Recent Reaction Dynamics Studies with light RIBs at Coulomb Barrier Energies

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Outline

I. Introduction

II. Recent Results

III. Facility EXOTIC at INFN-LNL

IV. Recent Results at EXOTIC

V. Summary

I. Introduction

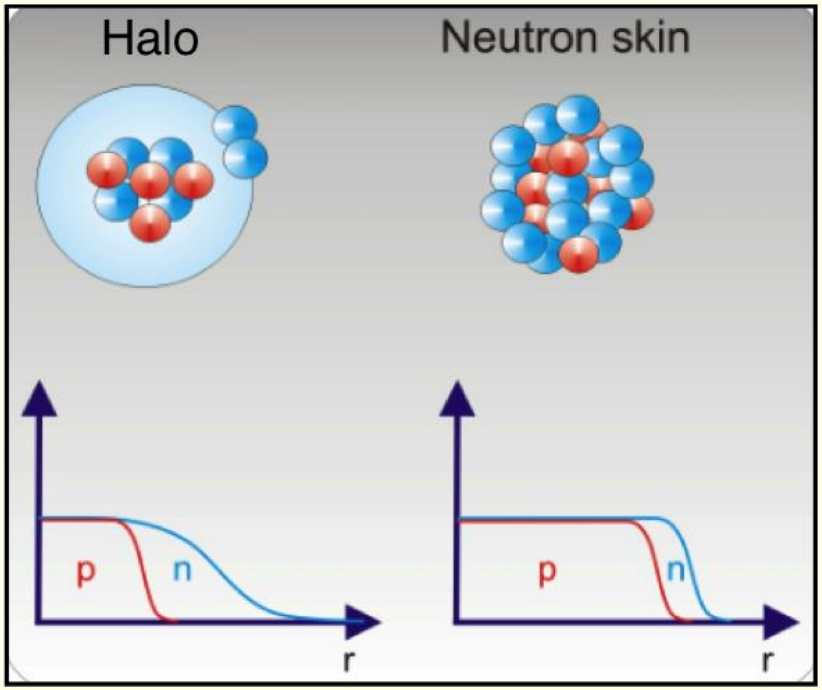
Light Exotic Nuclei

Many different features contribute to populate of **exotic nuclei** the light portion of the nuclide chart:

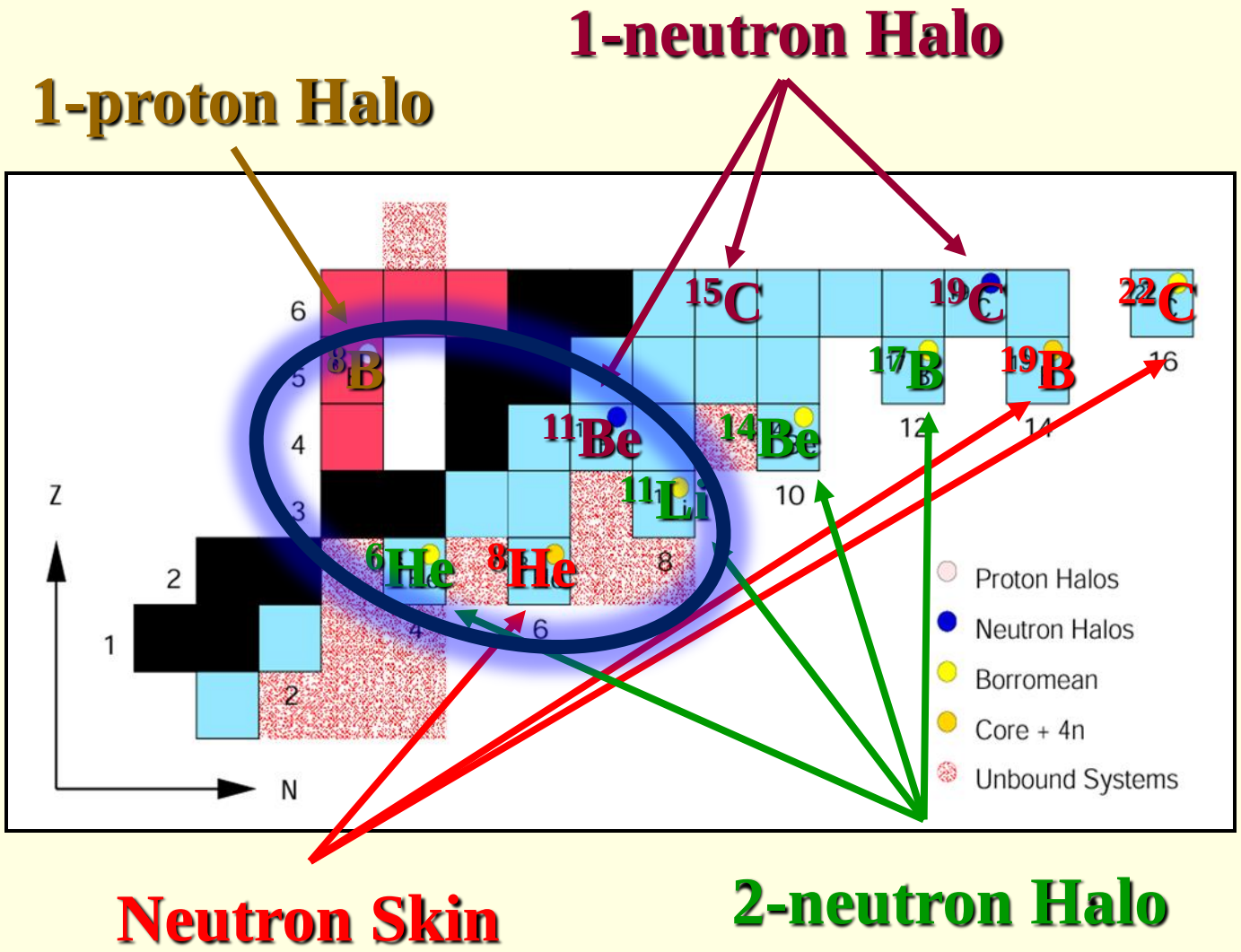
1. **Low Coulomb Barrier** (Z < 6);
2. **Low Centrifugal Barrier** (s, p orbits);
3. **Weak Binding Energy** (< 1.0 MeV).

Halo Nuclei:
rarified nuclear matter distribution surrounding a mostly inert core.

Neutron Skin Nuclei:
large neutron concentration around the nuclear surface.



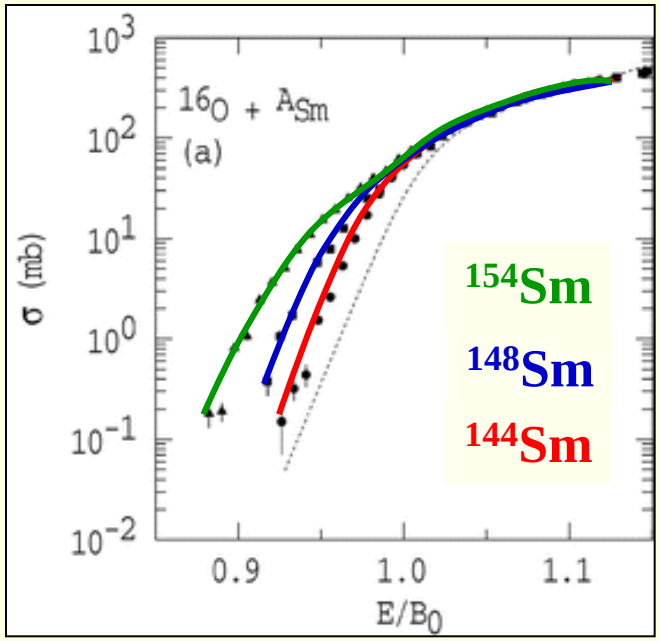
Halo and Neutron Skin Nuclei

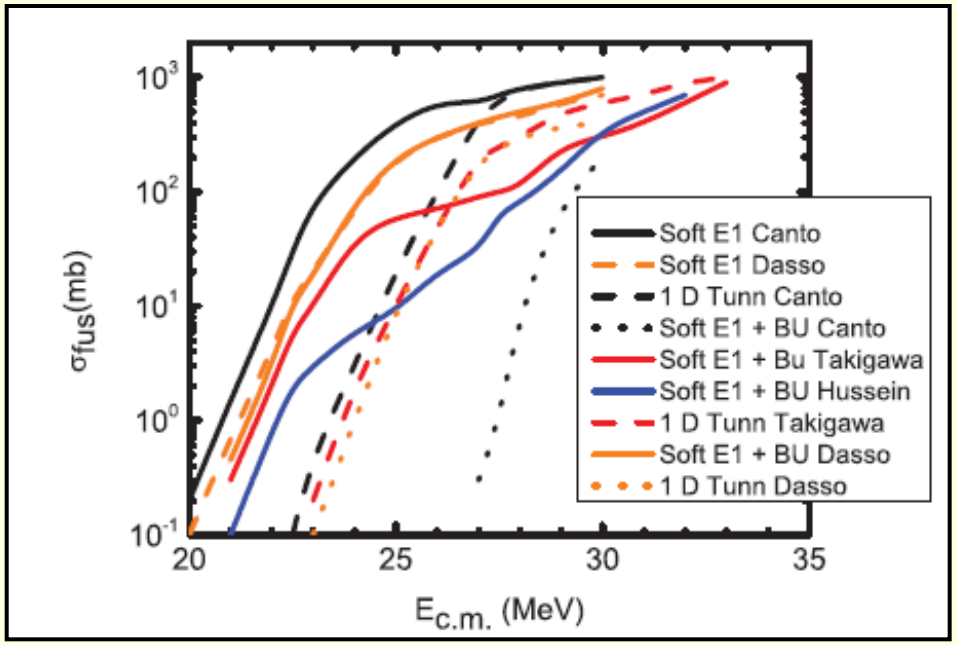


II. Recent Results

Sub-Barrier Fusion with RIBs

Static (e.g. deformation) and **dynamic (e.g. positive Q_{value} transfer channels)** effects enhance the sub-barrier fusion probability.





Predictions for the fusion cross section in the reaction **$^{11}Li + {}^{208}Pb$**.

Additional **open channels** + **extended distibution** → **Enhancement**

Weak binding energy → **Hindrance**

L.F. Canto et al, Phys. Rep. 424 (2006) 1 and B.B. Back et al., Rev. Mod. Phys. 86 (2014) 317

$^{6}He + ^{238}U$ at LLN

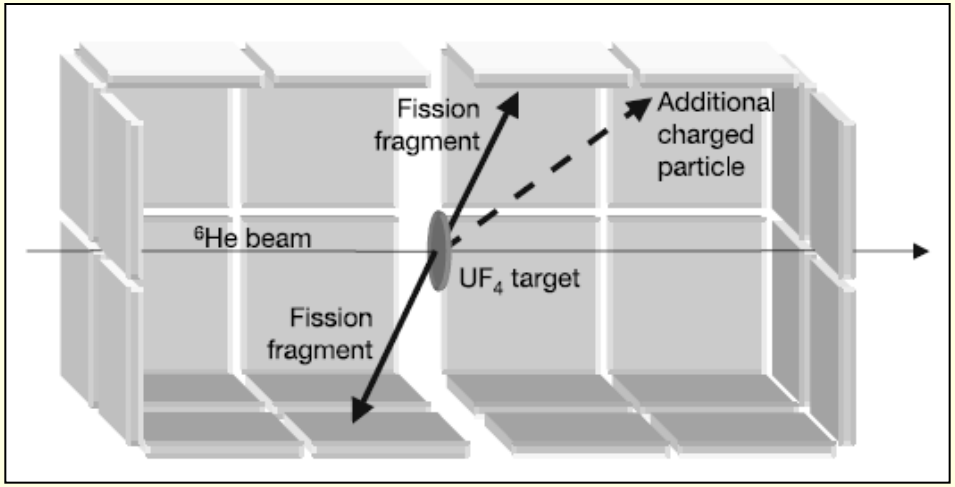
No enhancement of fusion probability by the neutron halo of ^{6}He

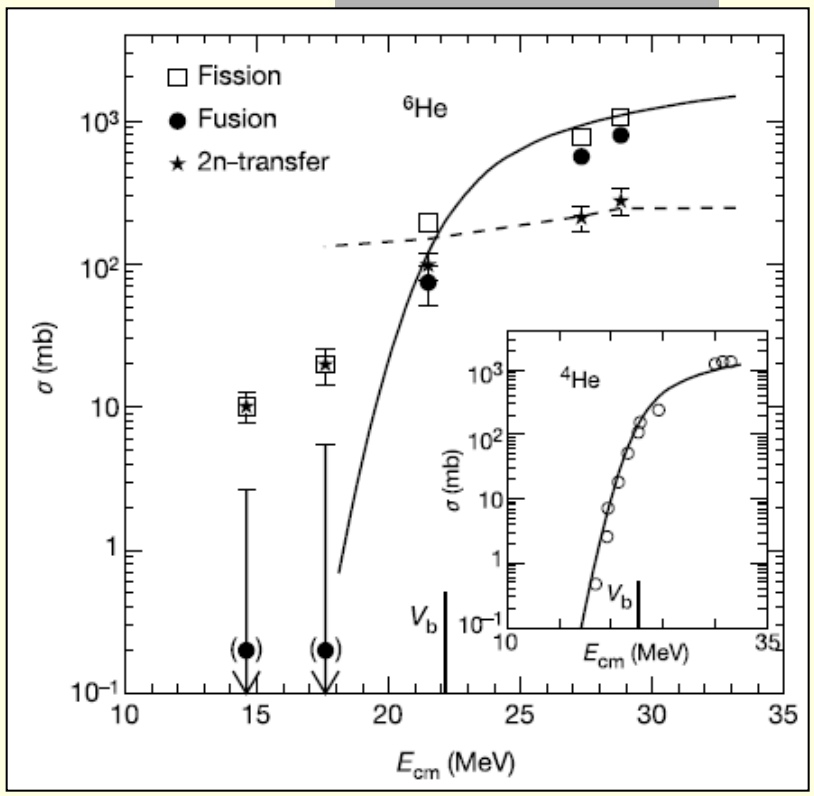
R. Raabe[1,2], J. L. Sida[1*], J. L. Charvet[1], N. Alamanos[1], C. Angulo[3], J. M. Casandjian[4], S. Courtin[5], A. Drouart[1], D. J. C. Durand[1], P. Figuera[6], A. Gillibert[1], S. Heinrich[1], C. Jouanne[1], V. Lapoux[1], A. Lepine-Szily[7], A. Musumarra[6], L. Nalpas[1], D. Pierroutsakou[8], M. Romoli[8], K. Rusek[9] & M. Trotta[8]

NATURE | VOL 431 | 14 OCTOBER 2004

Experiment performed at **LLN** (Belgium) with a **^{238}U fissile** target.

Very **high solid angle coverage**.





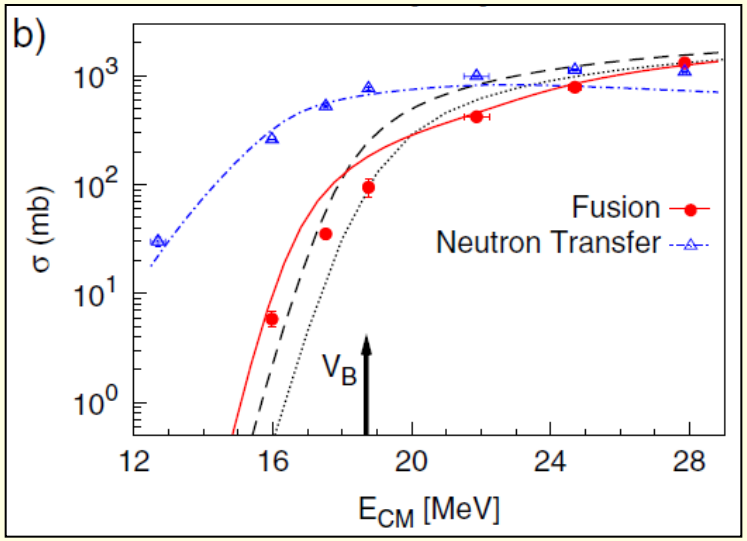
Enhancement of the **total reaction cross section** at **sub-barrier energies** due to the **2-neutron transfer**.

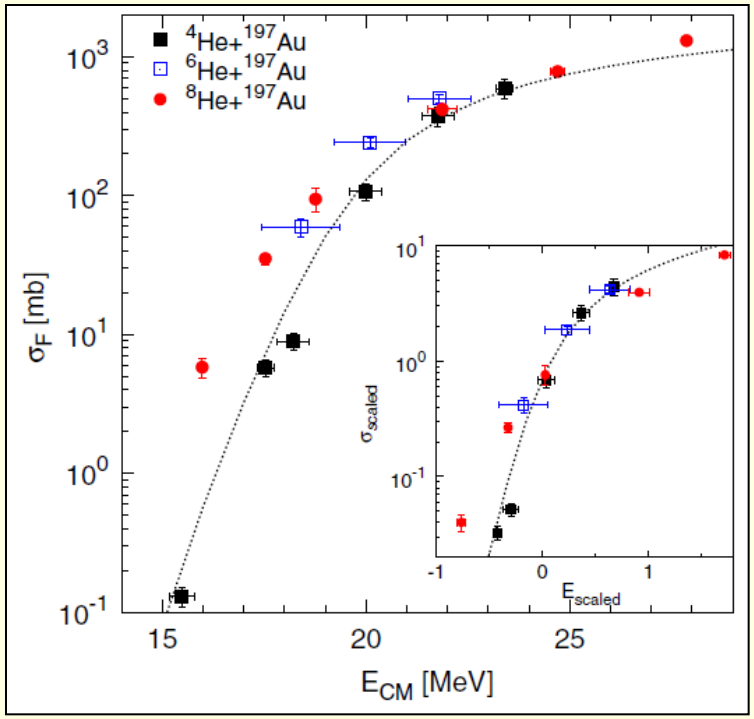
^{8}He + ^{197}Au at GANIL

Selected for a Viewpoint in *Physics*
PRL **103,** 232701 (2009) PHYSICAL REVIEW LETTERS week ending 4 DECEMBER 2009

Modern Rutherford Experiment: Tunneling of the Most Neutron-Rich Nucleus

A. Lemasson,[1] A. Shrivastava,[1,2] A. Navin,[1,*] M. Rejmund,[1] N. Keeley,[3] V. Zelevinsky,[4] S. Bhattacharyya,[5] A. Chatterjee,[2] G. de France,[1] B. Jacquot,[1] V. Nanal,[6] R. G. Pillay,[6] R. Raabe,[1] and C. Schmitt[1]

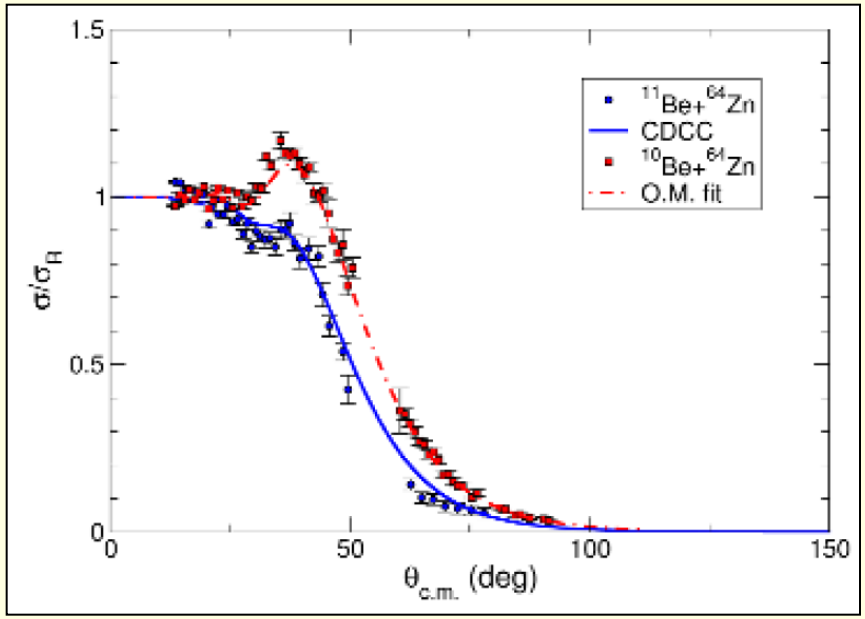




^{8}He+^{197}Au: Large dominance of **neutron transfer** channels.

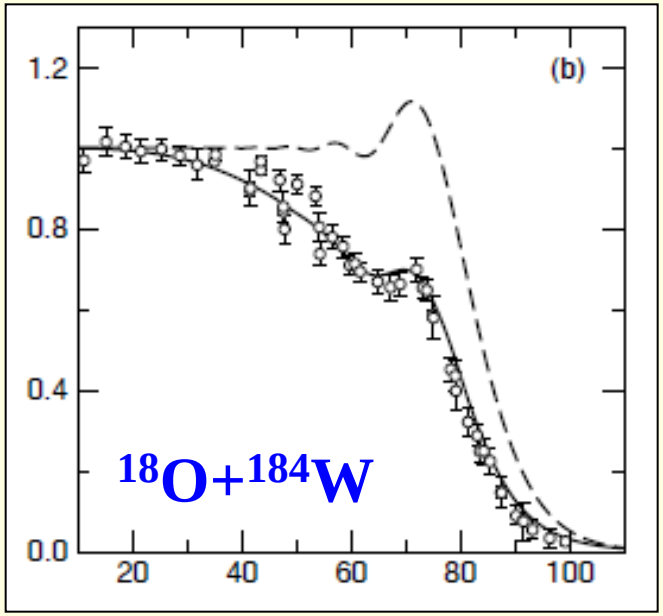
^{8}He+^{197}Au: **very moderate** (deep) **sub-barrier fusion enhancement**.

^{11}Be + ^{64}Zn at REX-ISOLDE



Factor 2 enhancement for the **^{11}Be total reaction cross section** with respect to ^{10}Be and **suppression of the Coulomb nuclear interference peak**.

A. Di Pietro et al., Phys. Rev. Lett. 105 (2010) 022701



The suppression of the so called **"Fresnel" peak** is a clear signature of **Strong Coupling Effects**.

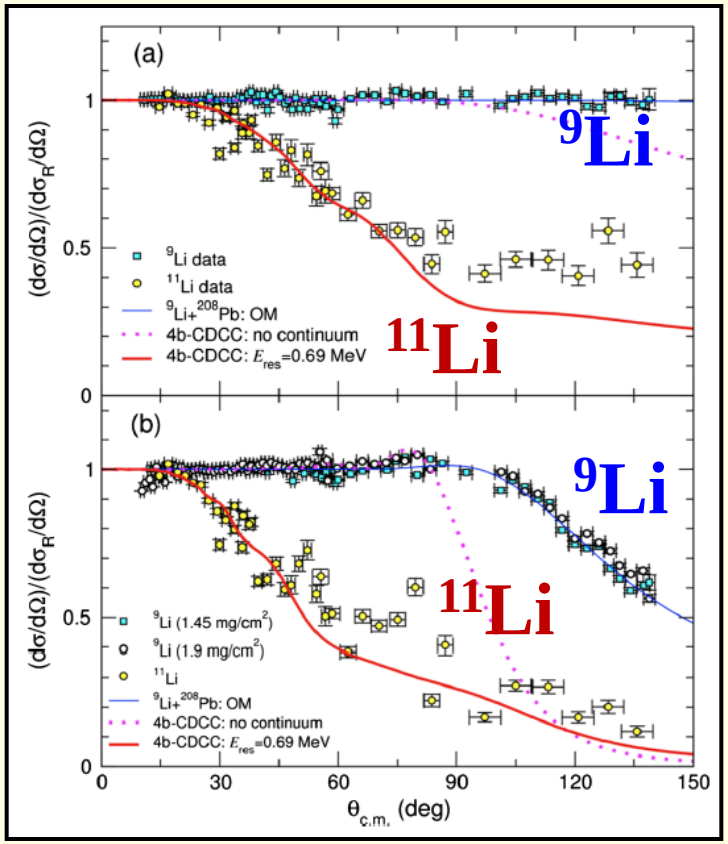
N. Keeley, K.W. Kemper and K. Rusek, Eur. Phys. J. A 50 (2014) 145.

^{11}Li + ^{208}Pb at TRIUMF

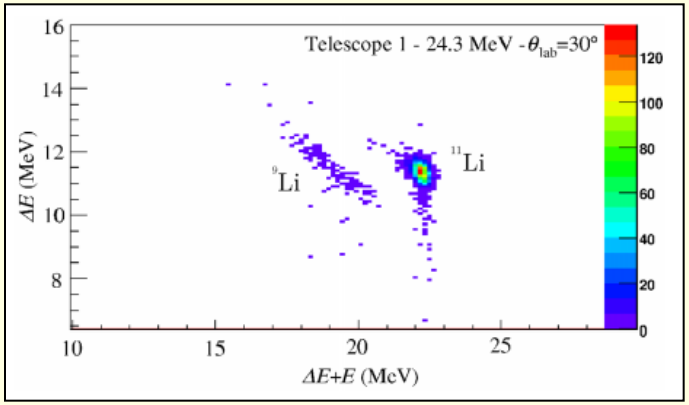
PRL **109**, 262701 (2012) PHYSICAL REVIEW LETTERS week ending 28 DECEMBER 2012

Do Halo Nuclei Follow Rutherford Elastic Scattering at Energies Below the Barrier? The Case of ^{11}Li

M. Cubero,[1,2] J. P. Fernández-García,[3,4] M. Rodríguez-Gallardo,[3] L. Acosta,[5] M. Alcorta,[1] M. A. G. Alvarez,[3,4] M. J. G. Borge,[6,*] L. Buchmann,[7] C. A. Diget,[8] H. Al Falou,[9] B. R. Fulton,[8] H. O. U. Fynbo,[10] D. Galaviz,[11] J. Gómez-Camacho,[3,4] R. Kanungo,[9] J. A. Lay,[3] M. Madurga,[6] I. Martel,[5] A. M. Moro,[3] I. Mukha,[4] T. Nilsson,[12] A. M. Sánchez-Benítez,[5] A. Shotter,[7,13] O. Tengblad,[6] and P. Walden[7]



Elastic scattering differential cross section very sensisitive to the **strenght** of **E1 transitons** just above the **breakup threshold**.



^{11}Li Breakup: J.P. Fernandez-Garcia et al., Phys. Rev. Lett. 110, 142701 (2013)

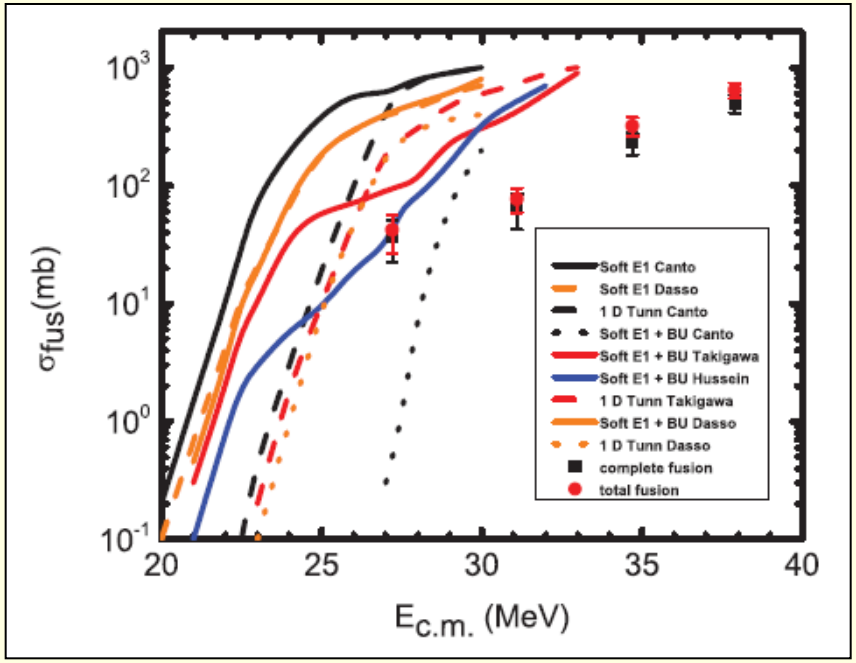
^{11}Li + ^{208}Pb: Fusion

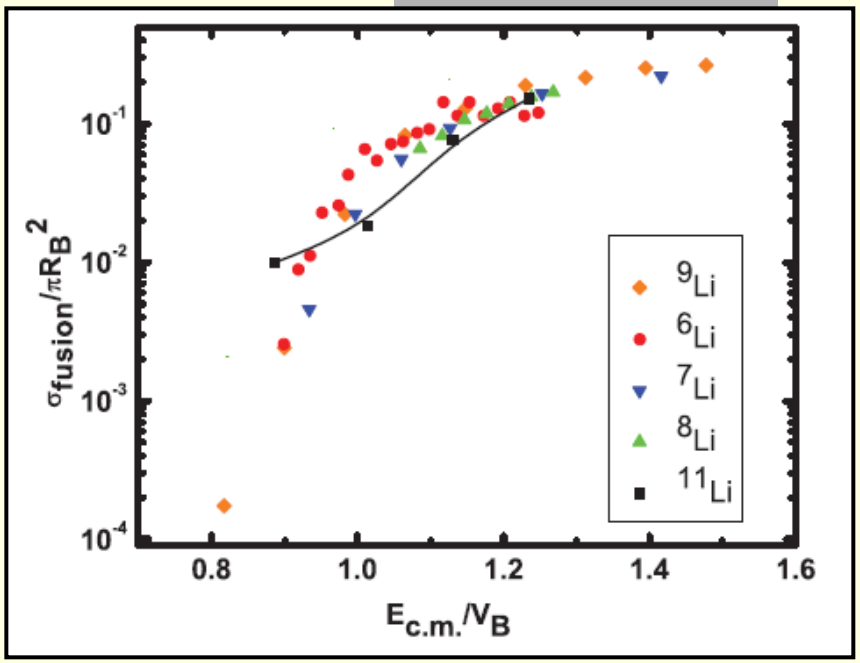
First fusion measurement performed at **TRIUMF (Canada)**

^{11}Li intensity: 1.25 kHz, 34 h

Stack of 4 targets.

A.M. Vinodkumar et al., PRC 87, 044603 (2013)

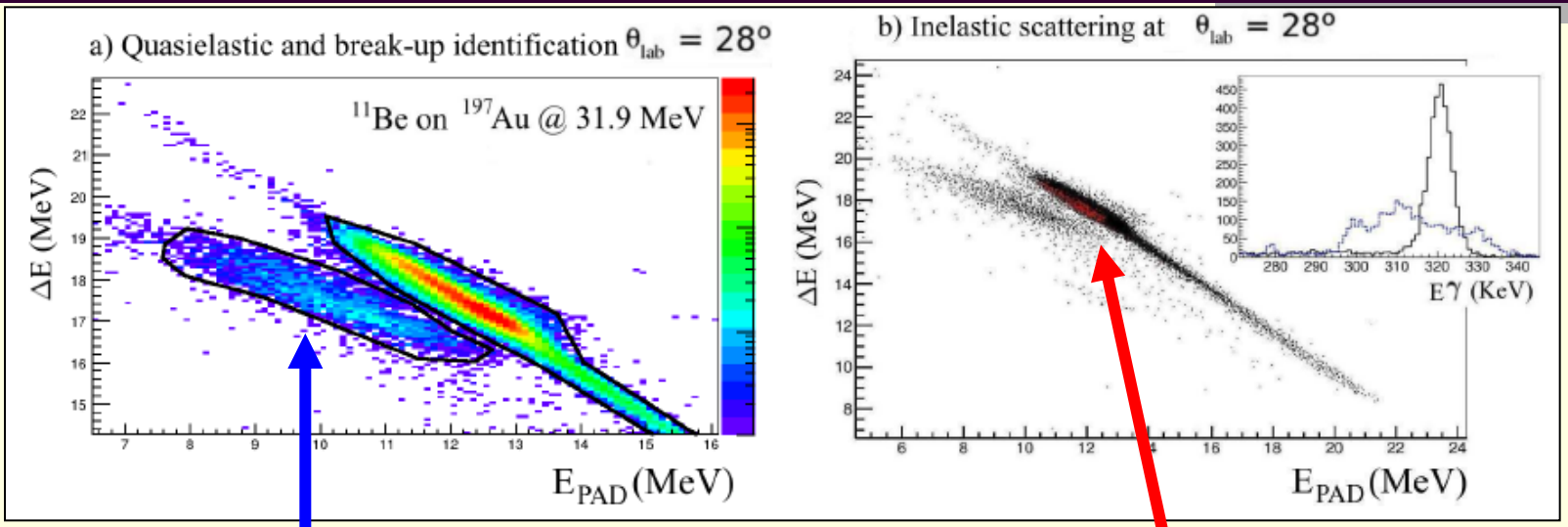


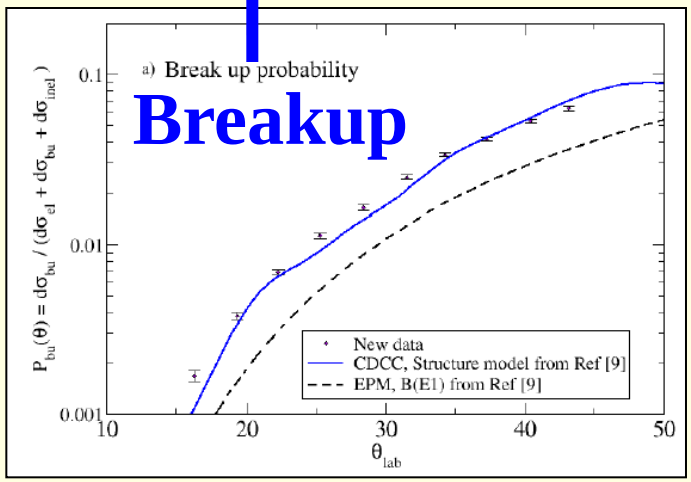


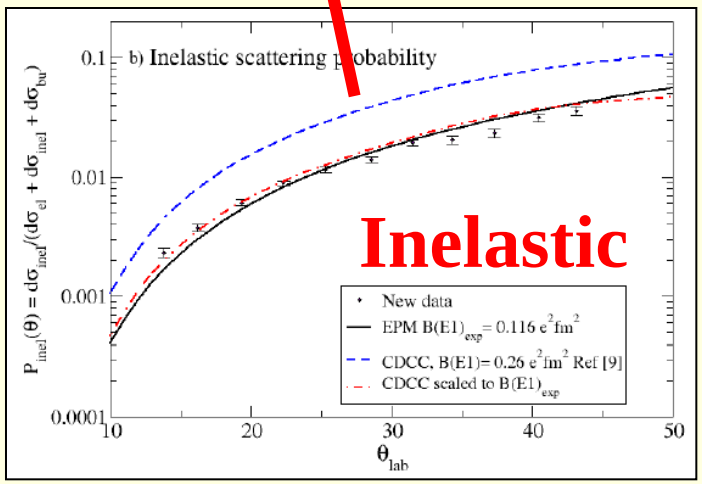
Differences between Li isotopes are **geometrical** in origin, except for ^{11}Li

Experimental data **below** most of the **theoretical predictions**.

^{11}Be + ^{197}Au at TRIUMF

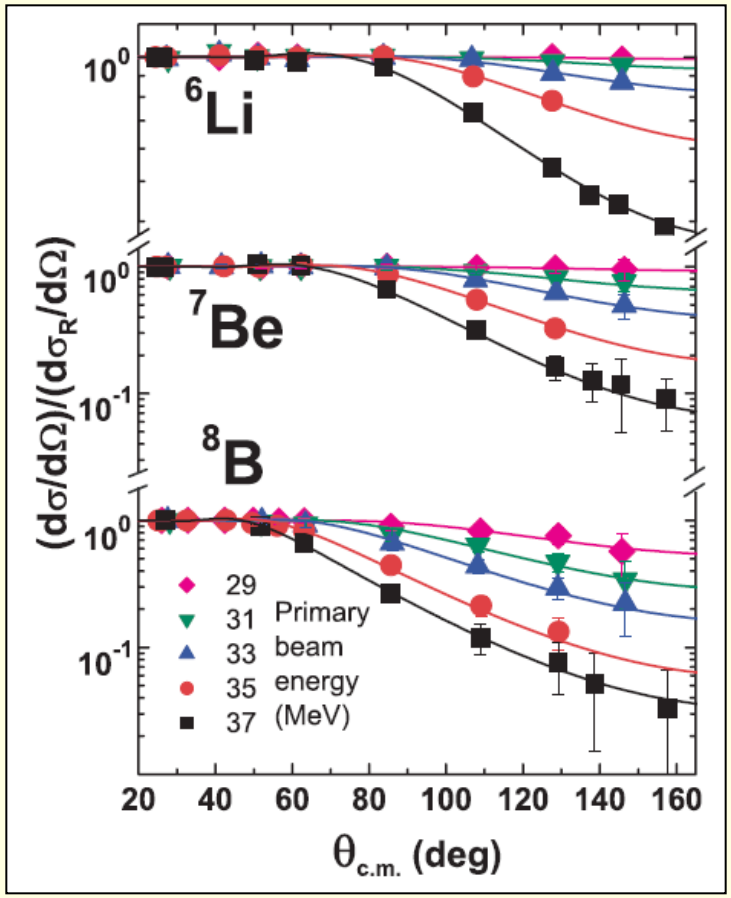






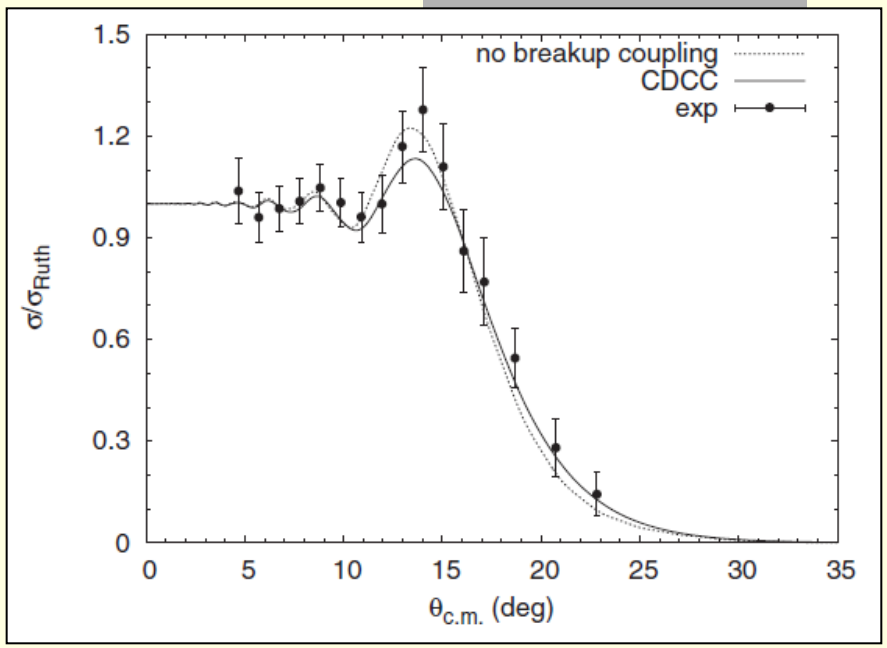
Upcoming Results! V. Pesudo et al., Acta Phys. Pol. 44 (2014) 375

^{8}B – Elastic Scattering



^{8}B+^{58}Ni (Notre Dame, USA)

E.F. Aguilera et al., Phys. Rev. C. 79, 021601



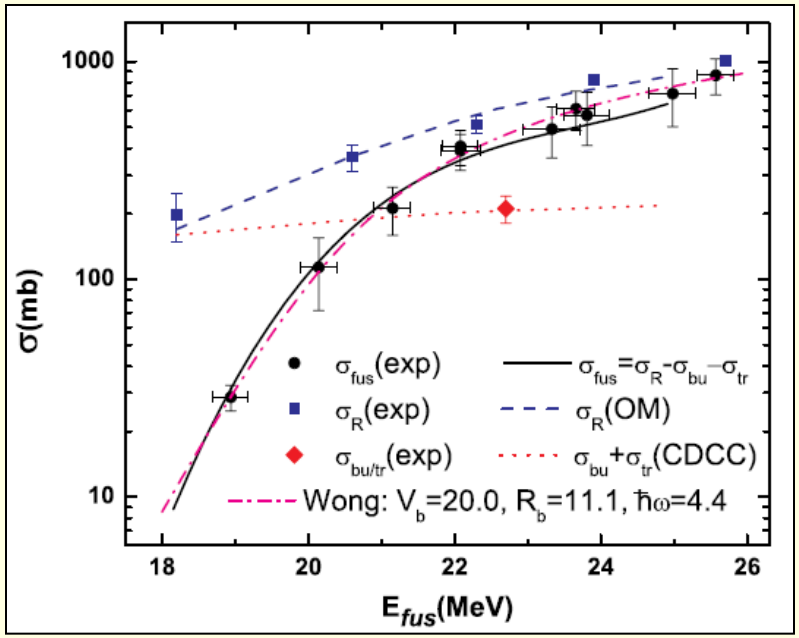
^{8}B+^{208}Pb (Lanzhou, China)

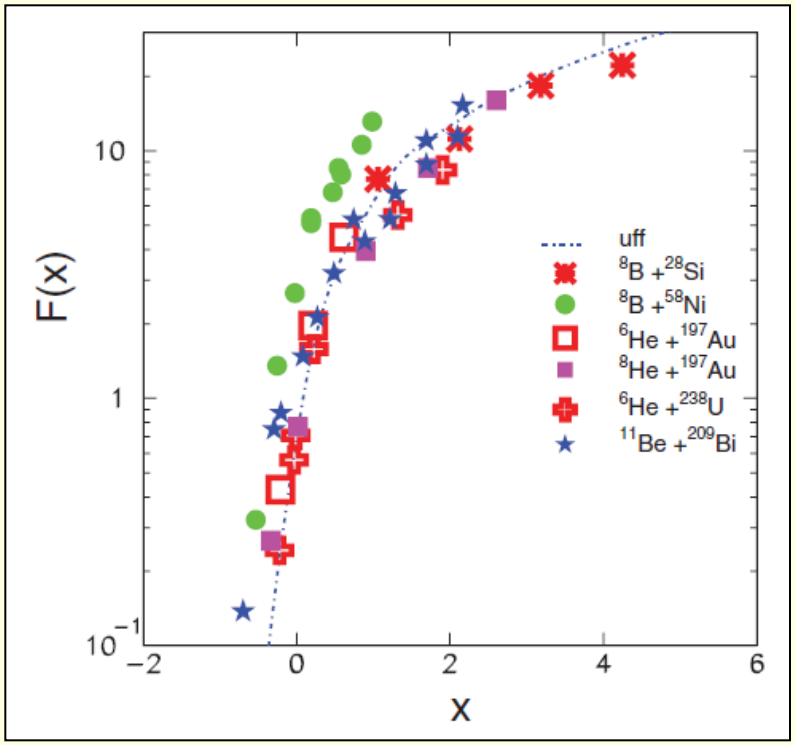
E = 170.3 MeV, i = 500 pps

Very **small breakup effects** on the elastic scattering at energies well above the Coulomb barrier

Y.Y. Yang et al., Phys. Rev. C. 87, 044613 (2013)

^{8}B Fusion Controversy





^{8}B+^{58}Ni: Fusion **enhancement** above the Coulomb barrier.

E.F. Aguilera et al., PRL 107 (2011) 092701

Fusion estimated from **proton evaporation** at backward angles.

J. Rangel et al., Eur. Phys. J. A 49 (2013) 57

^{8}B+^{28}Si: measured at EXOTIC (Italy) with the active target technique: **agreement with systematics (UFF)**.

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

III. Facility EXOTIC at INFN-LNL

The Project EXOTIC

Some 10 years ago we laid out a facility at the **Laboratori Nazionali di Legnaro (LNL)** of the **INFN** for the in-flight production of light weakly-bound **Radioactive Ion Beams**.

The production mechanism employs **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)

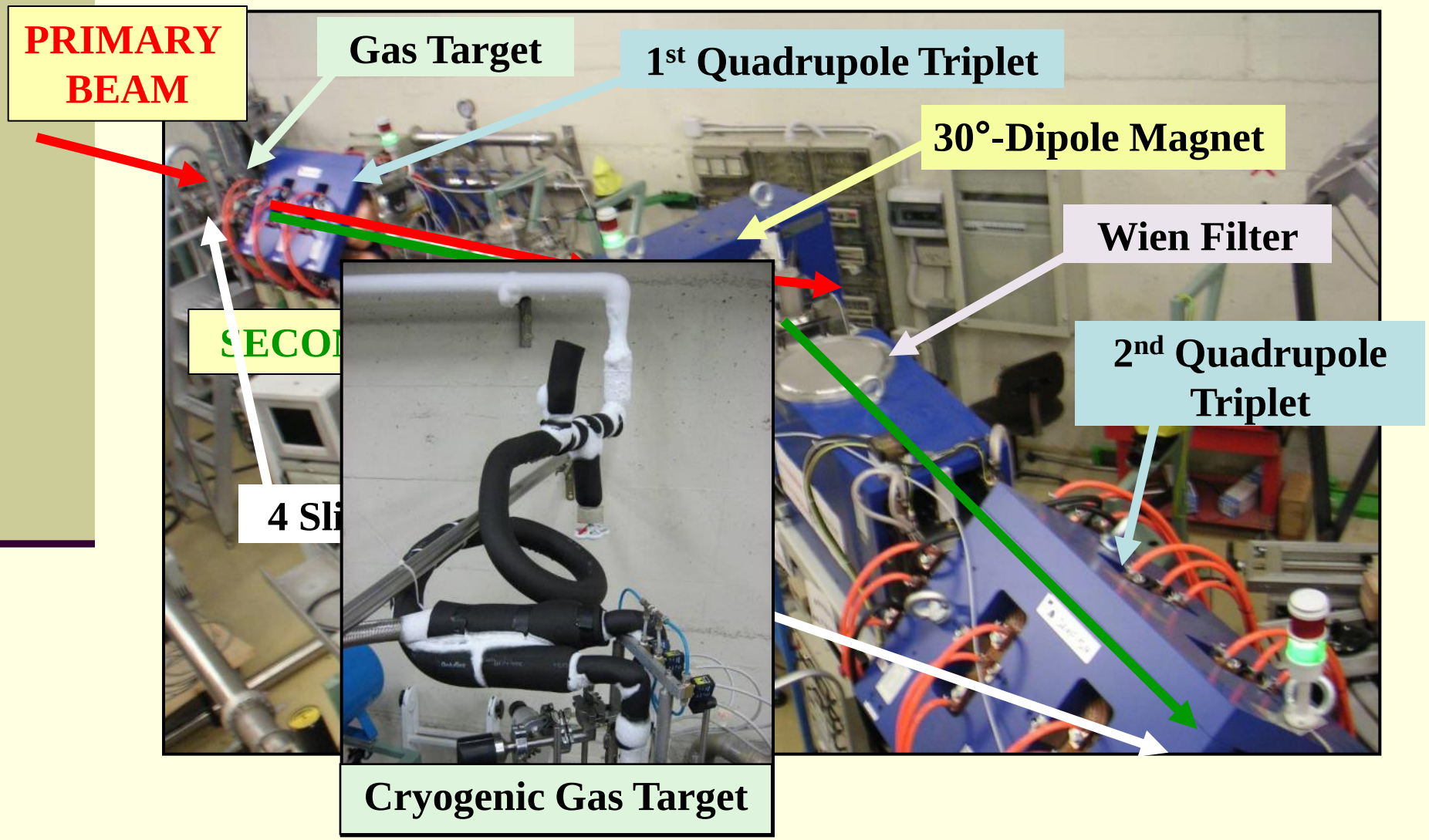
An **upgrade process** was subsequently performed in 2012.

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

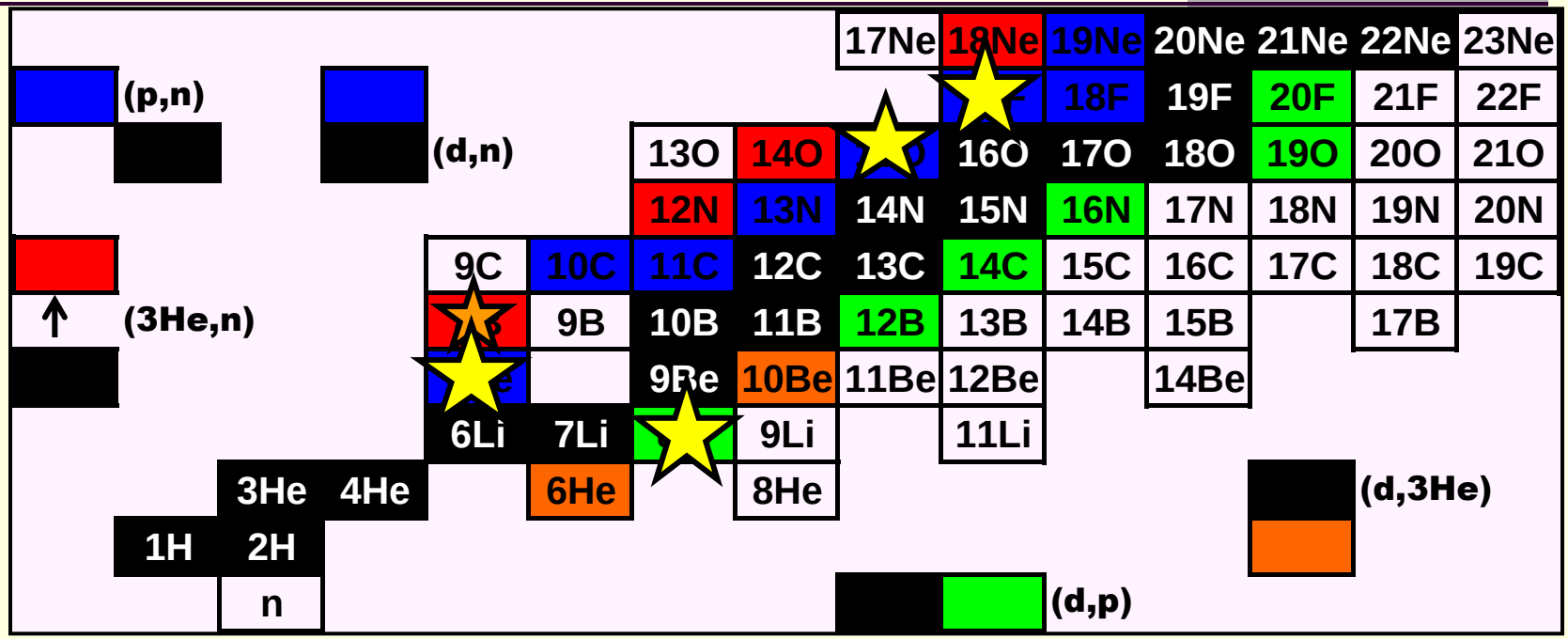
So far we have delivered **5 RIBs**:

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.

Facility EXOTIC at 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: **$3*10^5$ 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**

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., Acta Phys. Pol. B 45, 363 (2014)

Experiments (2013 - 2015)

^{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]

Spokespersons: A. Pakou, D. Pierroutsakou

^{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]

Spokesperons: D. Torresi, C. Wheldon

IV. Recent Results: EXOTIC

^{7}Be + ^{58}Ni at 22 MeV (LNL)

^{7}Be RIB:

E = 22.0 ± 0.4 MeV
Intensity = 250 kHz
Purity = 99 %

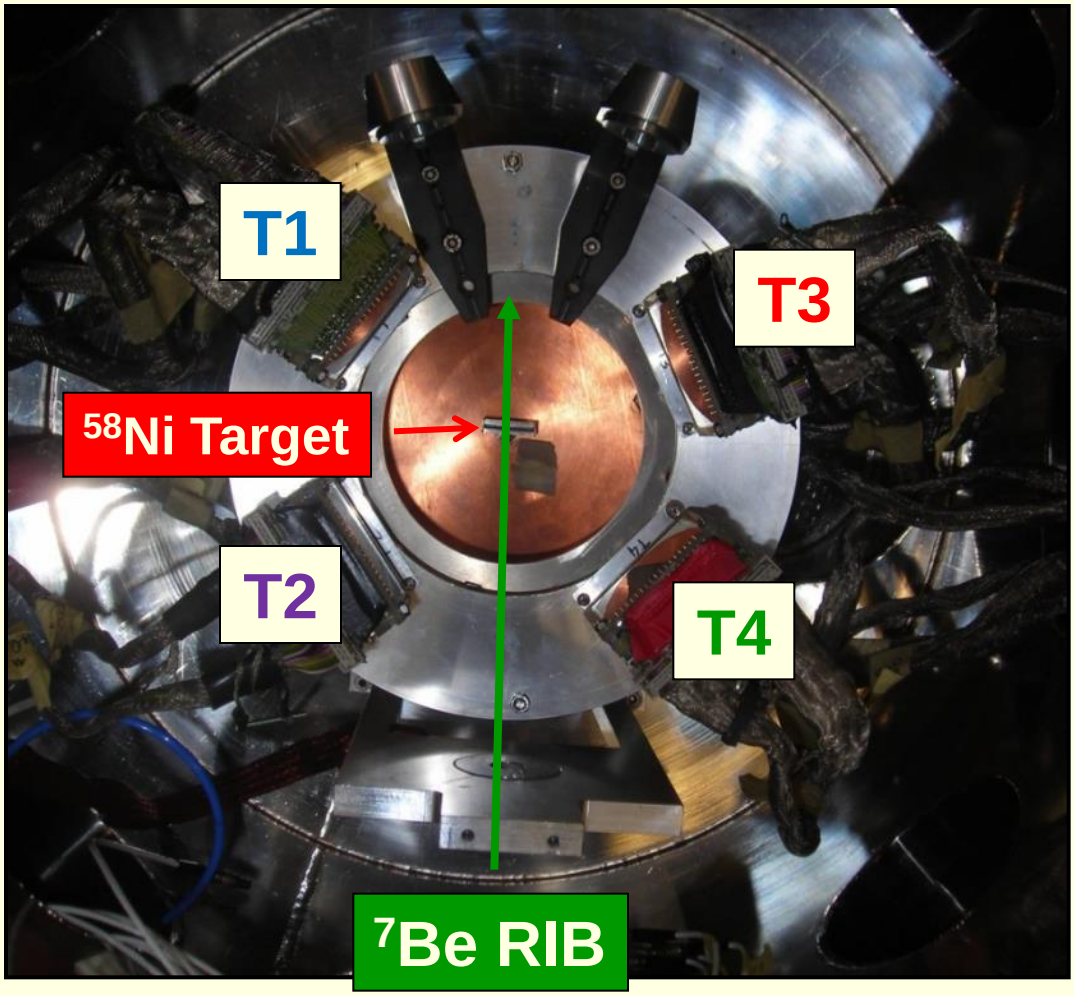
DINEX ARRAY (Huelva, Spain):

4 two-stage ΔE (DSSSD 40-42 μm) **- E_{res}** (DSSSD 1000 μm) telescopes.
Solid angle coverage: **~10%**.

EACH DSSSD:

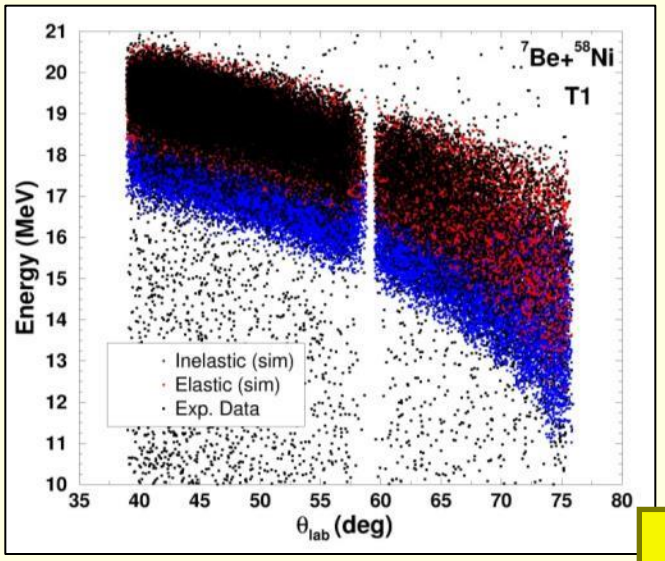
Active area: **48.5 x 48.5 mm^2**.
Front and back sides segmented into **16 strips**.

A.M. Sanchez-Benitez et al., J. Phys. G 31, S1953 (2005)

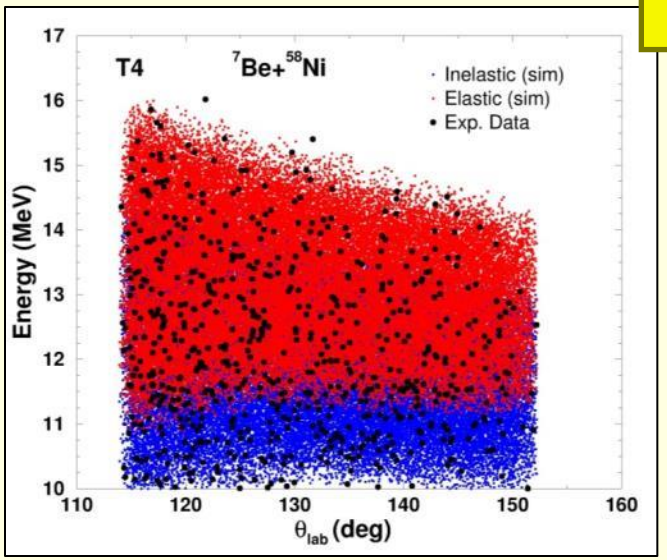


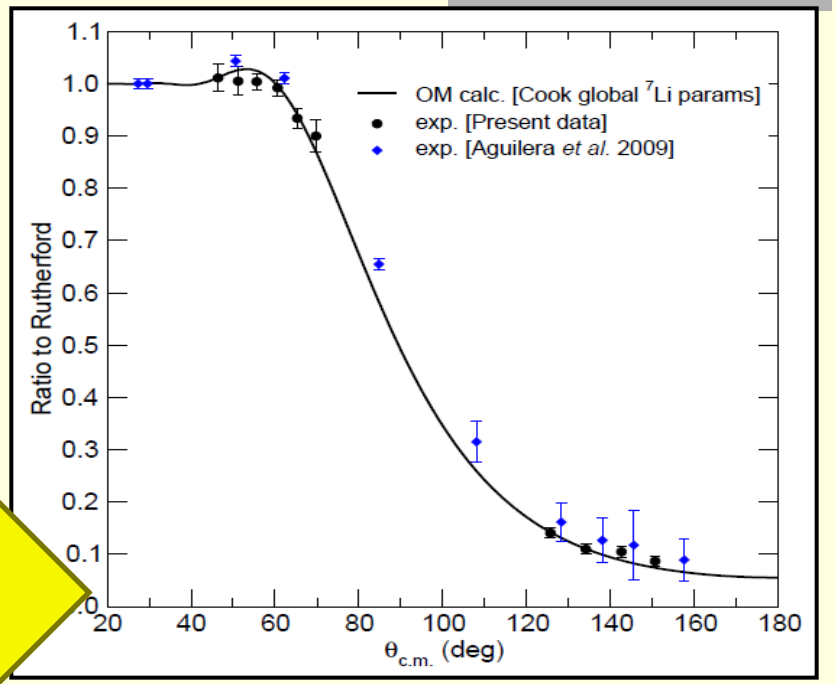
(Quasi-) Elastic Scattering

Forward Angles



Backward Angles





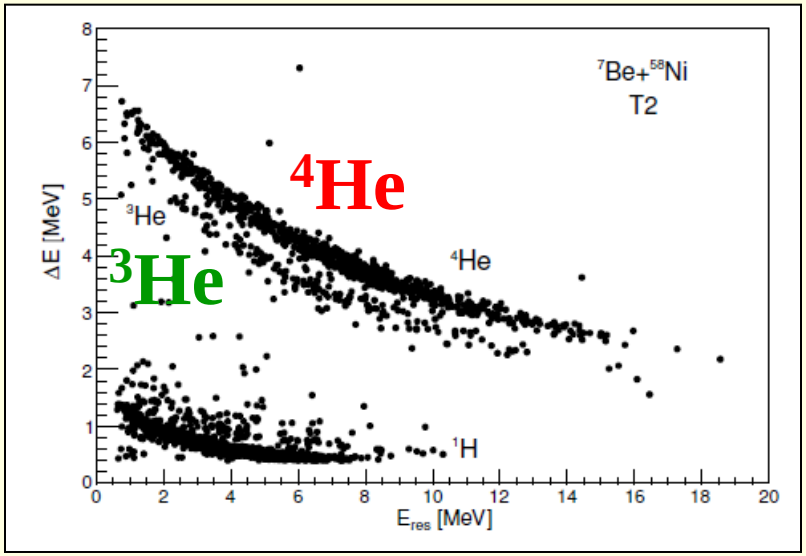
Quasi-elastic angular distribution at 21.5 MeV is in **good agreement** with a previous measurement

E.F. Aguilera et al., Phys. Rev. C 79, 021601 (2009)

and with **optical model calculations without free parameters**

J. Cook, Nucl. Phys. A 388, 153 (1982)

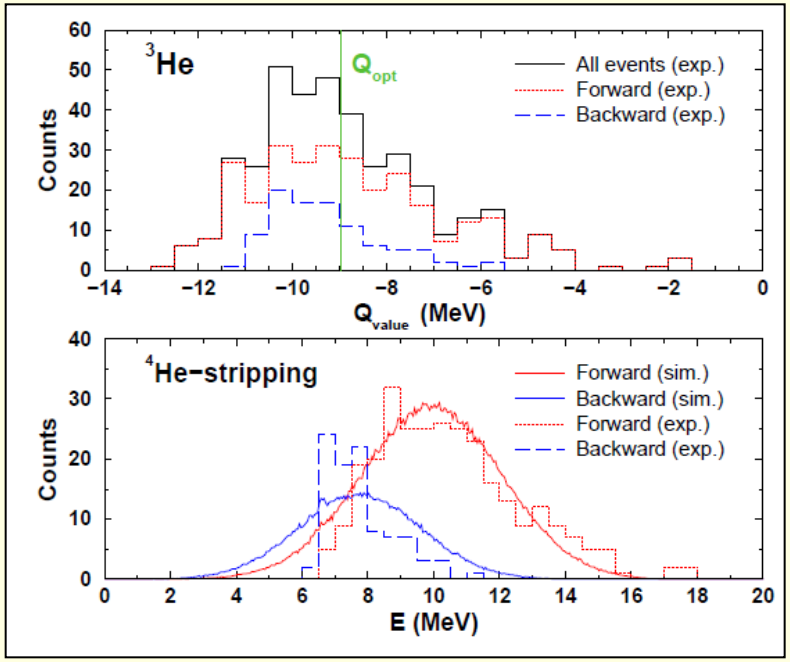
^{3}He and ^{4}He Production

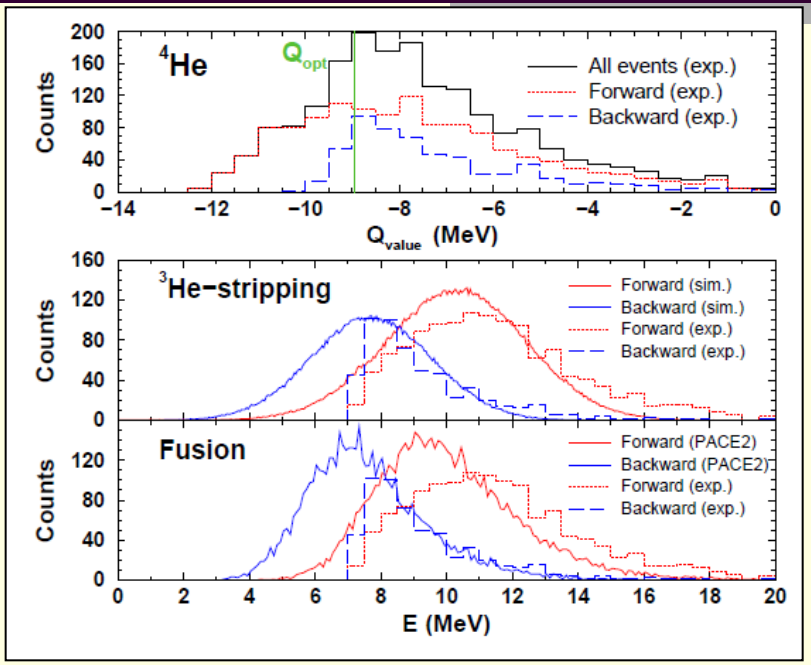


^{4}He are **4-5 times** more abundant than ^{3}He. In case the **Breakup Channel ^{7}Be → ^{3}He + ^{4}He** was dominating the reaction dynamics: **comparable** ^{3}He and ^{4}He yields would be expected.

^{3}He Production	^{4}He Production
Exclusive Breakup (^{3}He + ^{4}He)	Exclusive Breakup (^{3}He + ^{4}He)
COINCIDENCE DETECTION	1n-stripping (^{6}Be = α + p + p)
	1n-pickup (^{8}Be = α + α)
^{4}He-stripping	^{3}He-stripping
SINGLE DETECTION	Fusion-Evaporation

^{3,4}He Single Detection





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

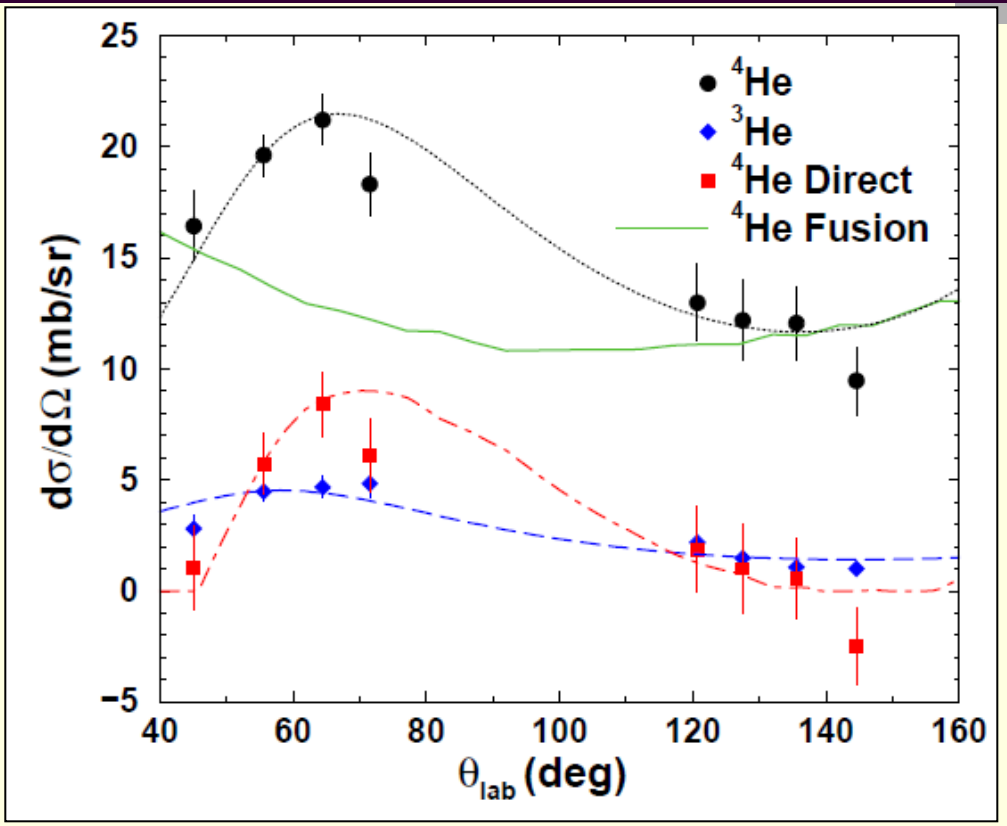
^{3}He reconstructed Q_{value} spectra compatible (within 0.5 MeV) with the **Q_{opt}** for the **^{4}He-stripping** process. (Q_{opt} ~ - 9 MeV)

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)

^{3,4}He Angular Distributions

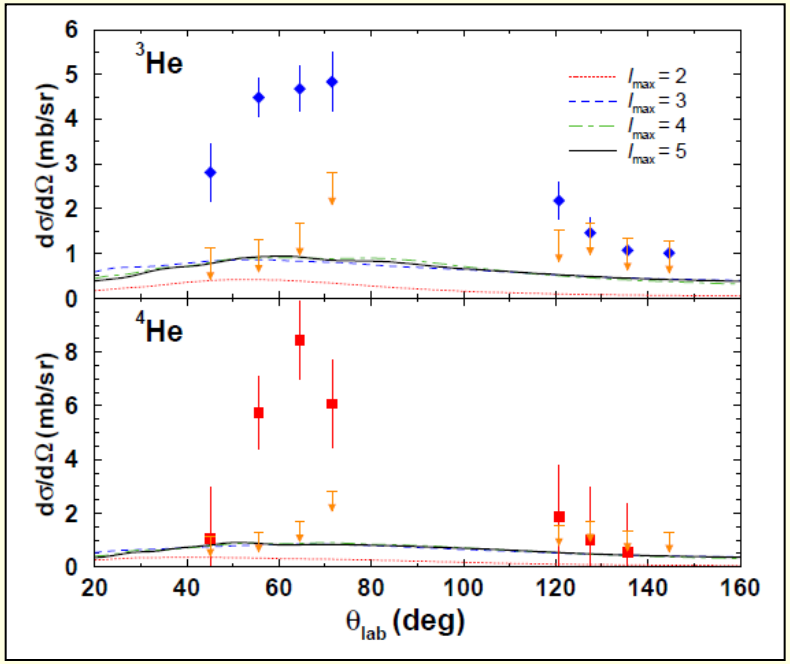


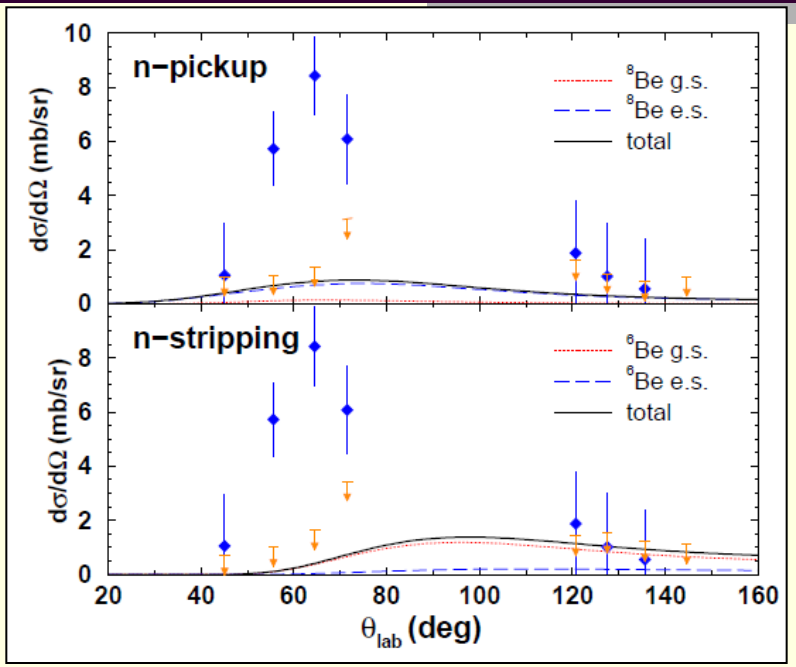
The **compound nucleus contribution (161.5 ± 11.5 mb)** was normalized to the data collecated at backward angles and subtracted to evaluate the contribution provided from **direct processes**.

Exp. **α-multiplicity (0.41 ± 0.12)** in agreement with PACE2 (0.43)

E. Martinez-Quiroz et al., Phys. Rev. C. 90, 014616 (2014)

^{3,4}He (No) Coincidence Detection





The **exclusive breakup** cross cross section was estimated within the Continuum Discretized Coupled Channels (**CDCC**) formalism.

$\sigma_{breakup}$ ~ 10.8 mb

The **1n-pickup** and the **1n-stripping** cross sections were computed with the Distorted Wave Born Approximation (DWBA).

$\sigma_{1n\text{-}pickup}$ ~ 6.0 mb

$\sigma_{1n\text{-}stripping}$ ~ 9.8 mb

^{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)

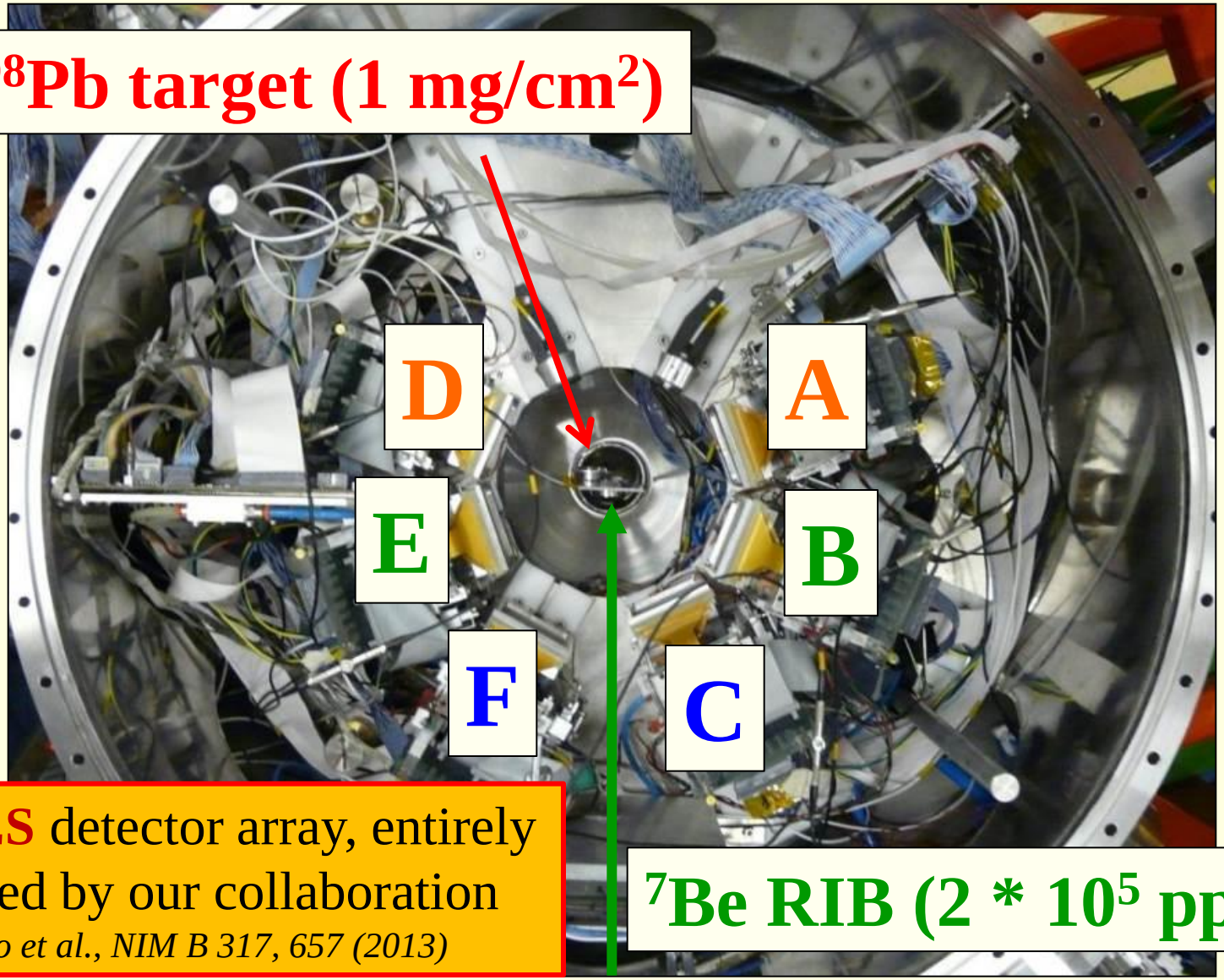
1n-stripping (9.8 mb)

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.

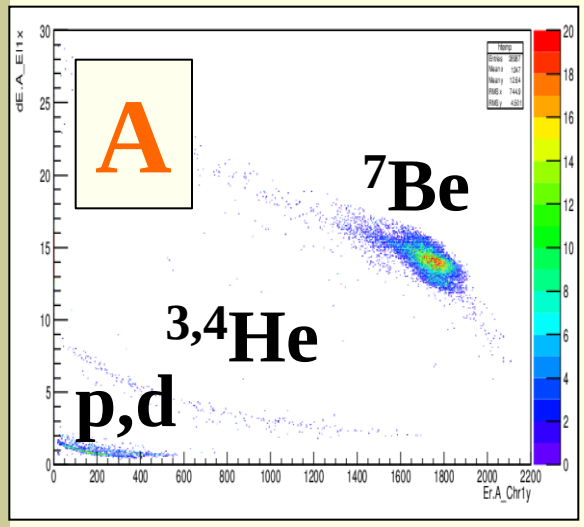
^{7}Be + ^{208}Pb (LNL, Nov 2013)

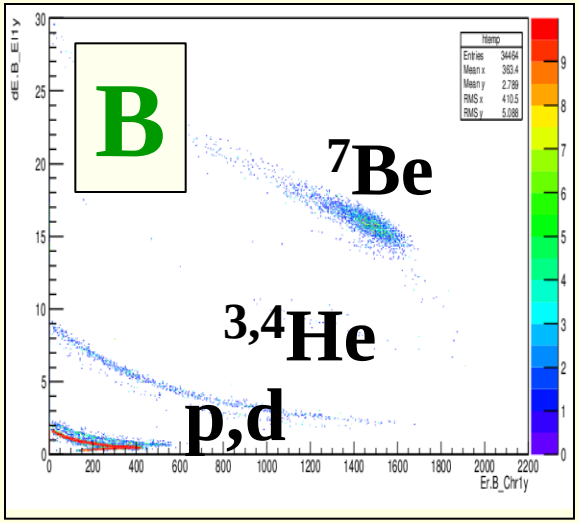


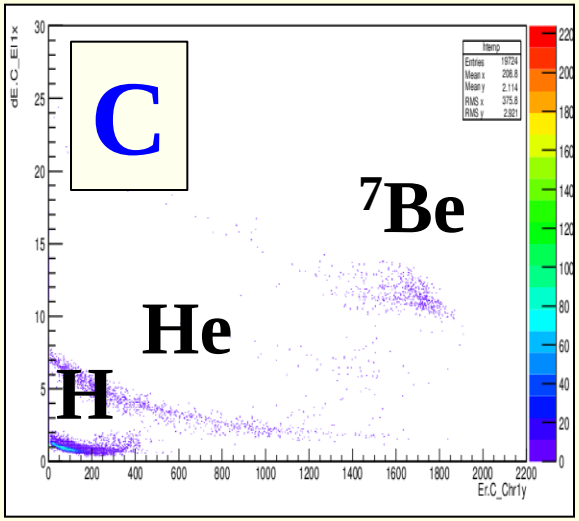
EXPADES detector array, entirely developed by our collaboration

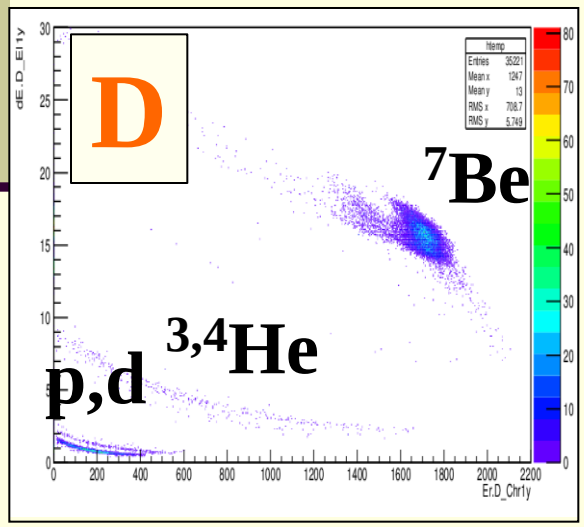
E. Strano et al., NIM B 317, 657 (2013)

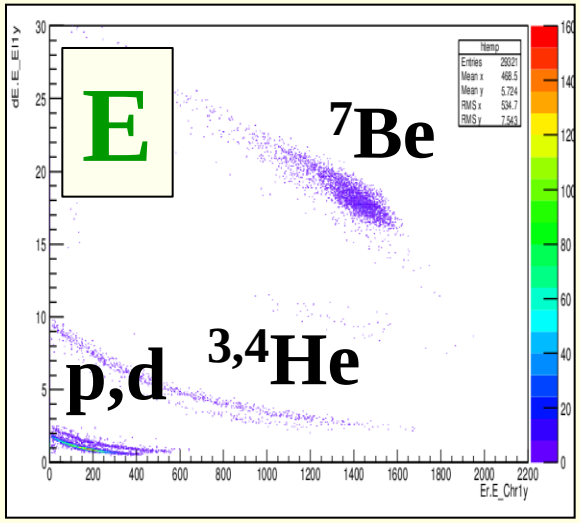
ΔE-E_{res} Plots

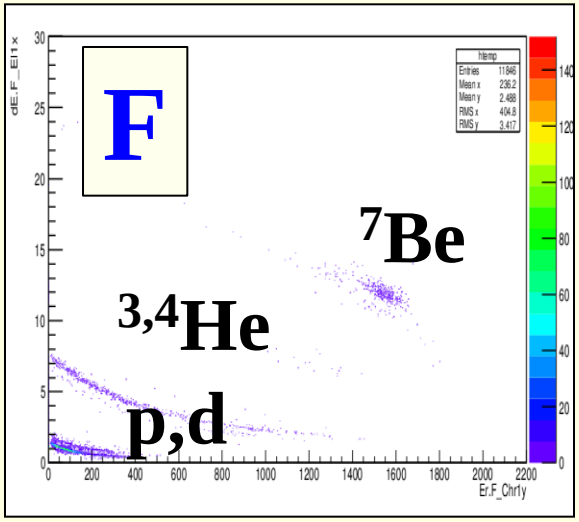




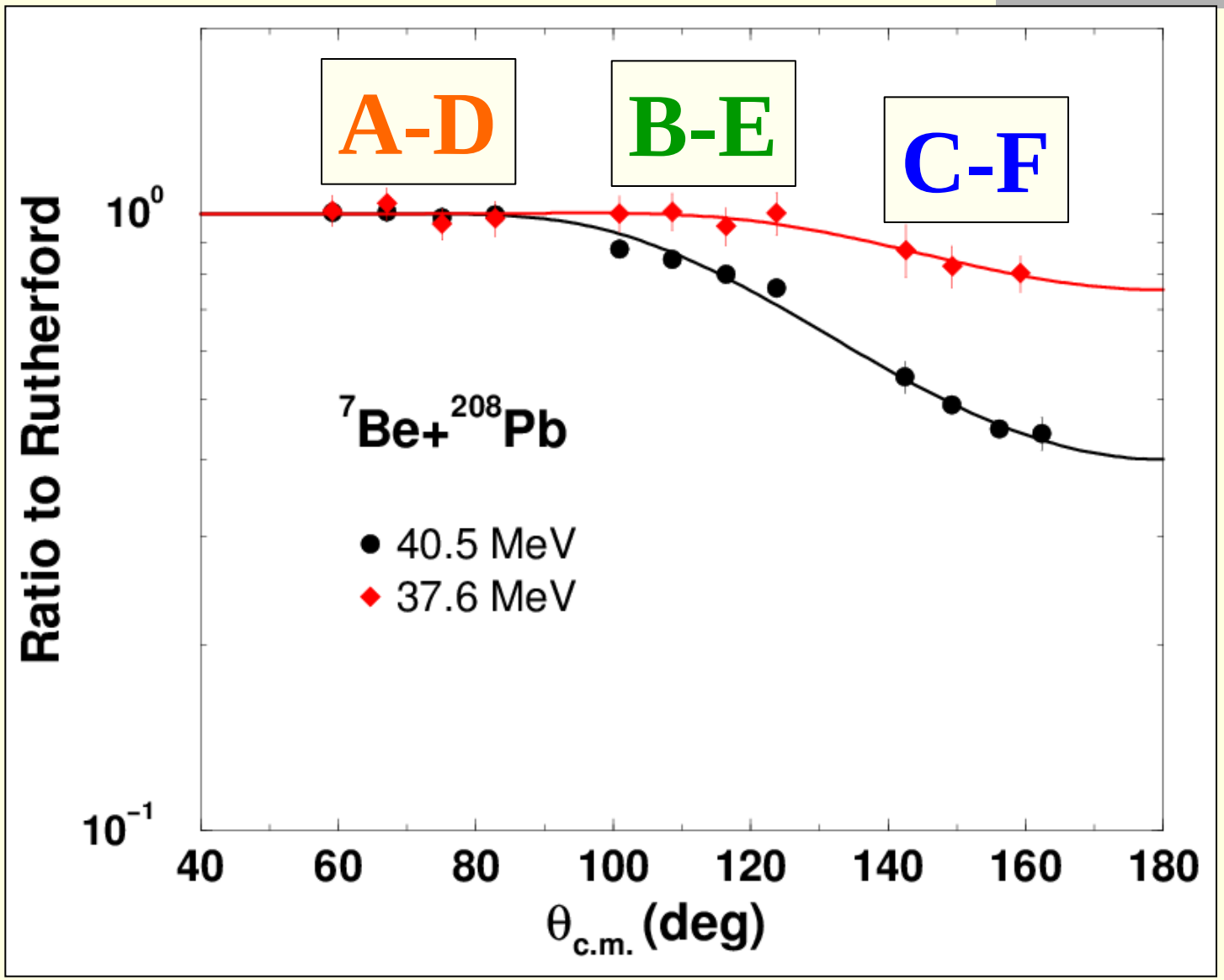




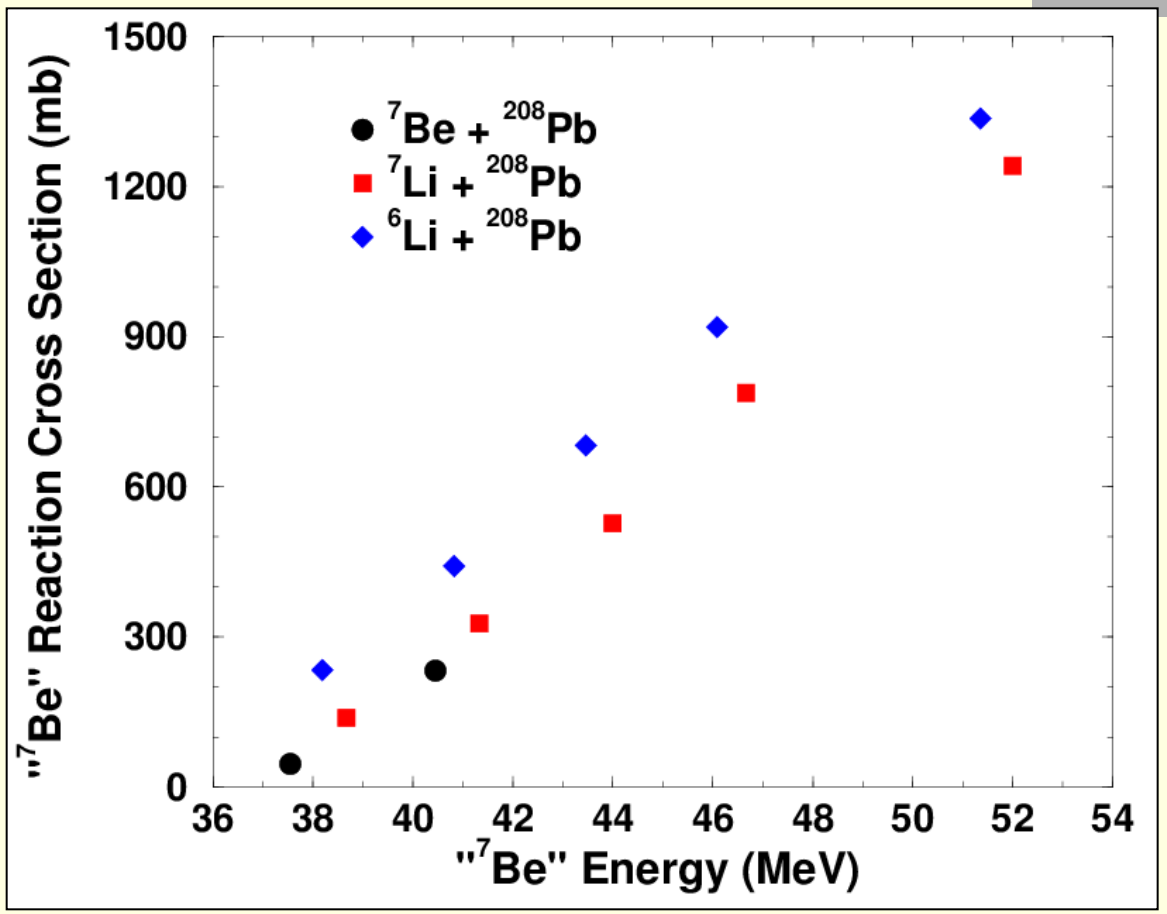




Elastic Scattering



Reaction Cross Section (preliminary)



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

^{7}Be + ^{208}Pb: Prel. Summary

QUASI-ELASTIC SCATTERING

Behaviour more similar to ^{7}Li than to ^{6}Li
(quite surprising, if confirmed)

FUSION

No measurement.
Some information might be extracted from the **^{4}He production**, however such a heavy compound system more likely evaporates **neutrons** rather than charged particles.

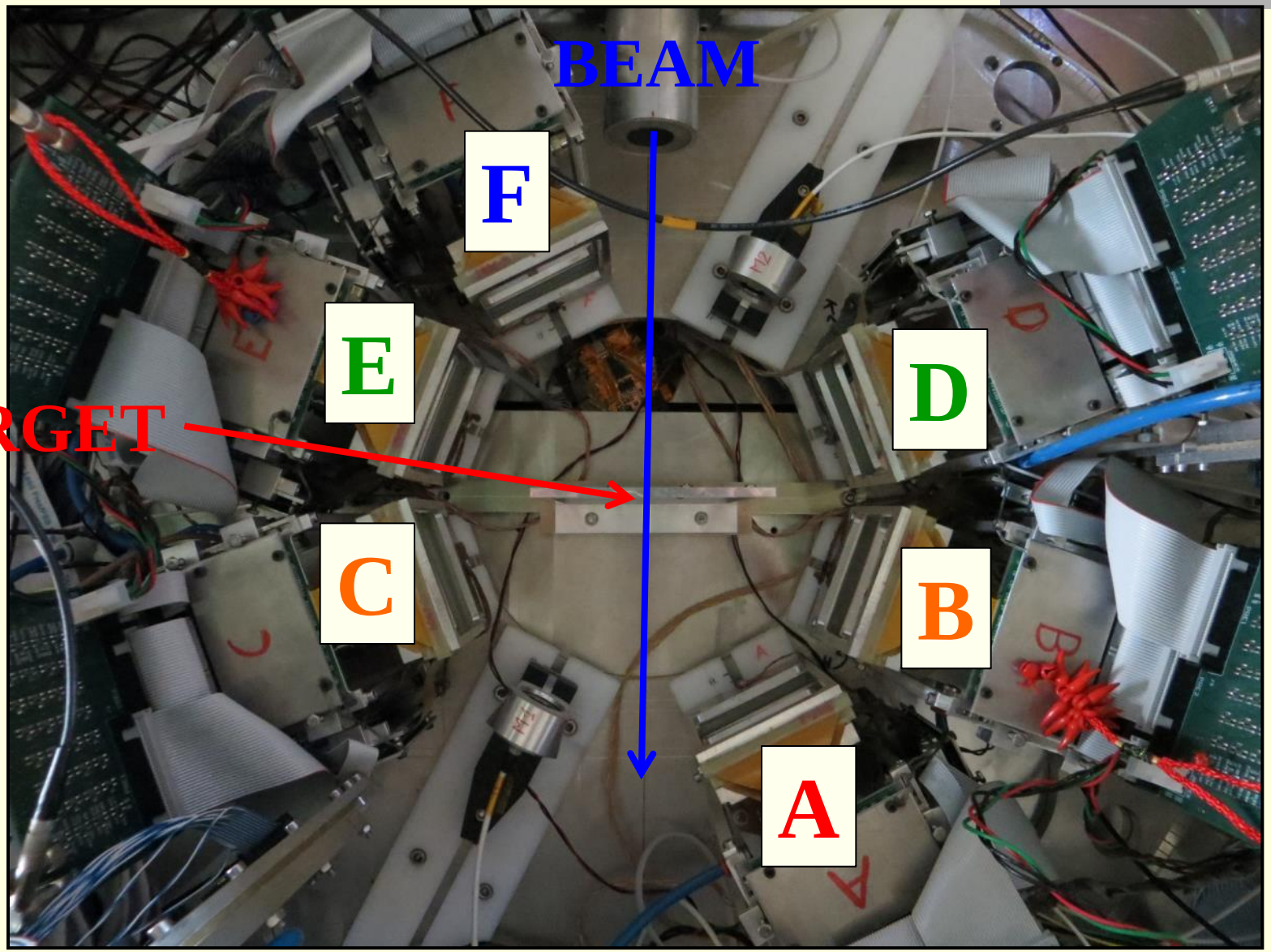
DIRECT PROCESSES: ^{4}He/^{3}He ratio

4.75 ± 0.60 (Tel. A-D, forward angles)

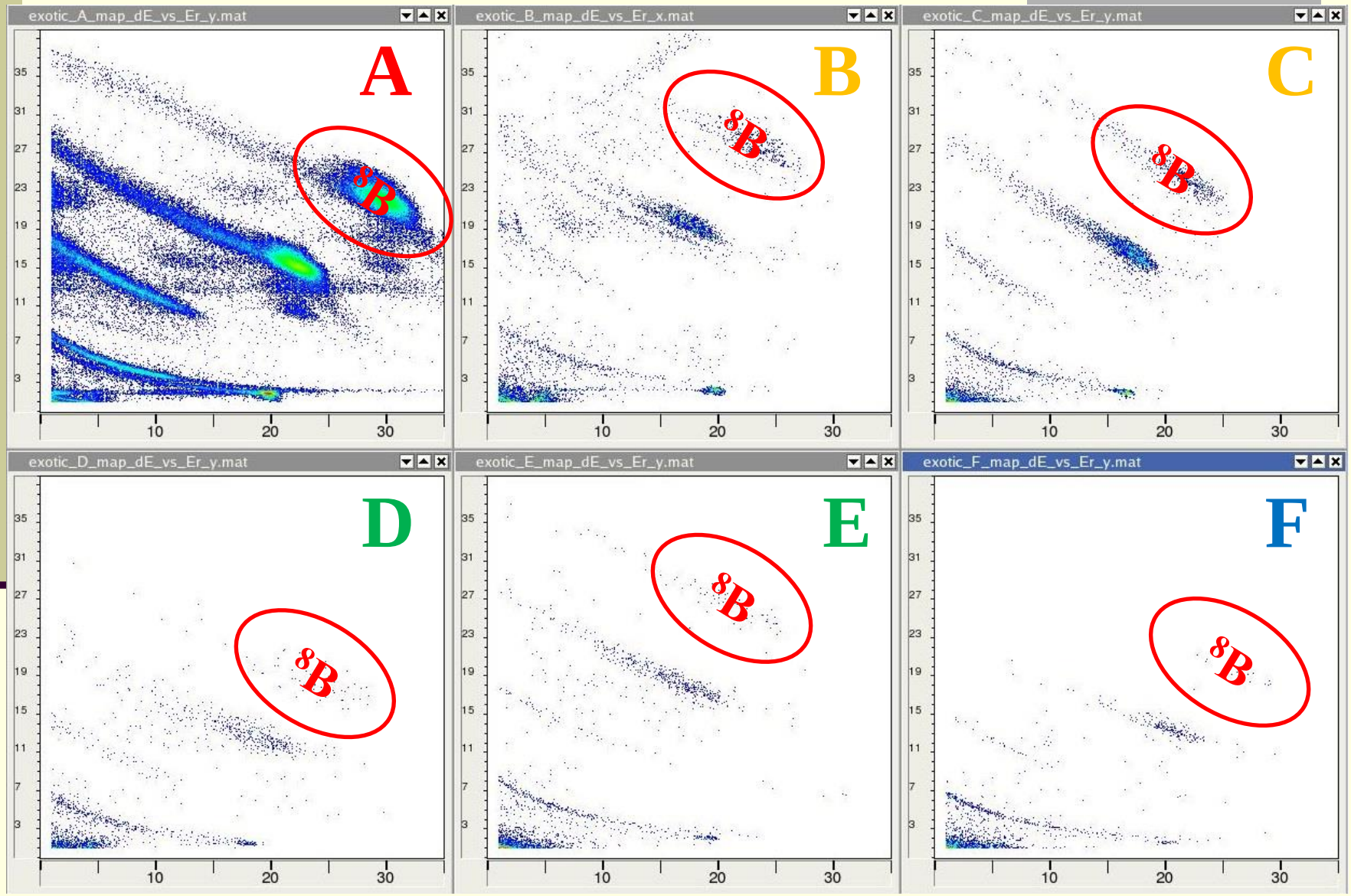
6.80 ± 0.53 (Tel. B-E, backward angles)

10.51 ± 1.05 (Tel. F, very backward angles)

$^{8}B + ^{208}Pb$ (CRIB, 2014)

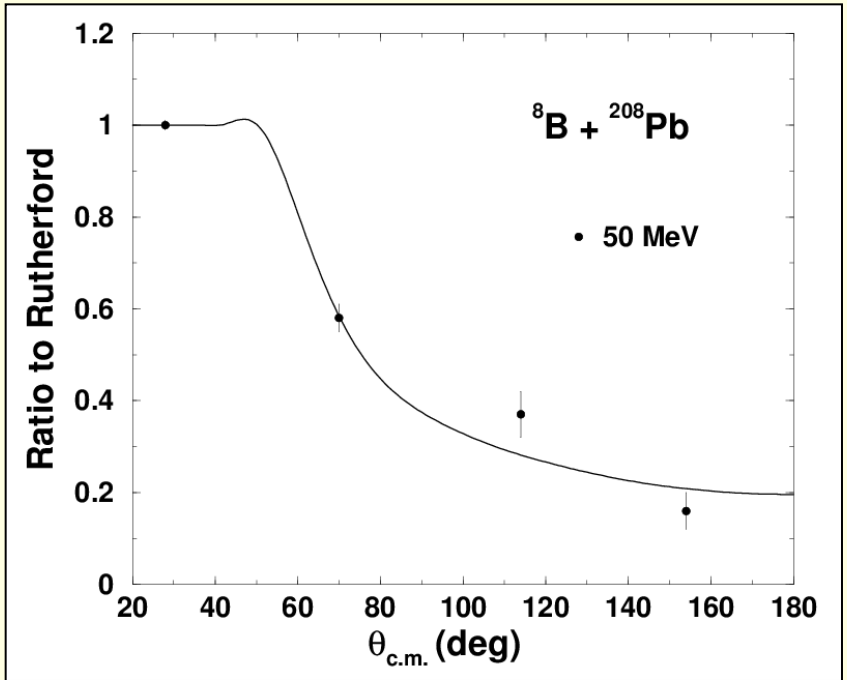


ΔE-E_{res} Plots



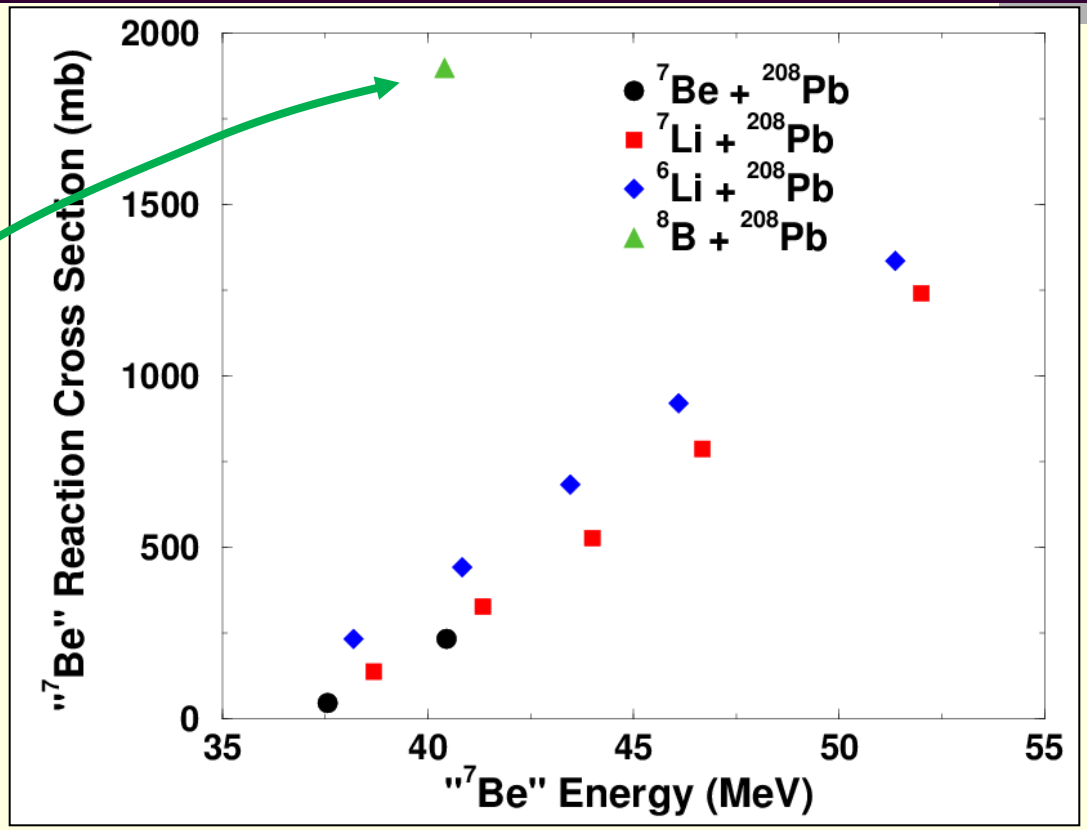
$^{8}B + ^{208}Pb$ Elastic Scattering

Telescope	$<\theta_{cm}>$	Exp.	Sim.	$d\theta/d\theta_R$	Stat. Err.
A	28°	71143	71131	1.00	0.01
B-C	70°	645	1121	0.58	0.03
D-E	114°	85	228	0.37	0.05
F	154°	15	95	0.16	0.04



70% of the collected statistics

Reaction Cross Section



An **extremely preliminary** optical-model best-fit analysis of the **^{8}B+^{208}Pb** elastic scattering angular distribution would suggest an **extraordinary large reaction cross section**.

V. Summary

The study of the **reaction dynamics** induced by light weakly-bound Radioactive Ion Beams (**RIBs**) at near-barrier energies is currently an **active research field** in Nuclear Physics.

The exotic features of many light RIBs **enhance** the **reaction probability** at sub-barrier energies rather than the **fusion**.

This **enhancement** is mainly due to **transfer processes** (especially the 2n-stripping) for **Helium** isotopes (^{6}He and ^{8}He) and to the **breakup** process for **^{11}Li**. Very soon, high quality data for **^{11}Be** will help complementing the established systematics.

The situation is still a bit **controversial** for **^{8}B**.

Our facility **EXOTIC** is **fully operational** at **INFN-LNL** and 5 RIBs for reaction dynamics studies have been delivered.

Very promising results have been already obtained for **^{7}Be** and, hopefully, the additional measurement performed at CRIB will help solving the **^{8}B controversy**.

EXOTIC Collaboration

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danke
merci
gracias
obrigado
thank you
bedankt
go raibh maith agat
teşekkür ederim
kop khun krap
sukriya
tapadh leat
dziękuję
mochchakkeram
hvala
terima kasih
謝謝
mauruuru
grazie
ngiyabonga
dakujem
takk
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sagolun
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choorakaloutioun
grazzi
Баярлалаа