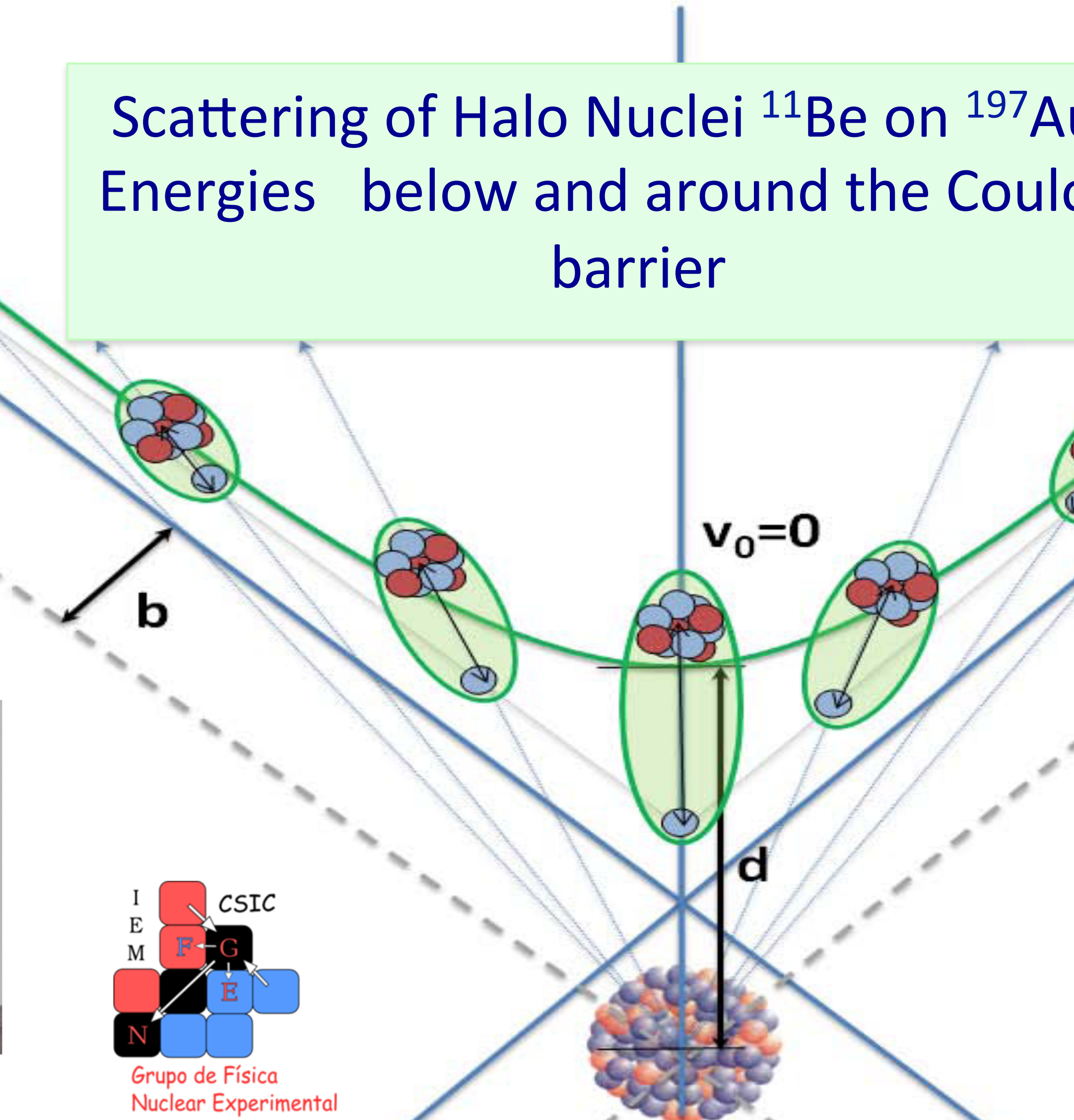
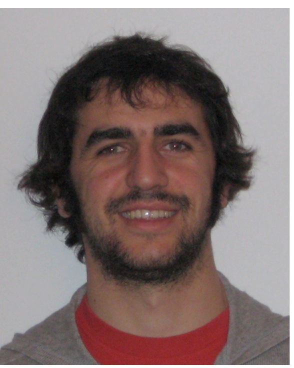
Scattering of Halo Nuclei ^{11}Be on ^{197}Au at Energies below and around the Coulomb barrier





V. Pesudo

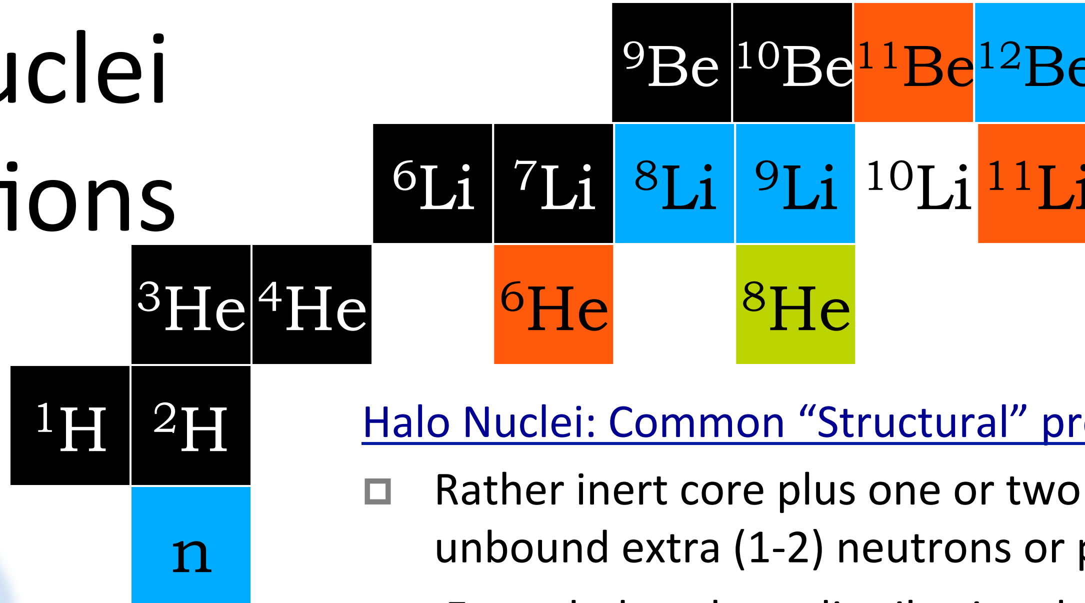
I E M CSIC F G E N
Grupo de Física Nuclear Experimental

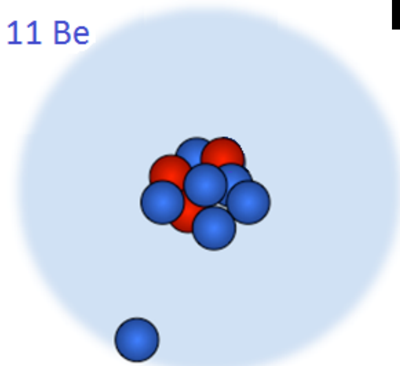
María J. G. Borge

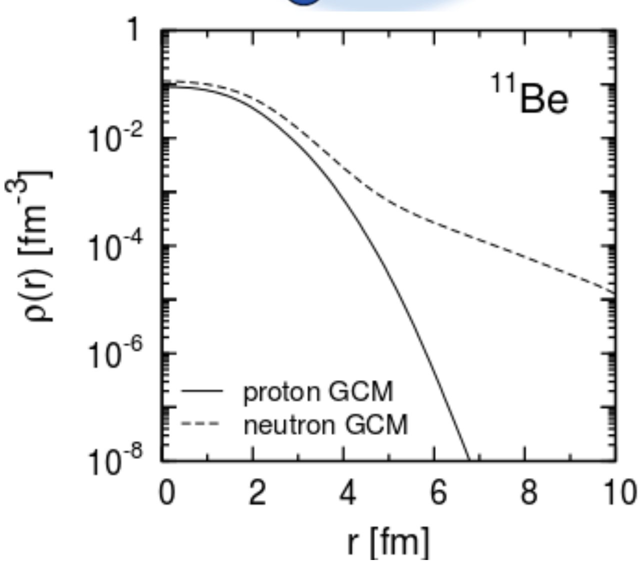
Instituto de Estructura de la Materia, CSIC, ISOLDE-EP, CERN

On behalf of the S-1202 Collaboration: IEM-CSIC –LNS-INFN- U. Aarhus - U. Chalmers - U. Huelva- U. Lisboa – U. St. Marys - U. Sevilla - U. York –TRIUMF

Halo nuclei & reactions







Descouvemont. Nucl. Phys. A 615 (1997) 261

Halo Nuclei: Common "Structural" properties

- Rather inert core plus one or two barely unbound extra (1-2) neutrons or protons
- Extended nucleon distribution, large "radius"→ "halo"
- Very few excited states –if any.
- Unique exotic structur → Insight into slow degrees of freedom

Reaction properties at near-barrier energies:

→ Strong absorption in elastic channel

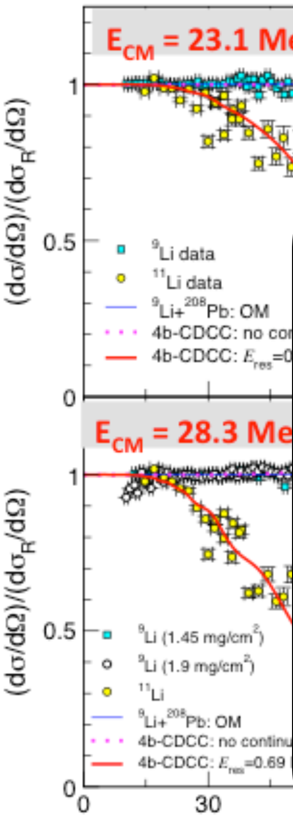
→ Large cross section for fragmentation

→ They are easily polarizable

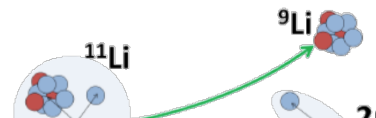
Interplay between Nuclear Structure & Reaction Mechanism

Scattering of ^{11}Li on ^{208}Pb near Coulomb barrier (≈28 MeV)

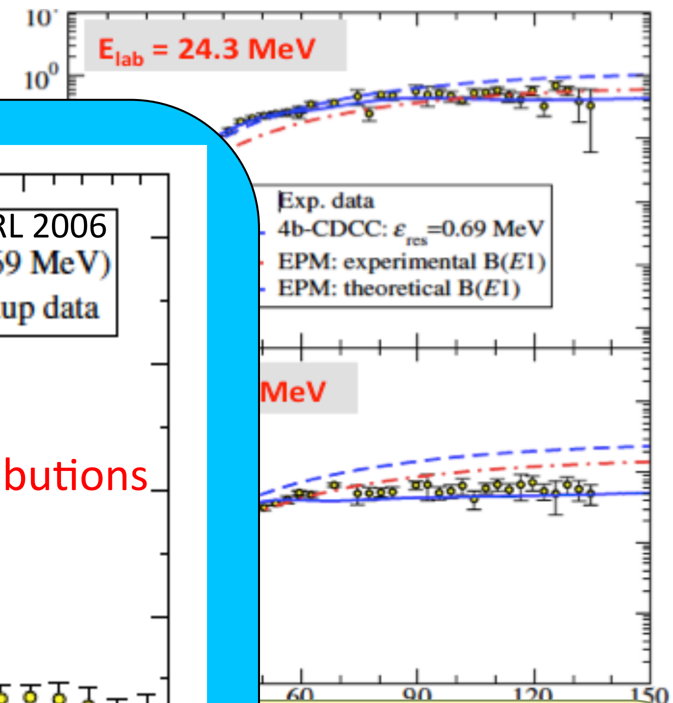
Elastic Scattering

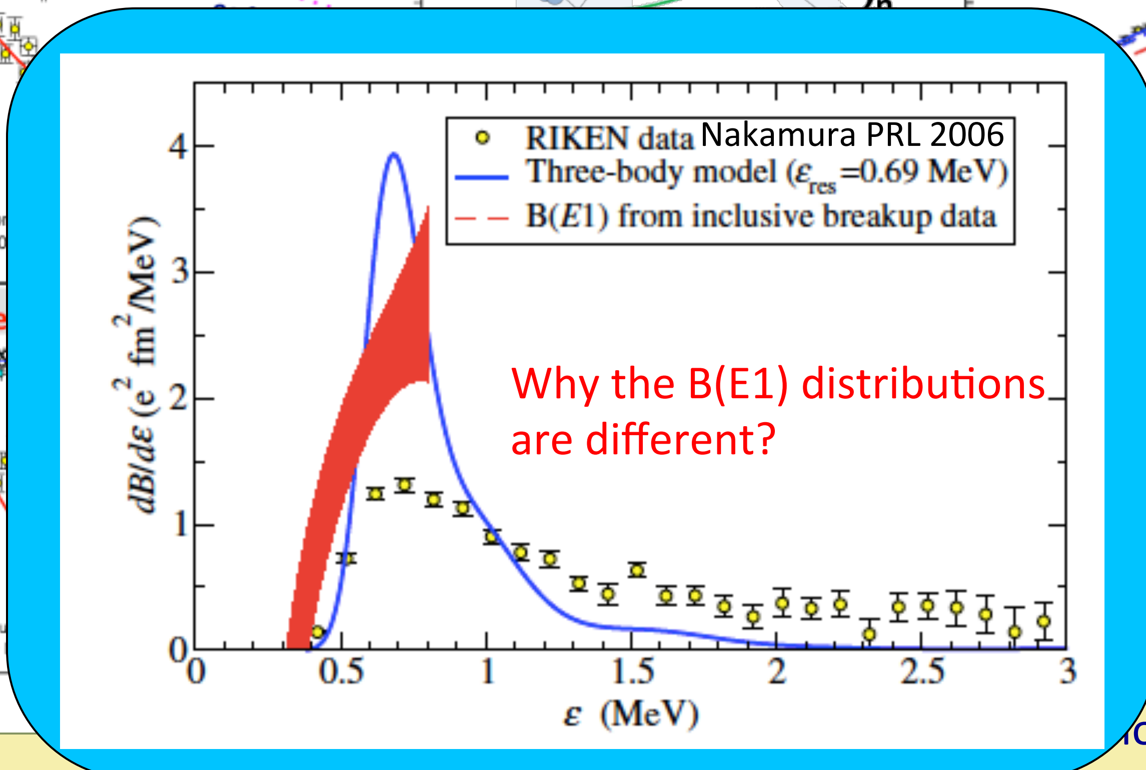


Direct Breakup



Breakup Probability





Scattering process dominated by:
- Dipole couplings (coulomb + nuclear)
- Coupling to continuum
- Good description in a 4-body model

Cubero et al, PRL109 (2012) 262701

ominates the process
lomb int.

✓ Dipole resonance **at 0.69 MeV** essential to reproduce the breakup data. Energy depends of 3-body interaction. Confimed by (p,p'), Tanaka

Fdez-Garcia, PRL110 (2013)142701

Why ^{11}Be is interesting?

- ^{11}Li & ^{11}Be are the archetype of halo nuclei.

(S_{2n} (^{11}Li)= 369.15(65) keV, S_n (^{11}Be)= 501.6 keV).

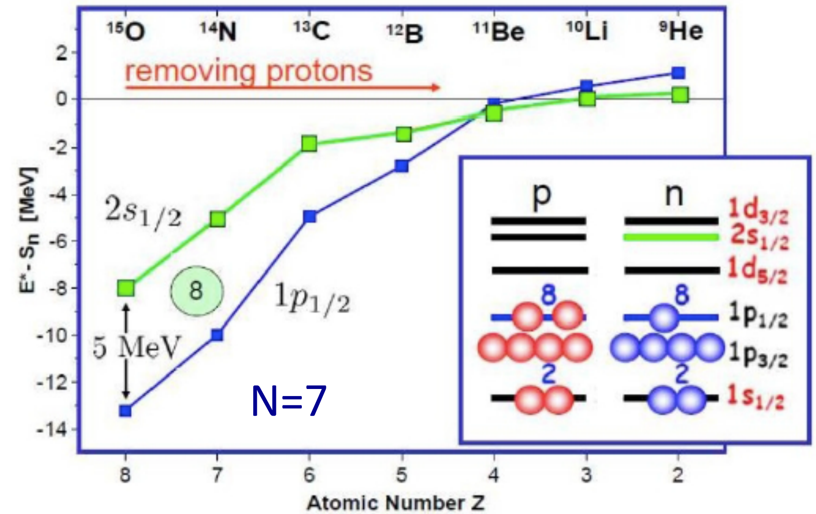
- ^{11}Be has 1 bound state @ 320 keV with $T_{1/2}$ = 166 (15) fs ; B(E1) =
  [Millener et al., PRC28(1983)497]

- The ^{11}Be ground state: result from coupling 1n to ^{10}Be mainly to the gs: $\alpha^2 \approx 0.8$

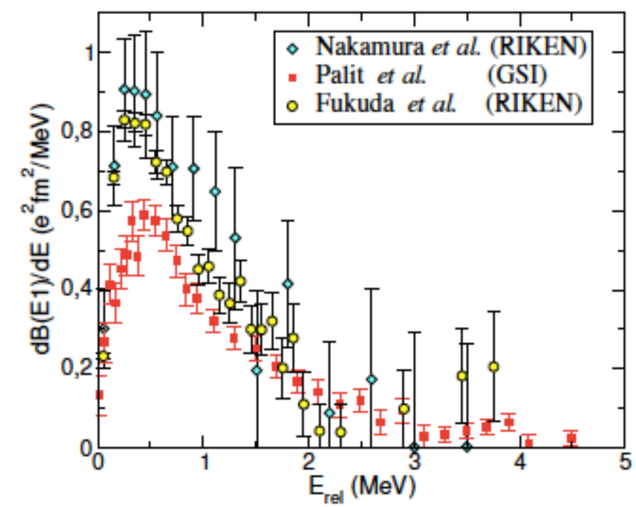
$$|^{11}\mathrm{Be(gs)}\rangle_{1/2+} = \alpha\, |^{10}\mathrm{Be}(0^+) \otimes \nu(s_{1/2})\rangle + \beta\, |^{10}\mathrm{Be}(2^+) \otimes \nu(d_{5/2})\rangle + \ldots$$

- Huge E1 strength at low break-up energy
  → Dipole polarizability

The elastic cross sections around the Coulomb barrier sensitive to the B(E1) strength close to the break-up threshold.



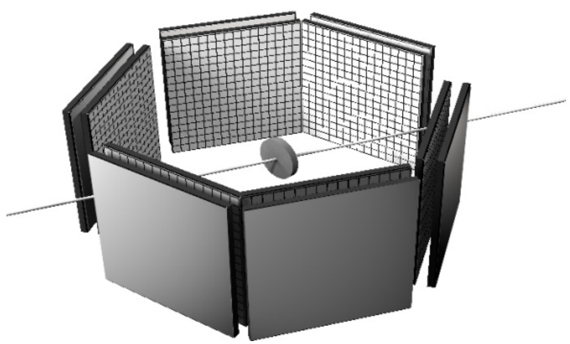
P.G. Hansen, NPA 682 (2001) 310C

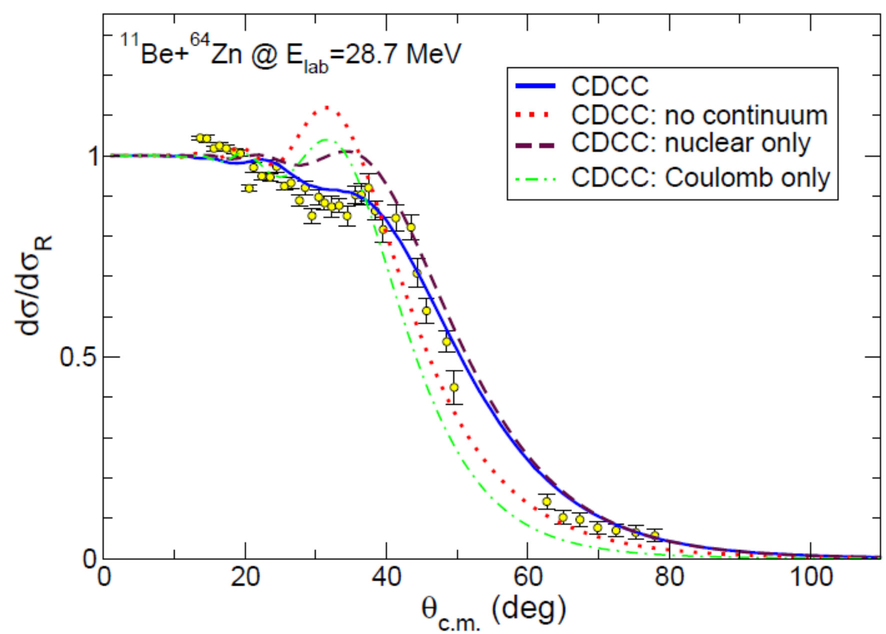


Nakamura et al., PLB 331 (1994) 296
Palit et al., PRC68(2003)034318
Fukuda et al., PRC70(2004) 054606

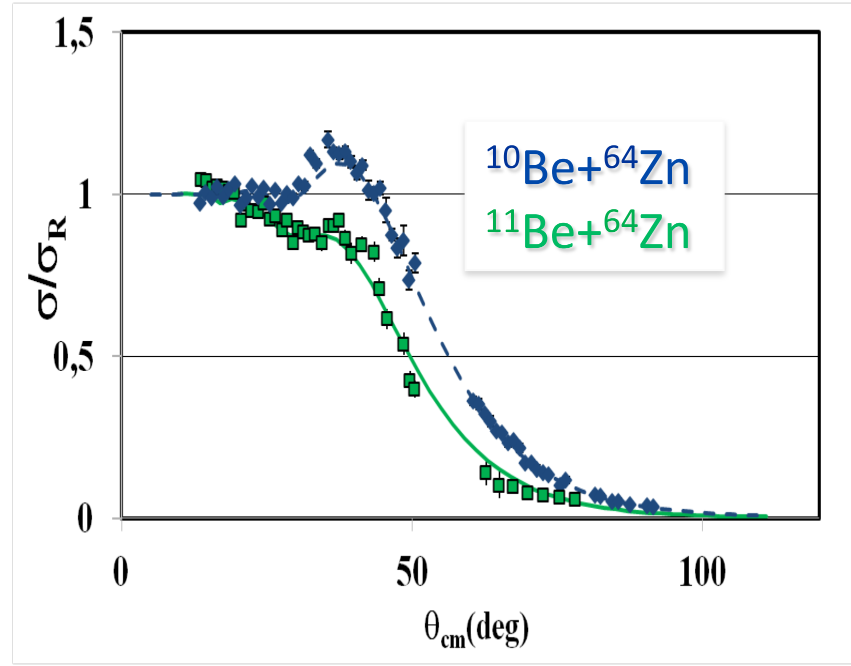
Previous Reaction Studies near Coulomb Barrier

^{10,11}Be+^{64}Zn & ^{11}Be+ ^{120}Sn @ ISOLDE (2.7 MeV/u)





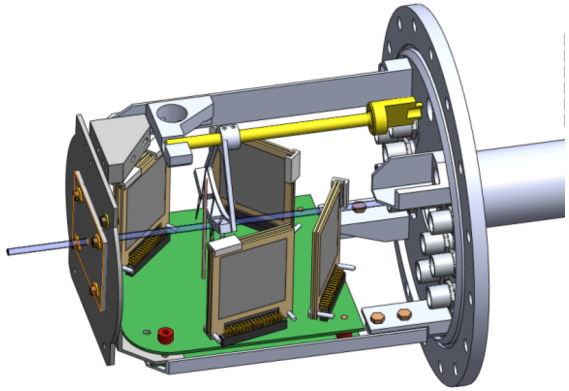
Di Pietro et al., PRC84(2013)064614



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

Experimental quasi-elastic cross section, reproduced only if coupling to continuum via the Coulomb and nuclear interactions is included

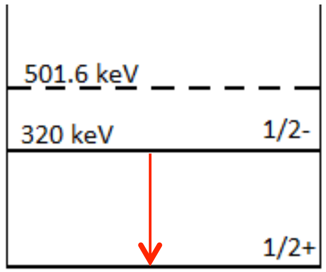
^{11}Be @TRIUMF



^{12}C @ 5.0 MeV/u.

- ^{11}Be @ 3.6 MeV/u.
- ^{11}Be @ 2.9 MeV/u.

V_b (^{11}Be+^{197}Au) ≈ 40 MeV

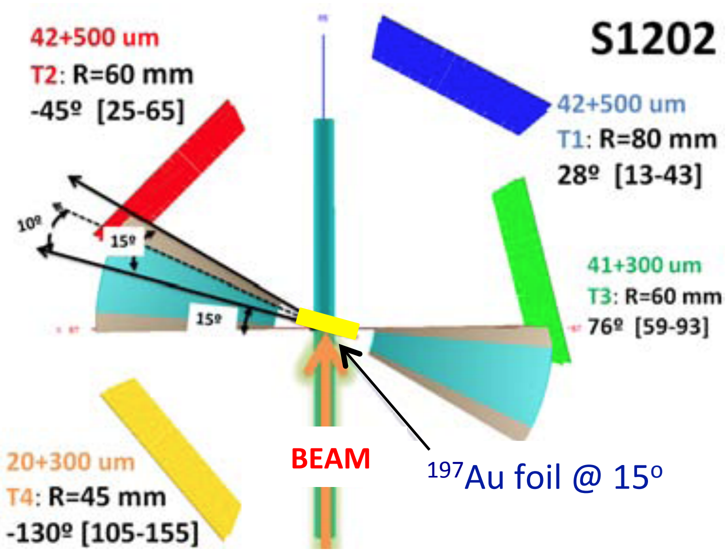


^{11}Be

Yield ≈ 10^5 ^{11}Be/s

-TARGET:

- **^{197}Au (1.9 mg/cm^2)**



Angular coverage of Setup

$15^o < \theta < 155^o$

Charged particles:

- 3 telescopes DSSSD 16x16 (40µm) + PAD (500 µm).

$-15^o < \theta < 95^o$

- 1 telescope SSSD 16 (20 µm) + DSSSD 16x16 (300 µm).

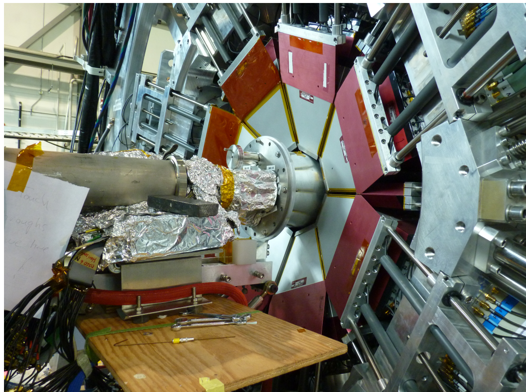
$-105^o < \theta < 155^o$

TIGRESS:

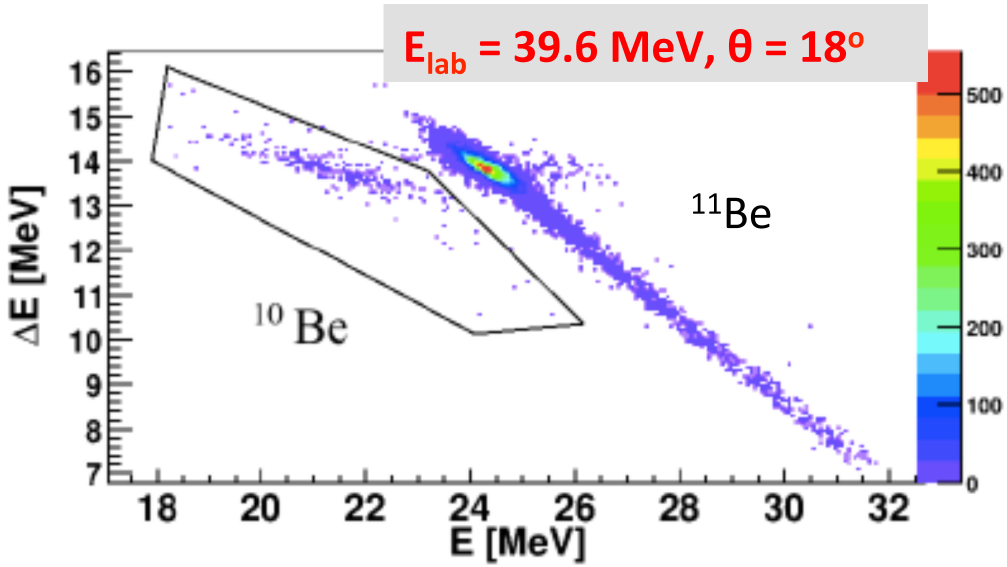
8+4 rings of HPGe Clover

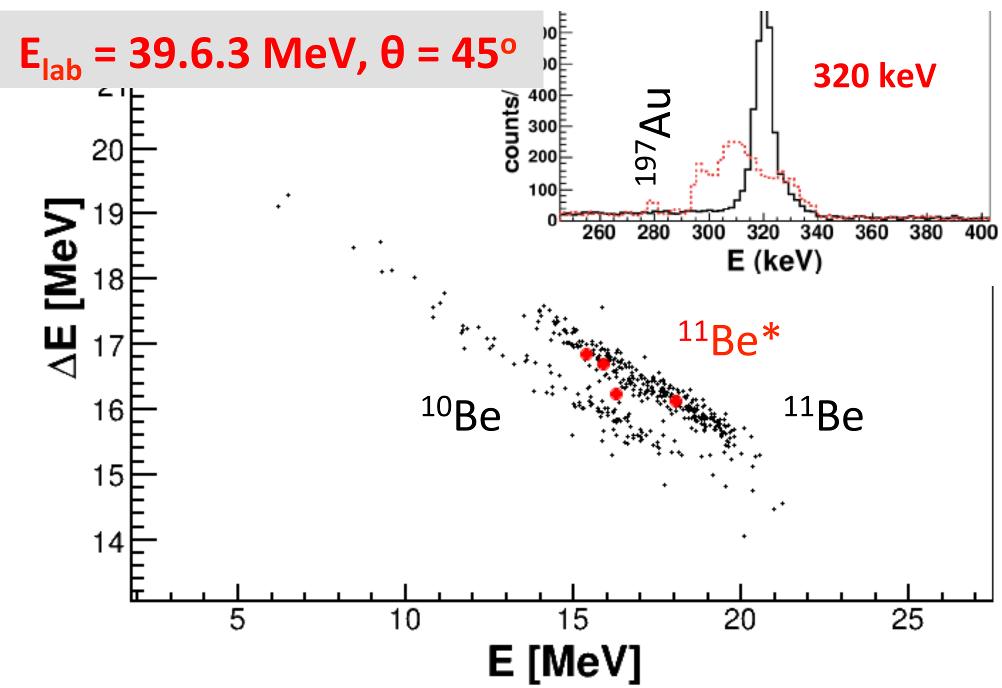
- Low efficiency configuration.
- More Compton supression.
- Espectra at 320 keV

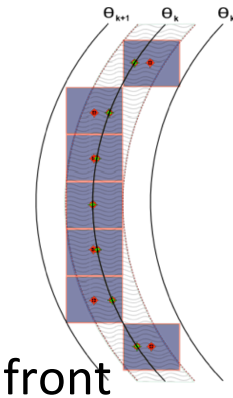
Efficiency ε(320keV) = 0.121(5).



^{11}Be + ^{197}Au Data Examples







Corrections

- ✓ Matching energy in the front and back strip of the pixel
- ✓ Considering incoming angle in the detector
- ✓ Angle of the pixel within the angular sector range of 3°
- ✓ Event separation by pixel when needed

Good Separation of the different channels:

-Elastic

-Inelastic

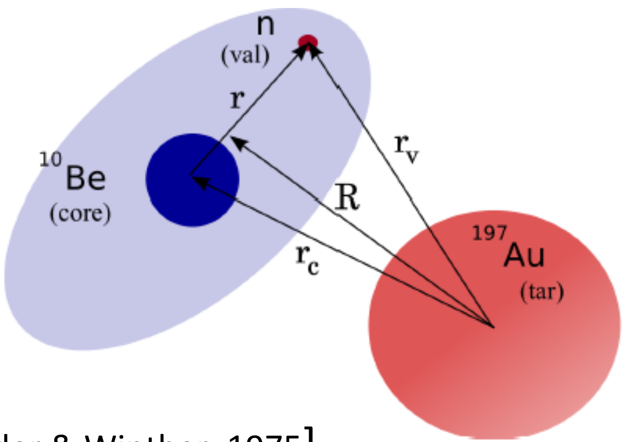
-Breakup

Theoretical Interpretation

Which is the mechanism responsible of the ^{11}Be scattering?

Are our data compatible with known B(E1) distribution obtained at higher energies?

Comparison of the experimental data with theoretical calculations.



Optical Model: effective potential

Semiclassical Calculations: Include Coulomb coupling at first order

$$P_{bu}(\Omega) = \left(\frac{Ze}{a_0 \hbar v}\right)^2 4\sin^4(\theta/2) \int_{\varepsilon_b}^{\infty} dE \, \frac{dB(E1)}{dE} \frac{df_{E1}}{d\Omega}$$

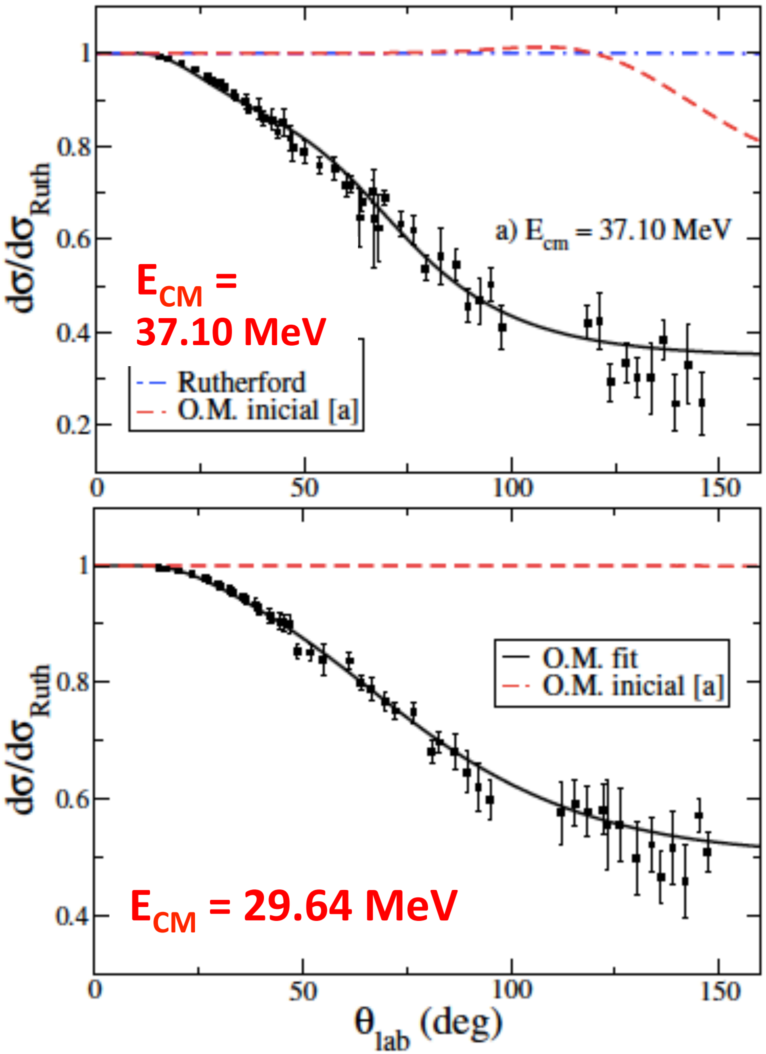
[Alder & Winther, 1975]

Continuum Discretised Coupled Channel (CDCC):

V[n-^{10}Be] + V[n-^{197}Au] + V[^{10}Be + ^{197}Au]

Continuum Discretised Coupled Channel (CDCC) + Structure Model of ^{11}Be:

$^{11}Be + ^{197}Au$: Optical Model



Effective Potential U(R) = V(R) + iW(R)
Wood Saxon

	Inicial $^{10}Be+^{208}Pb$ [a]	E_{cm} = 37.10 MeV	E_{cm} = 29.64 MeV	Ambas E
V (MeV)	113.	14.0	9.2	13.3
r_V (fm)	1.1	1.2	1.2	1.2
a_V (fm)	0.6	3.1	3.8	3.2
W (MeV)	169	0.21	0.179	0.188
r_W (fm)	1.196	1.2	1.2	1.2
a_W (fm)	0.30	8.68	8.73	8.39
χ^2		1.3	1.0	1.8

a J.J. Kolata et al. En: *Phys. Rev. C* 69 (2007), pág. 047601

- ✓ Deviation from Rutherford in the full angular range
- ✓ Importance of long range couplings
- ✓ Sensitivity at long distances
- ✓ Reaction dominated by Coulomb process

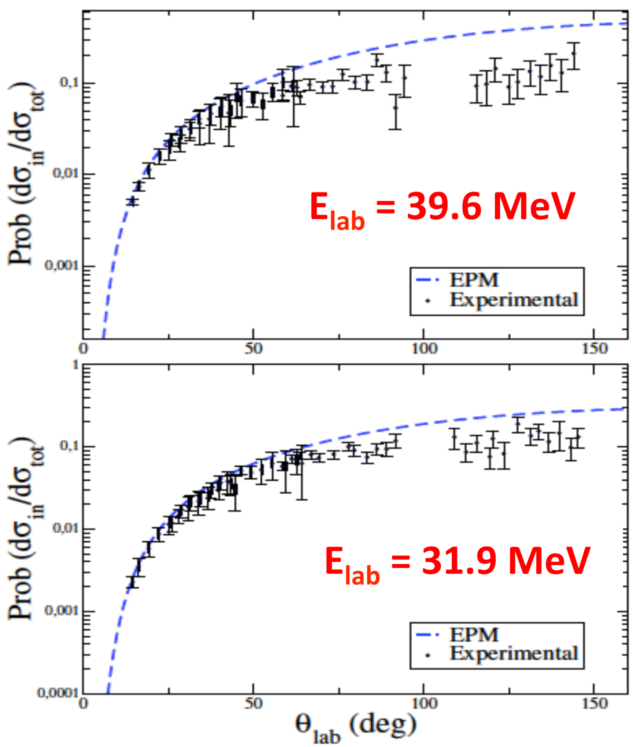
^{11}Be + ^{197}Au: Equivalent Photon Method

✓ Semiclassical calculation includes Coulomb excitation (E1) at first order, EPM

$$\frac{d\sigma_{E\lambda}}{d\Omega} = P(\theta, E\lambda)\frac{d\sigma_{Ruth}}{d\Omega}$$

P(θ, Eλ) depends on B(Eλ)

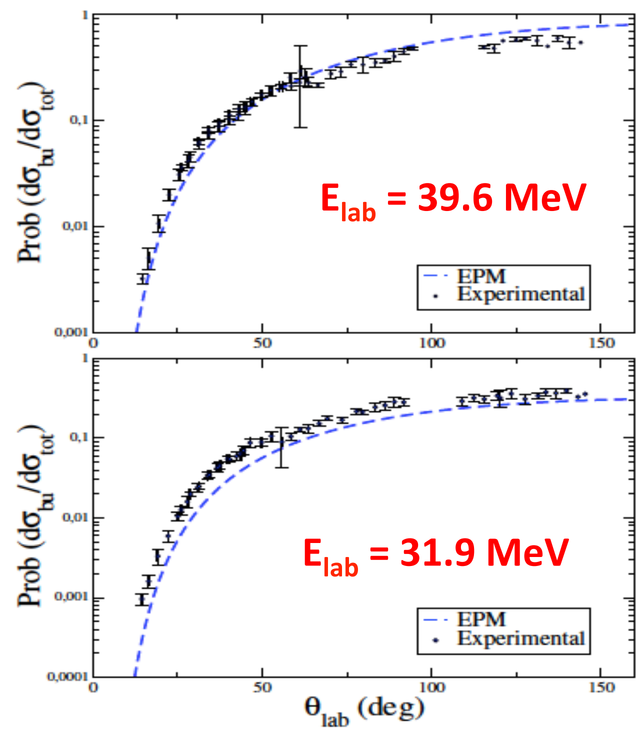
Inelastic Channel



$$P_{in} = \frac{N_{in}}{N_{tot}}$$

$$P_{bu} = \frac{N_{bu}}{N_{tot}}$$

Breakup Channel



✓ Good reproduction of Inelastic

✓ Θ > 50º nuclear or higher order effects

✓ Underestimation of the breakup in the full energy range mainly at low energies

^{11}Be + ^{197}Au: CDCC

- ✓ The CDCC considers 3 body (^{10}Be + n + ^{197}Au) and includes both Coulomb and nuclear couplings at all orders.

V(^{10}Be-n) from P. Capel et al, PRC70 (2004) 064605

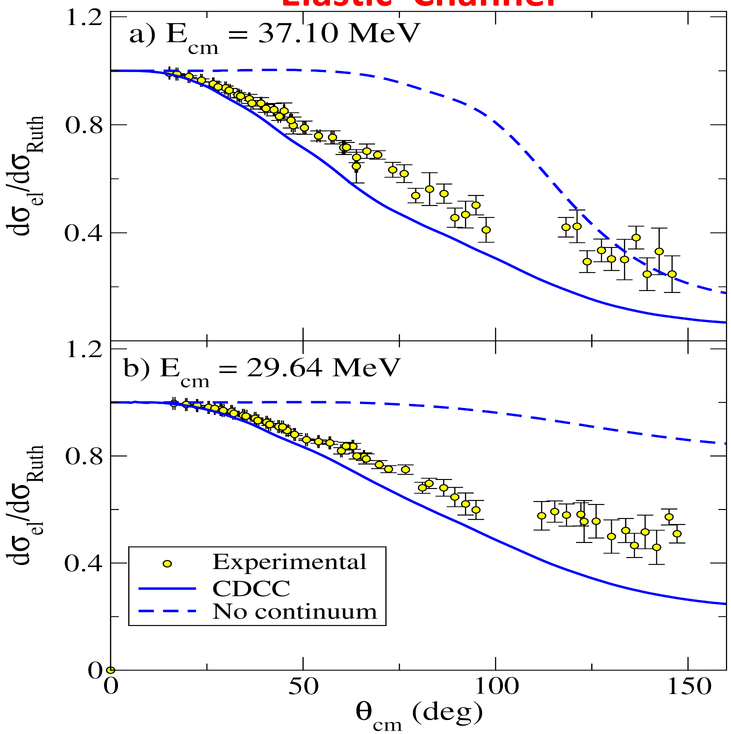
V(^{10}Be-^{197}Au) from [^{10}Be-^{208}Pb, J. J. Kolata et al,PRC69 (2004) 047601]

V(^{197}Au-n) A. J. Koning & J. P. Delaroche NPA713 (2003) 231

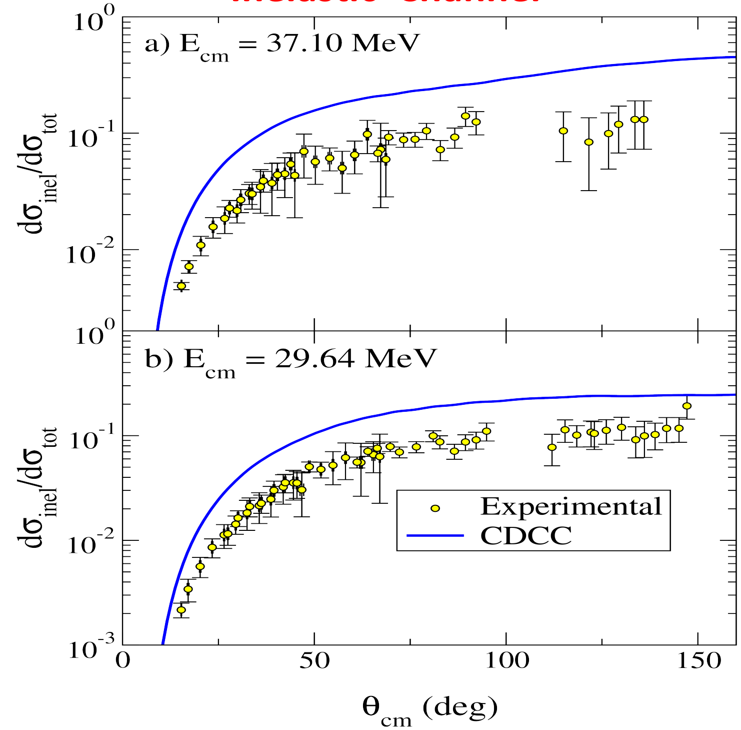
States up to 12-14 MeV

$J^{\pi} = 21/2^{+}$

Elastic Channel



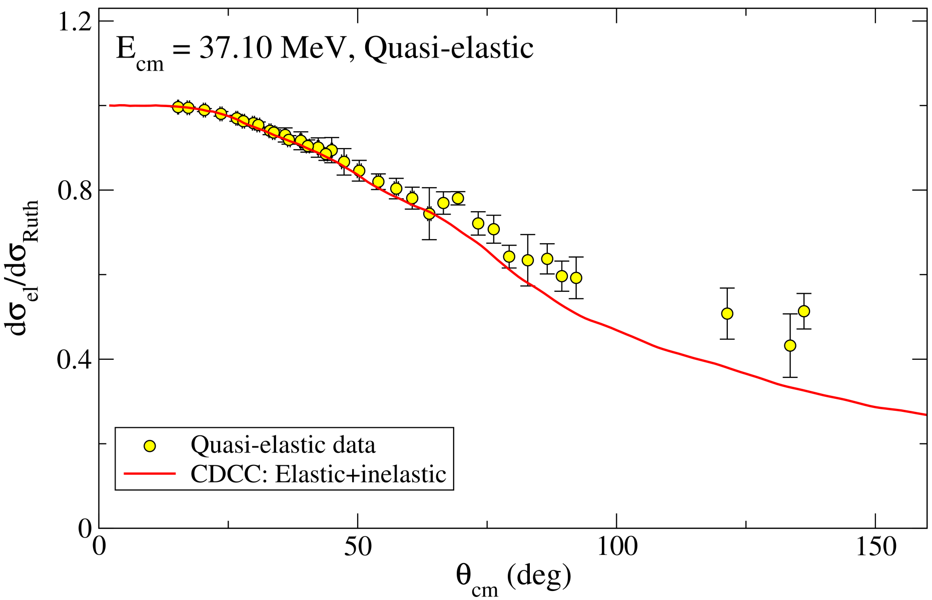
Inelastic Channel

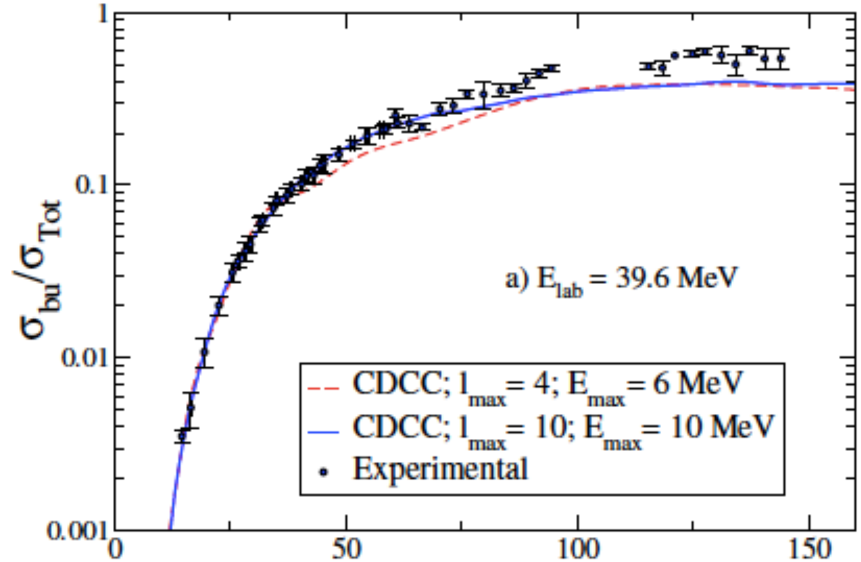


The calculation produces a B(E1; ½$^{+}$ → ½$^{-}$) = 0.26 e^{2}fm^{2} instead of exp. 0.116(12) e^{2}fm^{2}

$^{11}Be + ^{197}Au$: CDCC (II)

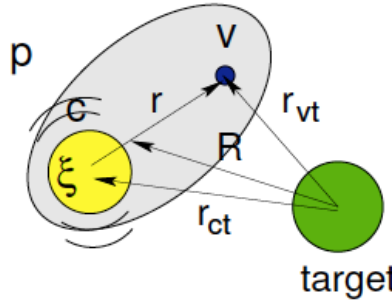
- Convergence obtained when many n-core partial-waves and high excitation energy in the continuum are included → **High order couplings are important.**





- The CDCC calculation is able to describe both the quasi-elastic and Coulomb breakup data, but fails in reproducing elastic and inelastic
- The SP model ignores the deformation of ^{10}Be → No core excited configurations in the description of ^{11}Be → PRM of Tarutina et al PRC67, 2003.

^{11}Be on ^{197}Au: XCDCC

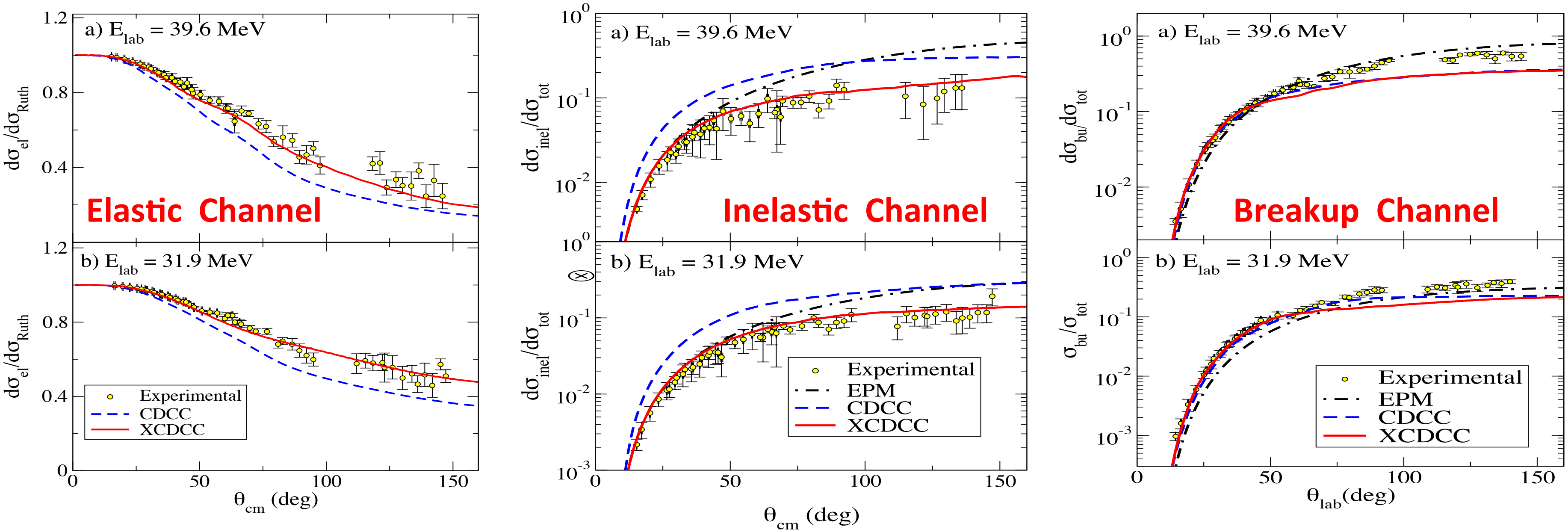


✓ The XCDCC includes a non-spherical ^{10}Be with deformation reproducing the B(E2) value. PRM of Tarutina et al PRC67, 2003.

$$|^{11}Be(gs)\rangle = \alpha|^{10}Be(gs) \otimes 2s_{1/2}\rangle + \beta|^{10}Be(2^+) \otimes 1d_{5/2}\rangle + \gamma|^{10}Be(2^+) \otimes 1d_{3/2}\rangle$$

J.A. Lay

We incorporate this structure model in the reaction formalism →
Core-halo entanglement + Core excitation due to interaction with target nucleus



❑ **The XCDCC calculation is able to reproduce the elastic, inelastic and breakup channels**

❑ **Target excitation and transfer are expected to be relevant in the breakup at large angles and high energy**

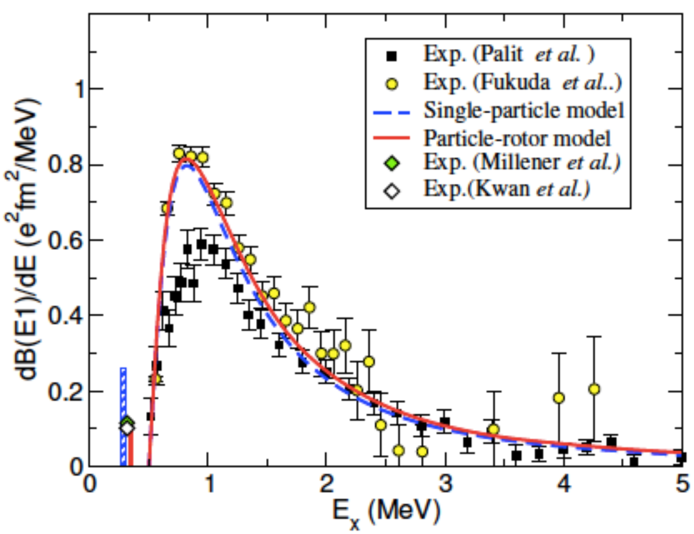
Conclusions

▪ ^{11}Be + ^{197}Au studied with efficient gamma-particle coincidences, obtained with high granularity, energy resolution has allowed to extract the differential elastic, inelastic and break-up cross sections measured in a wide angular range at energies below (31.9 MeV) and around (39.6 MeV) the Coulomb barrier (Vb ≈ 40 MeV). **Identification of the inelastic channel for first time in this energy regime**.

▪ The Inelastic and breakup channels are important even well below the Coulomb barrier → **Calculations including all processes and the continuum are required.**

- **For first time** state-of-art CC calculations describe the complex interplay between the halo and the core degrees of freedom (XCDCC)→ **Essential to describe the data consistently.**
- Validate the B(E1) of Fukuda et al. PRC 70, 2004

V. Pesudo et al., submitted to PRL



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Thanks to my Collaborators of S1202 @ TRIUMF

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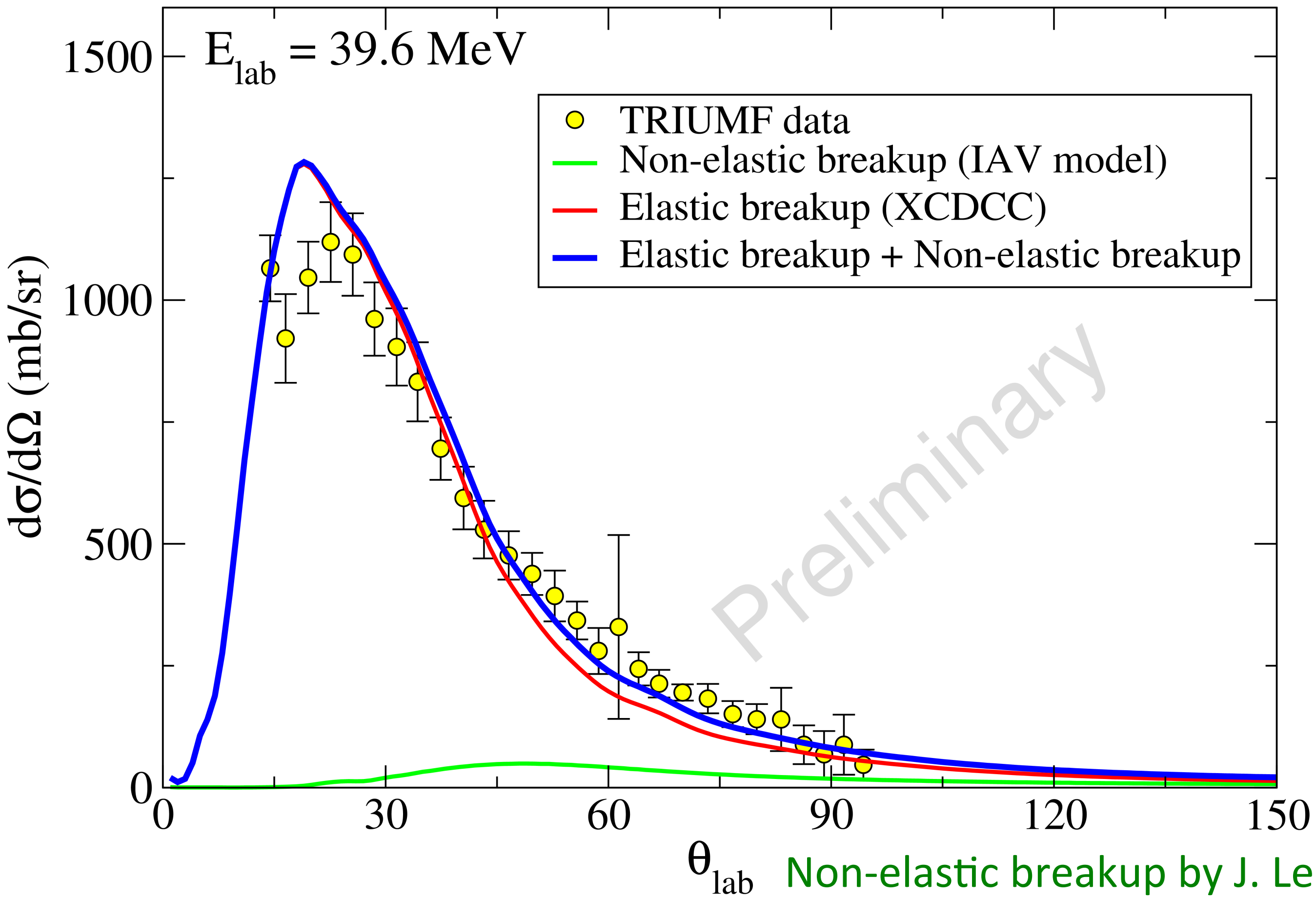
THANK YOU FOR THE ATTENTION !

Absolute Breakup Cross Section

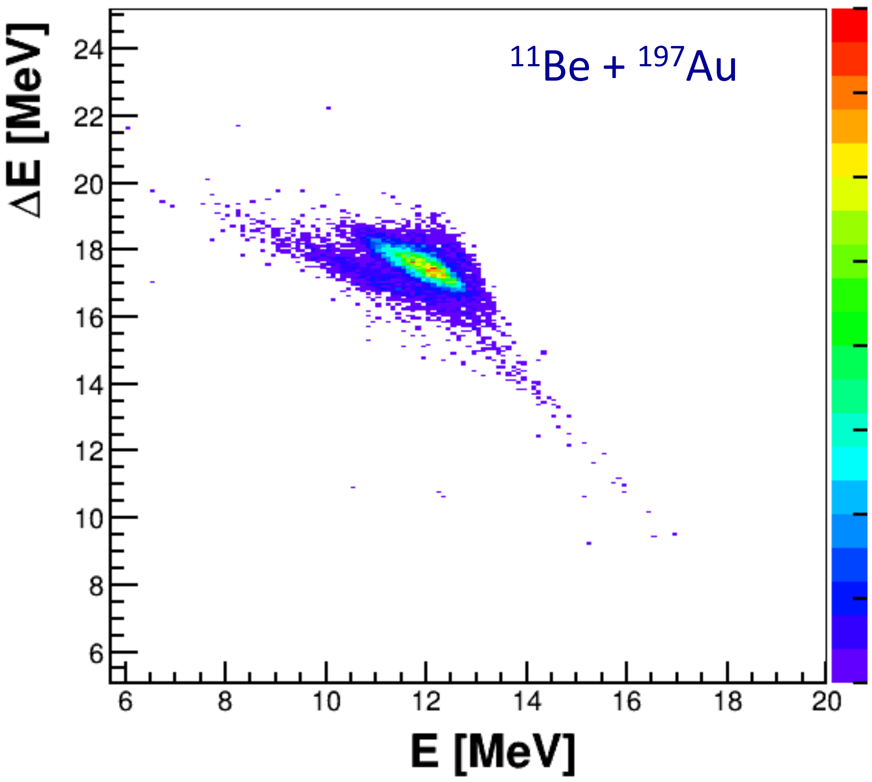


Non-elastic breakup by J. Lei

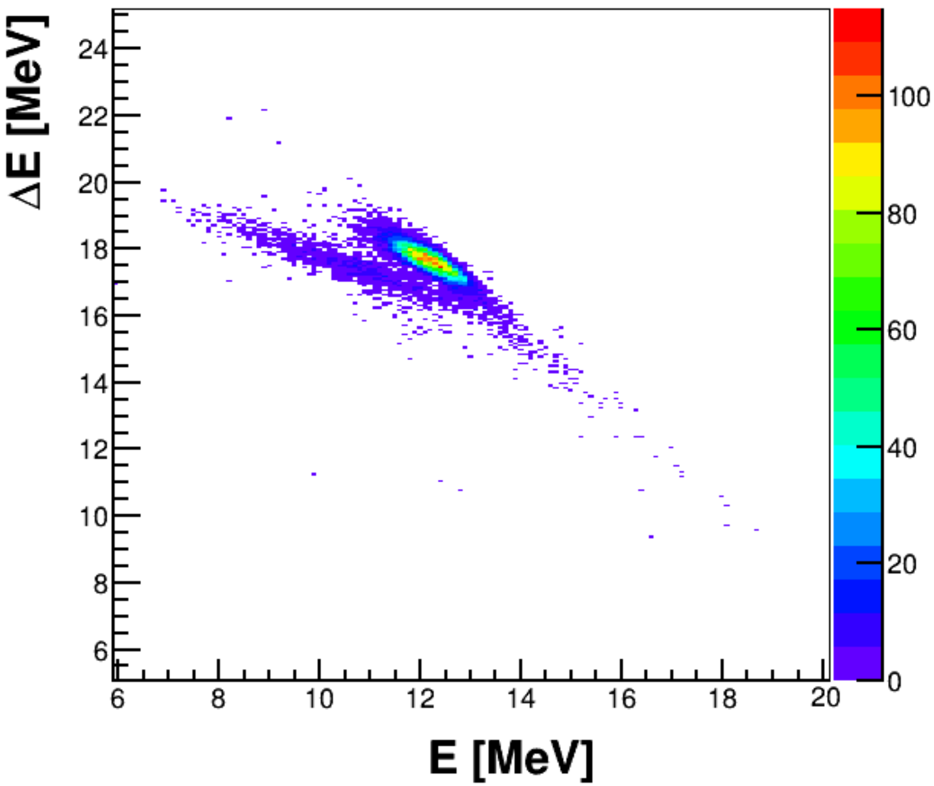
- ✓ Elastic breakup largely dominates the inclusive breakup process
- ✓ **Evidence of non-elastic breakup at large angles**

Corrections to improve Resolution

E_{lab} = 31.9 MeV, 65º < θ < 69º



Corrections



Previous Reaction studies near Coulomb barrier

- ✓ Halo nuclei are very challenging system.

Their slowly bound nucleons provide inside into degrees of freedom connected to slow processes.

The characteristic movement of a nucleon with

$B = 0.5$ MeV → $\tau = h/2\pi B = 1.3 \times 10^{-21}$ s — halo nucleon

$B = 8$ MeV → $\tau = h/2\pi B = 8 \times 10^{-23}$ s — Standard nucleon

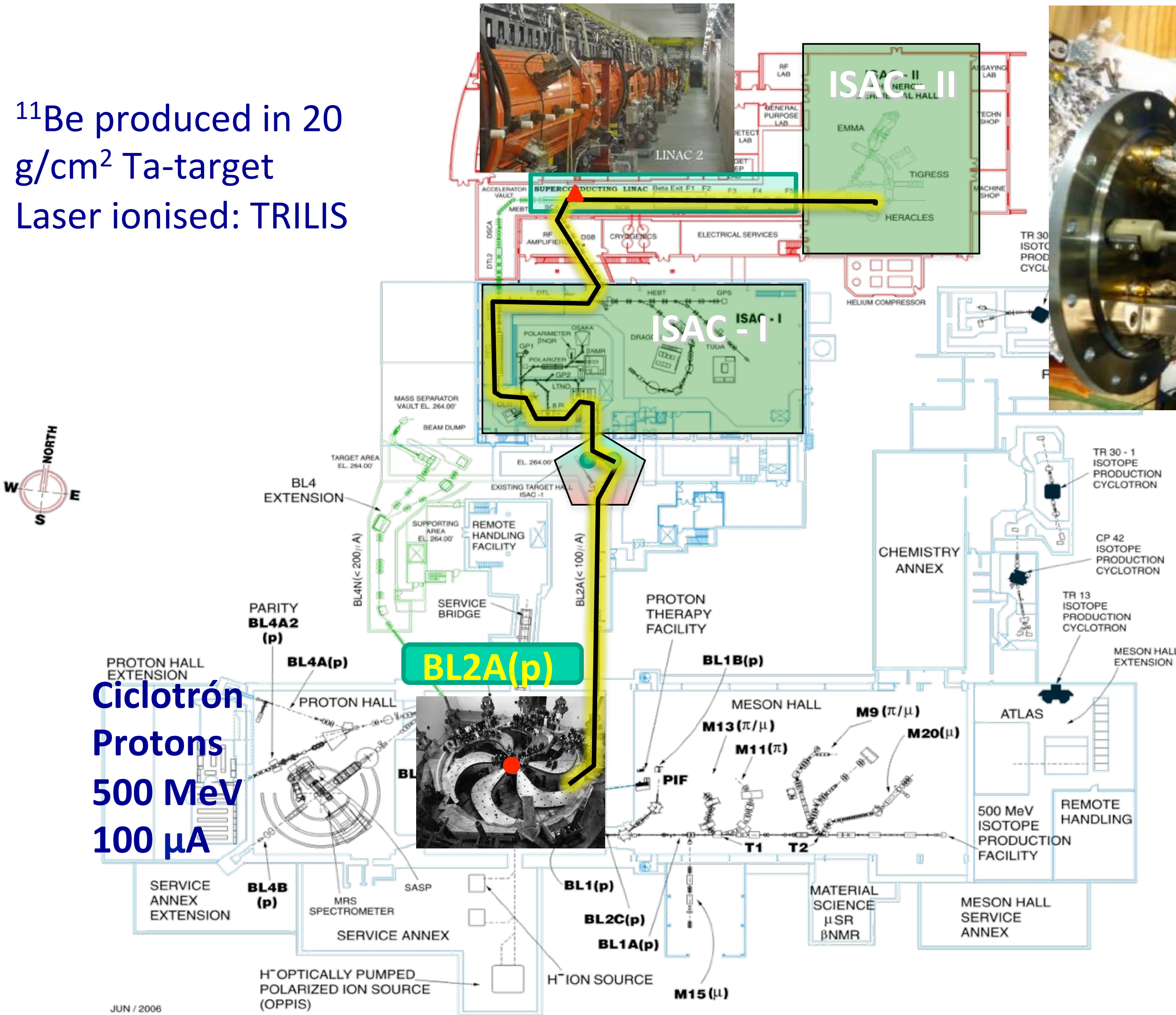
Coulomb excitation is the right tool to explore the slow degrees of freedom. In scattering reaction near the Coulomb barrier assuming R as the distance of closest approach: the collision time $\tau = R/v \approx 10^{-21}$s

Previous studies done for $^{11}Be + ^{64}Zn$.
Quasieleastic measurement

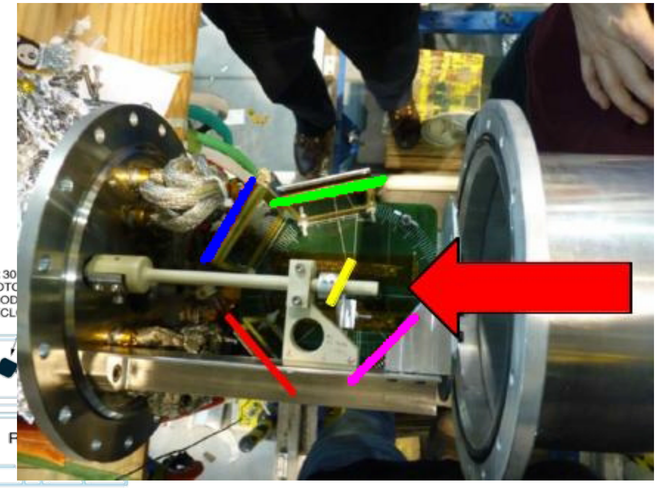
.

Experiment @TRIUMF

^{11}Be produced in 20 g/cm^2 Ta-target
Laser ionised: TRILIS



Ciclotrón
Protons
500 MeV
100 μA

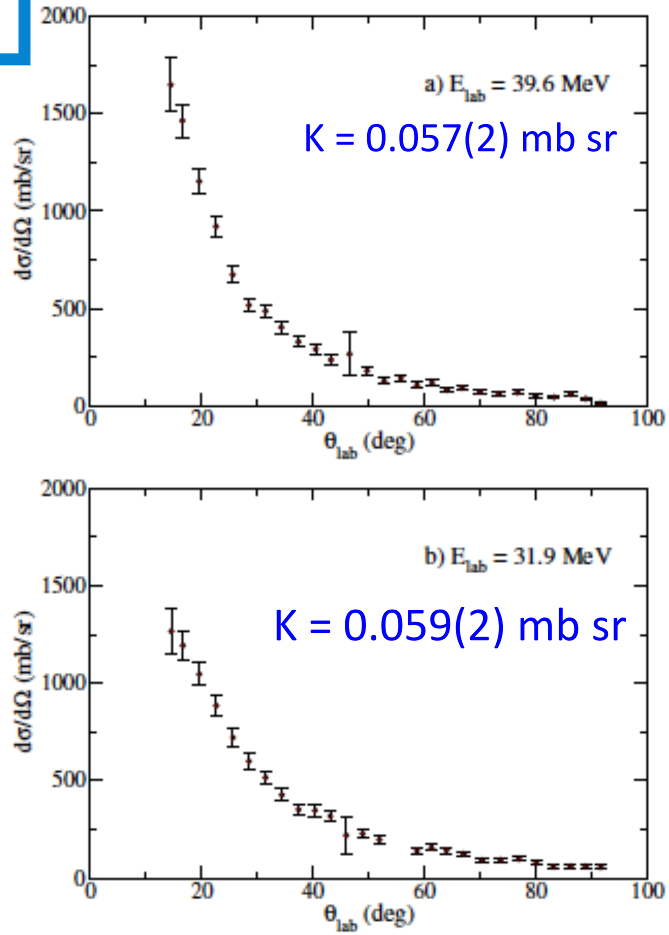


^{11}Be on secondary target
10^5 pps

Differential Cross Sections

$$k = \frac{\frac{d\sigma}{d\Omega}}{\frac{N}{\Delta\Omega}}$$

Elastic Channel



Break-up Channel