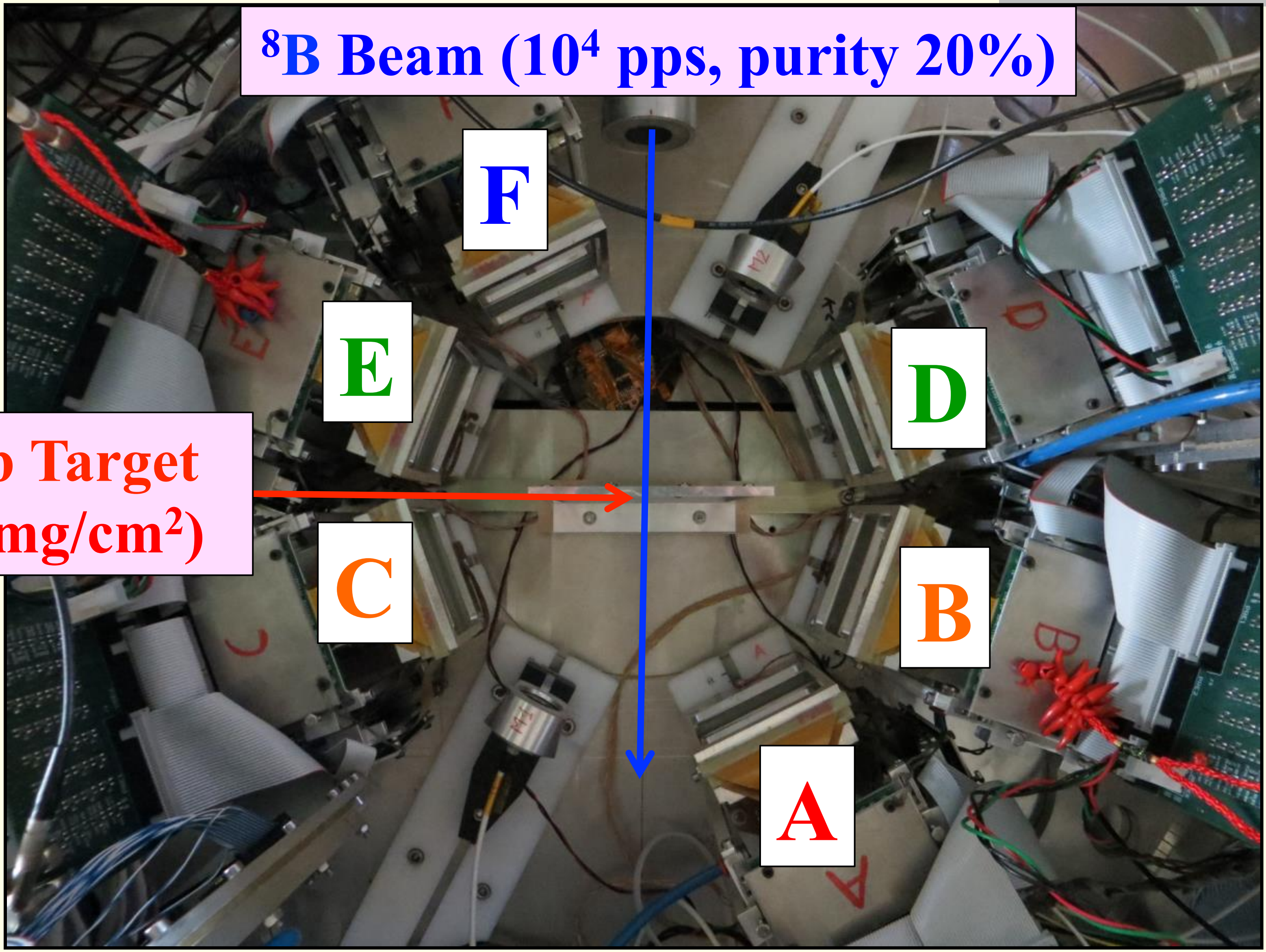
17 ^{4}He+p (open question? Evaporation?)



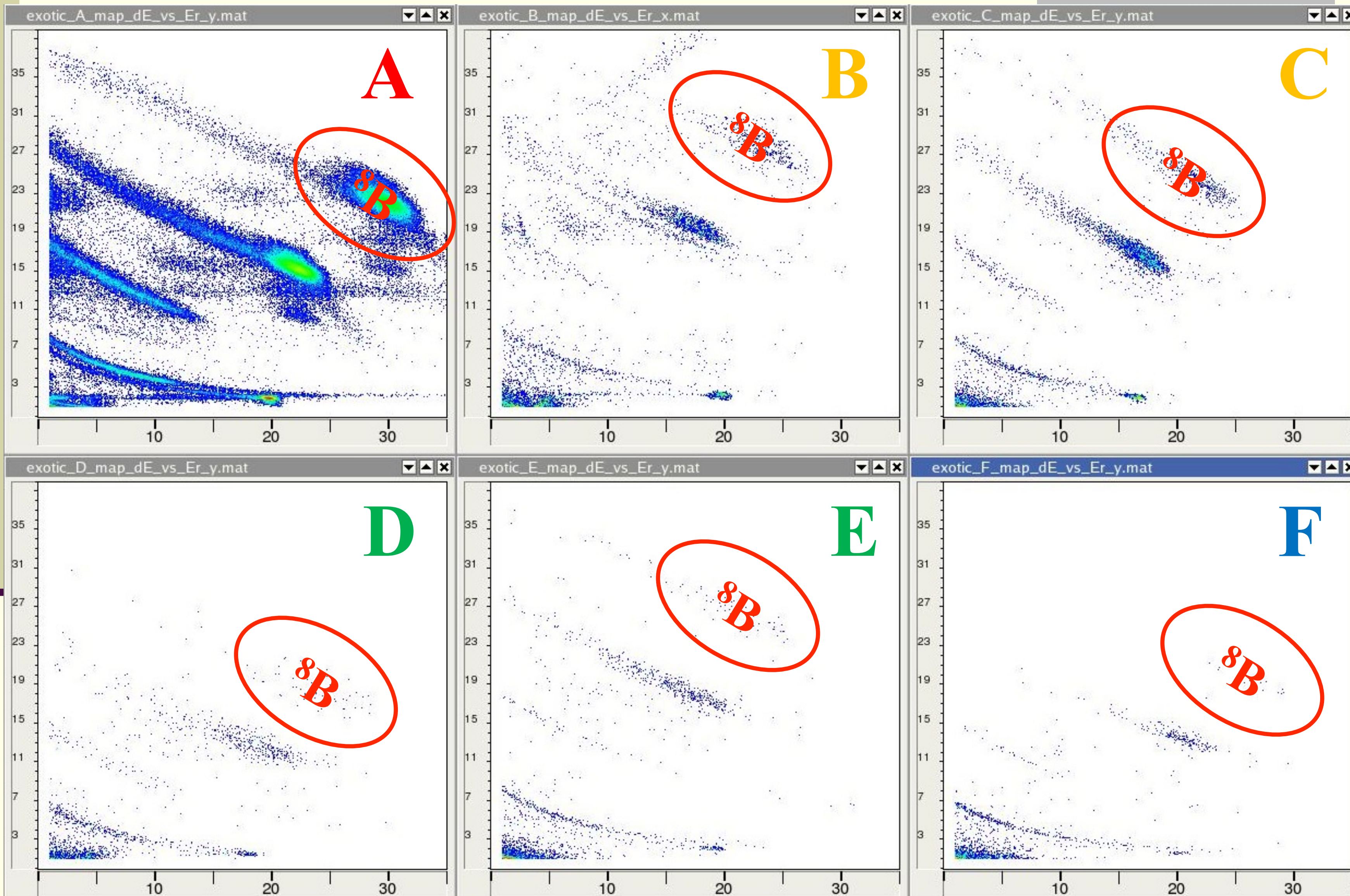


IV. ^{8}B + ^{208}Pb @ CRIB

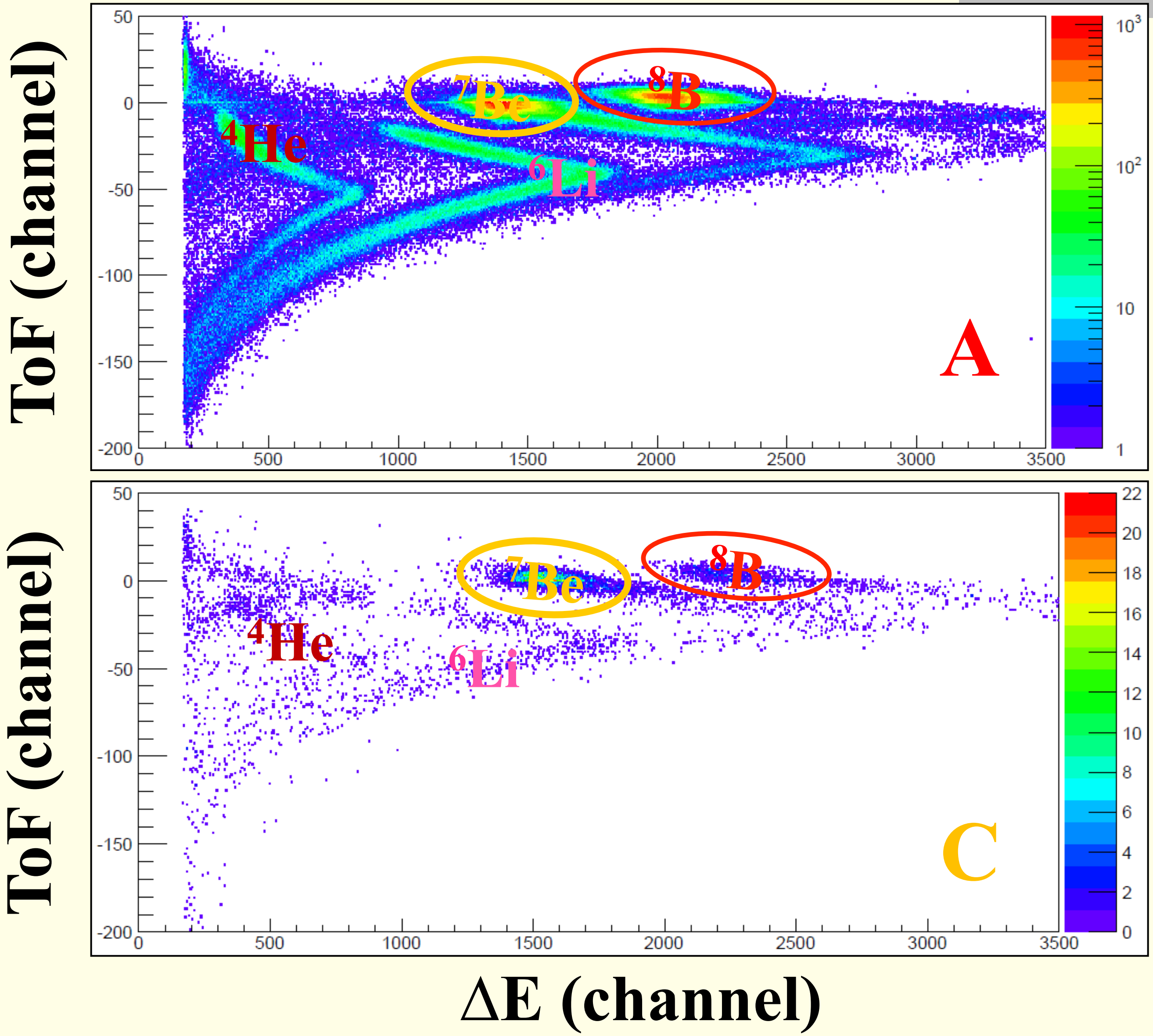
$^{8}B+^{208}Pb$ at 50 MeV



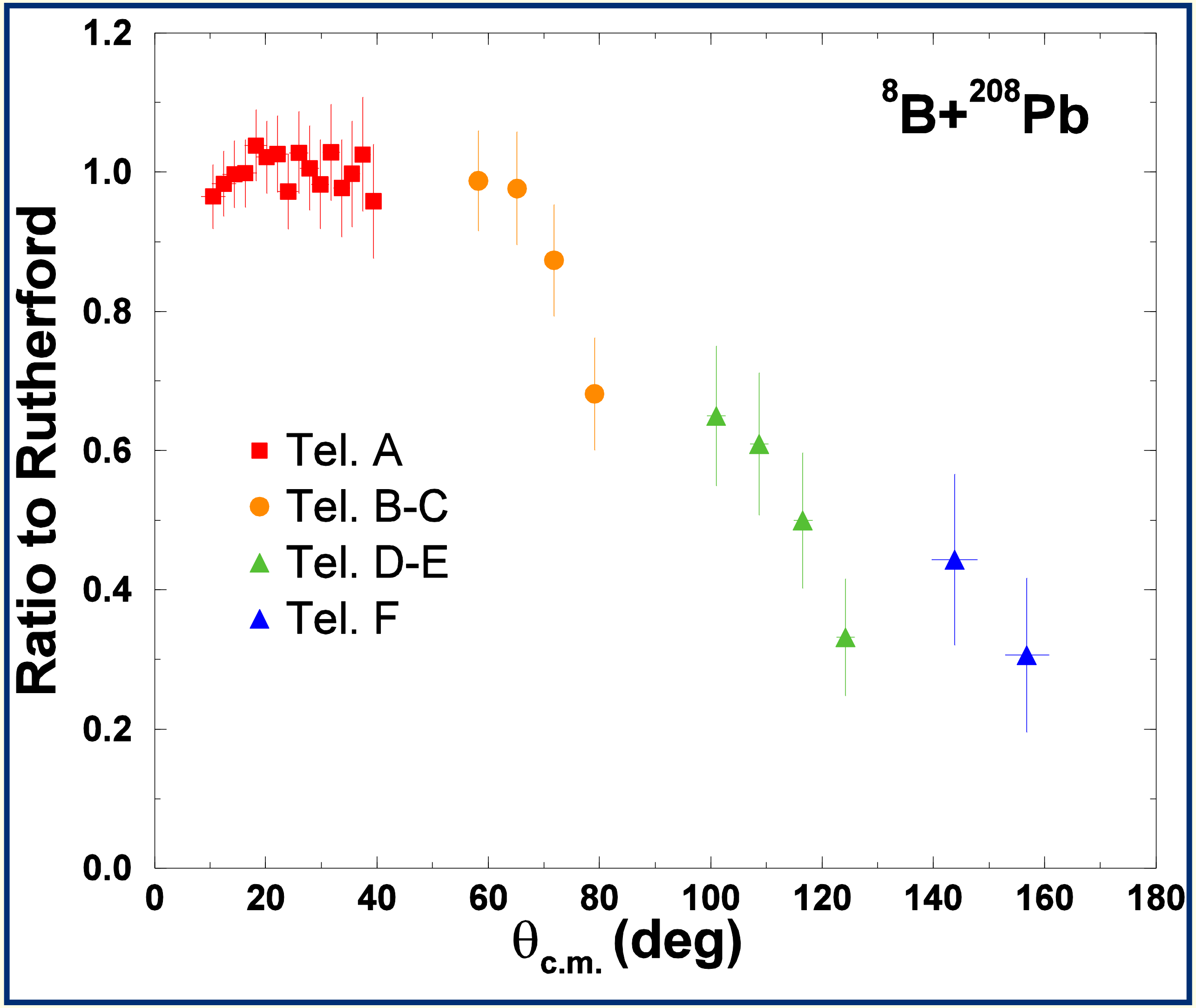
ΔE-E_{res} Plots



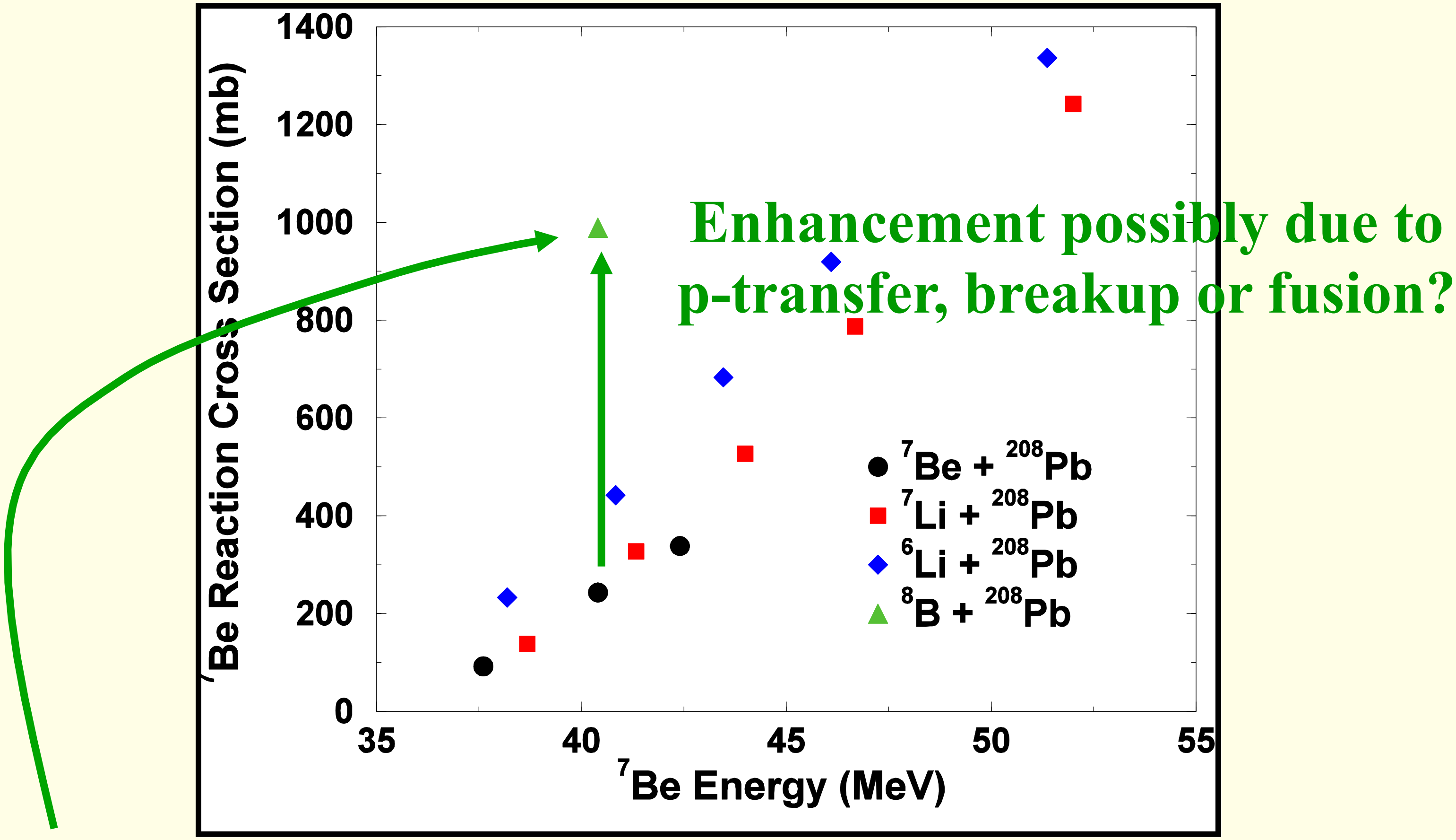
ΔE-ToF Plots



$^{8}B + ^{208}Pb$ Elastic Scattering



Reaction Cross Section



Very preliminary optical-model best-fit analysis of the **^{8}B+^{208}Pb** elastic scattering angular distribution would suggest a **total reaction cross section a factor of 3 larger** than for the reaction ^{7}Be+^{208}Pb.

V. Summary

- The study of the **reaction dynamics** induced by light weakly-bound Radioactive Ion Beams (**RIBs**) at near-barrier energies is currently a very **active research field** in Nuclear Physics.
- Our facility, **EXOTIC**, is **fully operational** at **INFN-LNL** and 7 light RIBs for reaction dynamics studies have been delivered.
- **Very promising results** have been obtained for the system **^{7}Be +^{208}Pb**: elastic scattering and ^{3,4}He production yields.
- **^{4}He** ions were found to be much **more abundant** than **^{3}He** and we detected a few **^{3}He+^{4}He** (exclusive breakup), **^{4}He+^{4}He** (n-pickup) and **^{4}He+p coincidence events**.
- The **elastic scattering** for the system **^{8}B+^{208}Pb** was measured at **CRIB (Japan)**. The **total reaction cross section** is enhanced by a **factor of 3** with respect to the reaction **^{7}Be+^{208}Pb**.

Honestly speaking, I hope we will be able to answer at least one of the open questions by the **FUSION17 Conference (in 5 months)** ☺

EXOTIC Collaboration… & Collaborators

Napoli: A. Boiano, M. La Commara, G. La Rana, D. Pierroutsakou, C. Parascandolo

Padova: M.M., C. Signorini, F. Soramel, E. Strano

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

Milano (Italy): C. Boiano, A.Guglielmetti

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

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

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

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

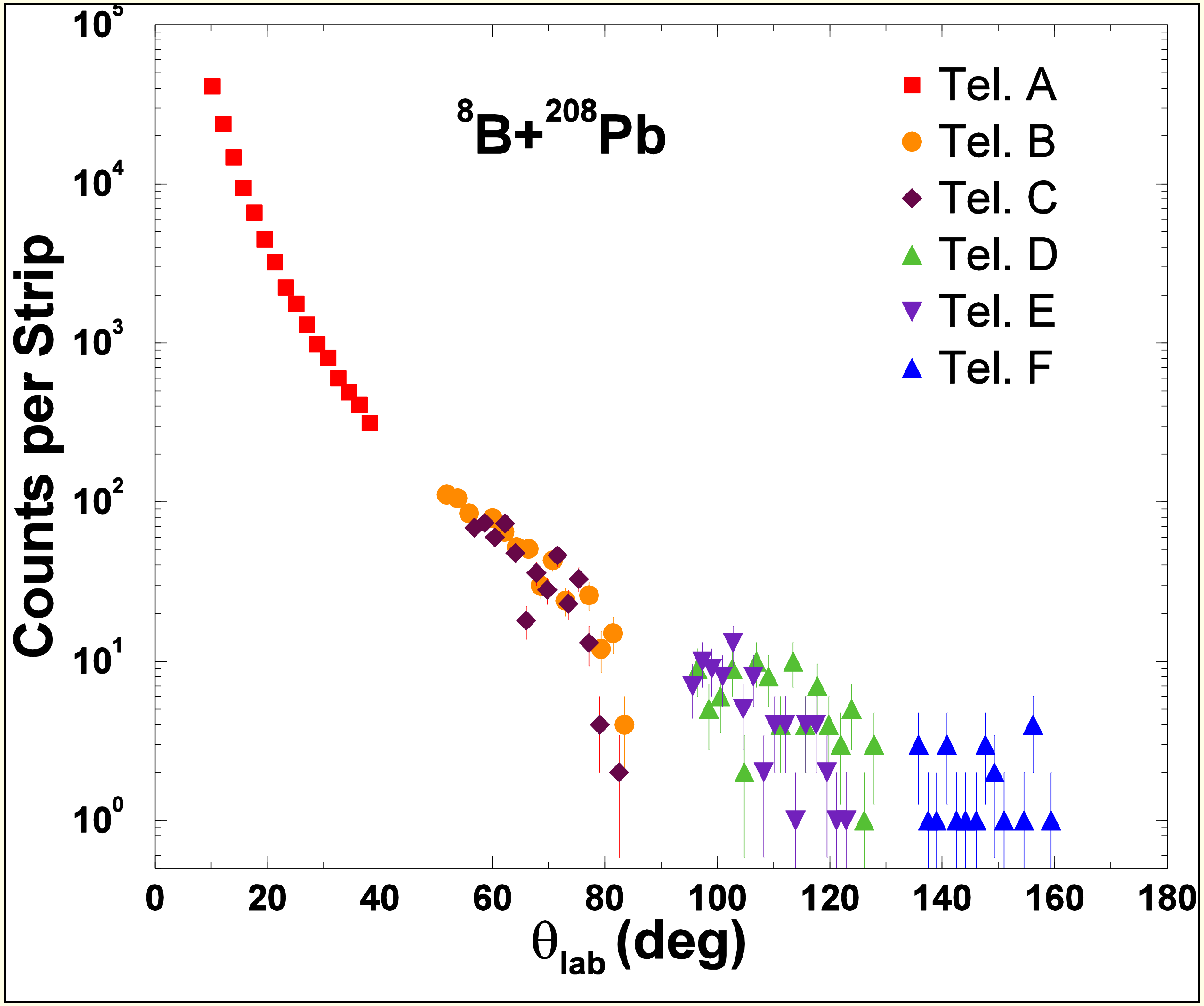
Huelva (Spain): I.Martel, L.Acosta, G.Marquinez-Duran, A.M.Sanchez-Benitez, H.Silva

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

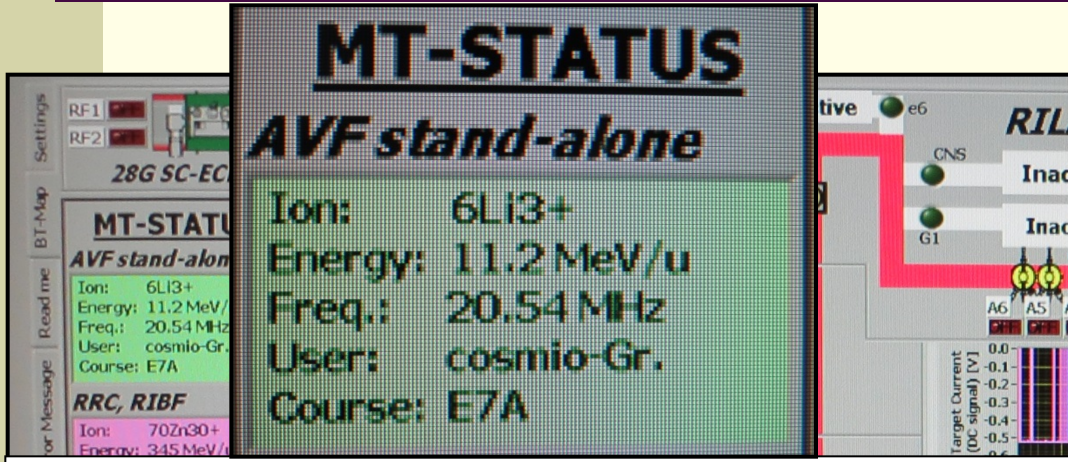
Thank You Very Much!!!

Backup

$^{8}B + ^{208}Pb$ Counting Statistics



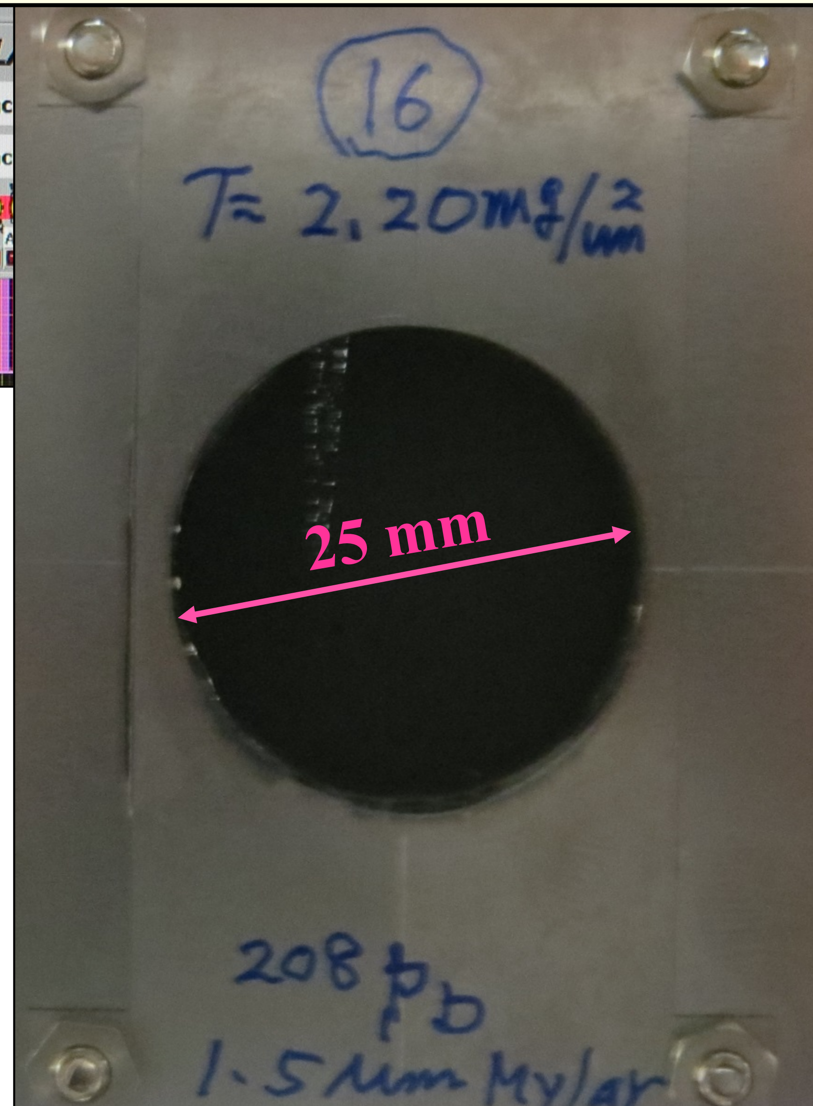
^{8}B Production at CRIB



^{6}Li Primary Beam: 3 eμA on target
Production Target: ^{3}He gas at 90 K and 1 bar

^{8}B Secondary Beam:
Energy: 50.0 ± 1.0 MeV (on target)
Intensity (on target): 10^{4} pps
Purity: 20 % (main contaminant: ^{7}Be and ^{3}He)

Reaction Target: 2.2 mg/cm^{2} **^{208}Pb**
evaporated on 1.5 μm of Mylar.
Diameter: 25 mm

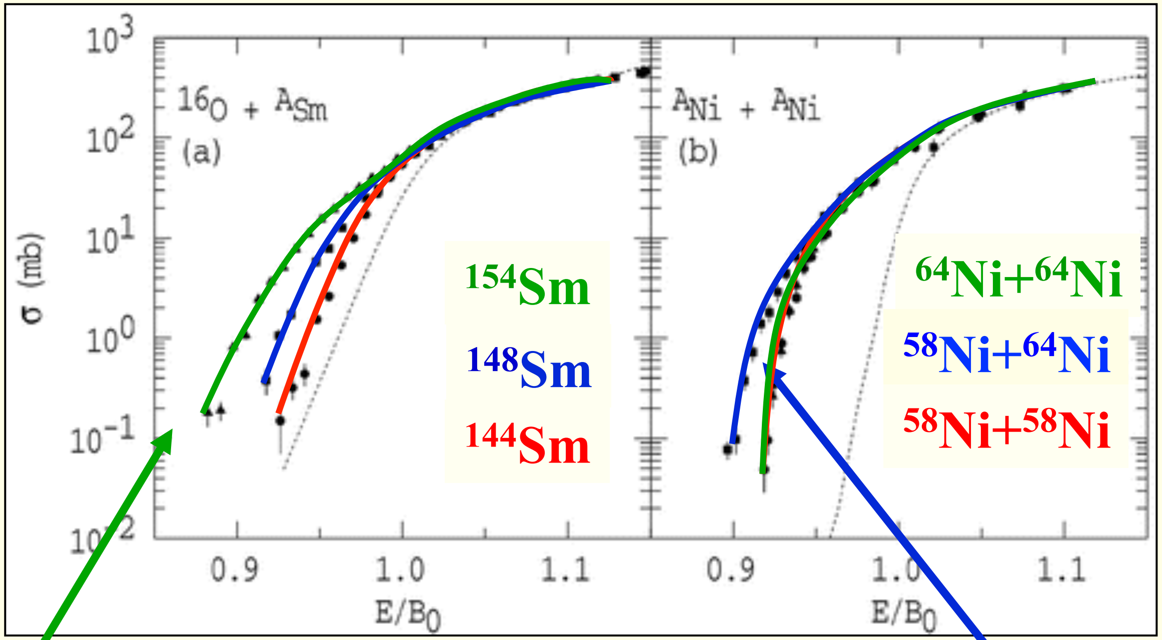


^{6,7}Li-^{7}Be Comparison

	^{6}Li+^{208}Pb	^{7}Li+^{208}Pb	^{7}Be+^{208}Pb
Breakup Thr.	**-1.475**	**-2.468**	**-1.586**
n-pickup	^{7}Li: -0.12	^{8}Li: -5.34	**^{8}Be: +11.53**
2n-pickup	^{8}Li: -4.82	^{9}Li: -8.01	**^{9}Be: +6.46**
p-pickup	^{7}Be: -2.40	**^{8}Be: +9.25**	^{8}B: -7.87
p-stripping	^{5}Li: -0.63	^{6}Li: -3.31	^{6}Be: -6.74
d-stripping	**^{4}He: +4.71**	^{5}He: -3.28	^{5}Li: -2.87
d-pickup	**^{8}Be: +9.65**	**^{9}Be: +4.06**	**^{9}B: +3.86**
^{4}He-stripping	^{2}H: -10.43	^{3}H: -11.42	^{3}He: -10.54
t-stripping	^{3}He: -10.73	**^{4}He: +2.59**	^{4}Li: -19.44
^{3}He-strripping	^{3}H: -10.18	^{4}H: -19.03	**^{4}He: +4.03**

Stable Projectiles - Fusion

In the Eighties a **significant enhancement** of the **fusion** cross section was observed at energies below the **Coulomb barrier.**



Static Effect (Target Deformation)

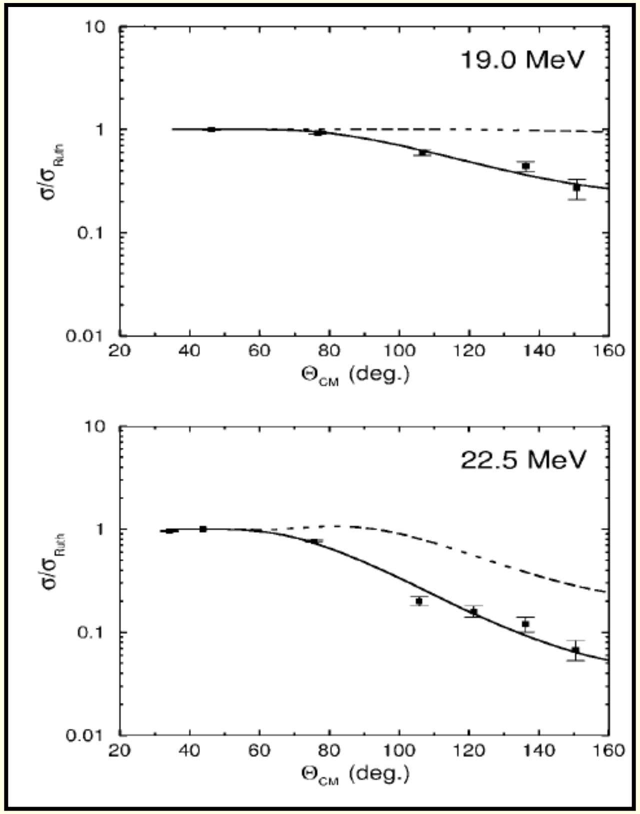
Dynamic Effect (Positive Q-value Transfer Channels)

Static and dynamic effects enhance the fusion probability.

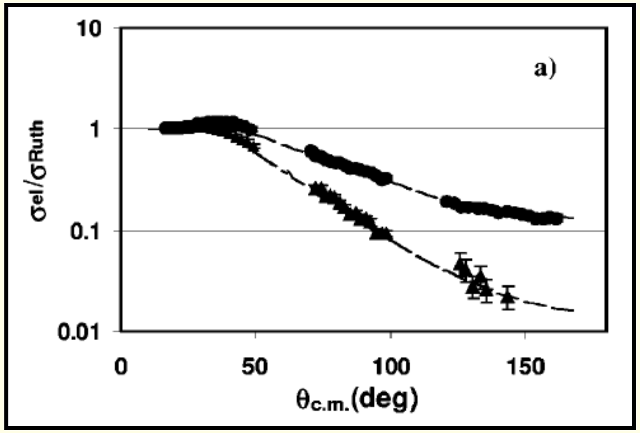
What will happen with weakly-bound/halo/neutron-skin RIBs?

Reaction Cross Section Enhancement

Breakup related effects turned out to increase the **total reaction cross section** rather than the fusion probability.



$^{4,6}He+^{209}Bi$: E.F. Aguilera et al., Phys. Rev. Lett. 84 (2000) 5058

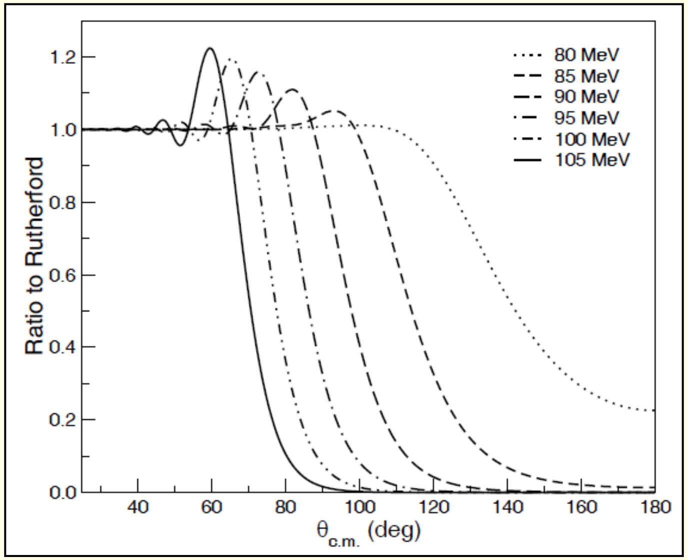


$^{4,6}He+^{64}Zn$: A. Di Pietro et al., Phys. Rev. C. 69 (2004) 044613

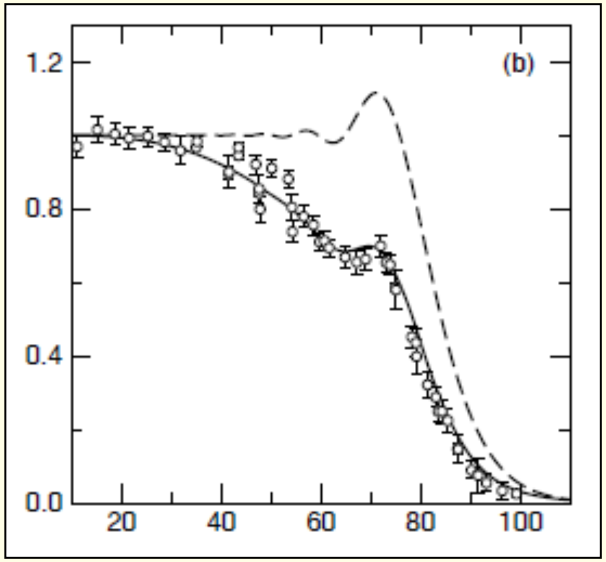
The quest has now moved towards understanding what **reaction mechanisms** are mainly responsibile for the **total reaction cross section enhancement**.

Stable Projectiles - Scattering

Elastic scattering differential cross sections at near-barrier energies usually develop a peak due to the **Nuclear-Coulomb interference**.



$^{16}O+^{208}Pb$:
No Strong Coupling Effects



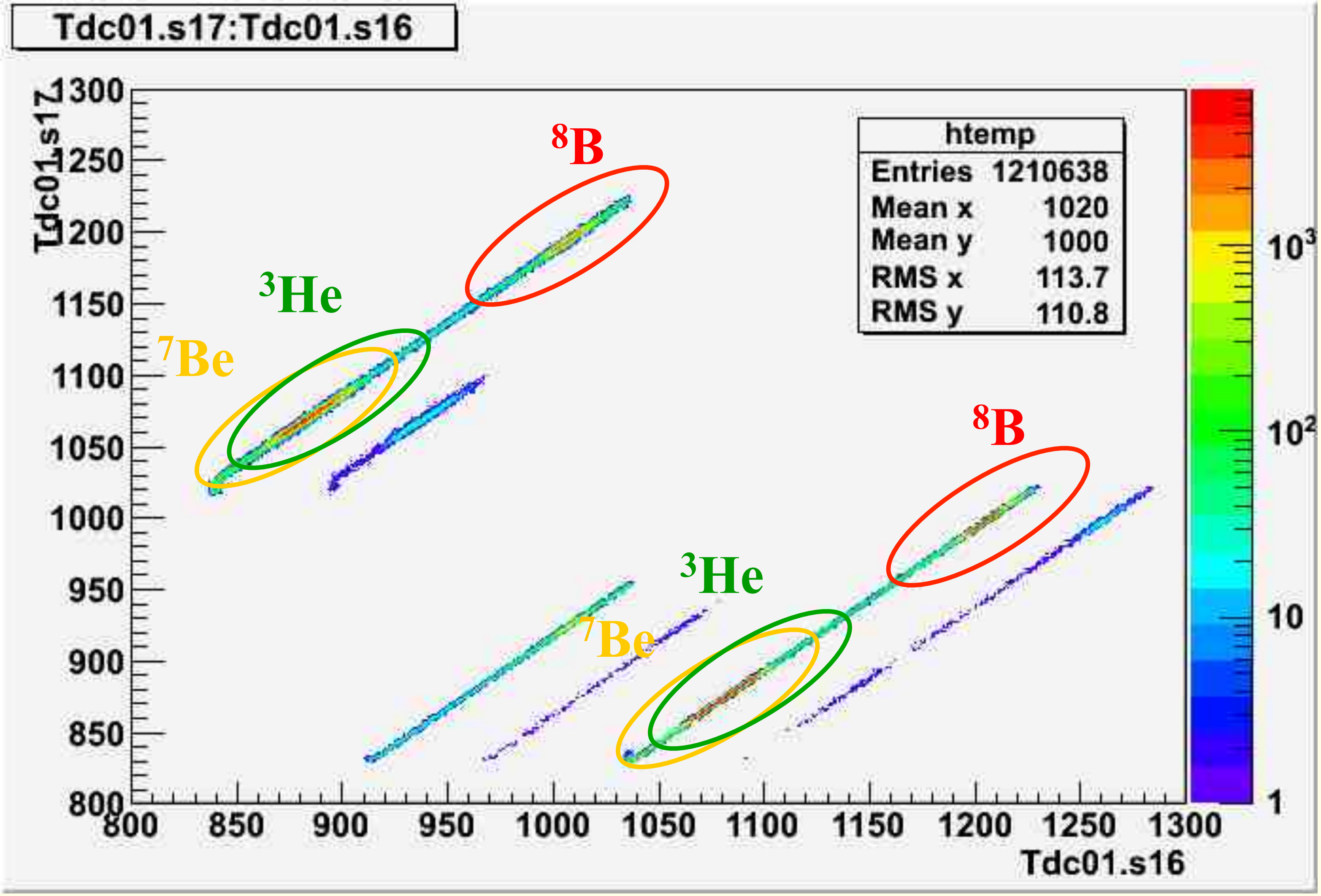
$^{18}O+^{184}W$: Strong Coupling Effects to Target Excitations

Strong Coupling Effects may suppress the “Fresnel” peak.

N. Keeley, K.W. Kemper and K. Rusek, Eur. Phys. J. A 50 (2014) 145.

What has been observed so far with weakly-bound RIBs?

Sorting the Data: Time Signal



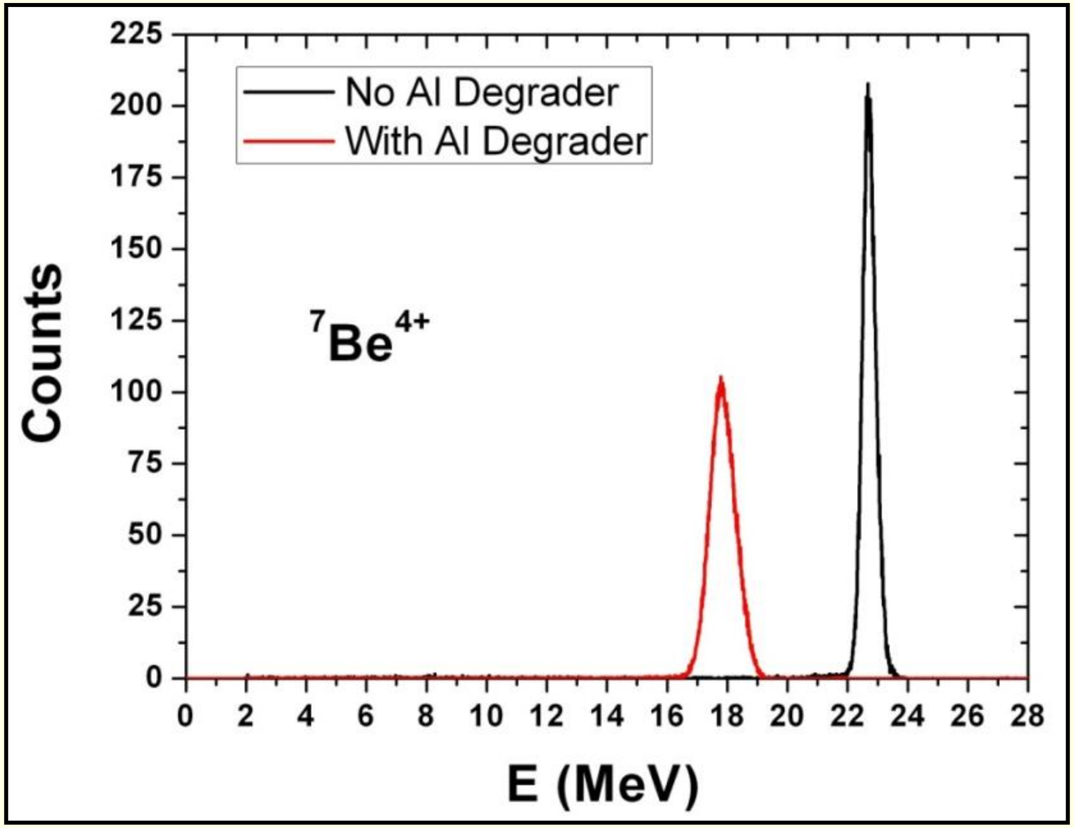
^{7}Be (S_α = 1.586 MeV)

^{7}Be: weakly-bound
^{3}He-^{4}He cluster structure
^{8}B core

^{7}Li Primary Beam
Energy: 34.2 MeV
Intensity: 100 pnA

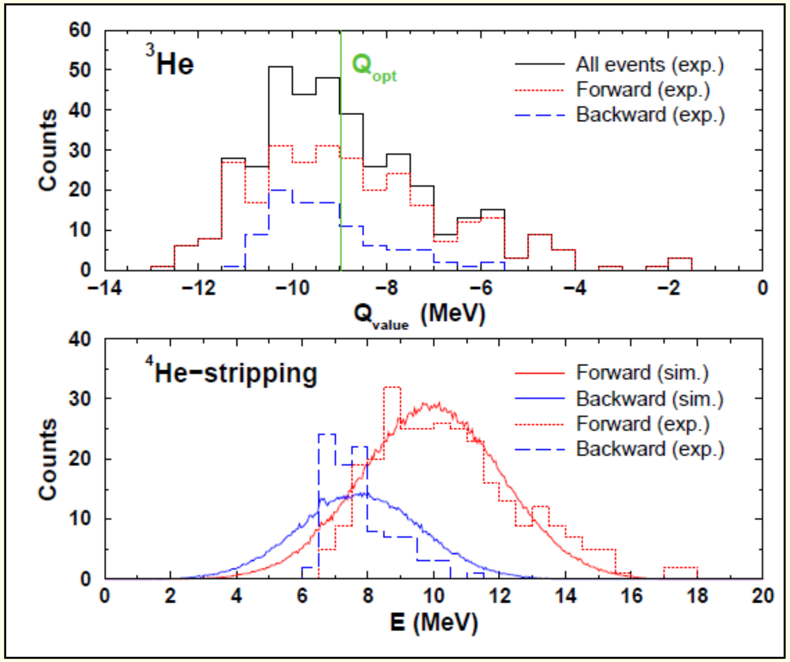
$^1H_2$ Gas Target
Pressure: 1 bar
Temperature: 90 K

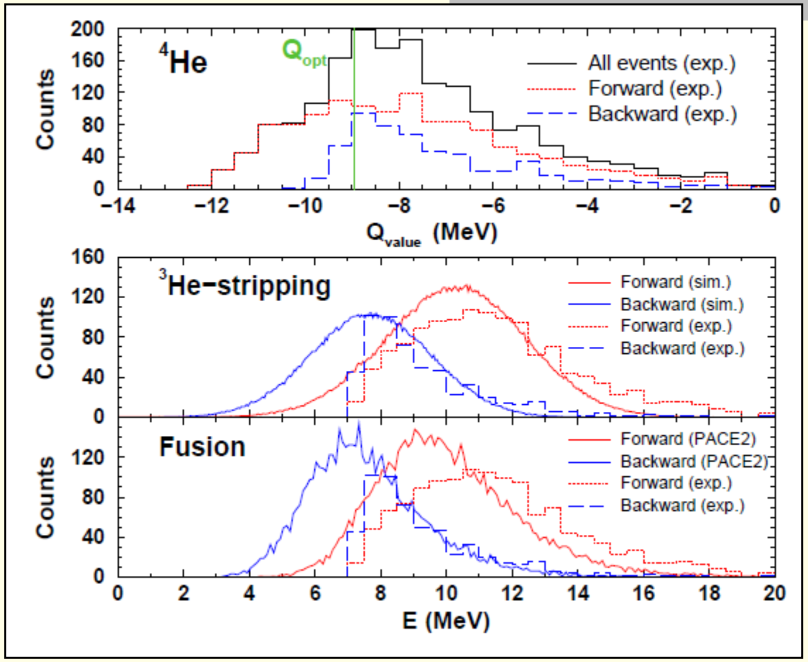
^{7}Be Secondary Beam
E_{lab}: (22.0 ± 0.4) MeV
Intensity: $2.5*10^5$ pps
Purity: > 99 %



^{58}Ni Target:1 mg/cm^2

^{3,4}He Single Detection





$$Q_{value} = E_{He} + E_{recoil} - E_{beam}$$

^{3}He reconstructed Q_{value} spectra compatible (within 0.5 MeV) with the **Q_{opt}** for the **^{4}He-stripping** process. (Q_{opt} ~ - 9 MeV)

D.M. Brink, Phys. Lett. B 40, 37 (1972)

^{3}He-stripping and **Fusion-Evaporation** foresee very similar **^{4}He energy** distributions. At **backward angles** we have an excellent agreement with the predictions of **PACE2**

A. Gavron, Phys. Rev. C 21, 230 (1980)

What's the ^{3}He/^{4}He origin?

^{3}He

1. **Exclusive Breakup:**
   ^{7}Be → ^{3}He + ^{4}He;

These processes require a **coincidence event** in the reaction exit channel:
NO COINCIDENCE DETECTED
(only upper limits can be provided)

^{4}He

1. **Exclusive Breakup**
   ^{7}Be → ^{3}He + ^{4}He;
2. **n-Stripping:**
   → ^{6}Be (= ^{4}He+2p) + ^{59}Ni
   (Q_{gg} = – 1.68 MeV);
3. **n-Pickup:** →
   ^{8}Be (= 2^{4}He) + ^{57}Ni (Q_{gg} =
   + 6.68 MeV);

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2. **^{4}He-Stripping:**
   ^{7}Be + ^{58}Ni → ^{3}He + ^{62}Zn
   (Q_{gg} = +1.78 MeV).

Single detection of ^{3}He and ^{4}He:
AS EXPERIMENTALLY OBSERVED

4. **^{3}He-Stripping:** ^{7}Be
   + ^{58}Ni → ^{4}He + ^{61}Zn
   (Q_{gg} = + 9.46 MeV);
5. ^{4}He evaporation after compound nucleus formation **(Fusion)**.

^{7}Be + ^{58}Ni: Summary

ELASTIC SCATTERING

Remarkable agreement with an earlier measurement and with DWBA calculations without free parameters.

FUSION

α-multiplicity in agreement with PACE2 predictions.

DIRECT PROCESSES

^{3}He (34.4 ± 6.3 mb)

Exclusive Breakup (10. 8 mb)

^{4}He-stripping (23.6 mb)

^{4}He (44.1 ± 9.9 mb)

Exclusive Breakup (10. 8 mb)

1n-stripping (9.8 mb)

1n-pickup (12.1 mb)

^{3}He-stripping (11.4 mb)

Remark: **Higher statistical accuracy** and **larger geometrical efficiency** for the detection of coincidences would be highly desirable.