Recent results for the dynamics of halo nuclei at barrier energies

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Outlook

- The developing of technology regarding beam production, charge particle detection and data acquisition systems is allowing to revisit some reactions involving weakly bound nuclei.

- During the last 7 years, we have developed a number of experiments in different laboratories involving reactions with weakly bound nuclei, mostly halo nuclei, impinging in medium mass and heavy targets at energies in the vicinity of Coulomb barrier.

- For several years, the analysis of this kind of reaction has shown a degree of differences in the elastic scattering comparing with stable similar nuclei in the same conditions.

- Moreover, the reaction products have shown in particular cases, the preference to follow not always the same process, when the reaction is measured in a wide angular range.

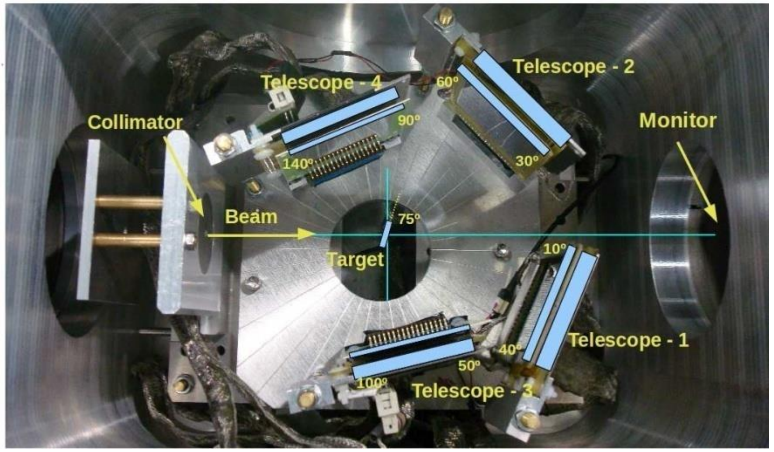
- The global conclusion shows that, not all the halos follow the same behaviour when their dynamics is tested at barrier energies.

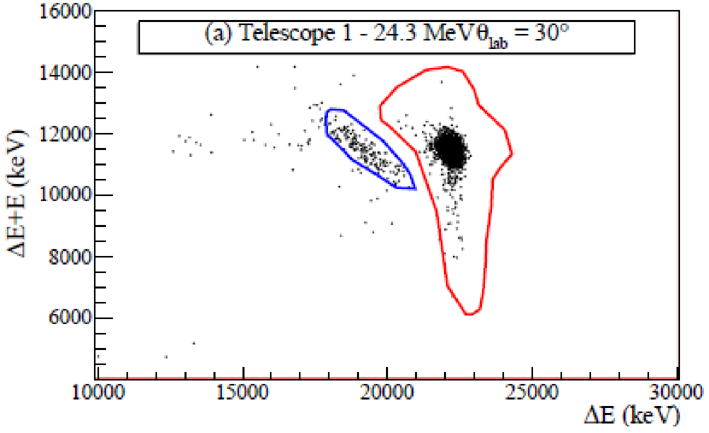
- In the present work, recent results regarding such nuclei and other recent visited cases will be presented, as well as a brief description of the instrumentation developed for such studies.

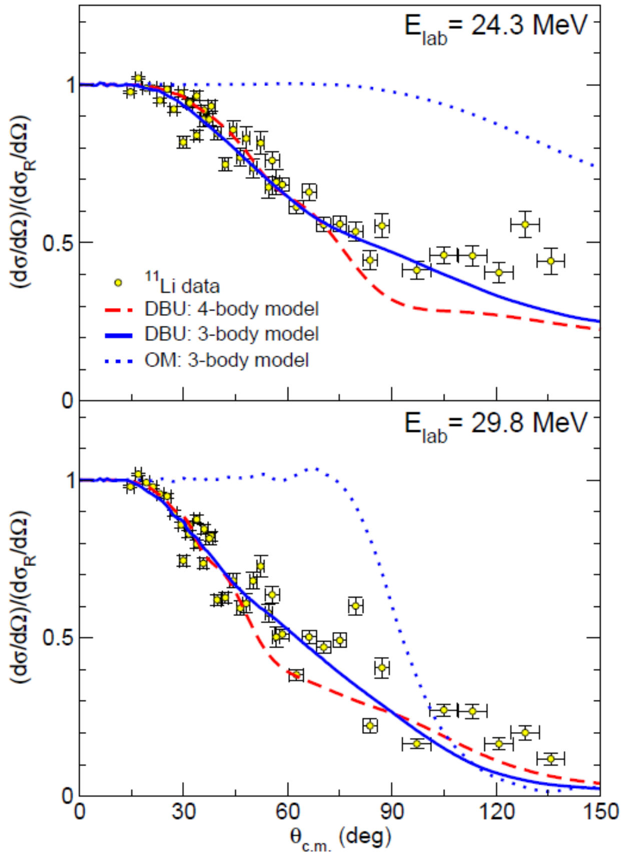
The ^{11}Be and ^{11}Li, scattering and products

^{11}Li + ^{208}Pb @ 24.3 y 29.8 MeV

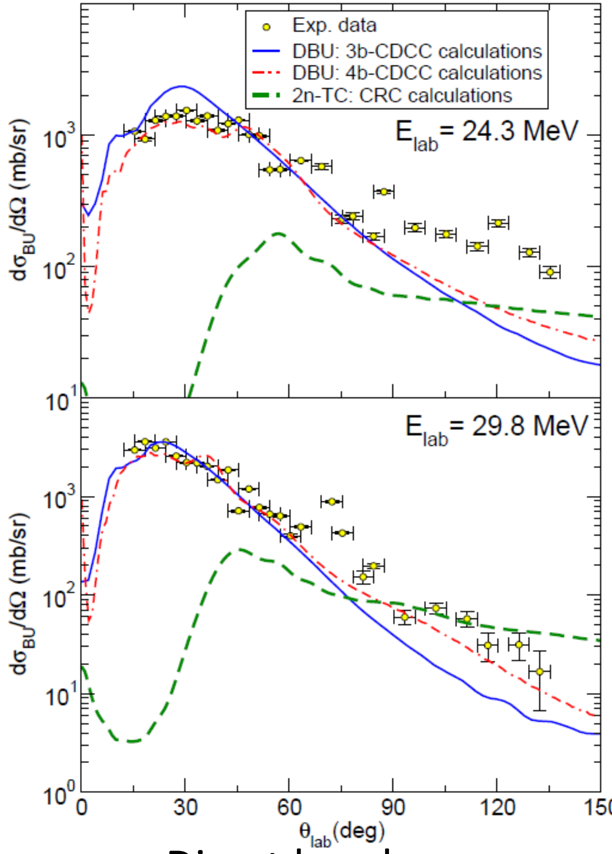
TRIUMF 2008-2009







elastic



Direct breakup

For the ^{11}Li (Borromean 2-neutron halo) the scattering close to the barrier shown strong absorption. This effect can be observed starting at very forward angles. The 3 and 4-body CDCC show this strong dipole coupling.

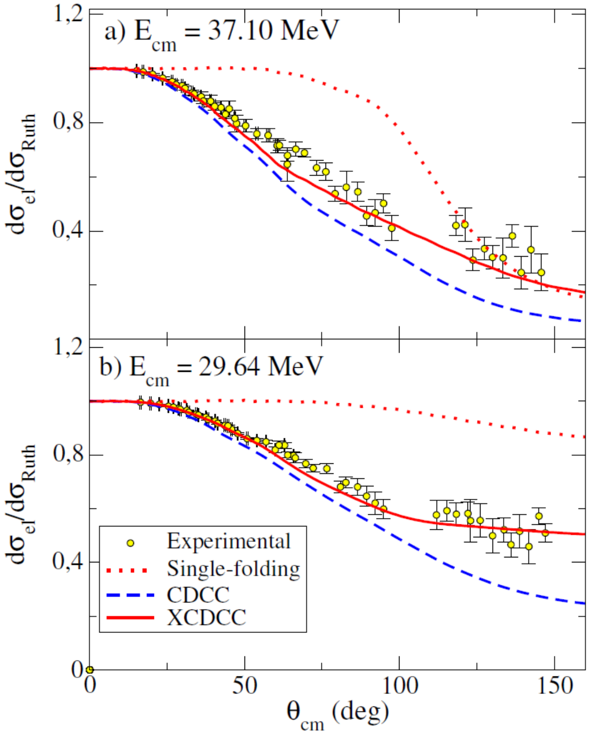
Due to the detectors position, a strange behavior is observed in some data.

The breakup follows in good way both calculations at forward angles, showing discrepancies for backward angles, where is possible to expect a competition between transfer a direct breakup.

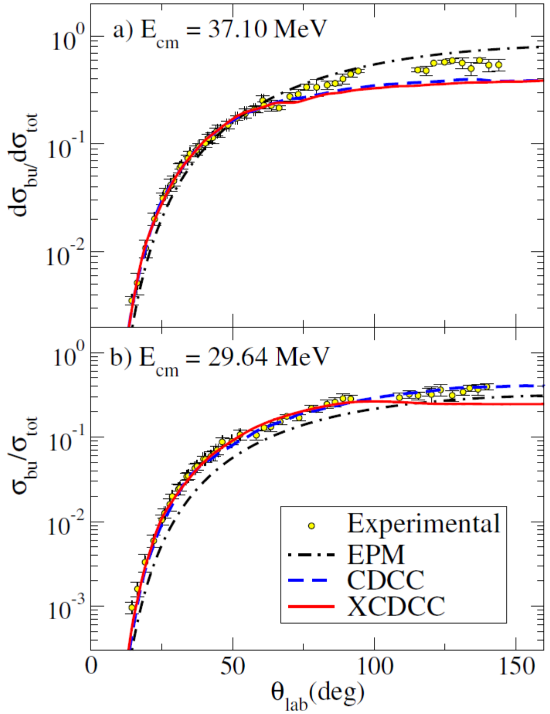
J. P. Fernández-García, PRL, 110, 142701 (2013).
M. Cubero, PRL 109, 262701 (2013)
J.P. Fernández-García, PRC 92, 044608 (2015).

The ^{11}Be and ^{11}Li products

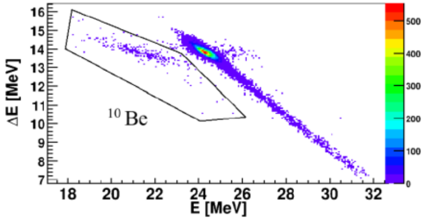
^{11}Be + ^{197}Au (29 and 37 MeV) TRIUMF (2011-2012)

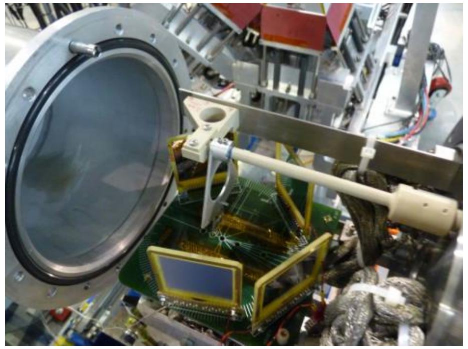


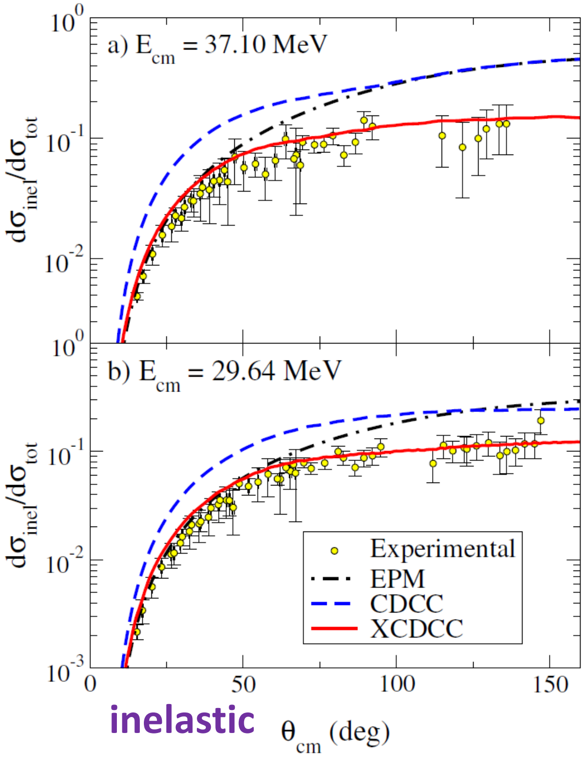
elastic



breakup





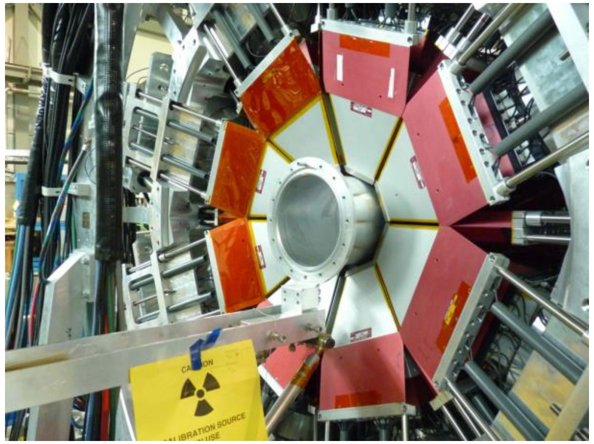


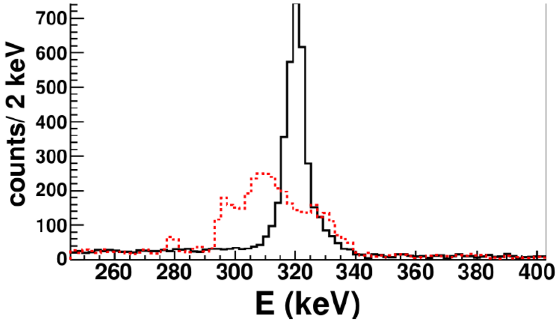
inelastic

First time that the single excited state of ^{11}Be is measured, by using the coincidence between gamma emission and the scattering on silicon detectors. As before, the strong absorption is observed this time in a wide angular range.

- First order semi-classical calculation including E1 couplings.
- CDCC calculation, including bound and unbound states of the ^{11}Be+n projectile and couplings among them to all orders;
- **Extended CDCC calculation (XCDCC) which incorporates the deformation of the ^{10}Be core in the structure of ^{11}Be, and the possible excitation of the core during the interaction.**

V. Pesudo et. al., PRL 118 152502 (2017)

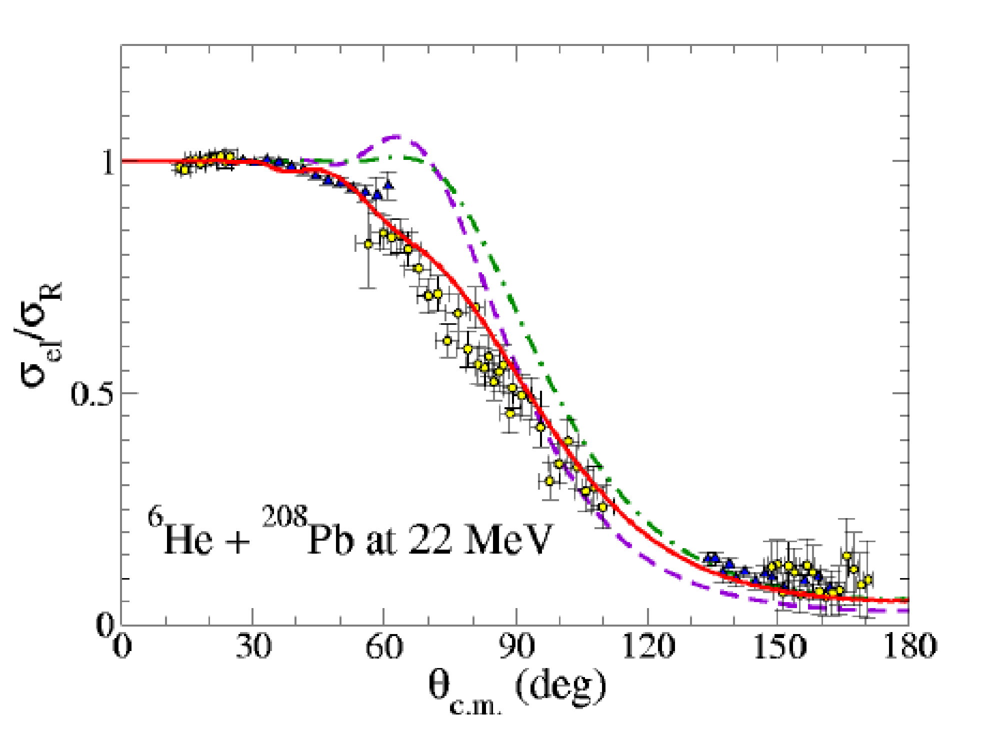




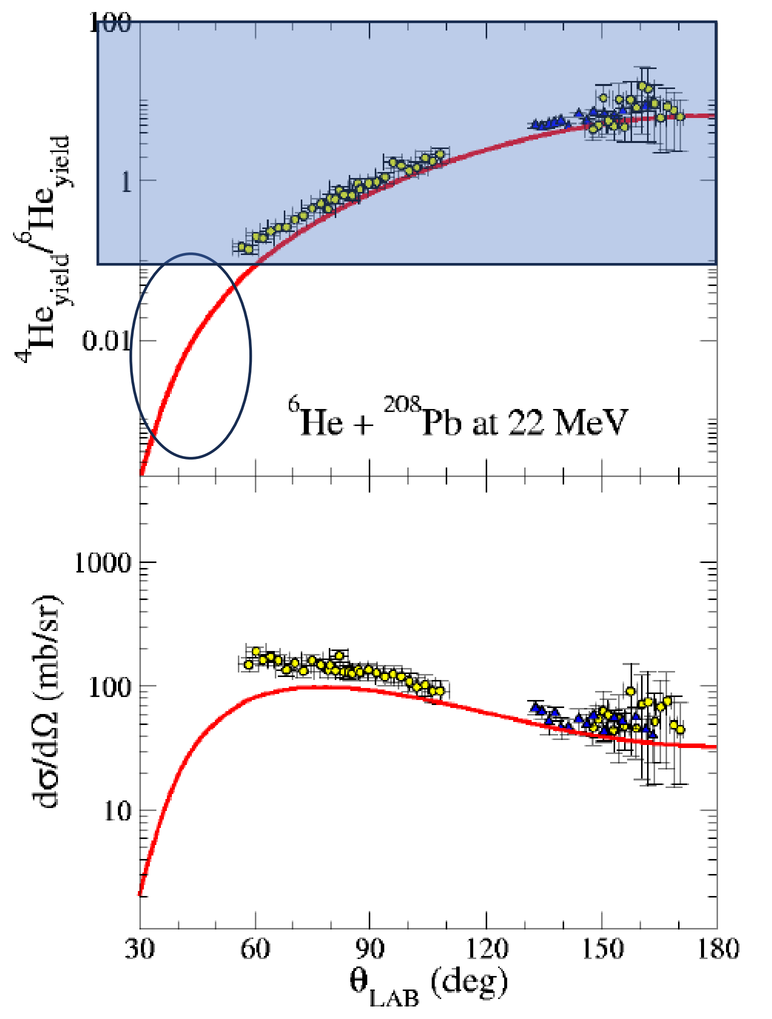
Partial γ-ray spectrum in coincidence with the T1 silicon detector (14º-43º). The red dashed line corresponds to the Doppler-shifted spectrum and the black solid line to the Doppler-corrected one.

The He radioisotopes, scattering and products

^{6}He + ^{208}Pb at 22 MeV. CRC U. Louvain-la-Neuve (2004-2005)



elastic



^{4}He products

(Purple) Simple Optical Model (1 channel)

(Green) CDCC including 2-neutron breakup channel (2 channels).

(Red) CDCC including breakup channel + the effect of dipole polarizability, by including the polarization potential, due to the important role of the B(E1) strength distribution in weakly bound nuclei scattering.

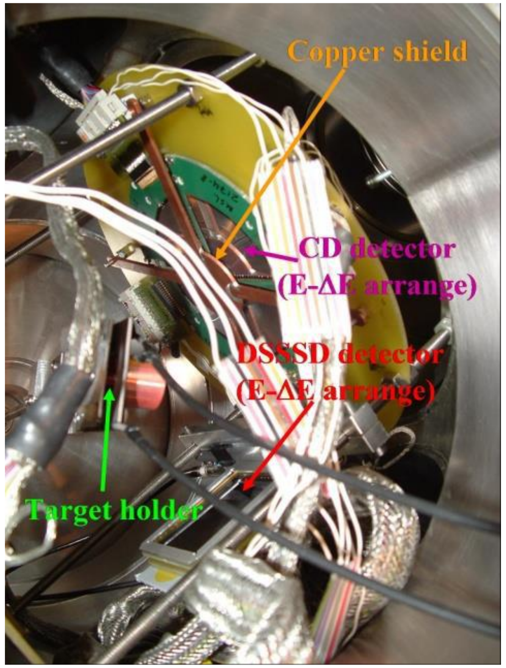
With this it can be probed that the coupling with the continuum states is contributing in a large scale to the absorption observed on the scattering.

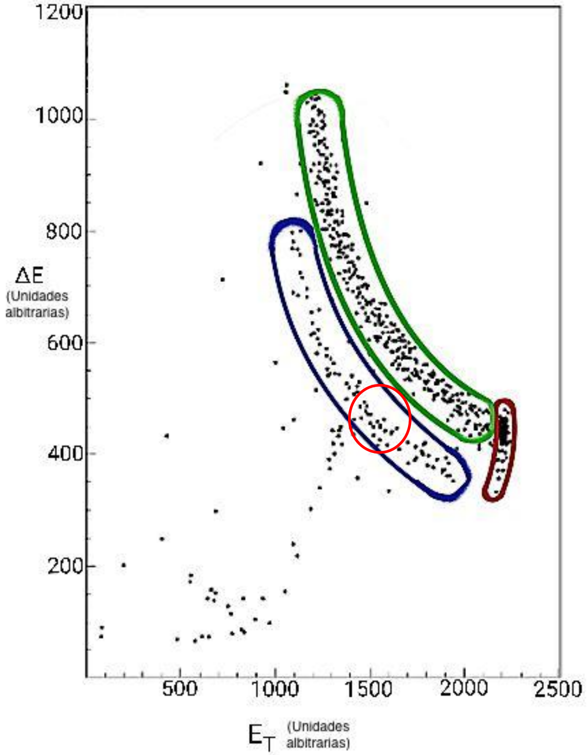
^{4}He products: The calculation is DWBA. It underestimates data at middle angles, however, it reproduces in a good way the alpha production at bigger angles.

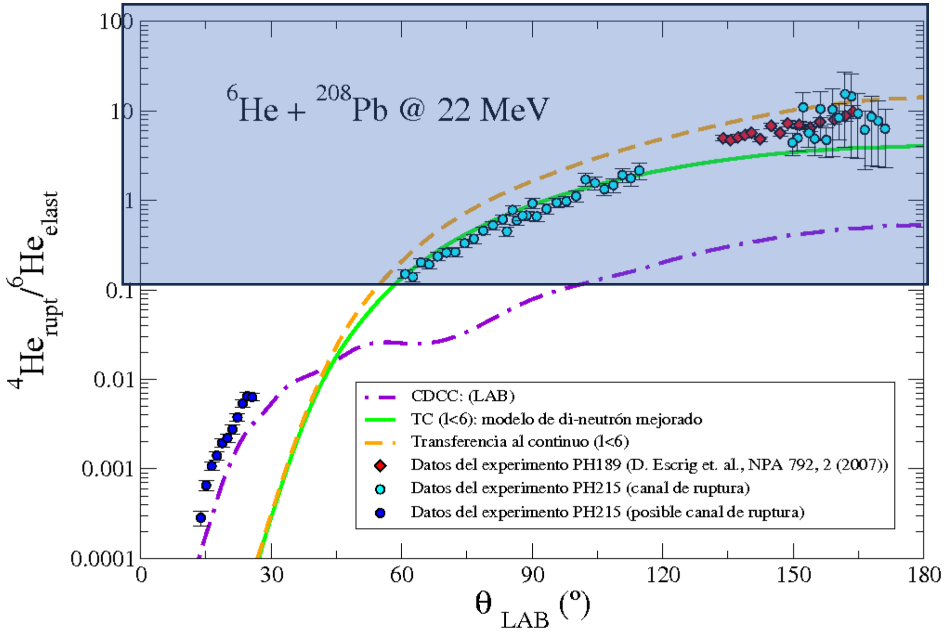
L. Acosta et al. PRC 84, 044604 (2011)
A.M. Sánchez-Benítez et. al., NPA, 803 (2008)
D. Escrig et. al., NPA 792 (2007)

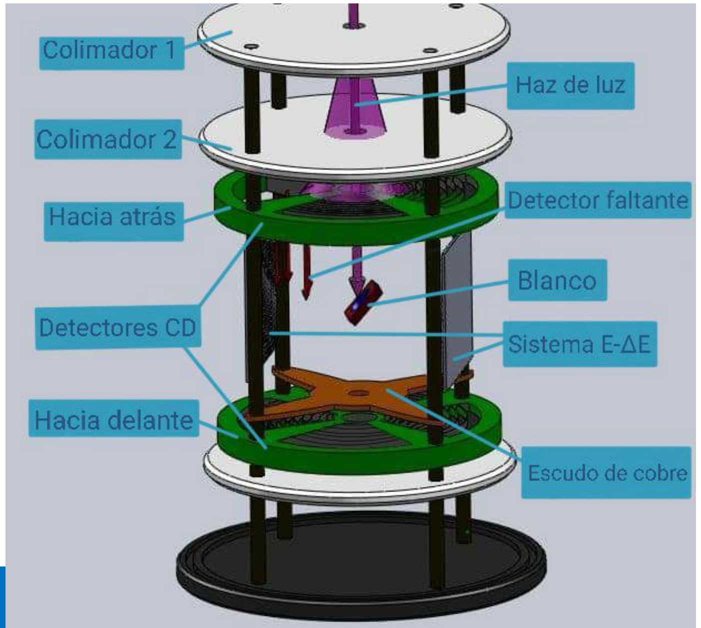
^{4}He produced at forward angles??? "Frame-scattering!!!

PhD. Thesis, L. Acosta (2009)

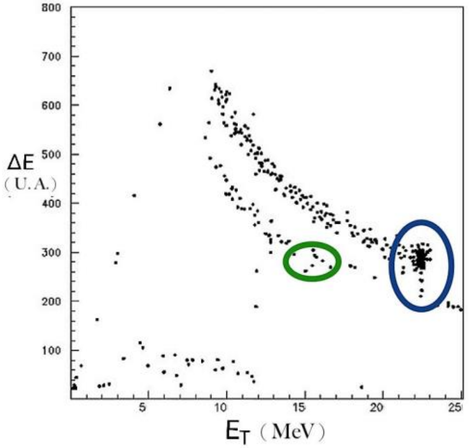


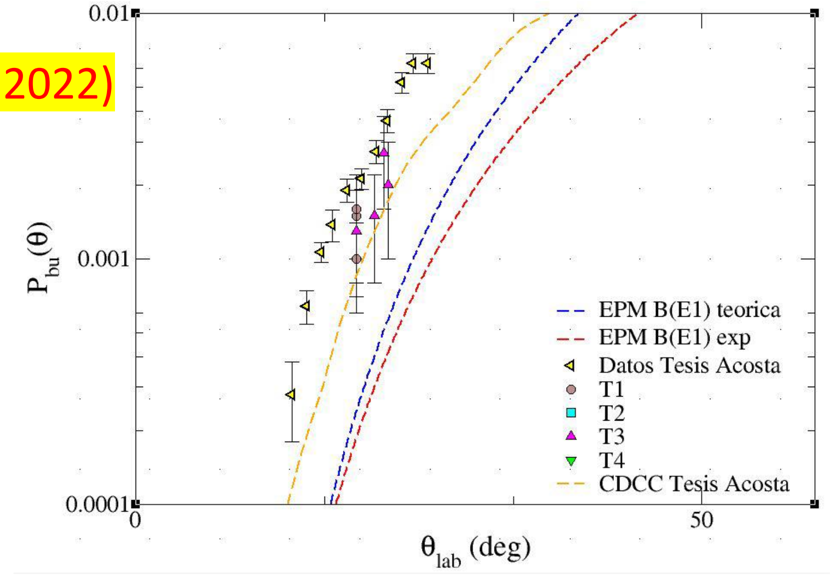






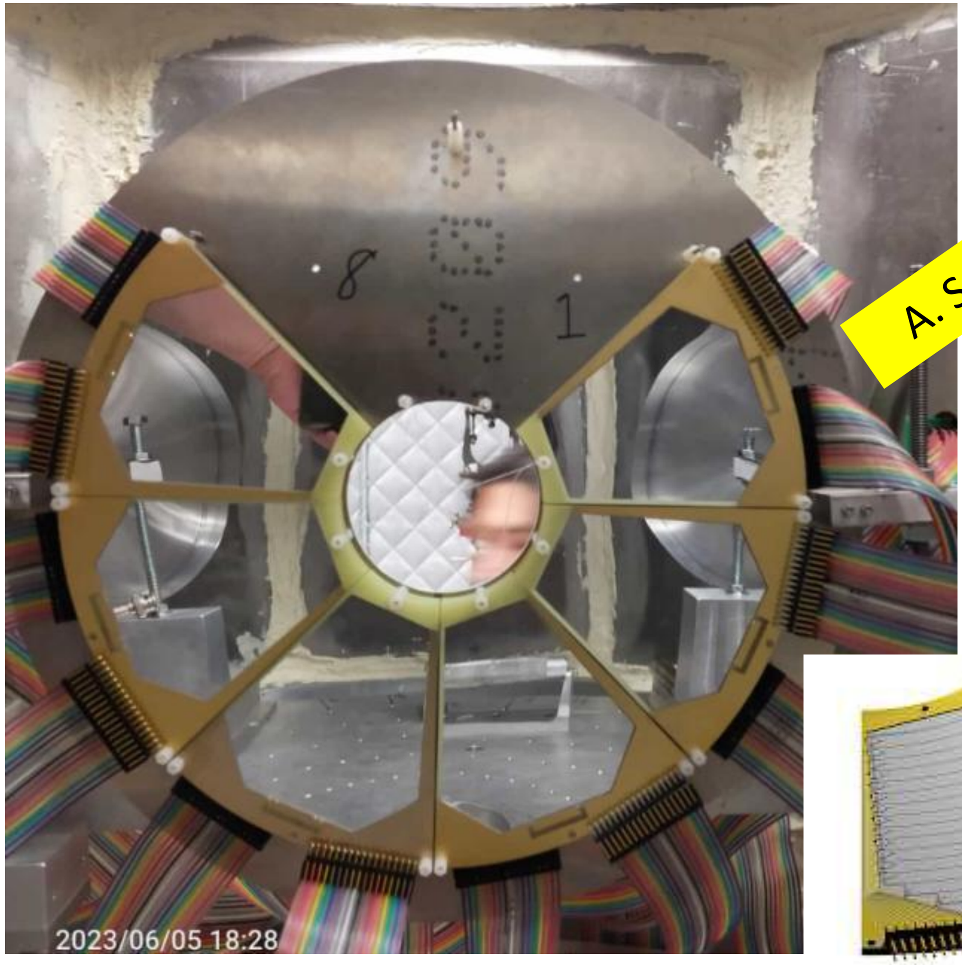
Bachelor Thesis in Physics, Jaqueline Perez (2022)





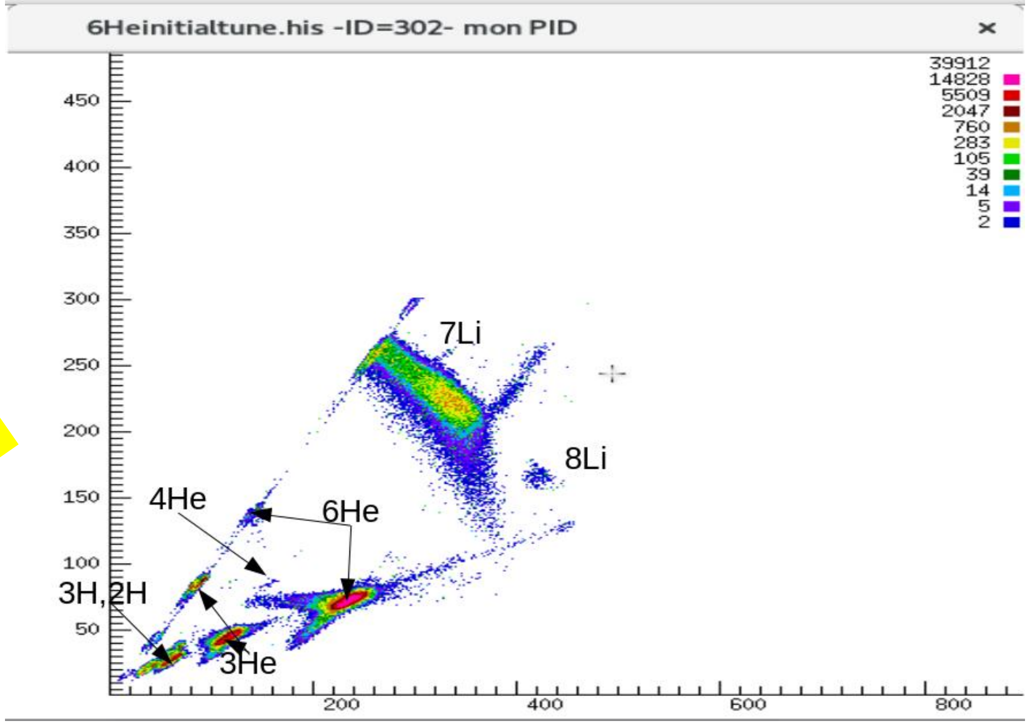
^{6}He + ^{208}Pb @ 19 MeV

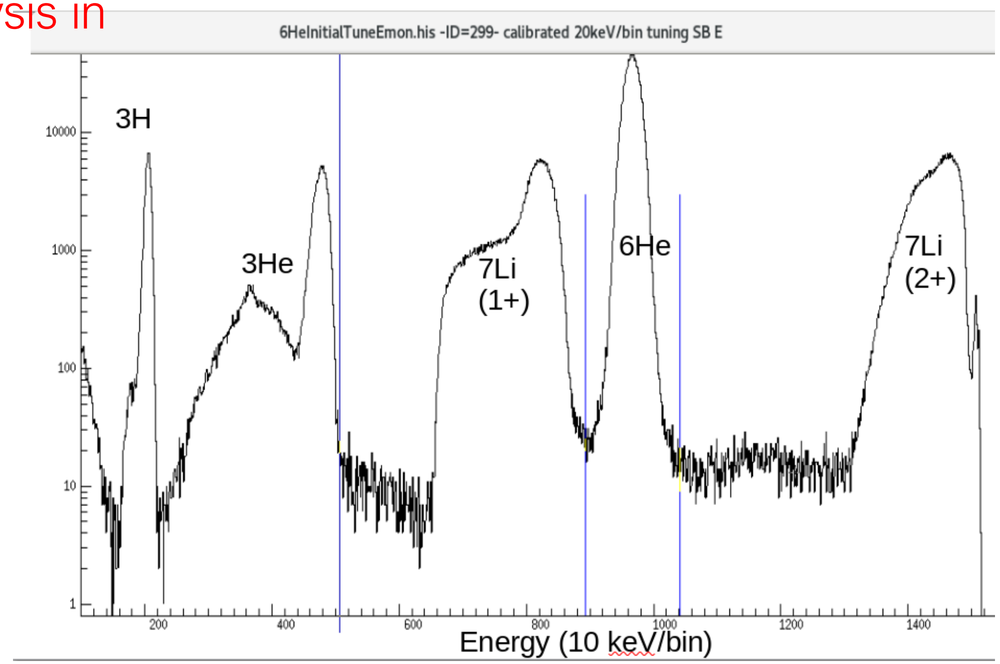
- TriSol Facility, Nuclear Science Laboratory University of ND (USA)
- 70 mm (16 SSSSD) + 1000 mm (PAD) wedge telescopes (6 of them)
- Reaction used to produce ^{6}He is ^{7}Li(d,^{3}He)^{6}He



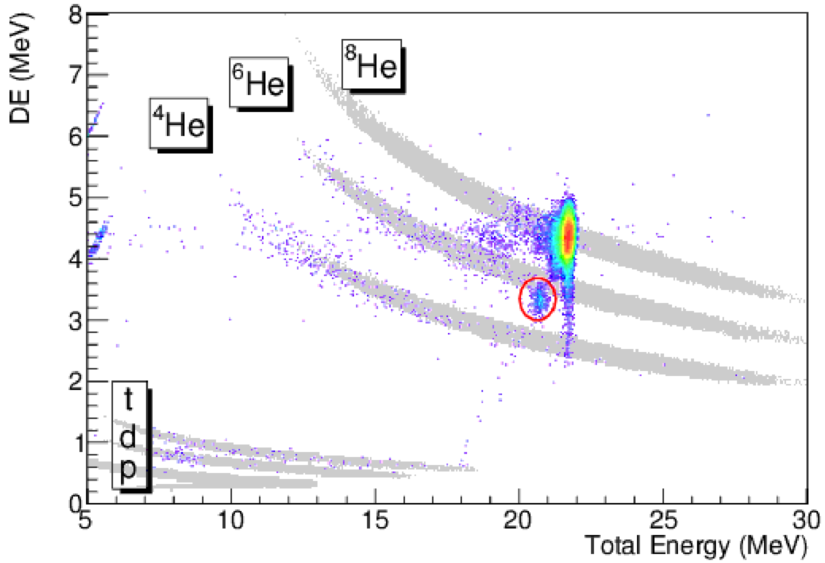
A. Sánchez Benítez TALK!

- Promising analysis in progress!!!





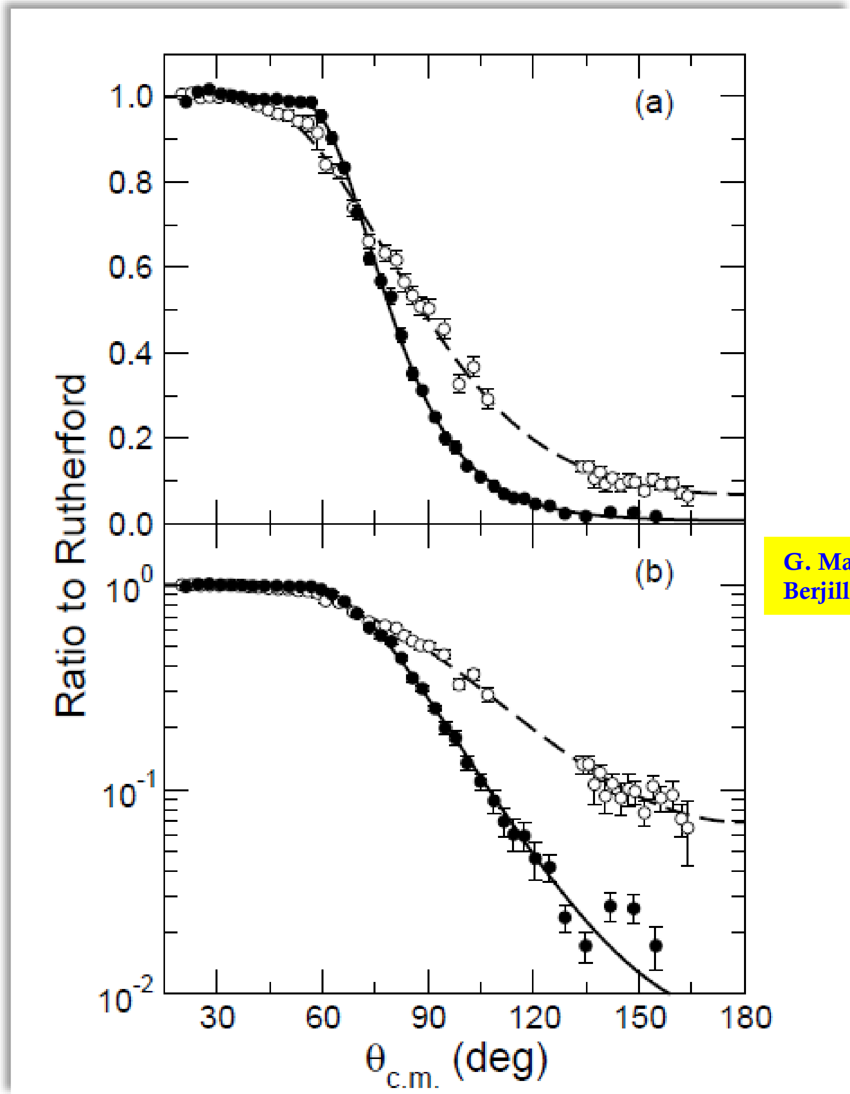
The skin nuclei ^{8}He



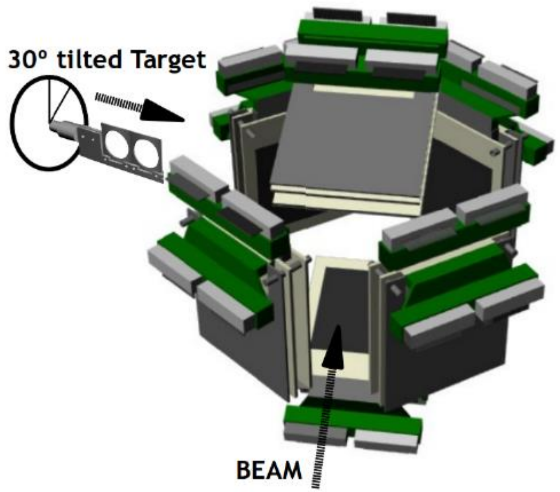
Reaction channels using Montecarlo simulations with the NPTool (Orsay-Must-2) code, based on GEANT4 and ROOT.

^{8}He + ^{208}Pb @ 22 MeV GANIL (2010)

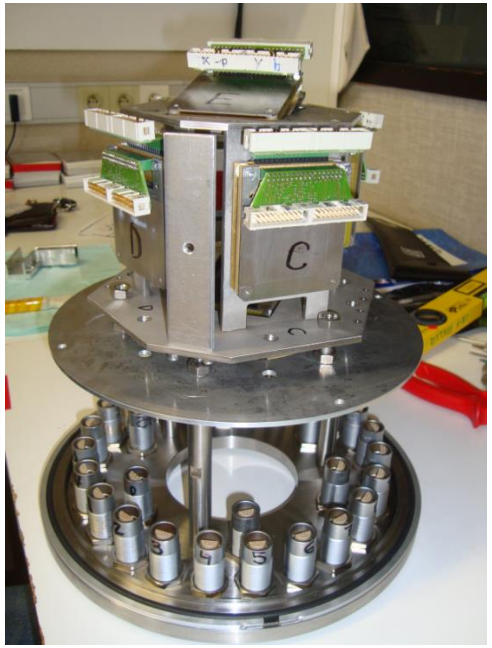
- For elastic scattering of ^{8}He this is the most complete angular distribution at Coulomb energies.
- The results shows the success of GLORIA array, considering the obtained well behavior of the whole distribution.
- Comparing with ^{6}He distribution at the same energy, the ^{8}He shows a larger absorption.
- This was not expected considering the binding energies of neutrons at the ^{8}He skin, bigger that those of ^{6}He.
- Seeing this, we can conclude that the dynamics and structure of ^{8}He still needs a depth studies.



G. Marquínez-Durán, et. al., Acta Phys.Pol. B. 47-3, (2016).
G. Marquínez-Durán et. al., PRC 94, 064618 (2016).

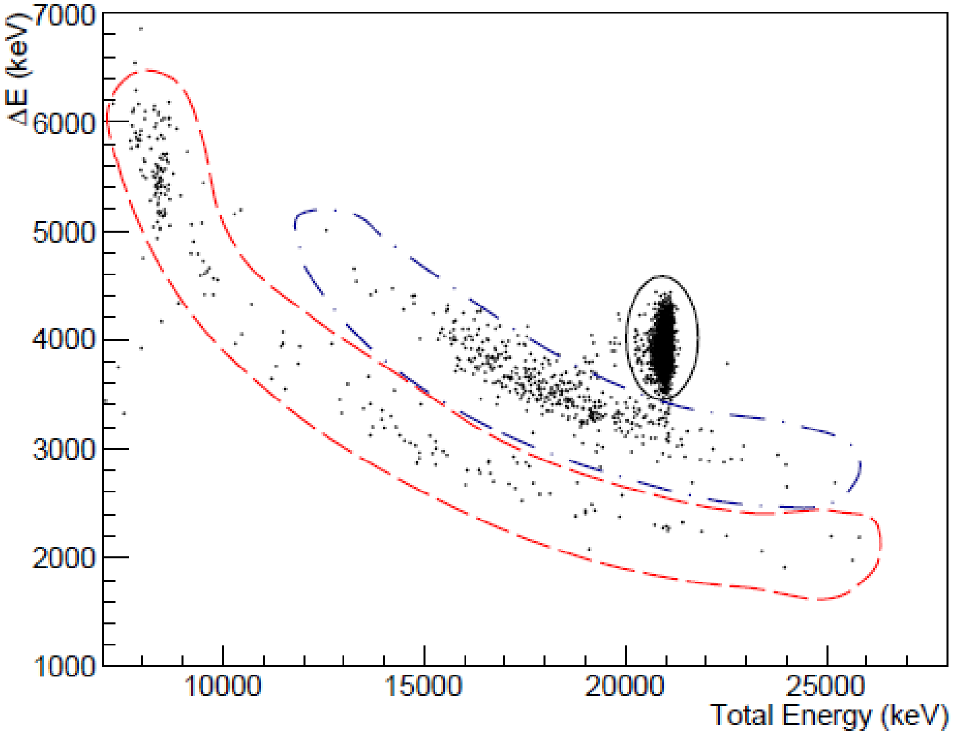


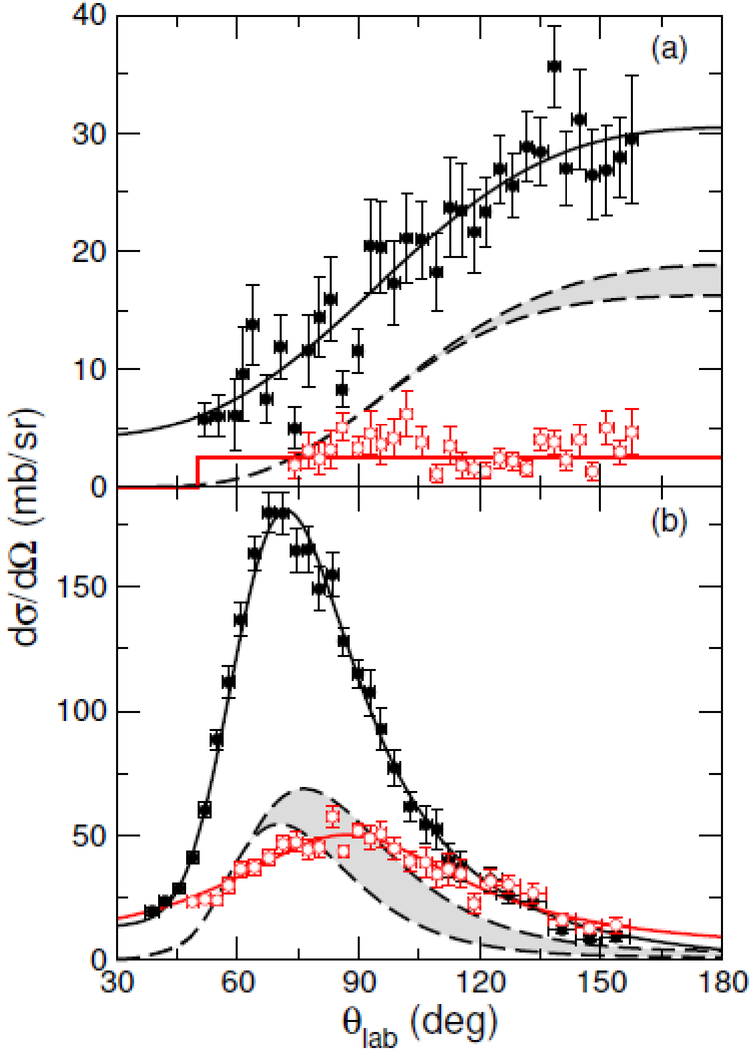
G. Marquínez-Durán, L. Acosta. I. Martel, A.M. Sánchez-Benítez, R. Berjillos, ,J.A. Dueñas, K. Rusek NIM-A 755 (2014).



The He radioisotopes, scattering and products

^{8}He products





16 MeV
^{6}He
^{4}He

22 MeV
^{6}He
^{4}He

In the spectra could be observed ^{6}He (blue) and ^{4}He (red), 16 (a) y 22 (b) MeV on the cross section figures.

Calculation are fits.

Dashed lines are DWBA for 1-neutron striping,

Theoretical representation allow to conclude that some other process are involved in the fragmentation.

The number of bodies appearing in the reaction make difficult to establish any more precise association to possible processes.

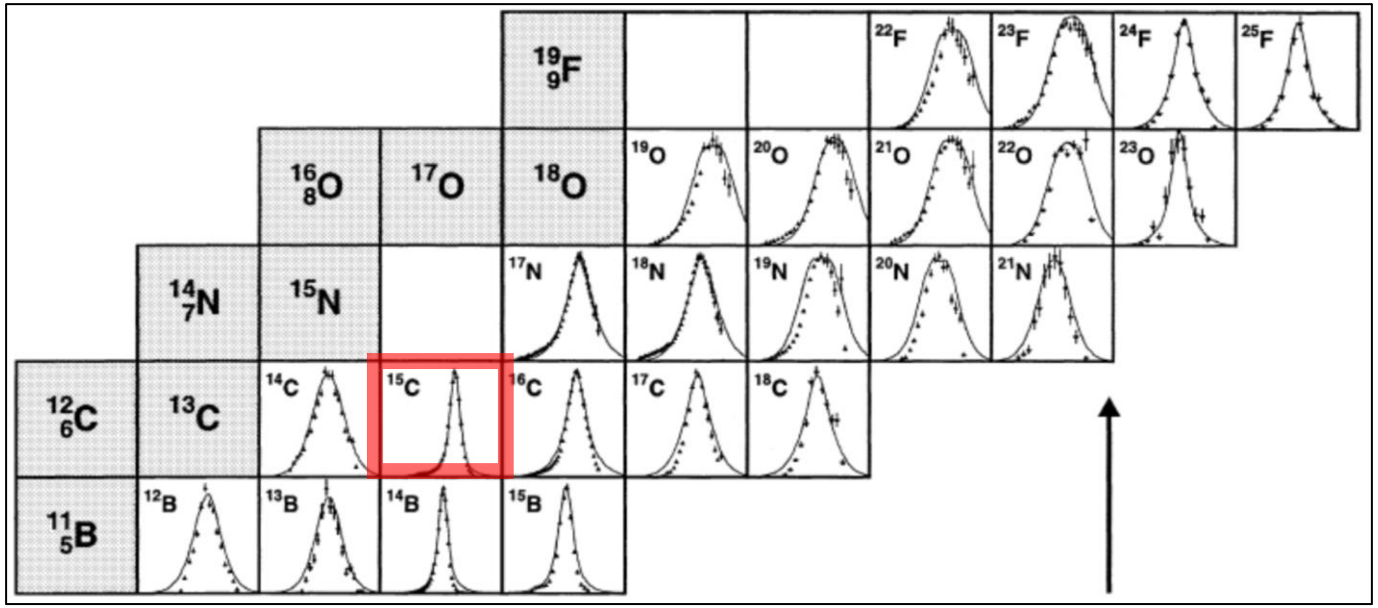
G. Marquínez-Durán, I. Martel, A. M. Sánchez-Benítez, L. Acosta, J. L. Aguado, R. Berjillos, A.R. Pinto, T. García, N. Keeley et. al., PRC **98**, 034615 2018.

The "1-neutron halo" ^{15}C (new measurement)

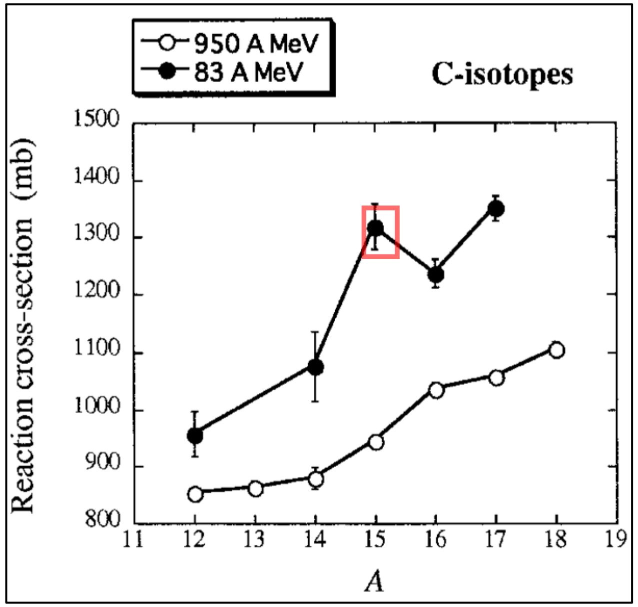
Motivation

- The halo structure of ^{15}C has been debated
- For ^{15}C, a high reaction cross section & a narrow longitudinal momentum distribution is found at relativistic energies (Γ = 67(3) MeV/c) although no as narrow as for the ^{11}Be or ^{11}Li cases (Γ = 40 MeV/c).
- A halo structure with a **pure s wave** as **ground state** and a ^{14}C core explains these features, despite the fact of having a relatively large separation energy S_n.

S_n = 1218 keV ; S_{2n} = 9394 keV



Auman EPJA26(2005)441



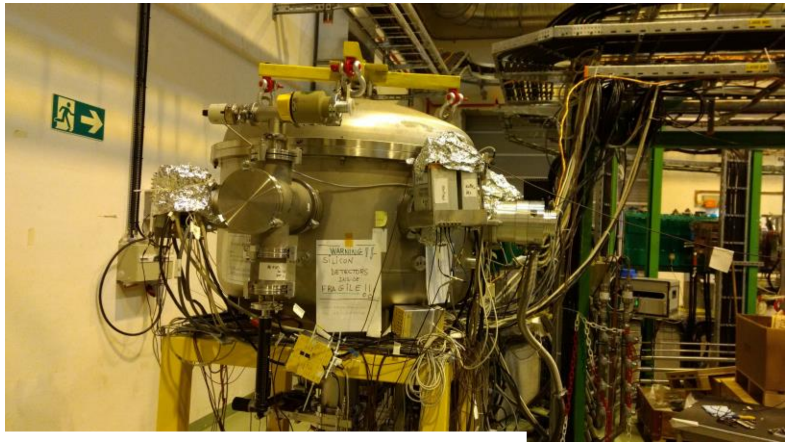
Ozawa. Nuc Phys A 738 (2004) 38

The "1-neutron halo" ^{15}C

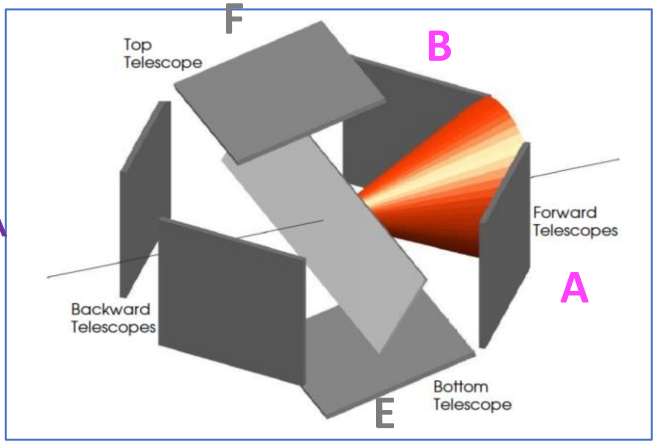
$^{15}C + ^{208}Pb$ @ 65 MeV ISOLDE-CERN (2017)

2017, IS619 I. Martel O. Tengblad Effects of the neutron halo in ^{15}C scattering at energies around the Coulomb barrier

- The loose bound structure near the strong electromagnetic field of target induces a dipole polarization in the projectile. These structure effects manifest on the angular distribution of the elastic cross section.

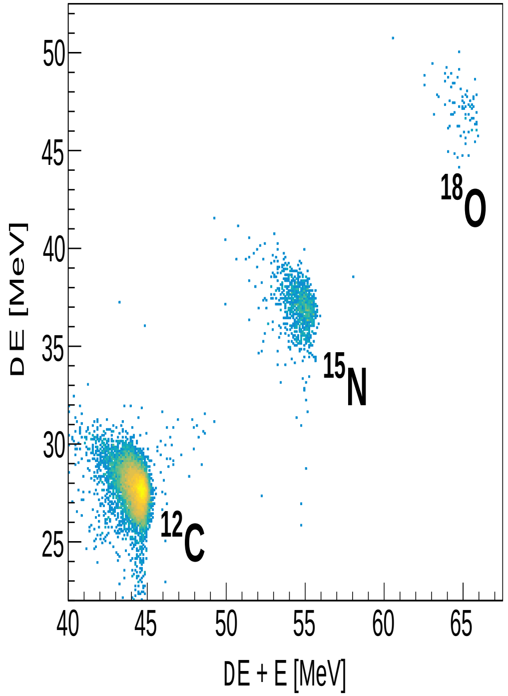


SEC + GLORIA

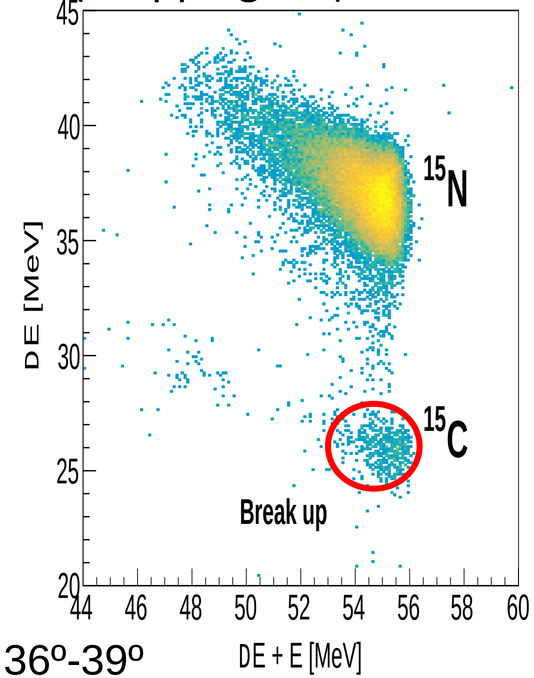


Cocktail beam A/q = 3 for calibration

$^{12}C^{4+} + ^{15}N^{5+} + ^{18}O^{6+}$ at 4.37 MeV/u



beam (Stripping foil)@ 4.37 MeV/u

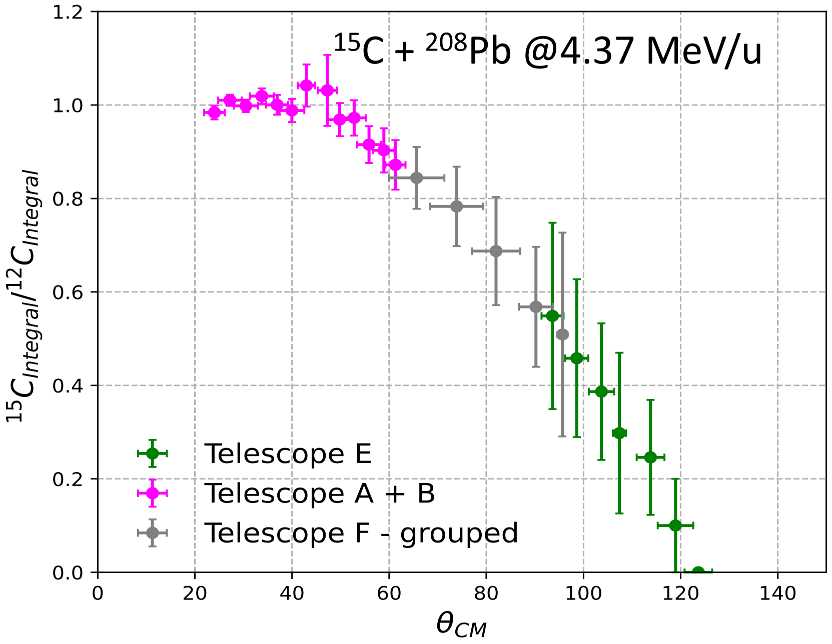


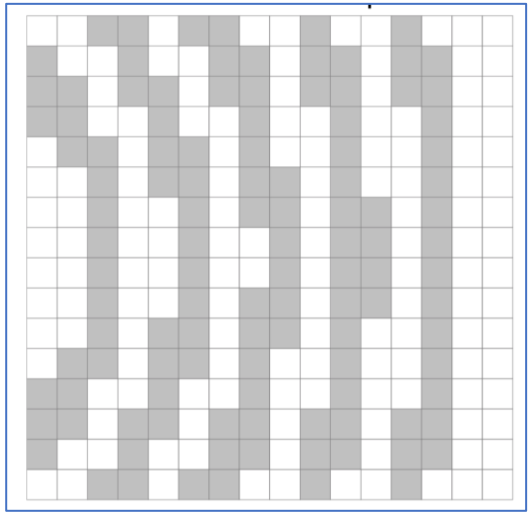
$\theta_{LAB} = 36^o$-39^o

Unexpected Difficulties

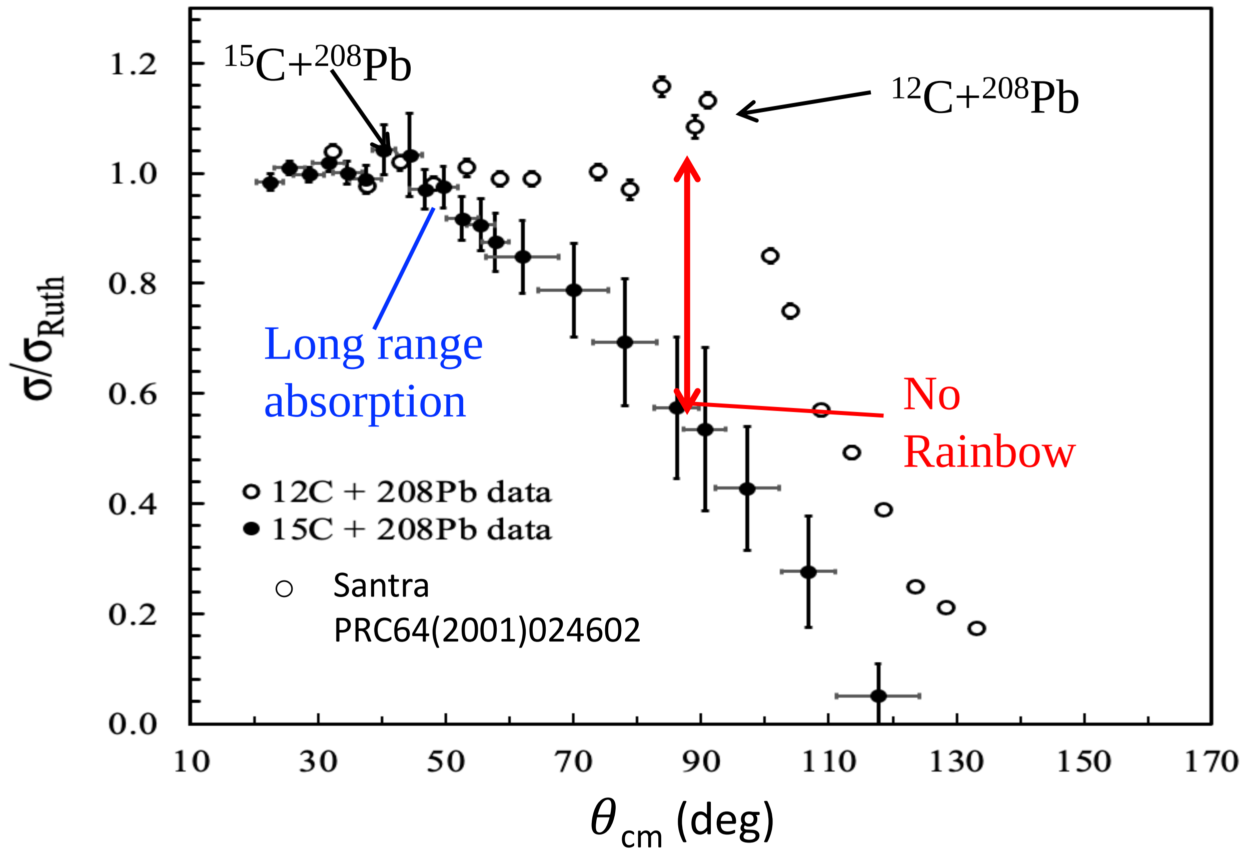
- Production of ^{15}C very low 1% of ^{15}N
- The $^{15}N + ^{208}Pb$ originally thought as calibration and reference could not be used. At intermediate angles the ^{15}N stopped in front detector.
- We then had to use for normalization the $^{12}C + ^{208}Pb$
- The scattered ^{15}N beam produced channelling effects that force to disregard central pixels

The "1-neutron halo" ^{15}C





Angular distribution on the DSSSD's

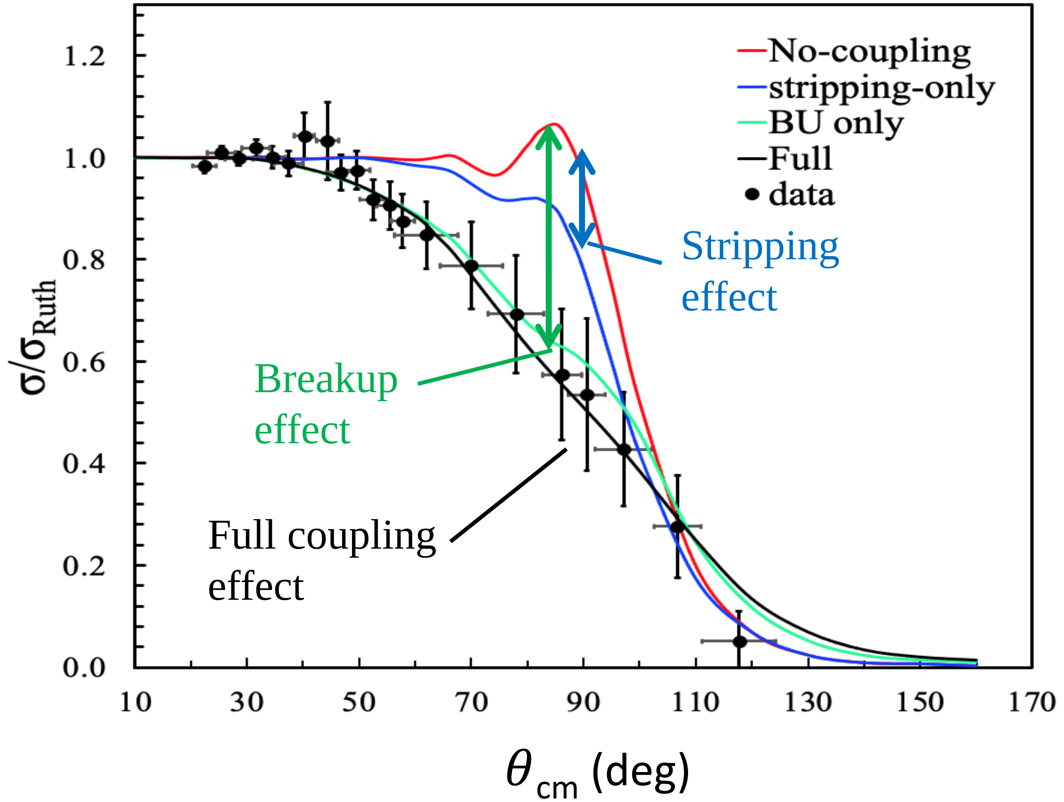


Halo effects in ^{15}C are clearly demonstrated:

- Complete lack of a Coulomb rainbow peak
- Long-range absorption -> ~50° Lab
- Single-neutron stripping and breakup can play an important role in this system – Keeley, Eur. Phys. J. A 50, 145 (2014).

Contents of last 3 slides, courtesy of M.J.G. Borge and I. Martel

Recent results for $^{15}C+^{208}Pb$ @ 4.37 MeV/u



Calculations by Nick Keeley for the proposal

Breakup Couplings CDCC (FRESCO): $^{15}C \rightarrow n + ^{14}C$

- ✓ ^{14}C inert core
- ✓ Optical Model potentials
  - ❖ n + ^{208}Pb – Koning & Delaroche, NPA713 (2003) 231
  - ❖ $^{14}C + ^{208}Pb$ – ^{12}C data S. Santra, PRC64, 024602 (2001)

Stripping Coupling: CRC (FRESCO) $^{208}Pb(^{15}C,^{14}C)^{209}Pb$

n+^{14}C potential + s.f (C^2S = 0.98); [Kovar NPA231 (1974) 266]

- Near-barrier elastic scattering of ^{15}C from a high-Z target (^{208}Pb) was measured for the first time
- The halo nature of ^{15}C is demonstrated by
  - the observation of the long-range absorption effect,
  - the disappearance of the Coulomb rainbow,
  - the large reaction cross section, 4 times larger than ^{12}C.
- The effects due to the halo are clearly seen as compared to ^{12}C

V.G. Távora, J.D. Ovejas, et. al., PLB (reviewed submitted May24)

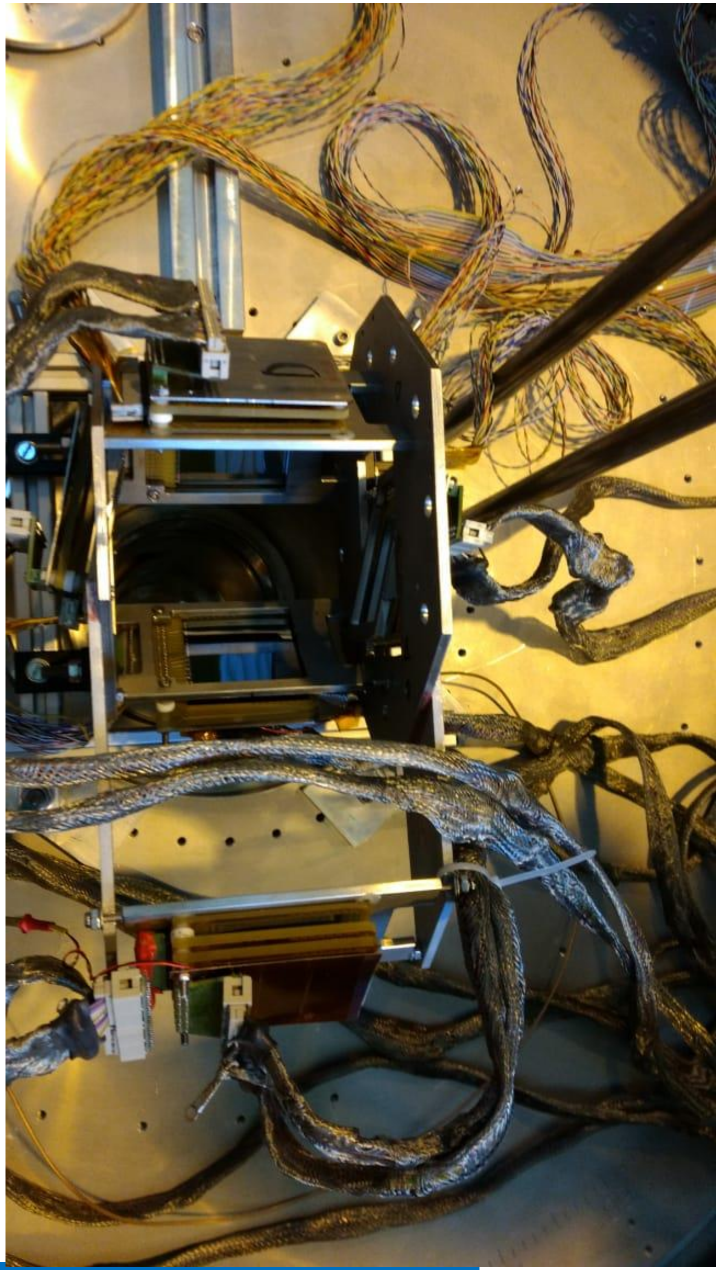
The proton halo ^{8}B (very recent results)

- 2018 Measurement
  - A. Di Pietro (INFN-LNS) “Reaction mechanisms in collisions induced by **^{8}B** beam close to the barrier”.
  - ISOLDE-CERN **IS616**: ^{8}B beam on ^{64}Zn at 38.5 MeV **(1.5 C.B.)**
  - GLORIA cover a wide angular range.
  - Unique beam existing post-accelerated.

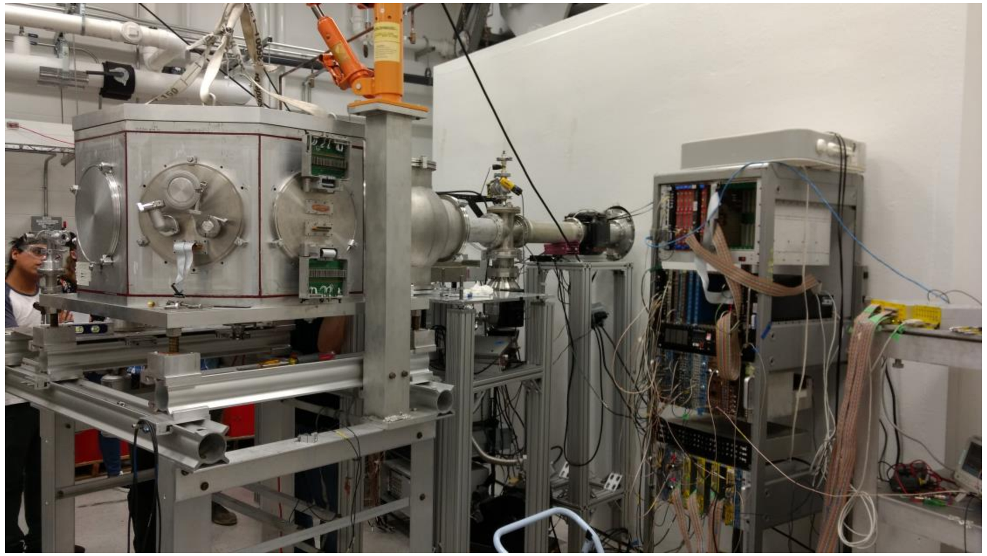
- 2019 Measurement
  - A. Pakou, L. Acosta, P. O’Malley, J.J. Kolata (U. Ioannina, IFUNAM, UND) “Fusion hindrance at sub-barrier energies for weakly bound nuclei on heavy targets: the ^{8}B + ^{208}Pb case”.
  - TwinSol Facility, Nuclear Science Laboratory University of ND. Cocktail beam including ^{8}B on ^{208}Pb at 30 MeV **(0.6 C.B.).**
  - SIMAS covering a particular angular range.
  - In-flight beam ^{8}B is identified in a cocktail beam using time filters.

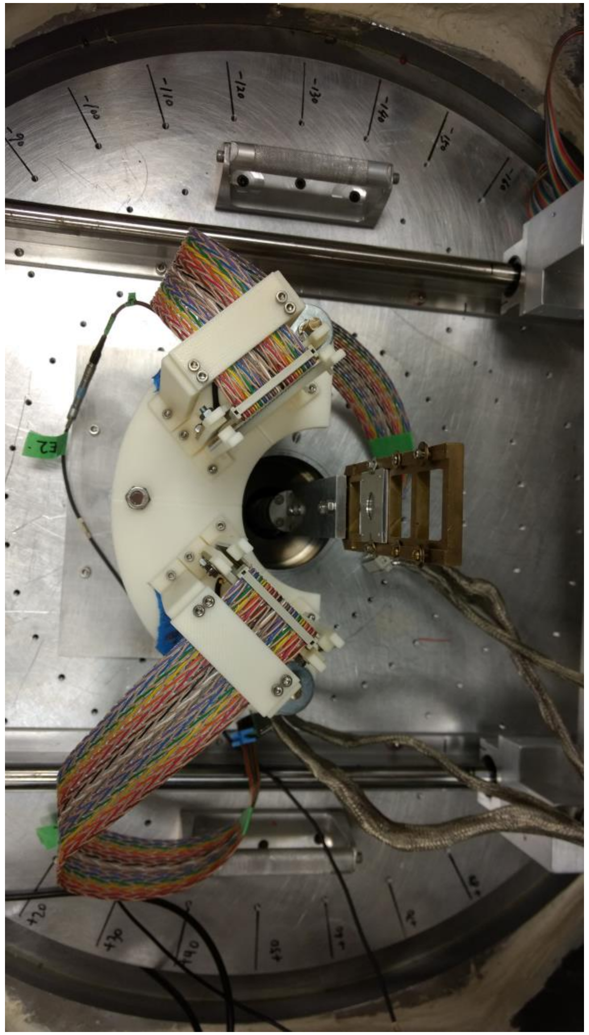
Experimental setups

SEC + GLORIA



TwinSol Chamber + SIMAS



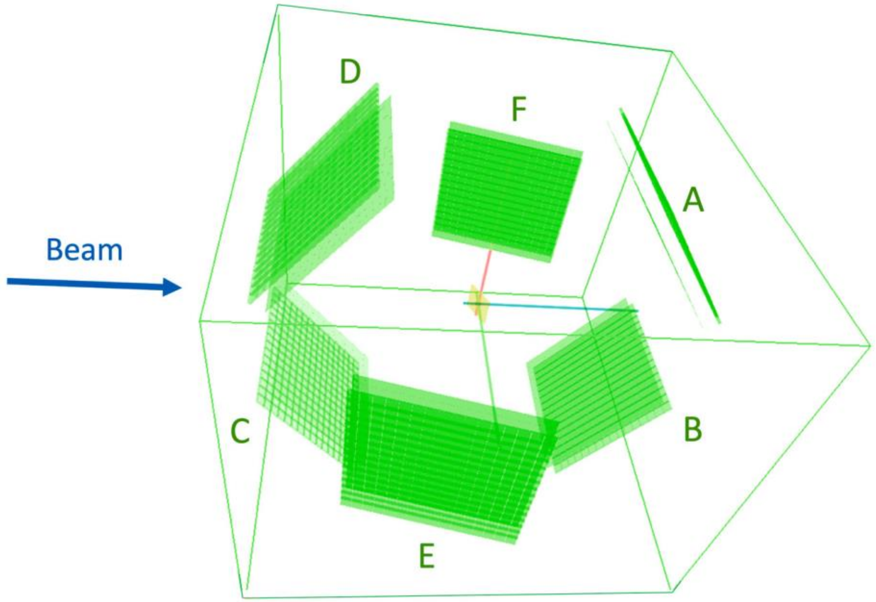


Scattering of ^8B on a ^{64}Zn Target (IS616) HIE-ISOLDE-CERN

First ^8B beam @ HIE-ISOLDE
Yield ~ 400 pps
E = 4.9 MeV/u (1.5 V_B ~ 30 MeV)
1,05 mg/cm^2 ^{64}Zn-target

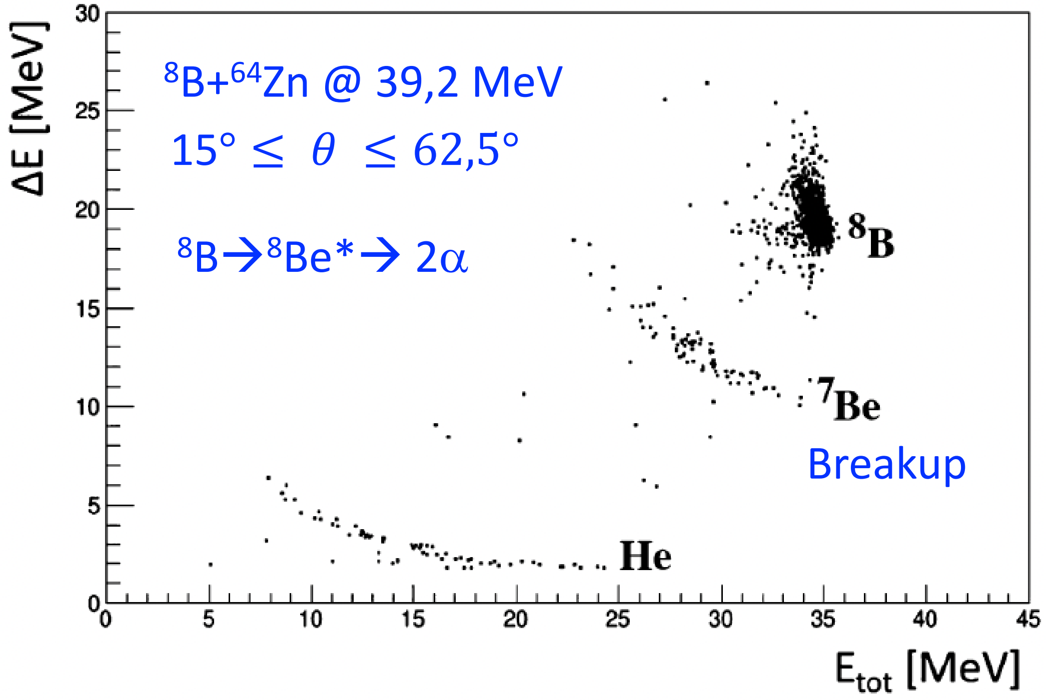
Aim

- Measure Diff Elastic Cross Section
- Measure Break-up & Transfer Distributions
- Total Cross Section
- Deduce the Nuclear & Coulomb Contributions

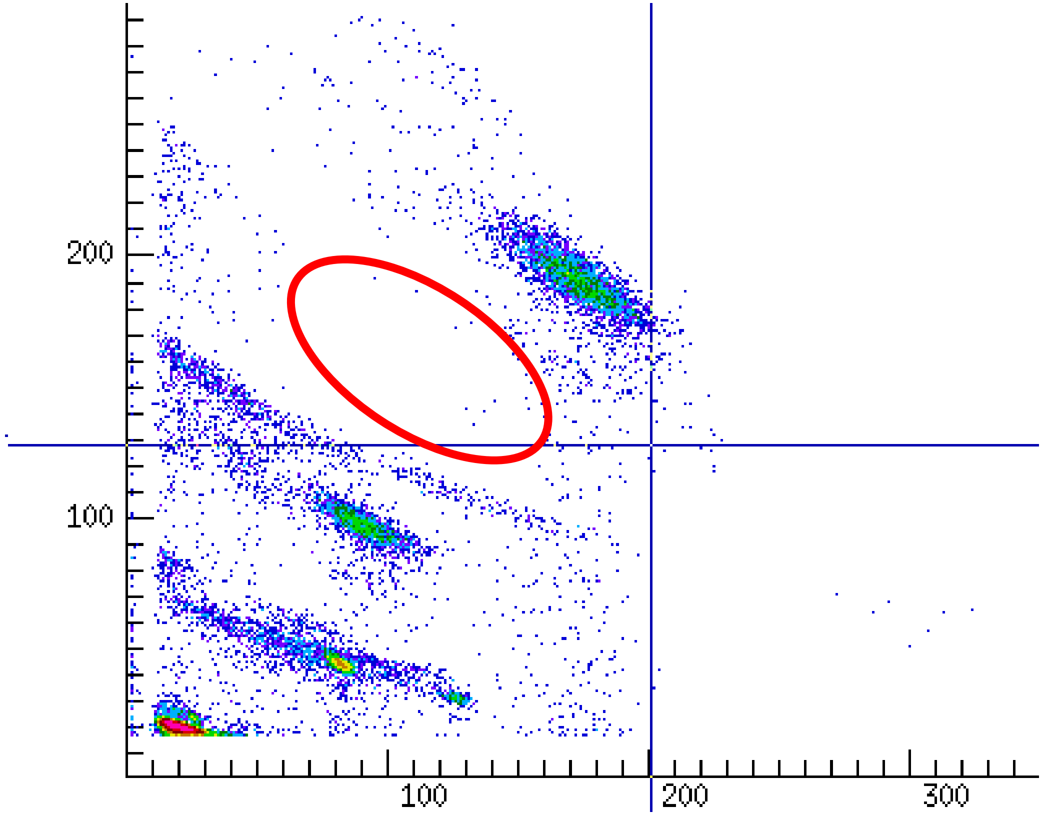


Large angular range-high granularity GLORIA

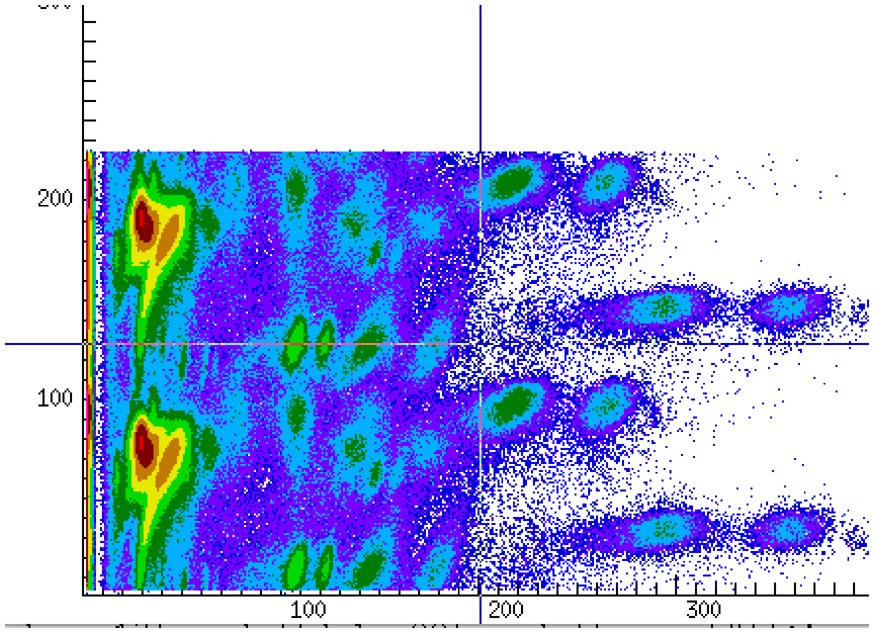
G. Marquinez-Durán et. al., NIM A 755 (2014) 69



Scattering of ^{8}B on a ^{208}Pb Target (TwinSol-UND)



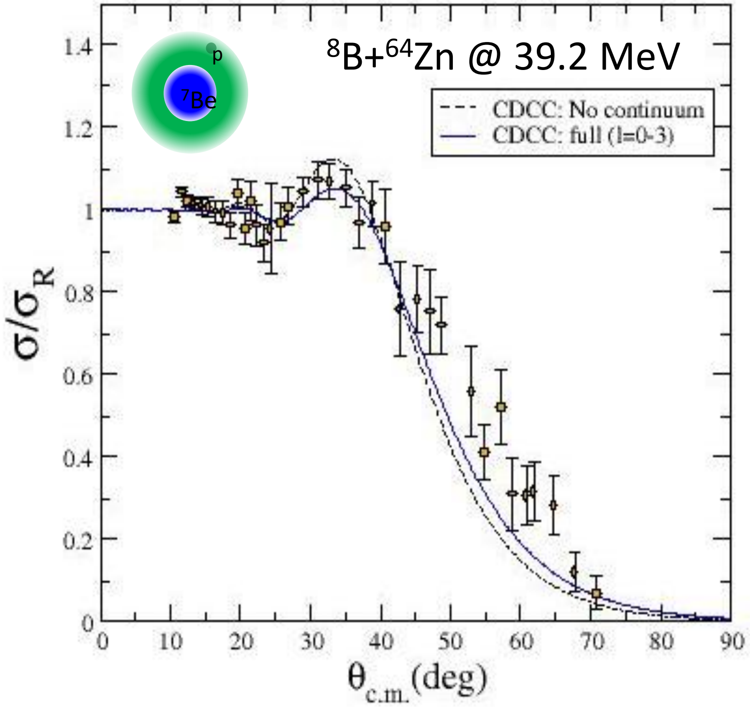
ΔE-E Spectrum, 2 days of ^{8}B beam
(ToF filter for ^{7}Be)



ToF Spectrum 2 days of ^{8}B beam

- two-proton transfer reaction $^{6}Li+^{3}He$. A primary bunched beam of ^{6}Li was accelerated at 37 MeV at the UND FN tandem and impinged on a gas target of 3He at a pressure of 1 atm.
- reaction products included in the secondary beam
  - ^{7}Li @ 13.1 MeV, ^{7}Be @ 22.4 MeV and ^{8}B @ 30.5 MeV.

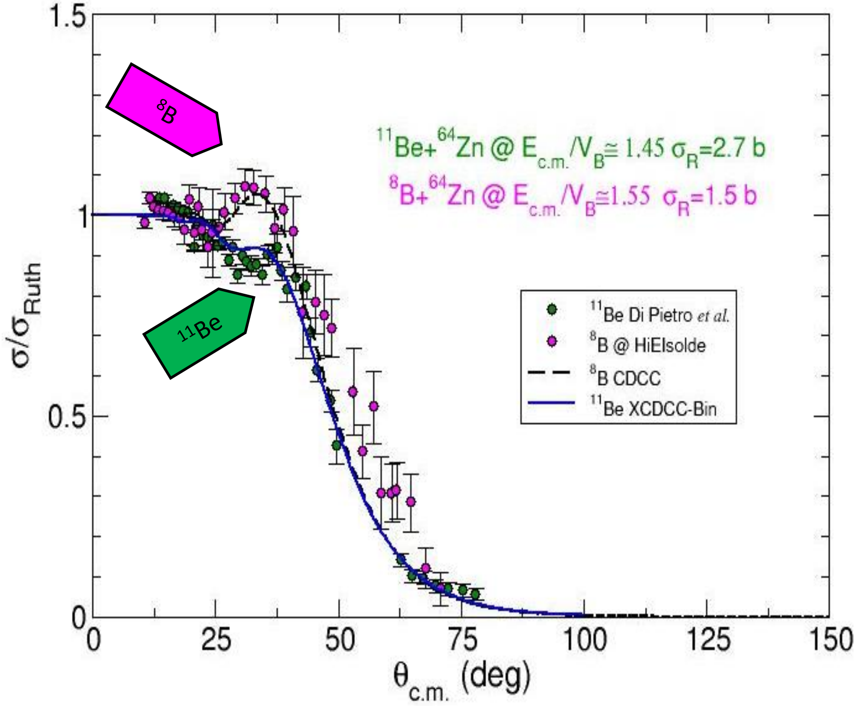
Results: Scattering of ^{8}B on a ^{64}Zn Target



R. Spartà et al. Phys. Lett. B 20(2021)136

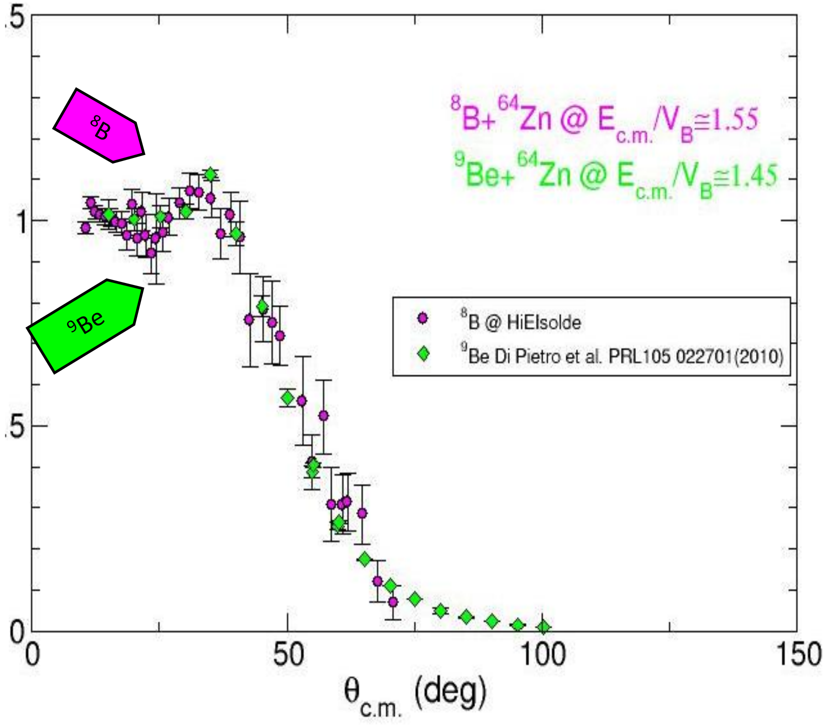
Contrary to the case of the 1n-halo ^{11}Be, almost no suppression of the Coulomb-Nuclear Interference peak

^{8}B,$^{11}Be+^{64}Zn$: p-halo *vs* n-halo



No suppression of rainbow
For ^{8}B total s_R a factor ~ 2 lower than in n-halo ^{11}Be

^{8}B,$^{9}Be+^{64}Zn$:
p-halo *vs* weakly bound

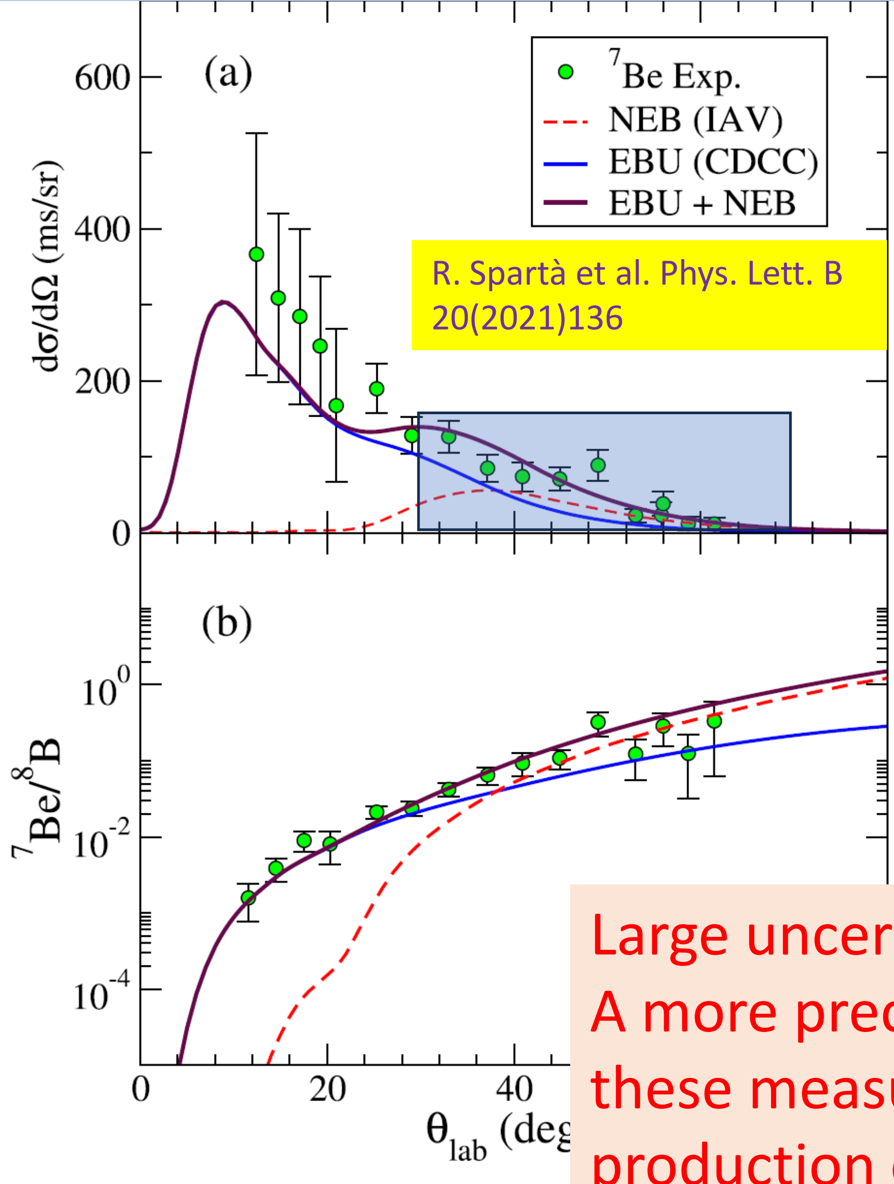


Total reaction cross-section for $^{8}B+^{64}Zn$ $\sigma_R \approxeq 1.5$ b similar to $^{9}Be+^{64}Zn$ at similar $E_{c.m.}$ / V_c
Proton halo behaves as a more bound nucleus ^{9}Be as predicted by
A. Bonaccorso et al. PRC 69, 024615 (2004)

Courtesy of M.J.G. Borge and A. Di Pietro

^{7}Be+p as reaction products below and above de barrier: ^{7}Be

ISOLDE results "well-above the barrier"



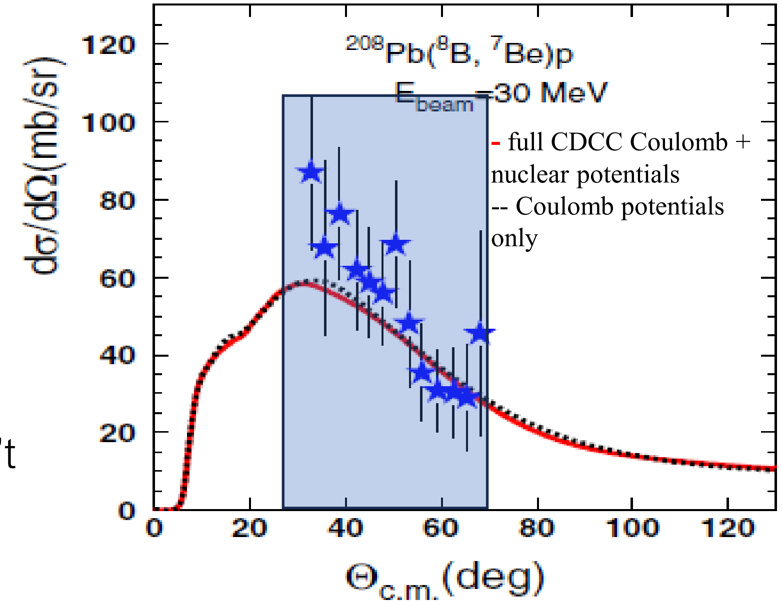
R. Spartà et al. Phys. Lett. B 20(2021)136

In the same angular region, the breakup behaviour is very similar, and the cross sections remains at similar levels.

Evidently, above the barrier at smaller angles, the breakup cross section is bigger.

Calculation below the barrier, doesn't show the higher peak at 10°. It shows just the direct breakup.

TwinSol results "well-below the barrier"



A. Pakou, L. Acosta, P. D. O'Malley et. al., PRC 102, 031601(R) (2020)

- Even when the estimate cross section are very similar (~300 mb in both cases) the calculation for the "above the barrier" case, is a sum of elastic and nonelastic breakup "NEB" i.e. the dissociated proton interacts non-

Large uncertainties in both cases make possible different interpretations. A more precise experiment is necessary. Nevertheless, the light shed by these measurements is very valuable, considering the complex production of ^{8}B beam.

^{8}B, ^{7}Be Experiment 2022

- "Reaction mechanisms at sub - barrier energies for weakly bound nuclei : the ^{8}B,^{7}Be + ^{90}Zr case".
- "SIMAS x 2" to "SIMAS x 4" (1 from LIFE-UHU)

K. Pally TALK more recent results!!!

K. Palli, et. al., PHYSICAL REVIEW C **107**, 064613 (2023)

K. Palli et. al., (Recently ACCEPTED)

Some conclusions...

- Very recent results related to the dynamics of weakly bound nuclei, along to previous ones were shown and compared (1n, 2n, 1p halo and 4n skin).

- While the elastic scattering in most of the cases shows a well identified behaviour -strong absorption (neutron halo) and "stable" behaviour (proton halo)- the reaction products not always seems to come from the same process: elastic breakup, transfer and nonelastic breakup (several kind of process) can occur.

- The exotic production is every time improved, as well as the detection systems and DAQ. In some of the cases, very precises and wide measurements have been reached.

- It is very important to continue the study of weakly bound nuclei to understand a number of reaction effects and considering their importance in several astrophysical processes.

Thank you for your attention.

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