Reaction dynamics studies for the interaction of the Radioactive Ion Beams ^{7}Be and ^{8}B with a ^{208}Pb target at Coulomb barrier energies

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Reaction Seminars

May 28th, 2020

Outline

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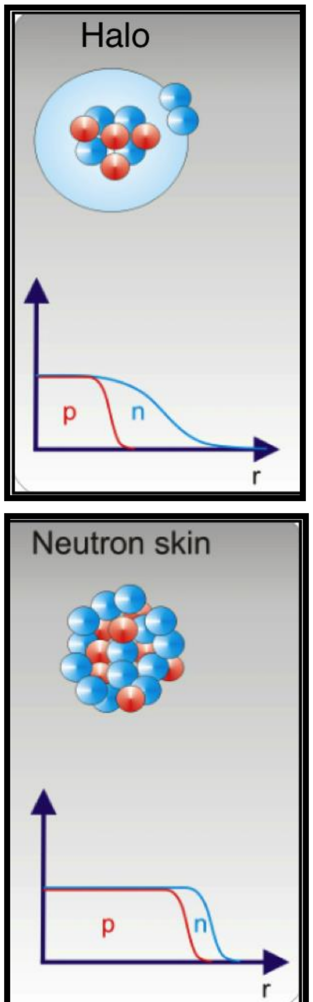
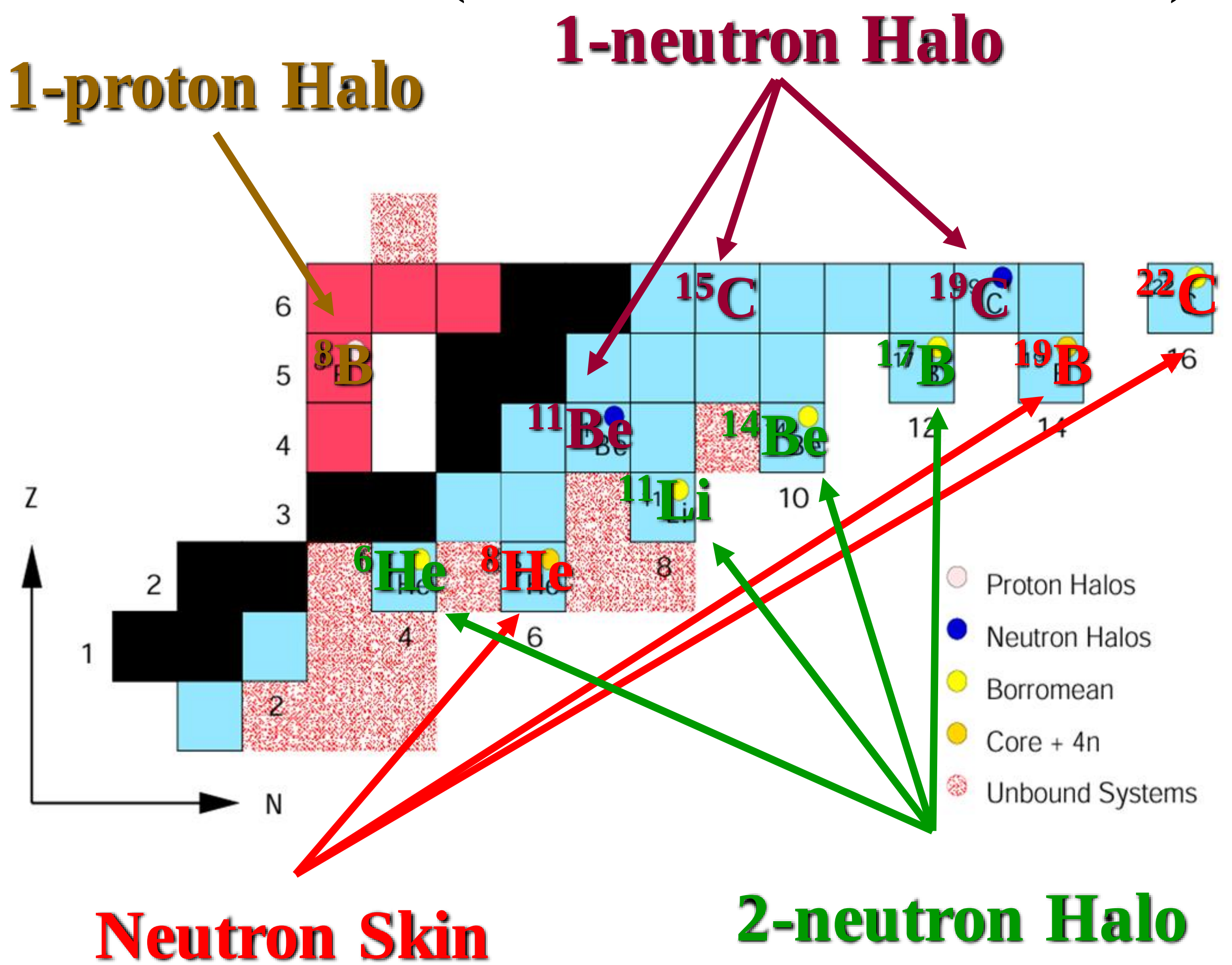
2. The Facility EXOTIC at LNL
3. Elastic Scattering
   a. ^{7}Be + ^{208}Pb @ LNL (Italy)
   b. ^{8}B + ^{208}Pb @ CRIB (Japan)
4. Other Reaction Products
   a. ^{3,4}He production in ^{7}Be + ^{208}Pb
   b. ^{7}Be production in ^{8}B + ^{208}Pb
5. Summary

1. 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).



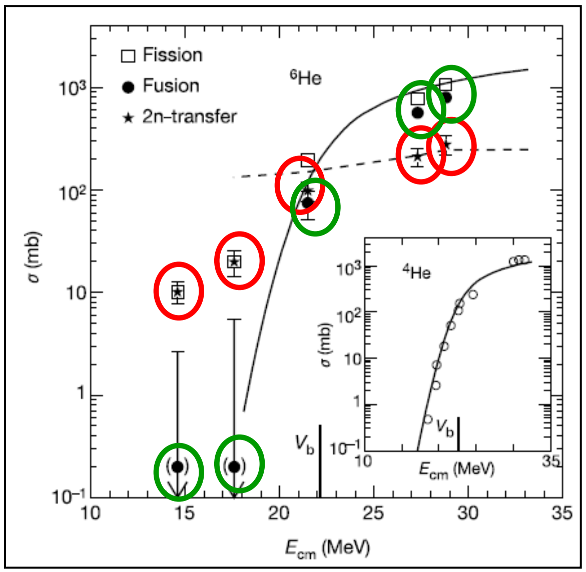


Near-Barrier Studies with RIBs

Reaction cross section enhancement at sub-barrier energies mostly due to **direct processes** (n-transfer for $^{6,8}He$, breakup for ^{11}Li and ^{8}B)

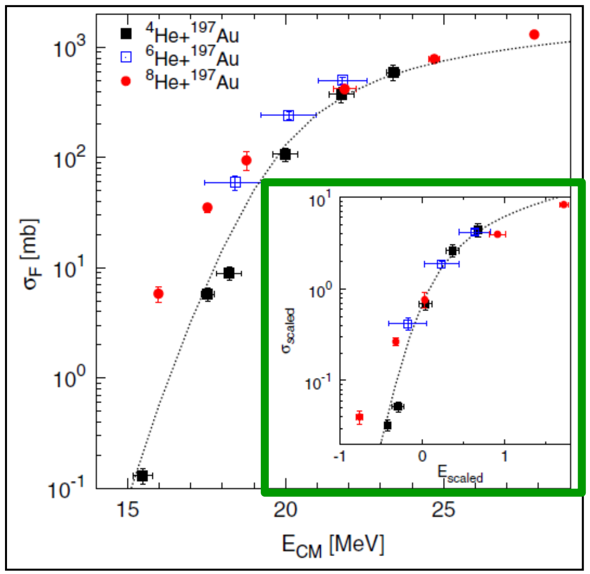
Very moderate (factor 2-5) **sub-barrier fusion enhancement**

Strong Coupling Effects (^{11}Li and ^{11}Be)



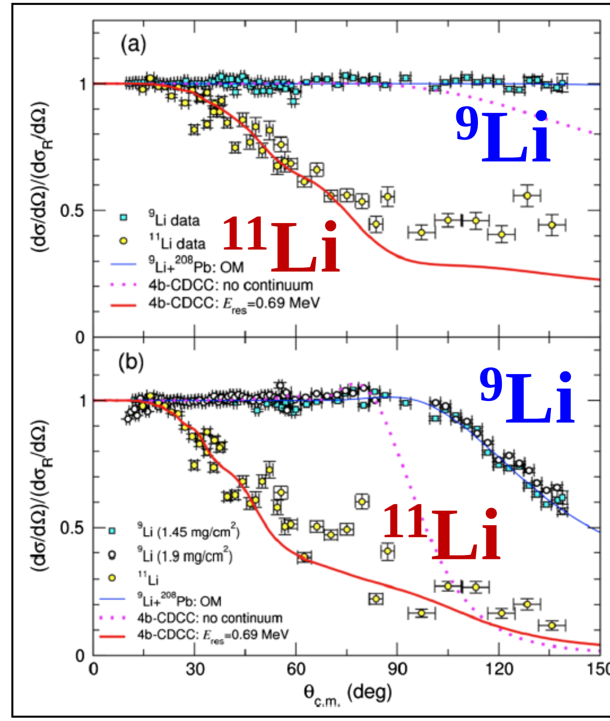
$^{6}He + ^{238}U$

R. Raabe et al., Nature 431 (2004) 823



$^{8}He + ^{197}Au$

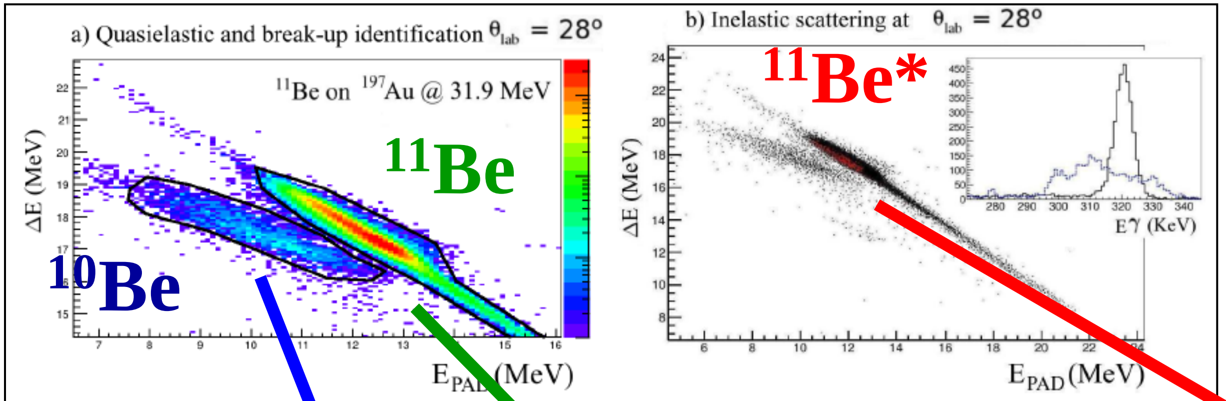
A. Lemasson et al., Phys. Rev. Lett. 103 (2009) 232701



$^{11}Li + ^{208}Pb$

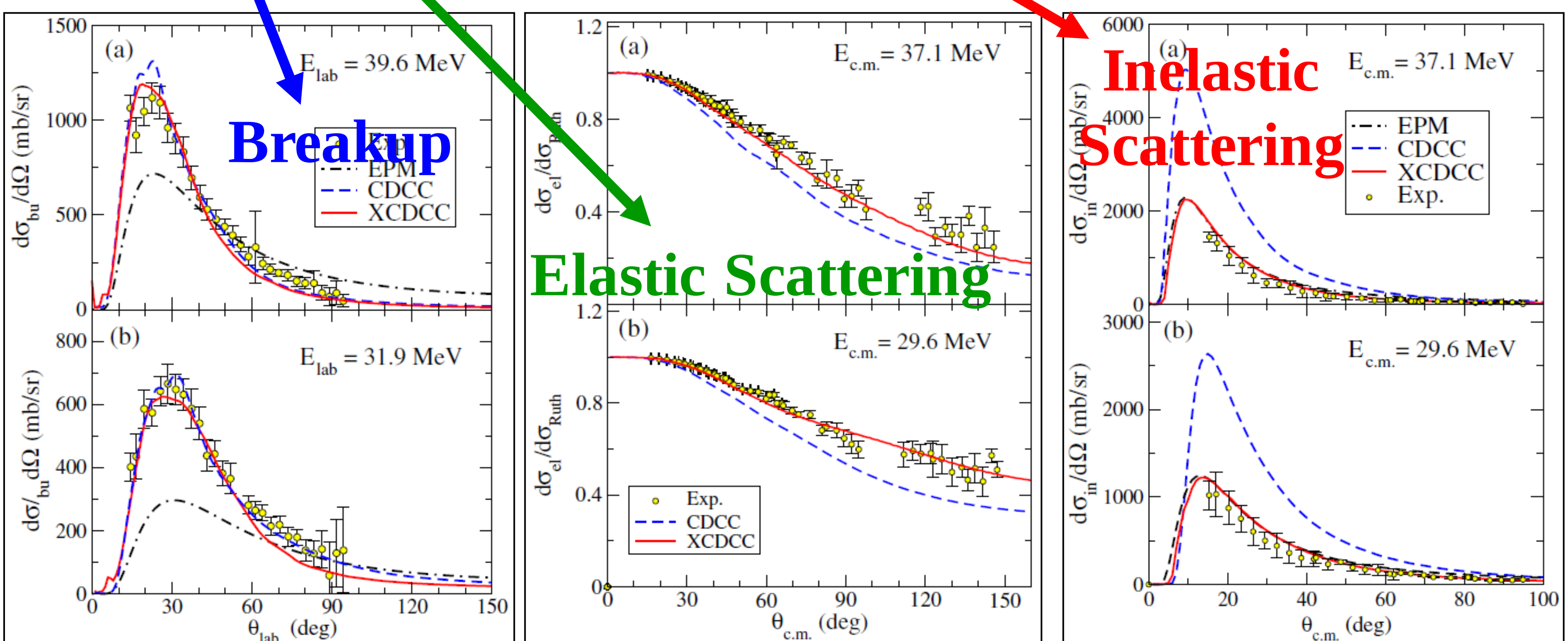
M. Cubero et al., Phys. Rev. Lett. 109 (2012) 262701

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

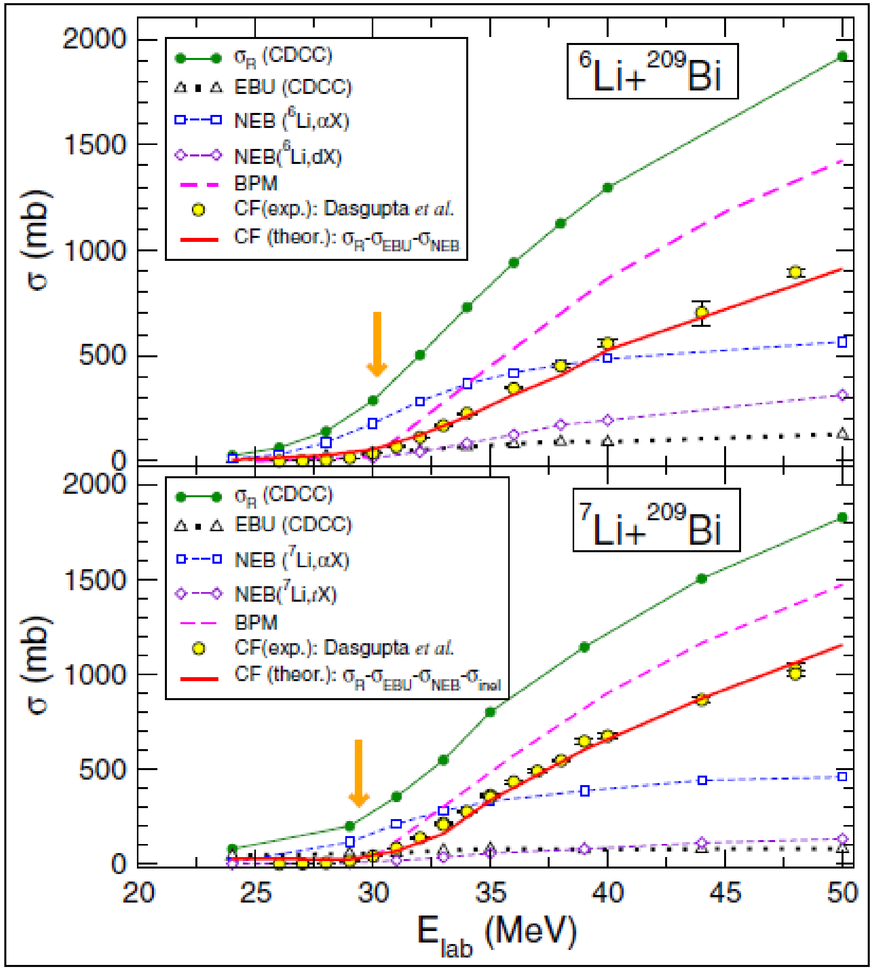


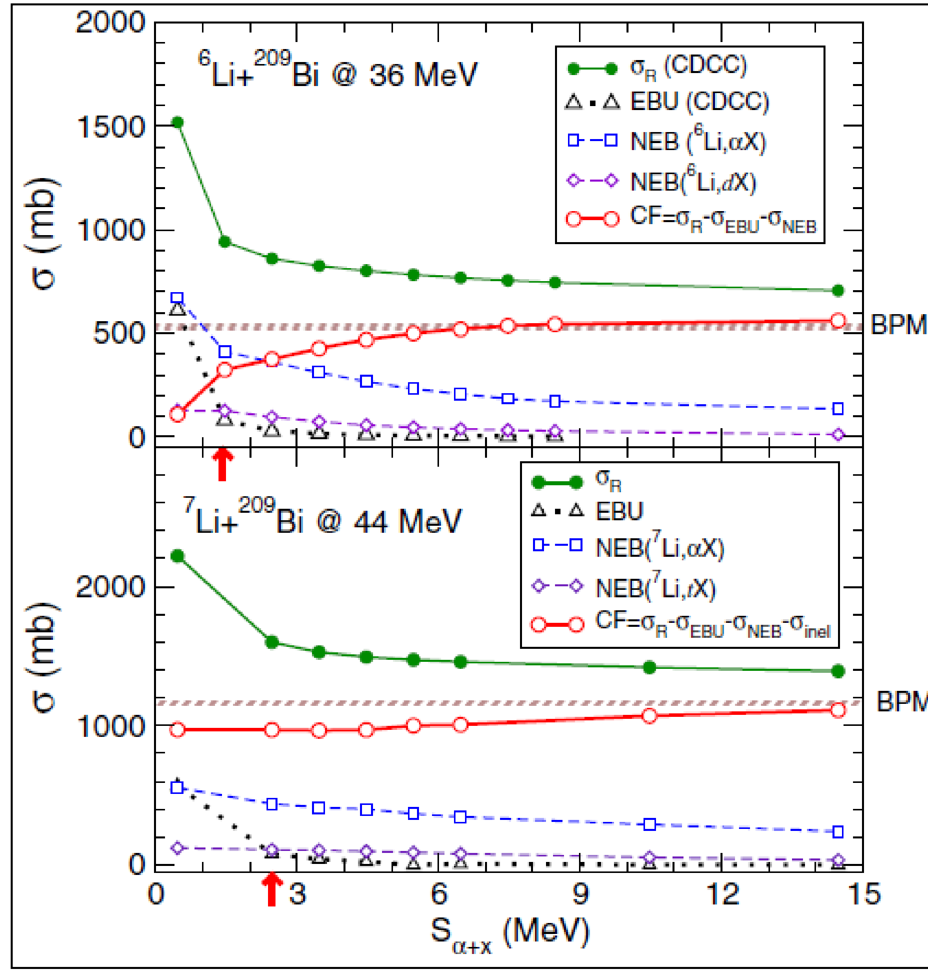
Very significant **devation** from the **Rutherford scattering below the barrier**. Inclusion of **^{10}Be core deformation** and **excitation** in the calculations.

V. Pesudo et al., Phys. Rev. Lett. 118 (2017) 152502



Trojan Horse Mechanism





Clustering and **weak binding** energy, triggering **NEB processes**, but **not breakup** in the usual sense, are responsible for the **CF suppression**.

Jin Lei, A.M. Moro, Phys. Rev. Lett. **122**, 042503 (2019) and Phys. Rev. Lett. **122**, 232501 (2019)

2. Facility EXOTIC at LNL

RIB 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)

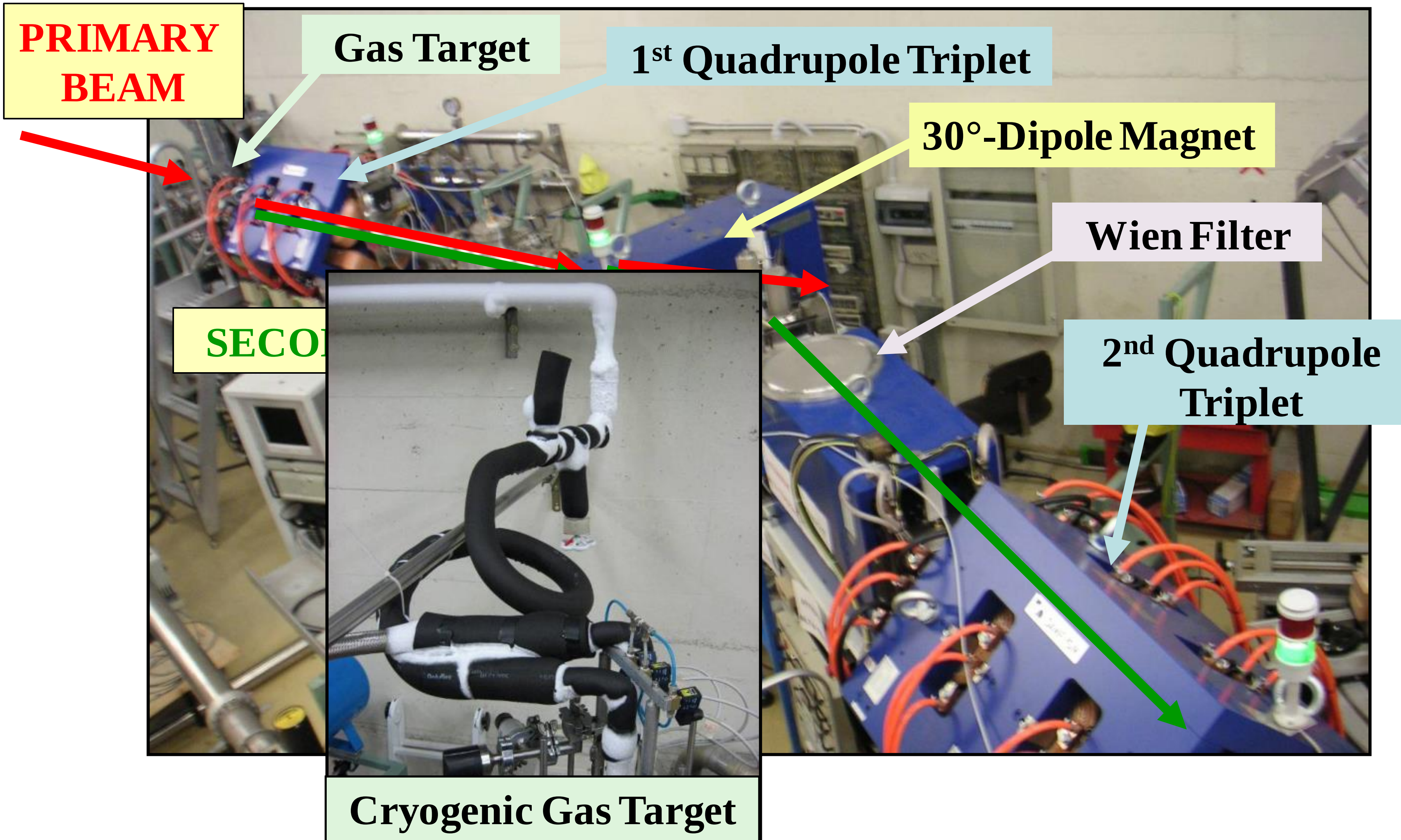
A **substantial upgrade process** was subsequently held in 2012.

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

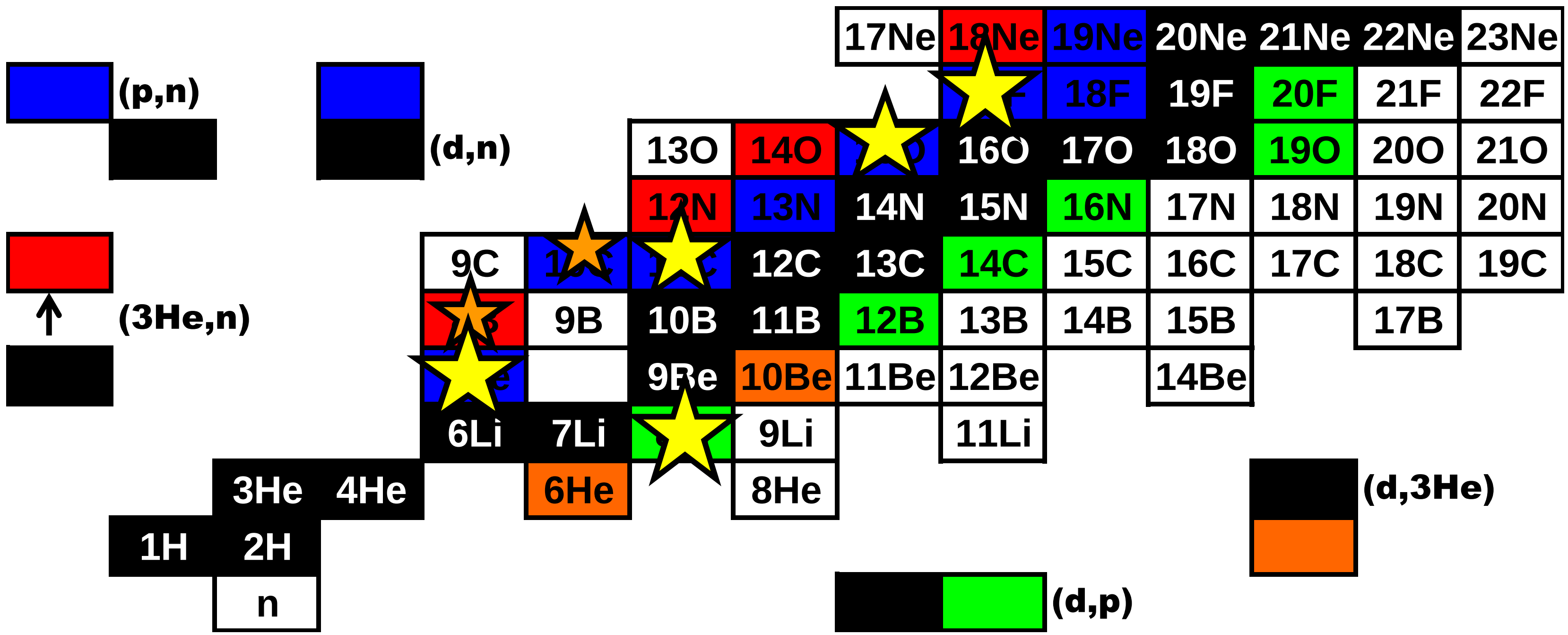
7 Radioactive Ion Beams have been delivered so far:

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 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 - 2020)

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

E. Strano, G. Montagnoli, A.M. Stefanini, M. Mazzocco et al., NIM A 877, 293-299 (2018)

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

M. Mazzocco, N. Keeley et al., Phys. Rev. C 100, 024602 (2019)

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

O. Sgouros, A. Pakou et al., Phys. Rev. C 94, 044623 (2016) and Phys. Rev. C 95, 054609 (2017)

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

Spokespersons: M. Mazzocco, D. Torresi – Data Analysis in Progress

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

A. Pakou at al., Eur. Phys. J. A 51, 55 (2015) and Eur. Phys. J. A 51, 90 (2015)

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

D. Torresi, C. Wheldon, Tz. Kokalova et al., Phys. Rev. C 96, 044317 (2017)

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

L. Lamia, M. Mazzocco, R.G. Pizzone, S. Hayakawa, M. La Cognata et al., Ap. J. 879, 23 (2019)

^{11}C + ^{4}He [Resonant Scattering]

Spokespersons: D. Torresi, C. Wheldon, C. Parascandolo – Data Analysis in Progress

^{8}B + ^{28}Si [Reaction Cross Section]

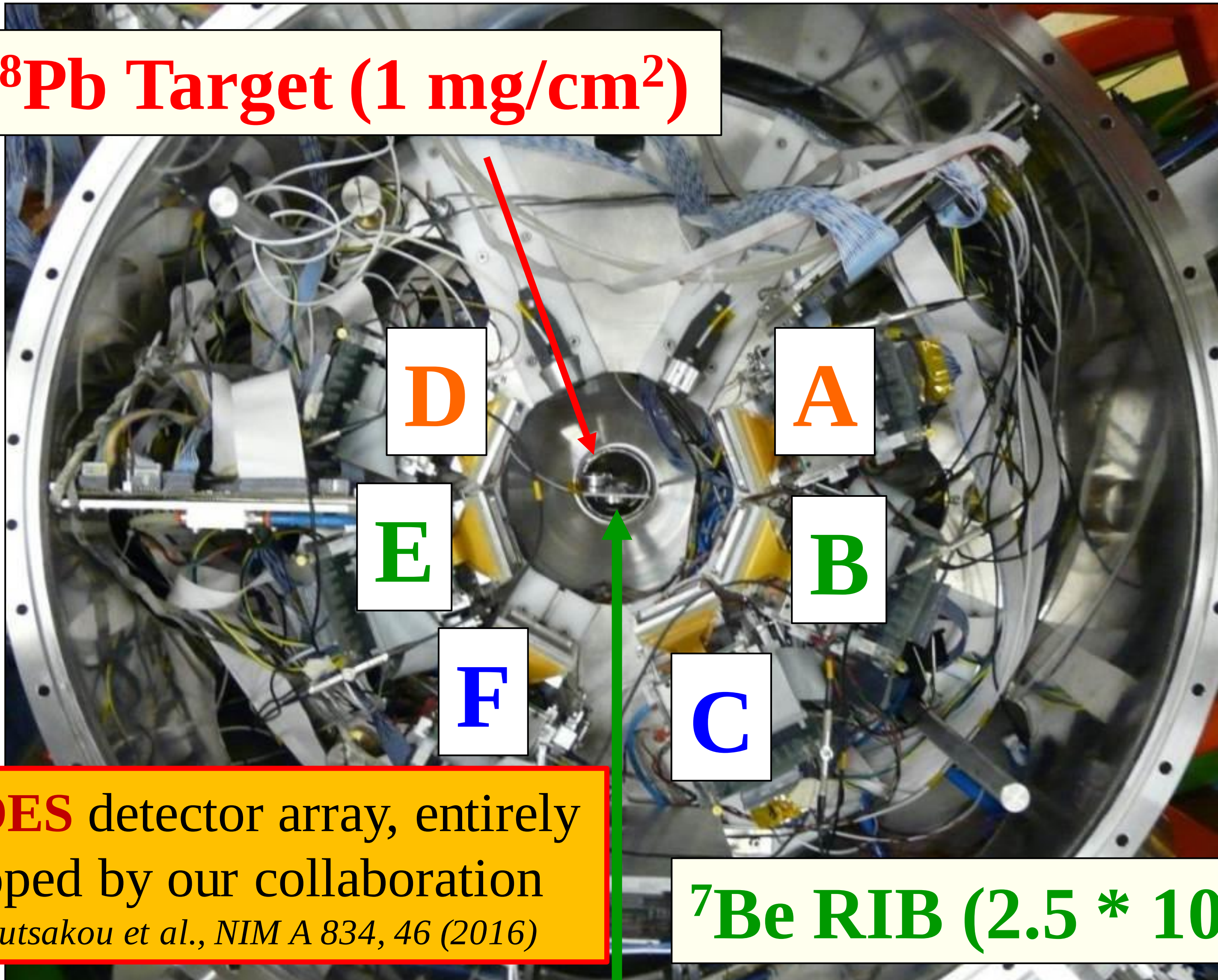
Spokespersons: C. Parascandolo, D. Pierroutsakou – Data Analysis in Progress

3. Elastic Scattering

a. $^{7}Be + ^{208}Pb$ @ LNL

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

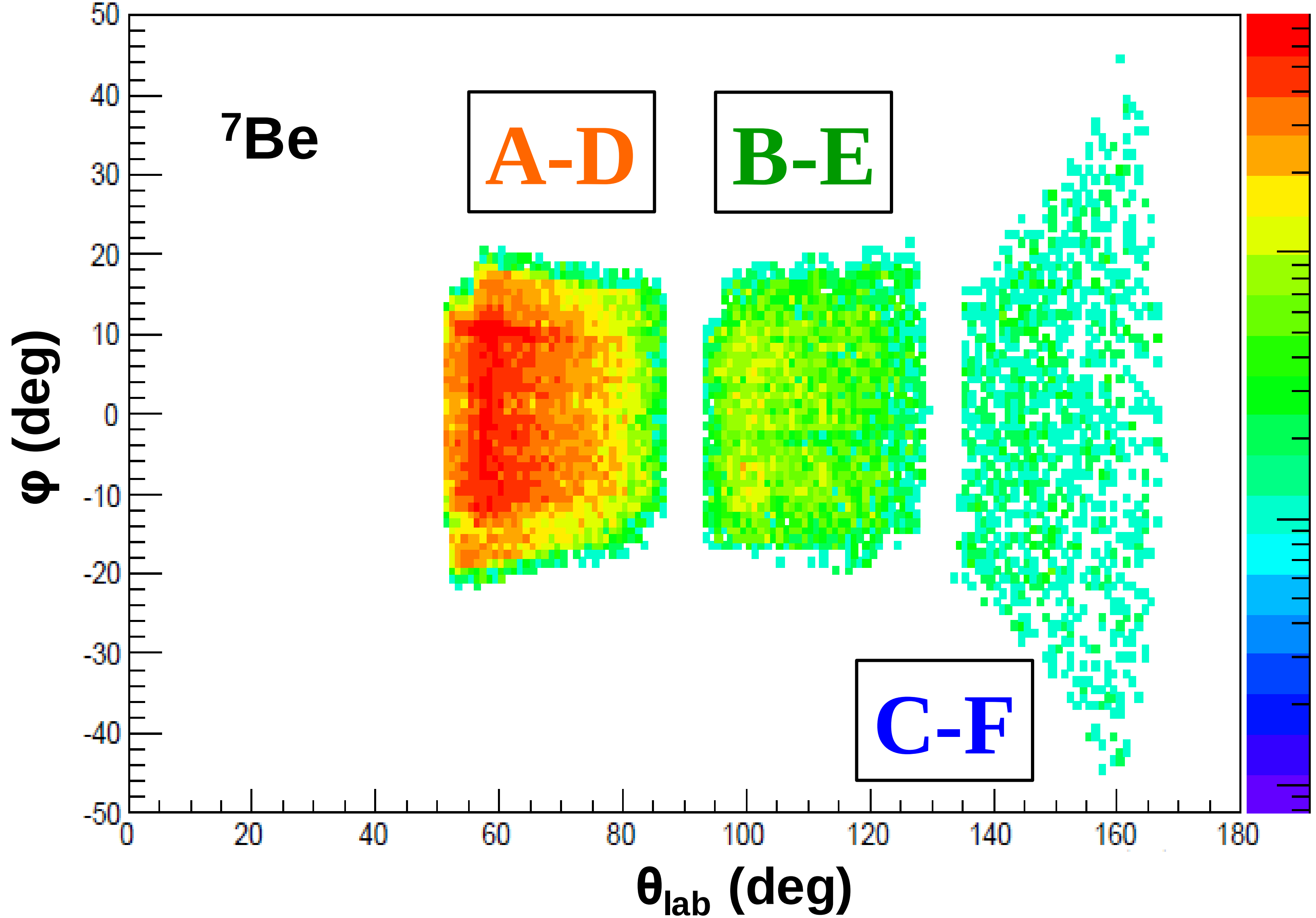
^{208}Pb Target (1 mg/cm^2)



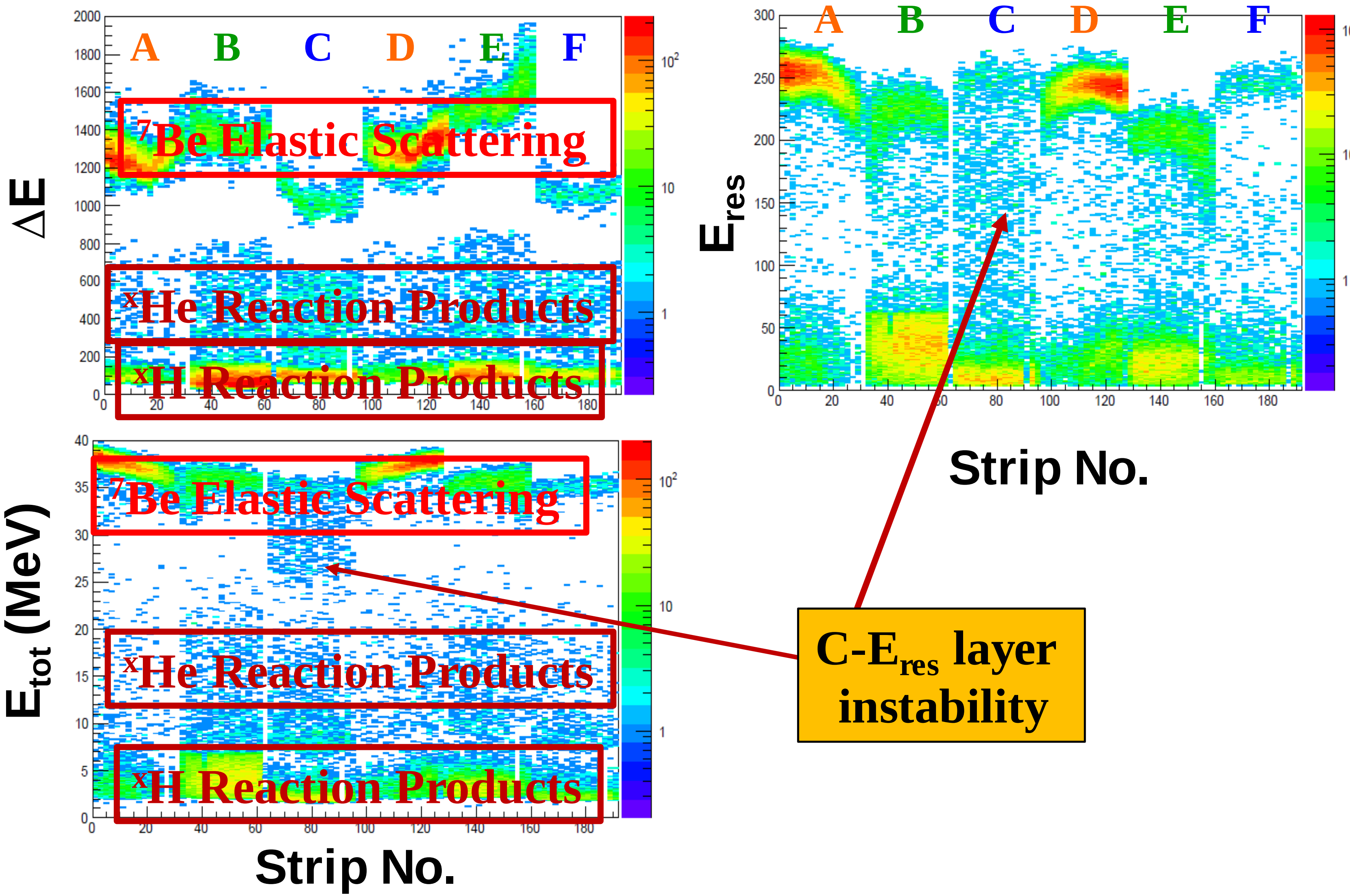
EXPADES detector array, entirely developed by our collaboration
D. Pierroutsakou et al., NIM A 834, 46 (2016)

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

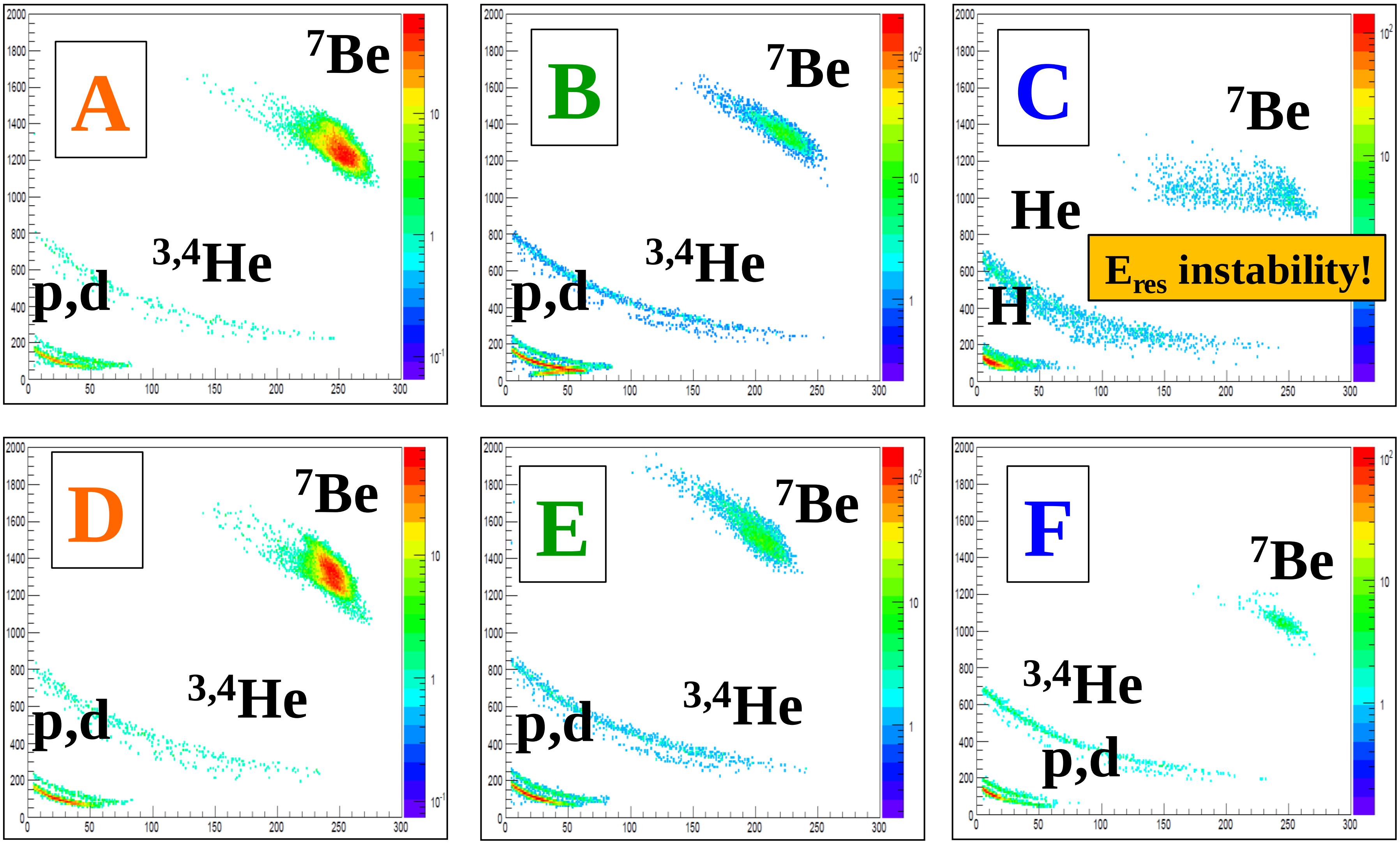
Solid Angle Coverage



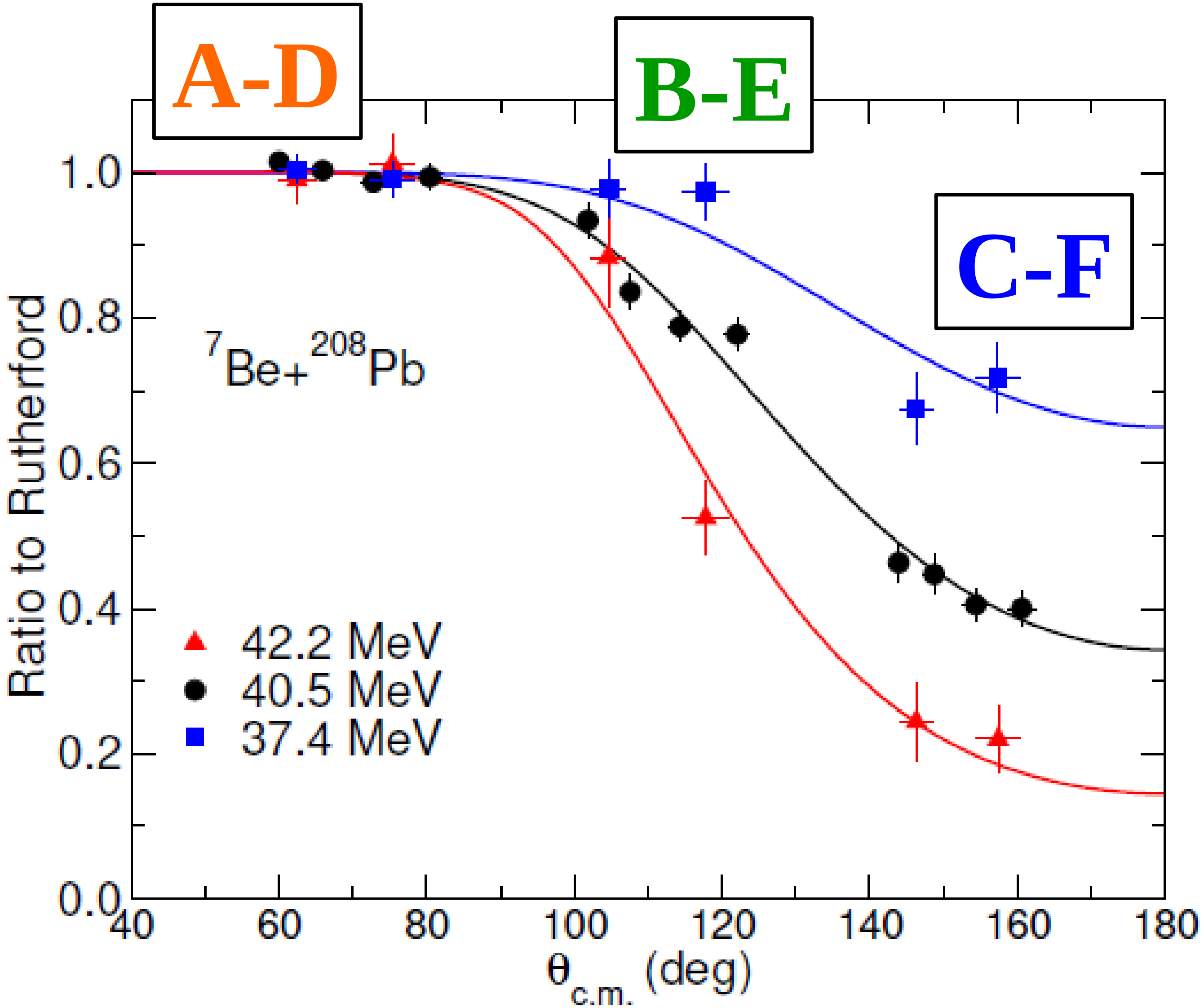
Strip Energy Spectra



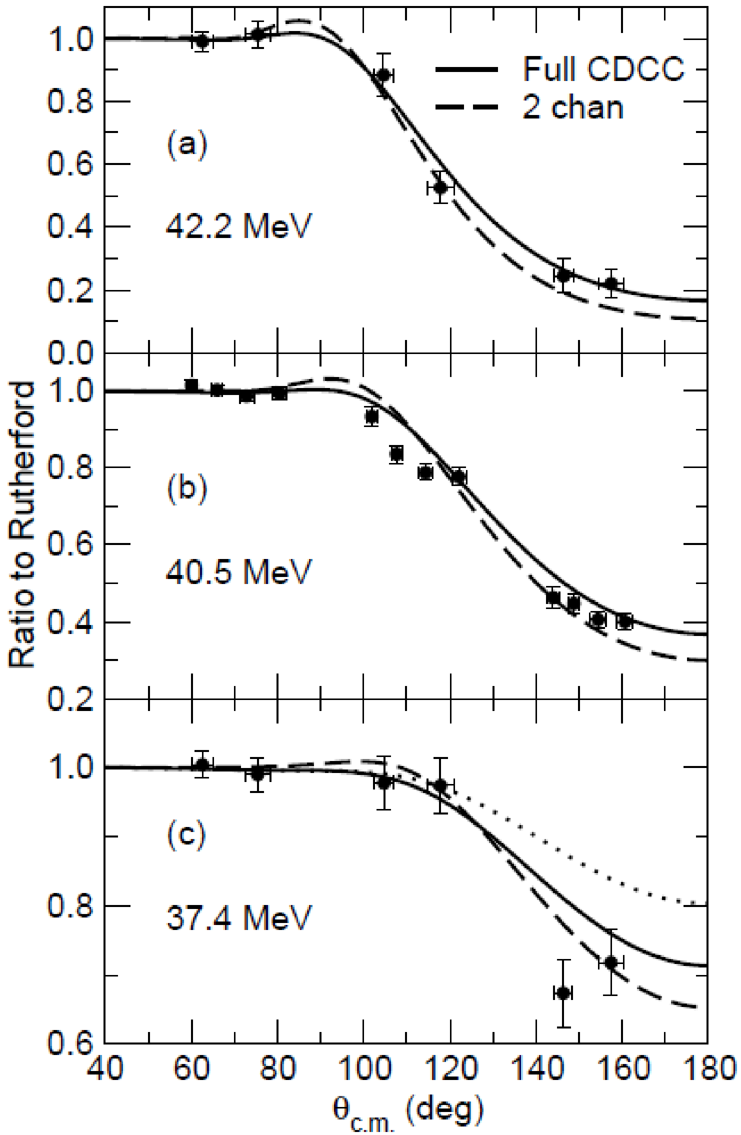
ΔE-E_{res} Plots



(Quasi-) Elastic Scattering



CDCC Calculations



Full CDCC:

^{3}He+^{4}He cluster folding model

1/2$^-$ ^{7}Be 1st ex. state at 0.429 MeV

L = 3h resonances (7/2$^-$ at 4.57 and 5/2$^-$ at 6.73 MeV)

λ = 0 – 4 non resonant continuum

continuum–continuum couplings

$\Delta k = 0.1 fm^{-1}$ up to **E_x = 9.88 MeV**

2 chan:

ground state reorientation and **1/2$^-$ ^{7}Be** 1st ex. state at 0.429 MeV

Total Reaction and Breakup

TABLE II. Total reaction (σ_R) and breakup (σ_{bu}) cross sections for $^{7}Be + ^{208}Pb$ obtained from the CDCC and 2 channel calculations, see text for details.

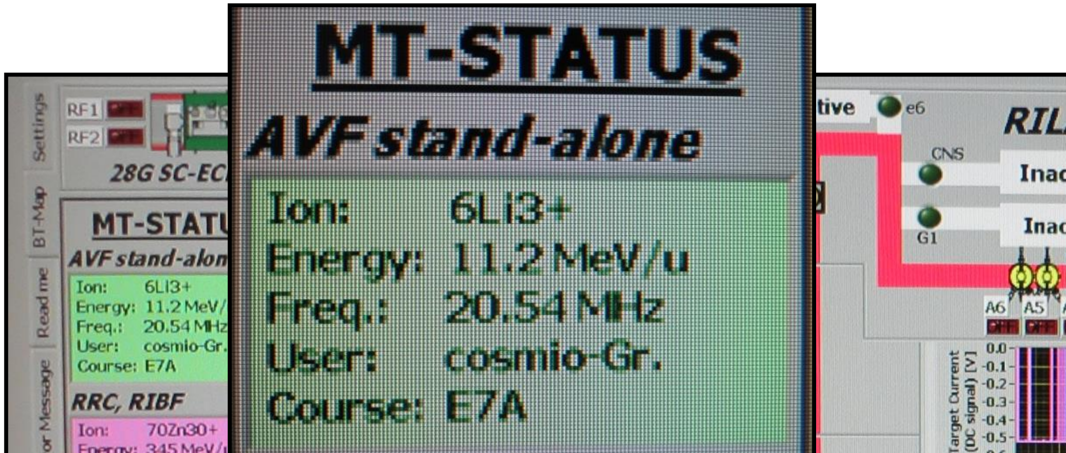
Energy	2 channel	Full CDCC
42.2 MeV	$\sigma_R = 475$ mb	$\sigma_R = 463$ mb
		$\sigma_{bu} = 38$ mb
40.5 MeV	$\sigma_R = 339$ mb	$\sigma_R = 337$ mb
		$\sigma_{bu} = 30$ mb
37.4 MeV	$\sigma_R = 222$ mb	$\sigma_R = 225$ mb
		$\sigma_{bu} = 20$ mb

According to the CDCC calculations, **breakup cross sections** are a relatively **small fraction** of the total reaction cross section (about 10%).

3. Elastic Scattering

b. $^{8}B + {}^{208}Pb$ @ CRIB

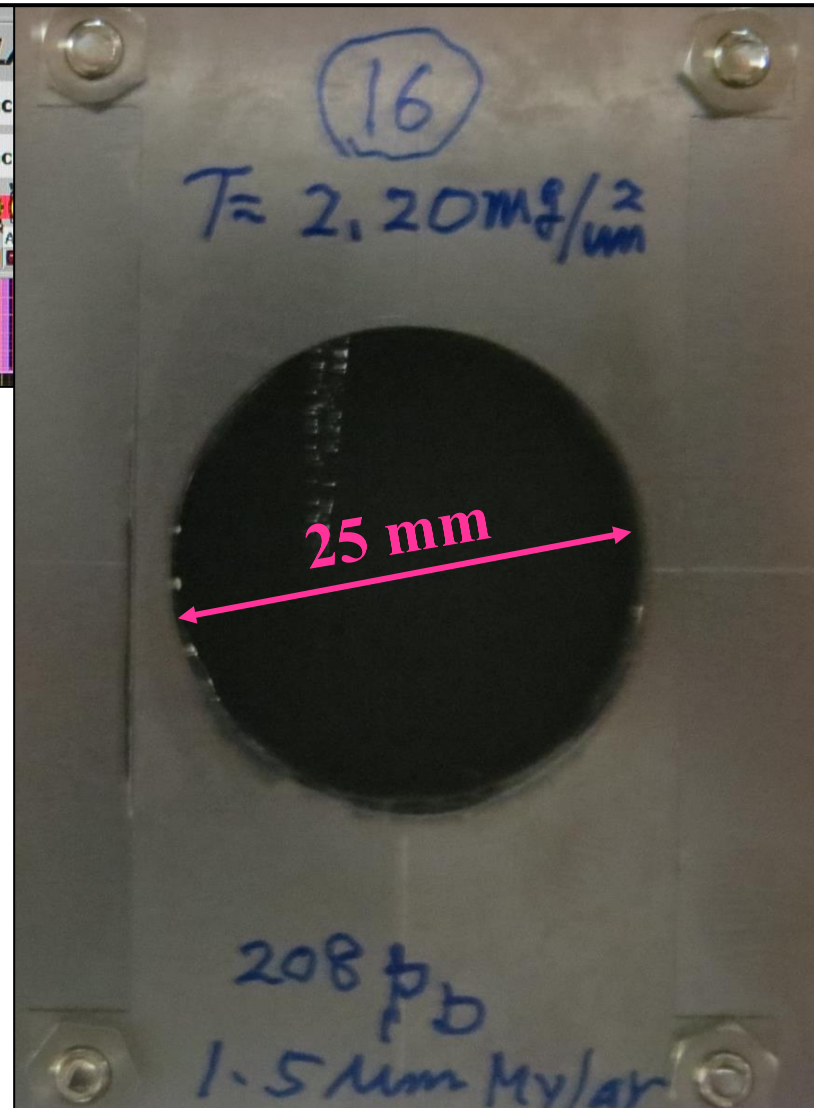
^{8}B Production at CRIB



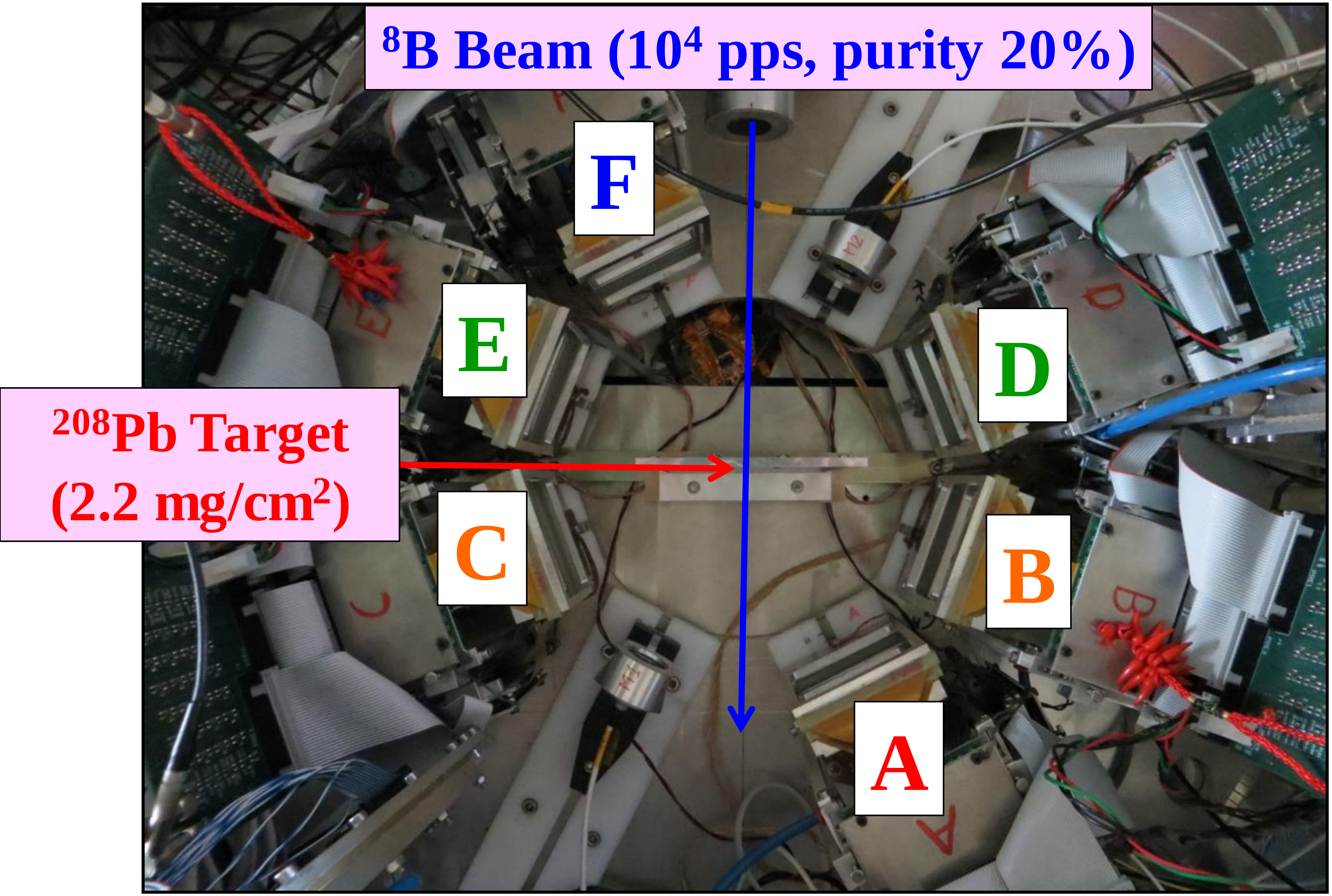
^{6}Li Primary Beam: 3 eμA on target
Production Target: ^{3}He gas at 90 K and 1 bar

^{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)

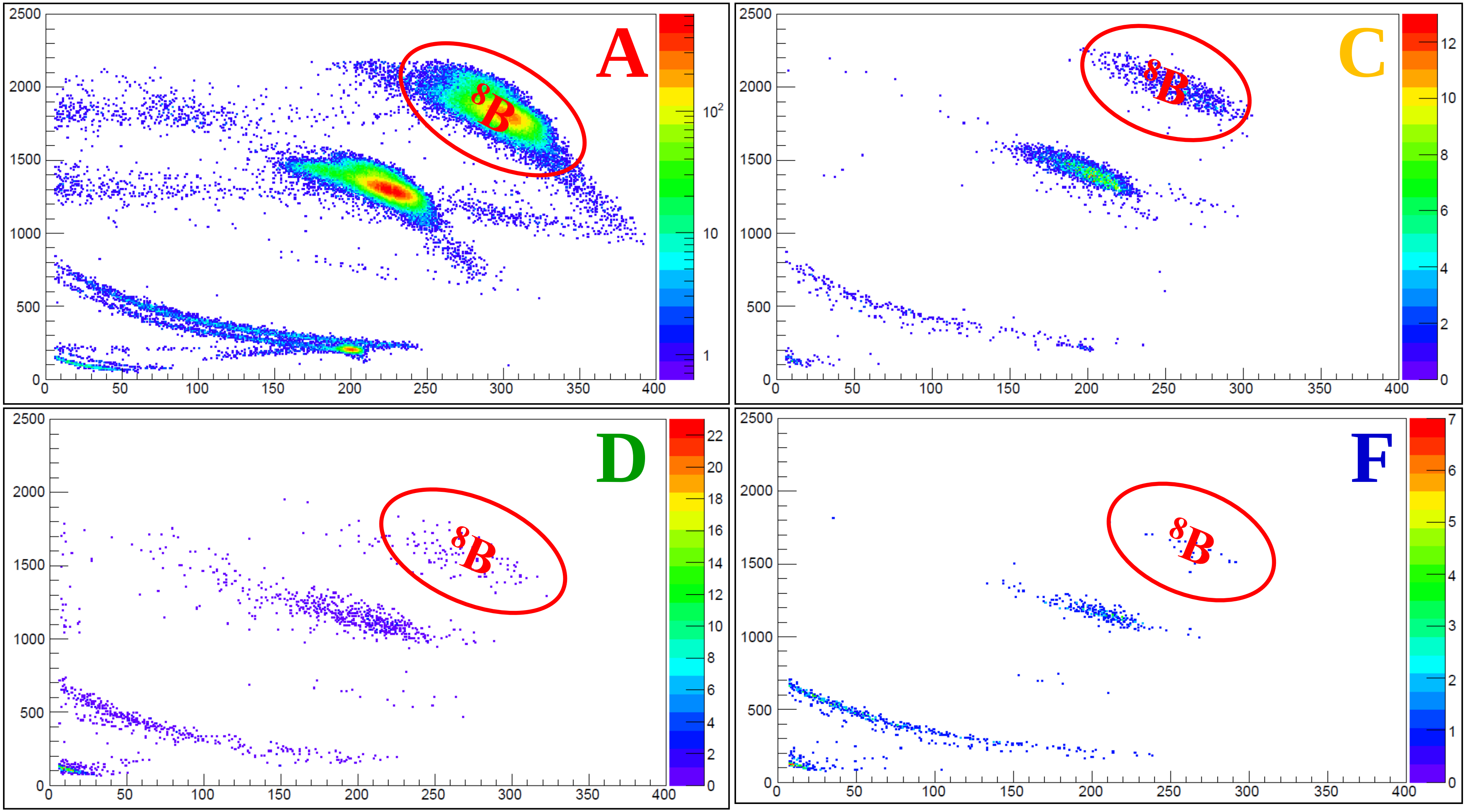
Reaction Target: 2.2 mg/cm^2 **^{208}Pb**
evaporated on 1.5 μm of Mylar.
Diameter: 25 mm



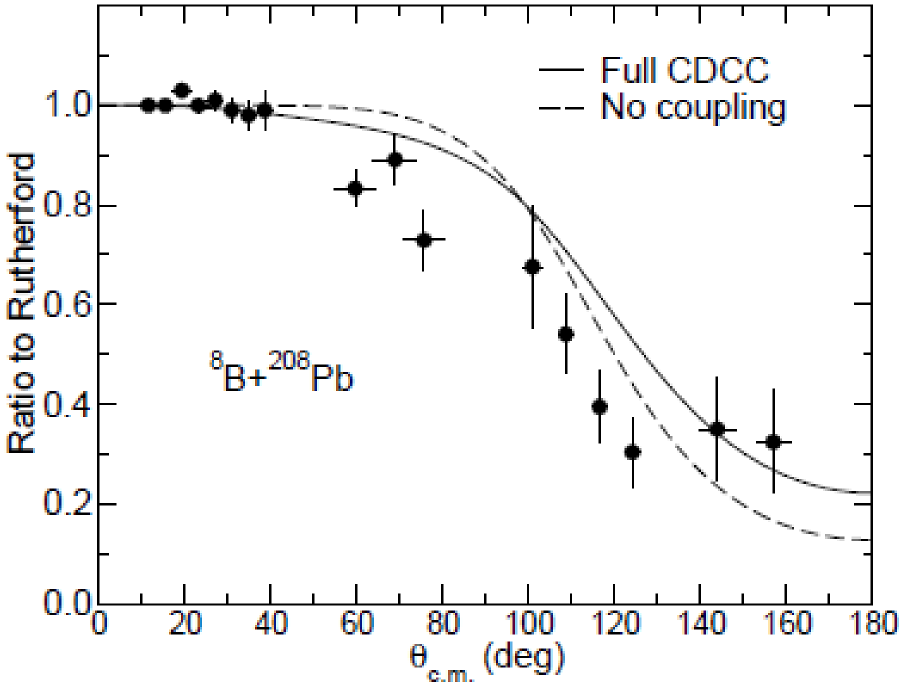
$^{8}B+^{208}Pb$ at 50 MeV



ΔE-E_{res} Plots



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



Full CDCC:

^{7}Be+p cluster folding model

^{7}Be spinless and **inert**

proton in a pure **$p_{3/2}$** state

$\lambda = 0 – 5\hbar$ non resonant continuum

continuum–continuum couplings

$\Delta k = 0.1 fm^{-1}$ up to **E_x = 11.7 MeV**

No resonances included

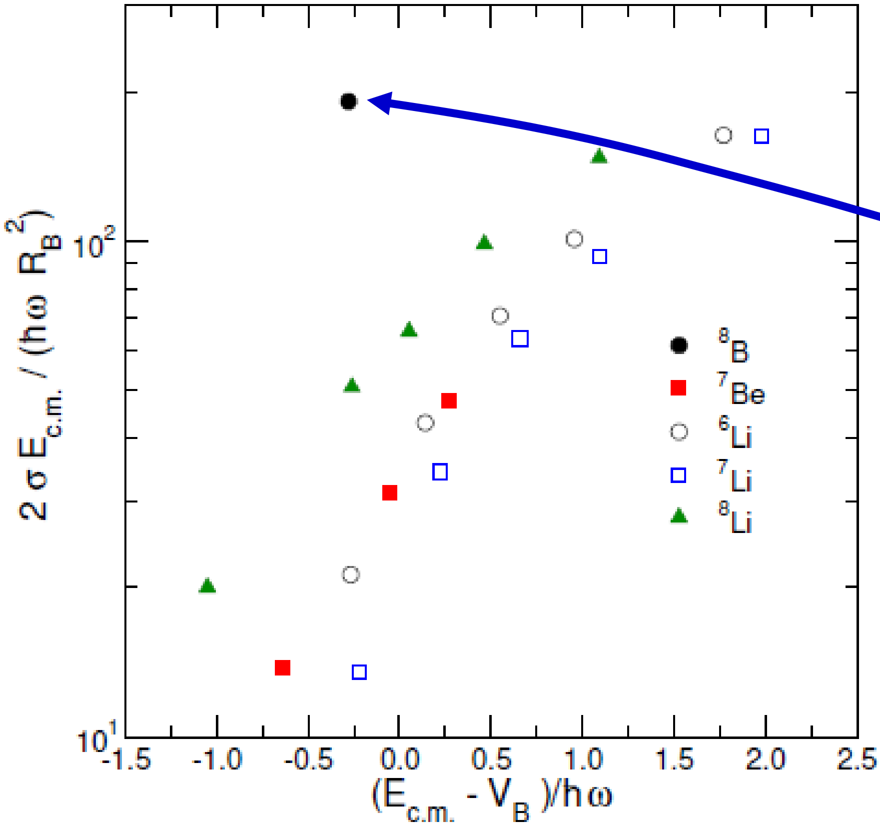
No core excitation included

Cross Sections:

Total Reaction: **1020 mb**

Breakup: **610 mb**

Total Reaction Cross Section



Enhancement probably due to the breakup process

^{7}Be + ^{208}Pb reaction cross section data follow the **^{6}Li trend**, having the two projectiles very similar binding energies. The **^{8}B + ^{208}Pb total reaction cross section** is **largerly enhanced**, with respect to the reaction of the core **^{7}Be (+ ^{208}Pb)** and of the mirror projectile **^{8}Li (+ ^{208}Pb)**.

Elastic scattering for the ^{8}B and ^{7}Be + ^{208}Pb systems at near-Coulomb barrier energies

M. Mazzocco,[1,2,*] N. Keeley,[3] A. Boiano,[4] C. Boiano,[5] M. La Commara,[6,4] C. Manea,[2,†] C. Parascandolo,[4] D. Pierroutsakou,[4] C. Signorini,[1,2] E. Strano,[1,2] D. Torresi,[1,2,‡] H. Yamaguchi,[7] D. Kahl,[7,§] L. Acosta,[8,9,‖] P. Di Meo,[4] J. P. Fernandez-Garcia,[9,¶] T. Glodariu,[10,#] J. Grebosz,[11] A. Guglielmetti,[12,5] Y. Hirayama,[13] N. Imai,[7,13] H. Ishiyama,[13] N. Iwasa,[14] S. C. Jeong,[13,15] H. M. Jia,[16] Y. H. Kim,[13] S. Kimura,[13,**] S. Kubono,[7,17] G. La Rana,[18,4] C. J. Lin,[16] P. Lotti,[2] G. Marquínez-Durán,[8] I. Martel,[8,19] H. Miyatake,[13] M. Mukai,[13] T. Nakao,[7] M. Nicoletto,[2] A. Pakou,[20] K. Rusek,[21] Y. Sakaguchi,[7] A. M. Sánchez-Benítez,[22,23] T. Sava,[10] O. Sgouros,[20,‡] V. Soukeras,[20,‡] F. Soramel,[1,2] E. Stiliaris,[24] L. Stroe,[10] T. Teranishi,[25] N. Toniolo,[26] Y. Wakabayashi,[17] Y. X. Watanabe,[13] L. Yang,[16,7] Y. Y. Yang,[27] and H. Q. Zhang[16]

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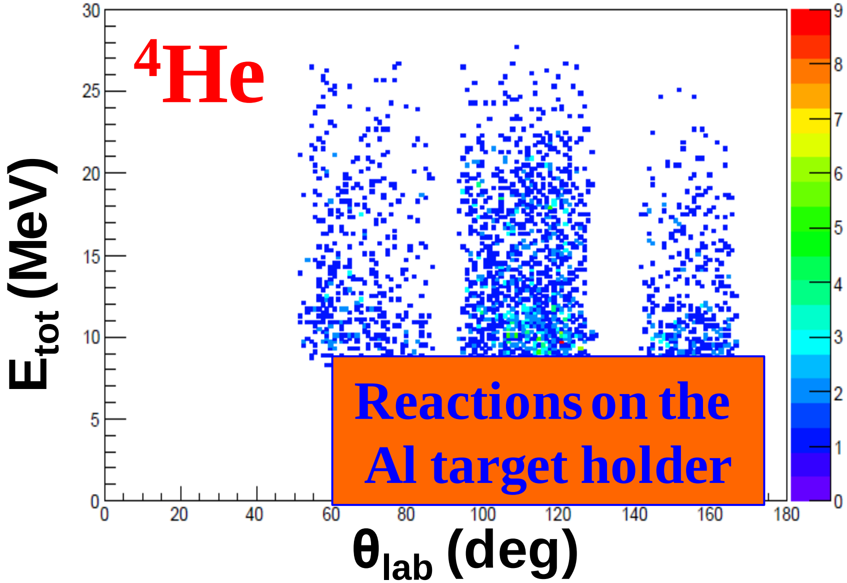
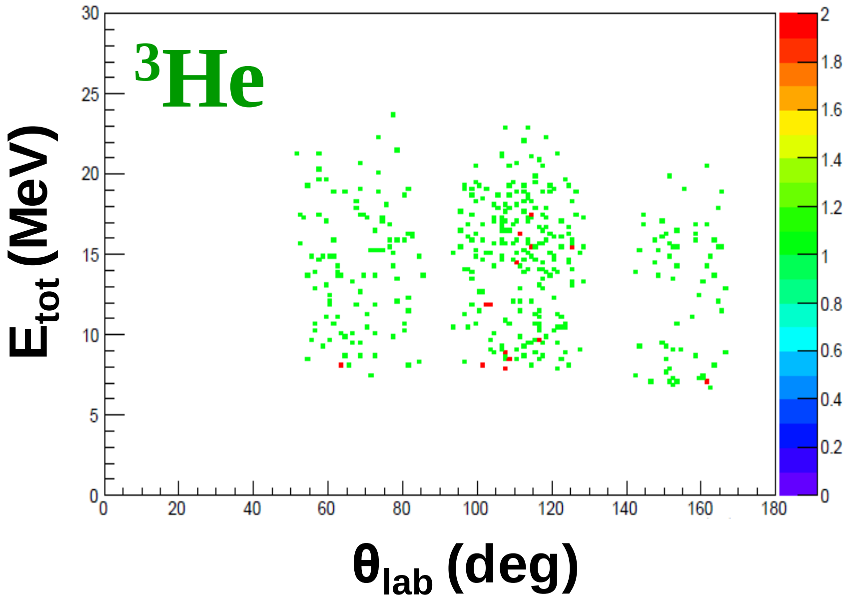
4. Other Reaction Channels

a. $^{3,4}He$ production in ^{7}Be + ^{208}Pb

^{7}Be Breakup Fragments





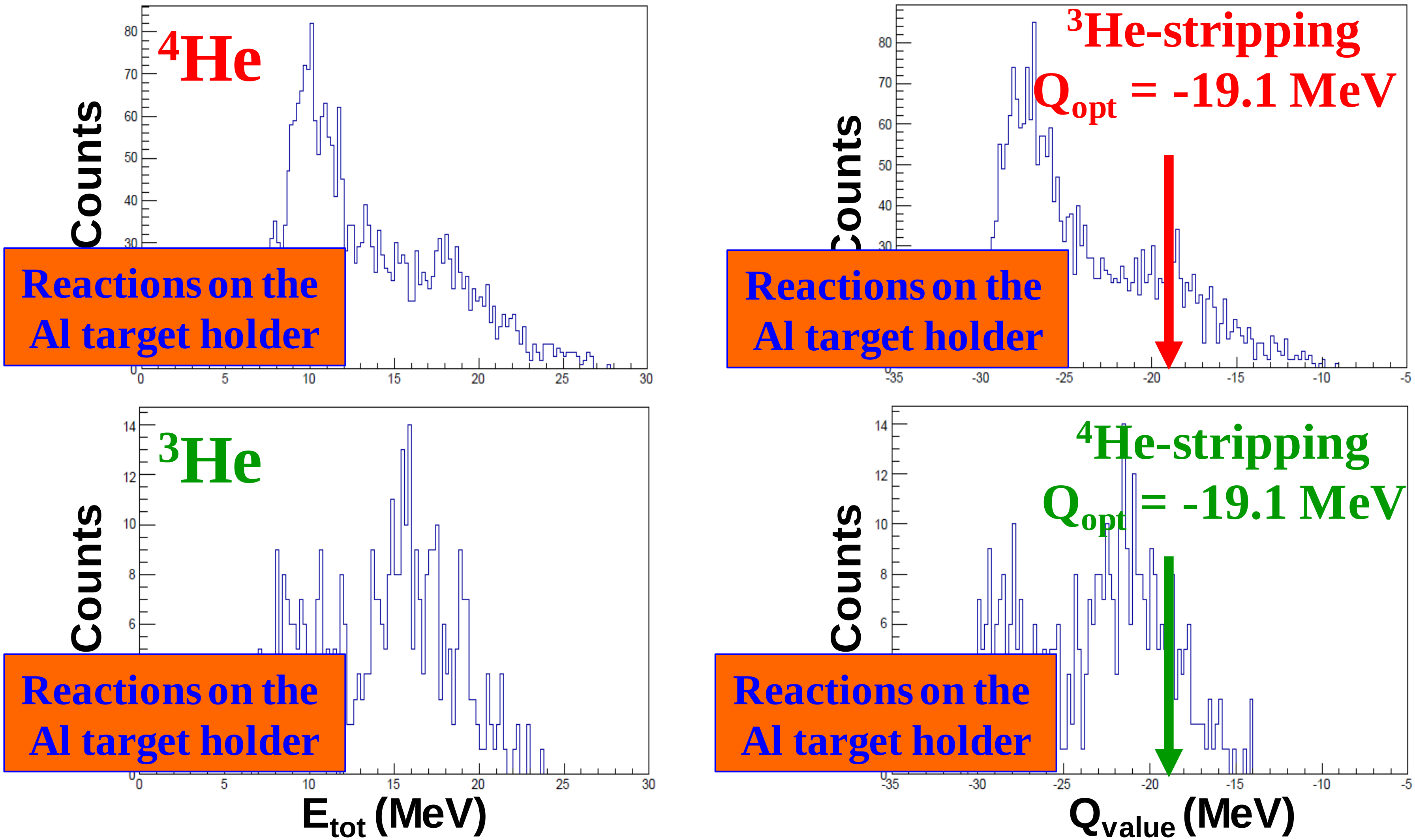
^{3}He (97.5%) and **^{4}He (99.5%)** mostly detected as **single events**.

^{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** production yield, **qualitatively confirming** our previous result for the system **^{7}Be + ^{58}Ni** [Phys. Rev. C 92, 024615 (2015)]

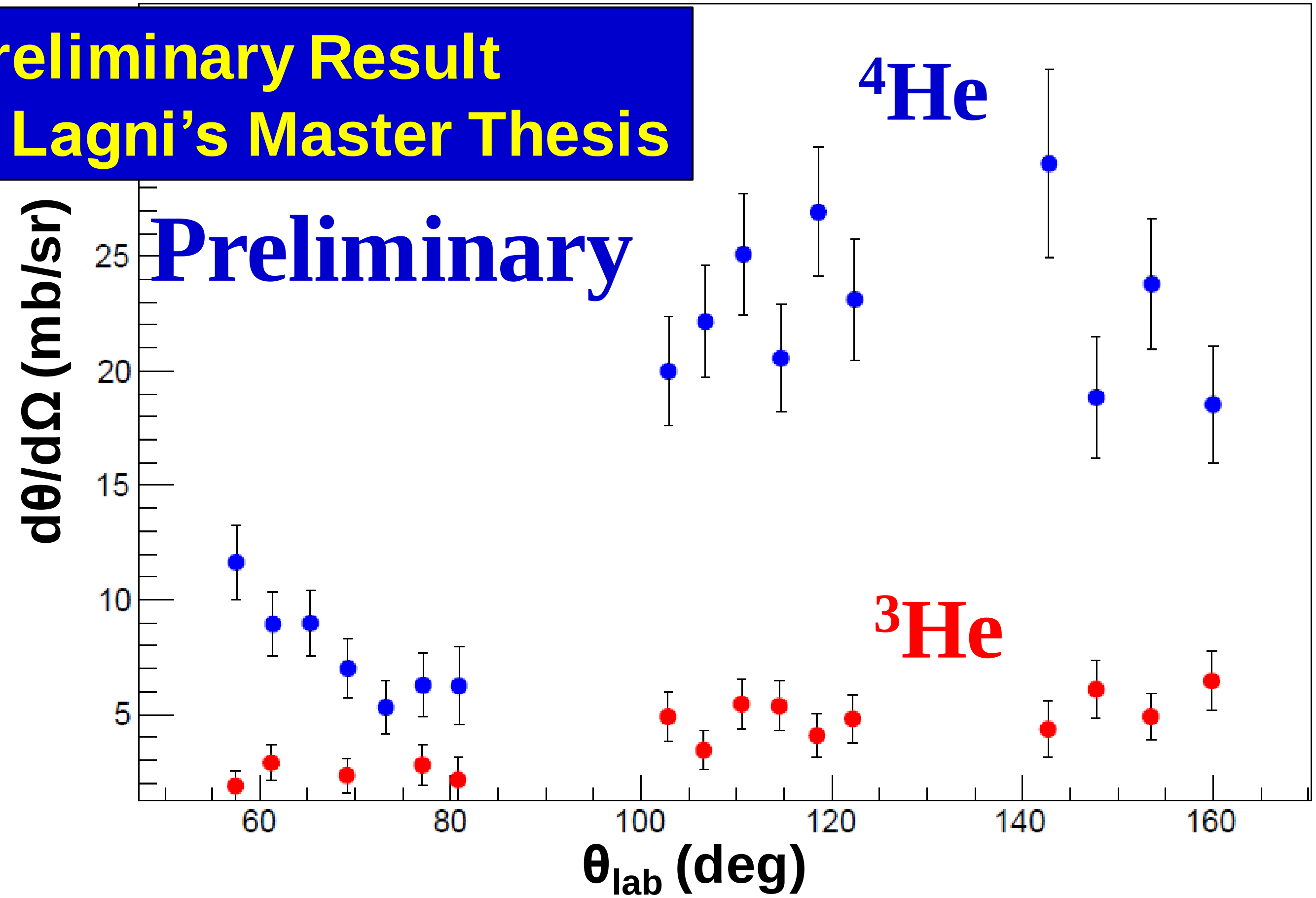
Origin of ^{3,4}He

Q_{value}-reconstruction assuming a **2-body kinematics**



$^{3,4}He$ Angular Distributions

Preliminary Result
Andrea Lagni's Master Thesis



^{3}He production cross section ≈ **30 mb** (mostly **breakup**)

^{4}He production cross section ≈ **140 mb** (several processes)

Coincidences

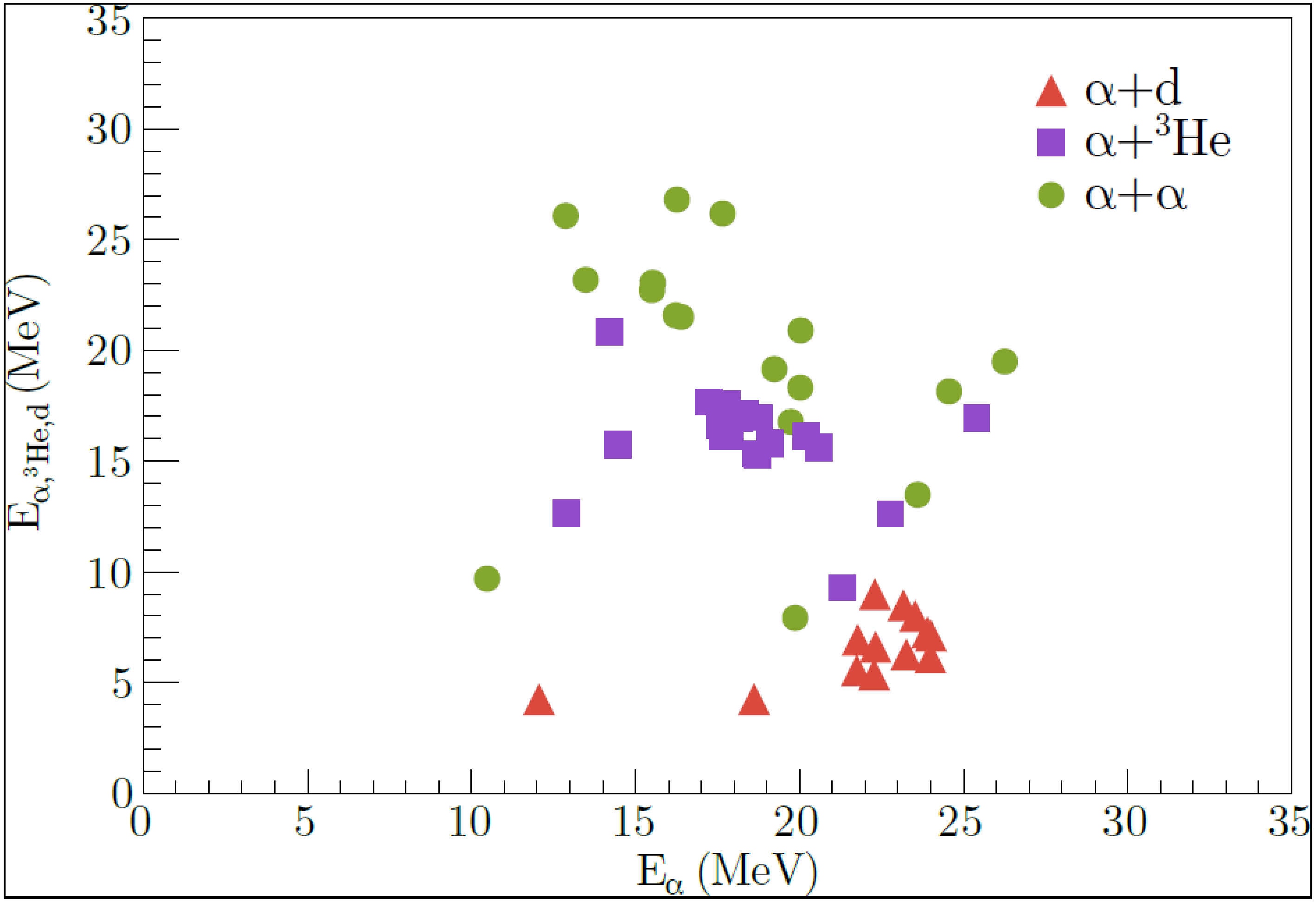
17 - ^{3}He + ^{4}He: Exclusive Breakup
(S_{α} = 1.586 MeV)

15 - ^{4}He + ^{4}He (^{8}Be): n-pickup
$^{7}Be + ^{208}Pb \rightarrow ^{8}Be + ^{207}Pb$ (Q_{gg} = +11.53 MeV)

11 - ^{4}He + d (^{6}Li): p-stripping
$^{7}Be + ^{208}Pb \rightarrow ^{6}Li + ^{209}Bi$ (Q_{gg} = -1.81 MeV)

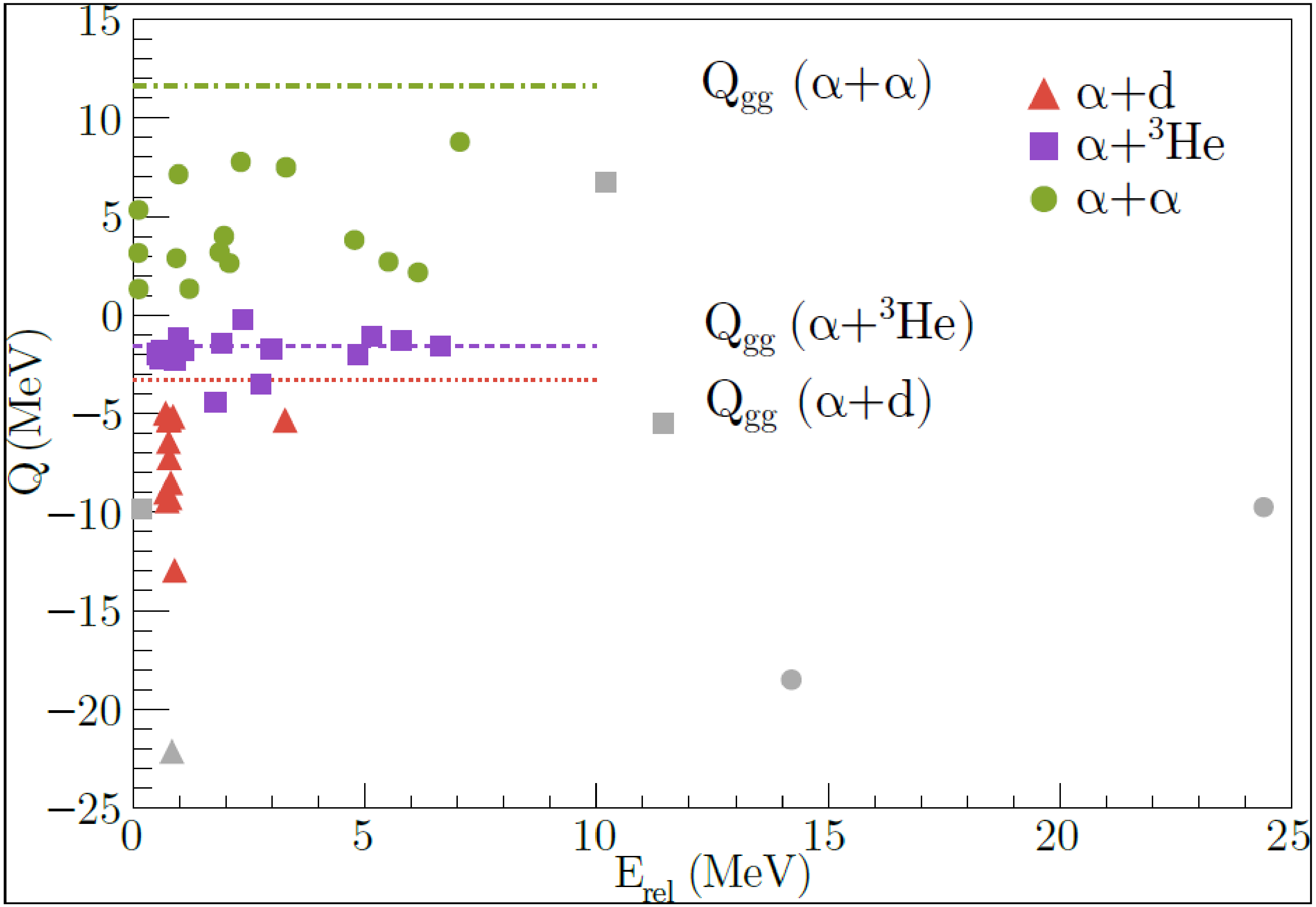
We performed the **Q_{value}** and **Relative Energy (E_{rel})** reconstruction, getting information of the **target** and **projectile** excitation during the nuclear collision.

$E_1 - E_2$ Energy Correlation



Courtesy of K.J. Cook

Q_{value} *vs.* E_{rel}

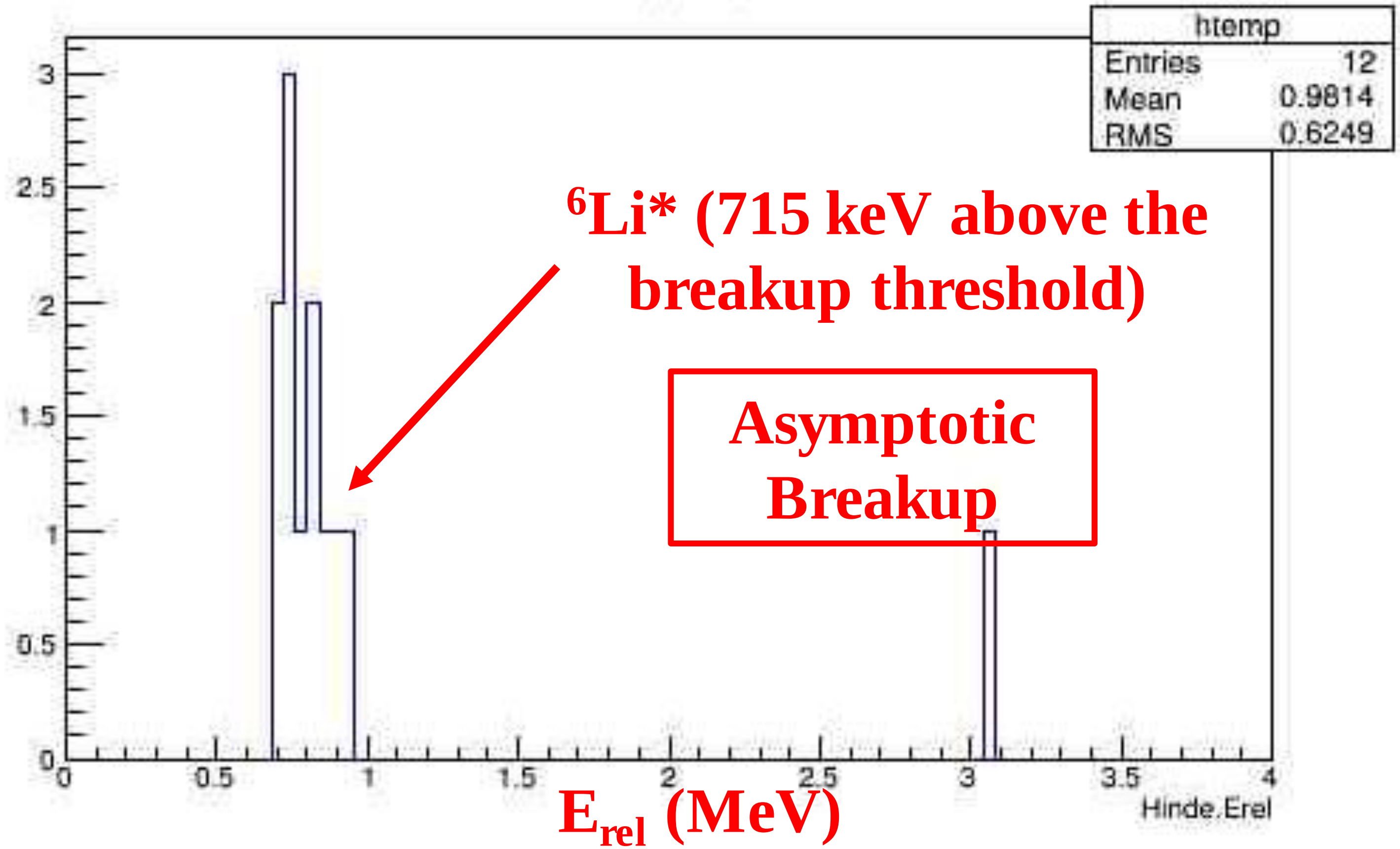


Courtesy of K.J. Cook

^{7}Be: ^{4}He – ^{2}H Coincidences

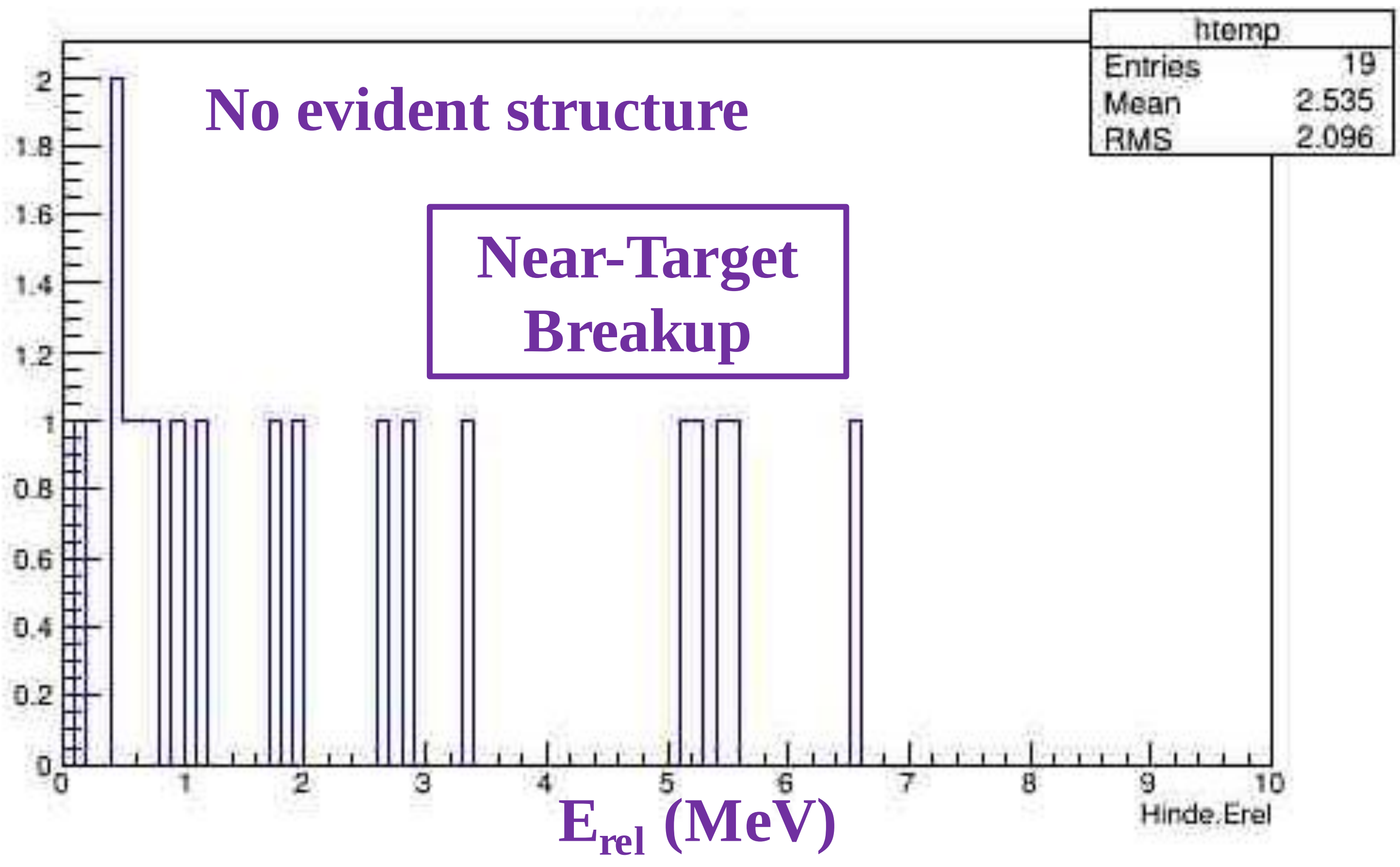
p-stripping

^{7}Be + ^{208}Pb → ^{6}Li + ^{209}Bi (Q_{gg} = -1.81 MeV)



^{7}Be: ^{4}He – ^{3}He Coincidences

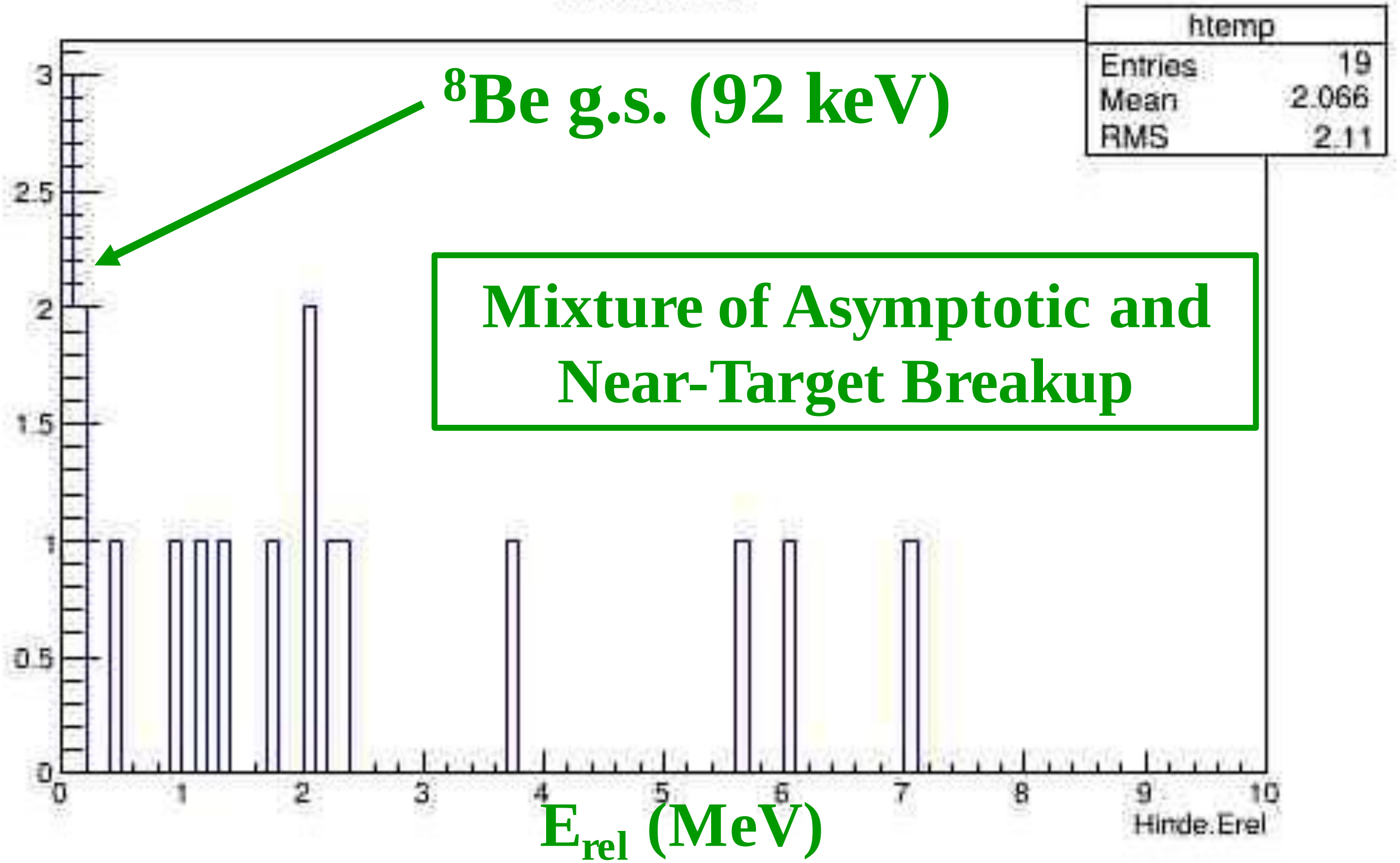
Exclusive Breakup
(S_α = 1.586 MeV)



^{7}Be: ^{4}He – ^{4}He Coincidences

n-pickup

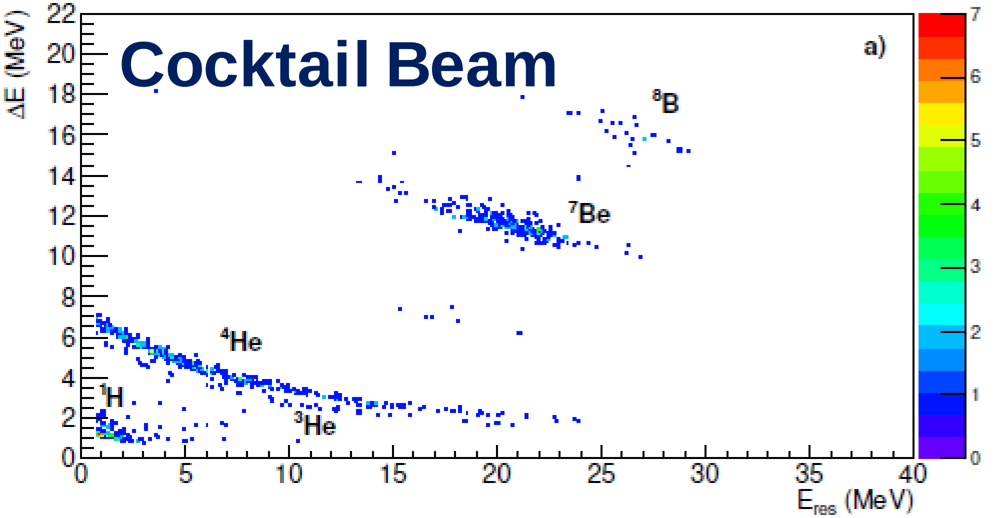
$^{7}Be + ^{208}Pb \rightarrow ^{8}Be + ^{207}Pb$ (Q_{gg} = +11.53 MeV)

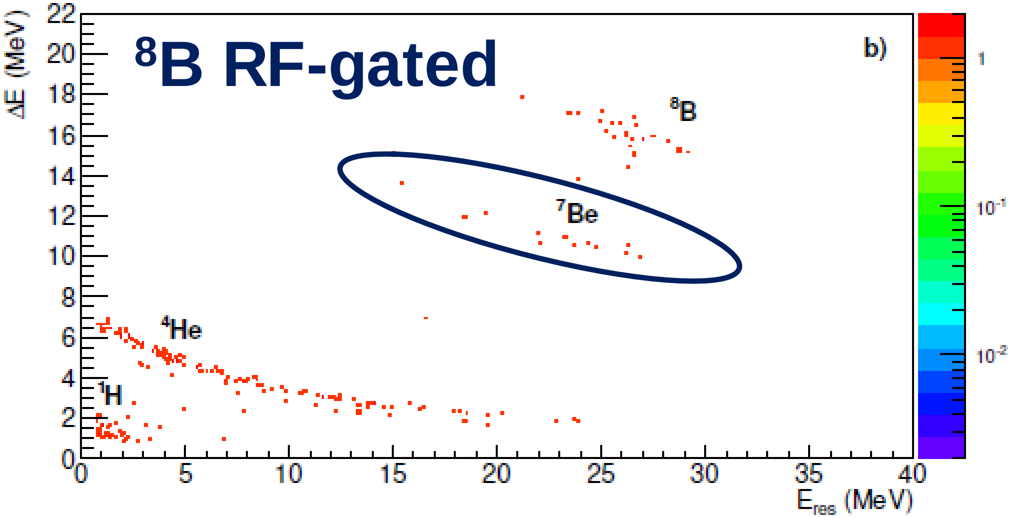


4. Other Reaction Channels

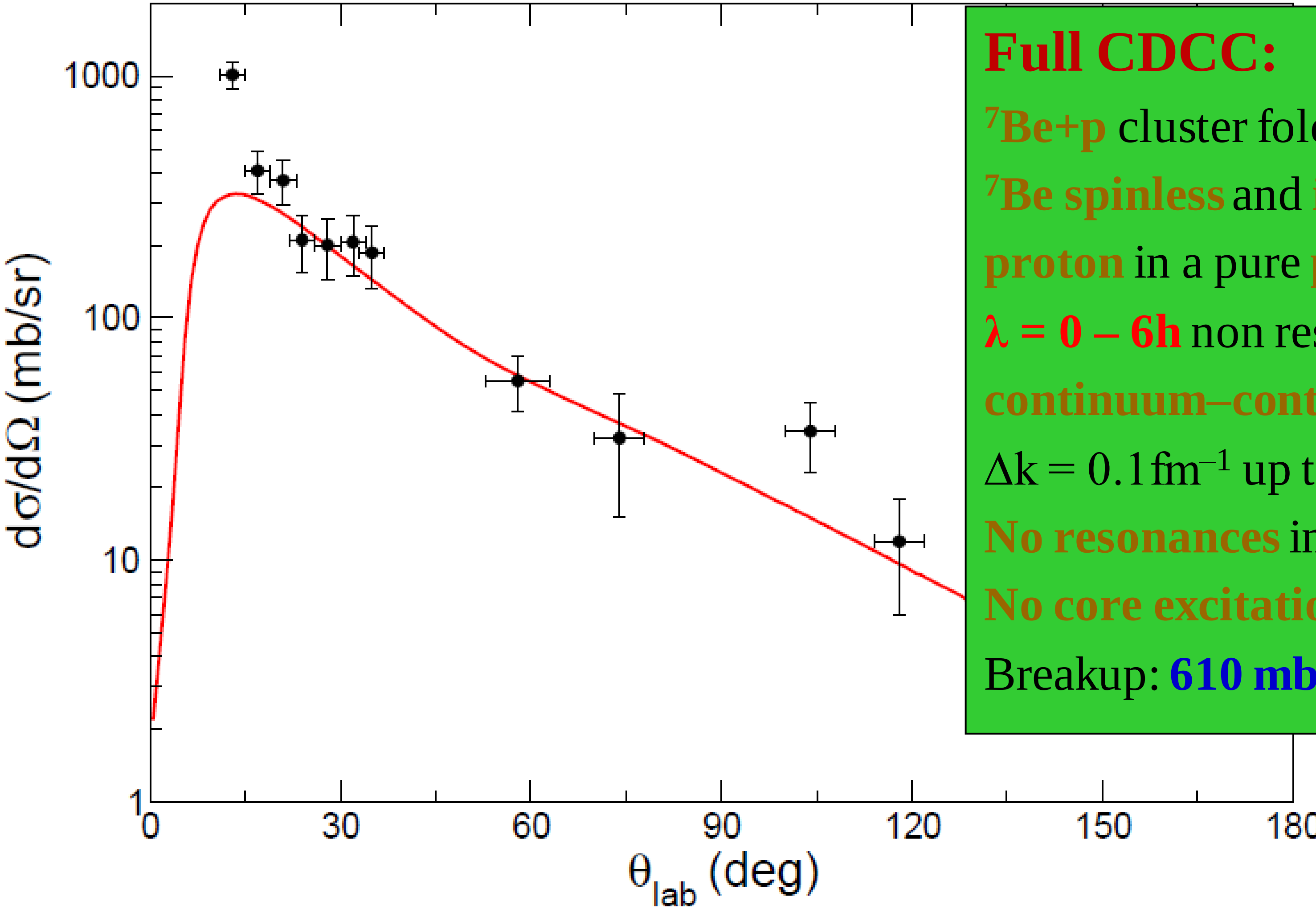
b. ^{7}Be production in $^{8}B + ^{208}Pb$

^{8}B Breakup Fragment





^{7}Be Angular Distribution



Full CDCC:

^{7}Be+p cluster folding model

^{7}Be spinless and **inert**

proton in a pure **$p_{3/2}$** state

λ = 0 – 6h non resonant continuum

continuum–continuum couplings

$\Delta k = 0.1\,fm^{-1}$ up to **E_x = 11.7 MeV**

No resonances included

No core excitation included

Breakup: **610 mb**

^{8}B + ^{58}Ni Breakup

VOLUME 84, NUMBER 9 PHYSICAL REVIEW LETTERS 28 FEBRUARY 2000

Nuclear and Coulomb Interaction in ^{8}B Breakup at Sub-Coulomb Energies

V. Guimarães, J. J. Kolata, D. Peterson, P. Santi, R. H. White-Stevens, and S. M. Vincent
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F. D. Becchetti, M. Y. Lee, T. W. O'Donnell, D. A. Roberts, and J. A. Zimmerman
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(Received 24 September 1999)

The angular distribution for the breakup of $^{8}B \rightarrow {}^{7}Be + p$ on a ^{58}Ni target has been measured at an incident energy of 25.75 MeV. The data are inconsistent with first-order theories but are remarkably well described by calculations including higher-order effects. The comparison with theory illustrates the importance of the inclusion of the exotic proton halo structure of ^{8}B in accounting for the data.

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Breakup of ^{8}B at sub-Coulomb energies

J. J. Kolata, V. Guimarães,* D. Peterson,† P. Santi,‡ R. H. White-Stevens, and S. M. Vincent§
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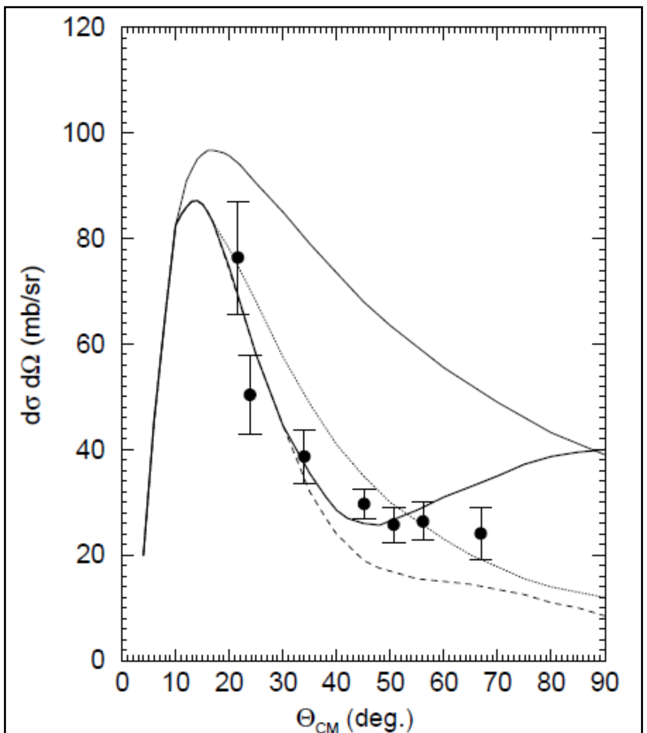
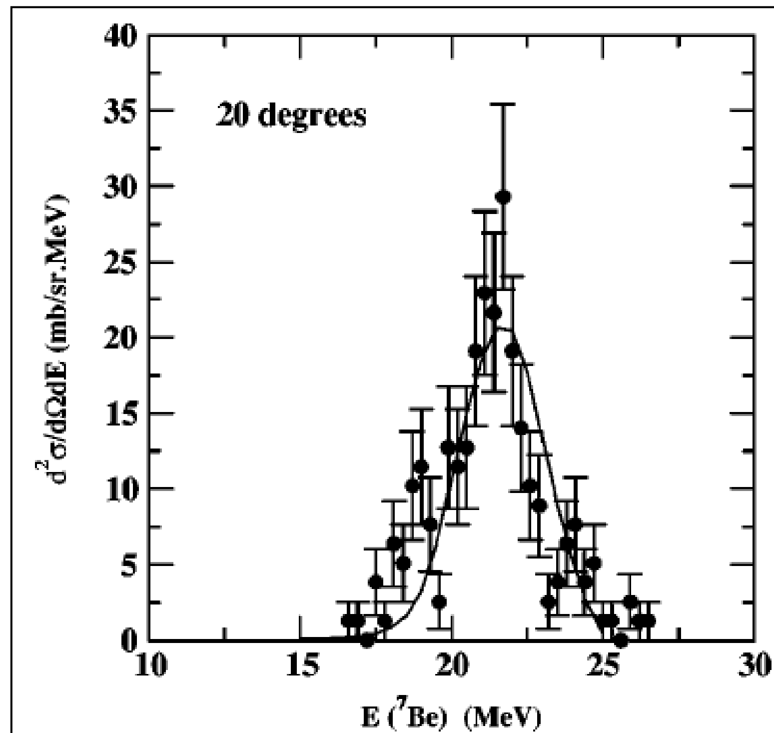
(Received 2 October 2000; published 25 January 2001)

Energy distributions for outgoing ^{7}Be fragments from breakup of ^{8}B on a ^{58}Ni target have been measured at an incident energy of 25.75 MeV, which is below the Coulomb barrier. The data are compared with coupled-channels calculations that include higher-order couplings in the continuum.





5. 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.

Interesting and consisting results have been obtained for the system **^{7}Be+^{208}Pb**: **elastic scattering** and **^{3,4}He** production yields and **^{4}He** ions resulted to be **more abundant** than **^{3}He**.

The **elastic scattering** for the system **^{8}B+^{208}Pb** was measured at **CRIB (Japan)** and the **total reaction cross section** results to be enhanced by a **factor of 3** with respect to the reaction **^{7}Be+^{208}Pb**.

CDCC calculations suggest that the **breakup process** could account for **~ 60%** of the total reaction cross section.

Experiments in Collaboration with…

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Thank You Very Much for the Attention!