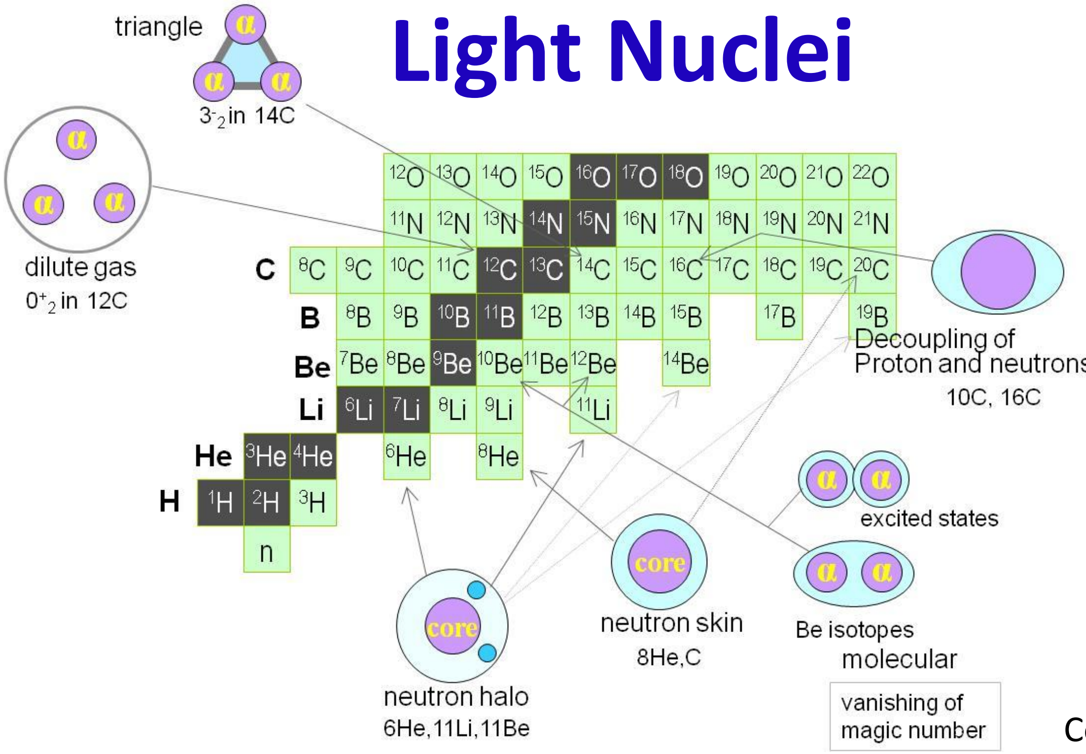
Scattering of ^{15}C on ^{208}Pb at energies near the Coulomb barrier

María José García Borge
(on behalf of J. D. Ovejas, V. G Távora)

Light Nuclei



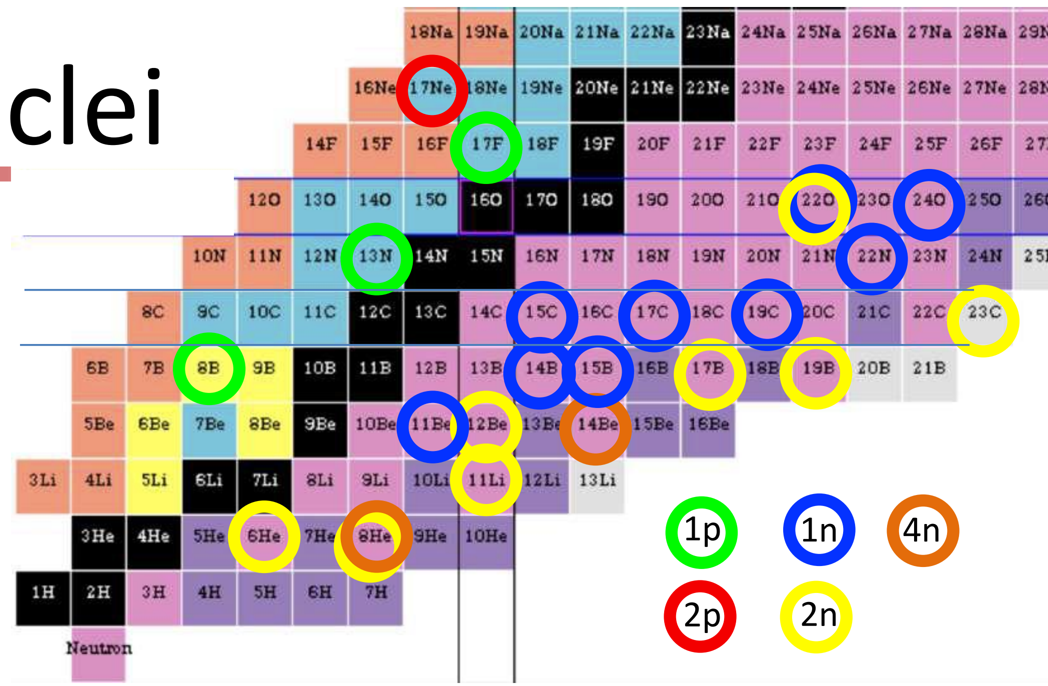
Courtesy Kanada-En'yo

Light nuclei: a quantum mechanics laboratory

- Quantum mechanics plays a role in creating peculiar structures in ground states of light nuclei: nuclear skins and/or nuclear halos, nuclear clusters, nuclear molecules, gas condensate ….
- Theoretical understanding of the structure of light drip-line nuclei is challenging → Ab-Initio calculations are reaching good description of structure of light nuclei.
- In order to handle new observables and exotic structures → New theoretical models needs to be able to describe reaction dynamics

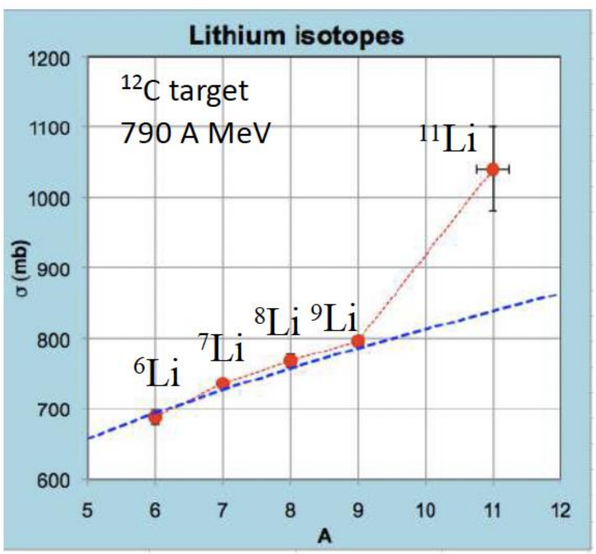
Halo Nuclei

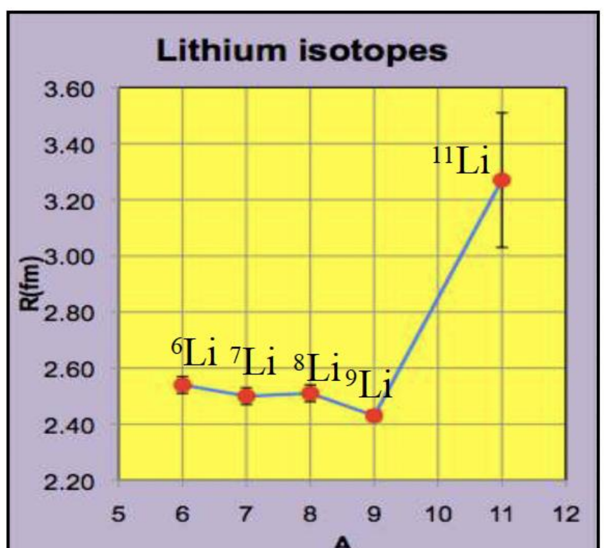
The nuclear halo is a threshold effect arising from the very weak binding energy (0.1-1 MeV) of the outer nucleon(s)



G. Sawhney et al, J. Phys G Nuc part Phys 41 (2014) 055101

- Extended mass distribution
- Large rms radius
- Large reaction cross section
- Narrow momentum distribution following fast fragmentation
- Concentration of B(E1) close to BU threshold





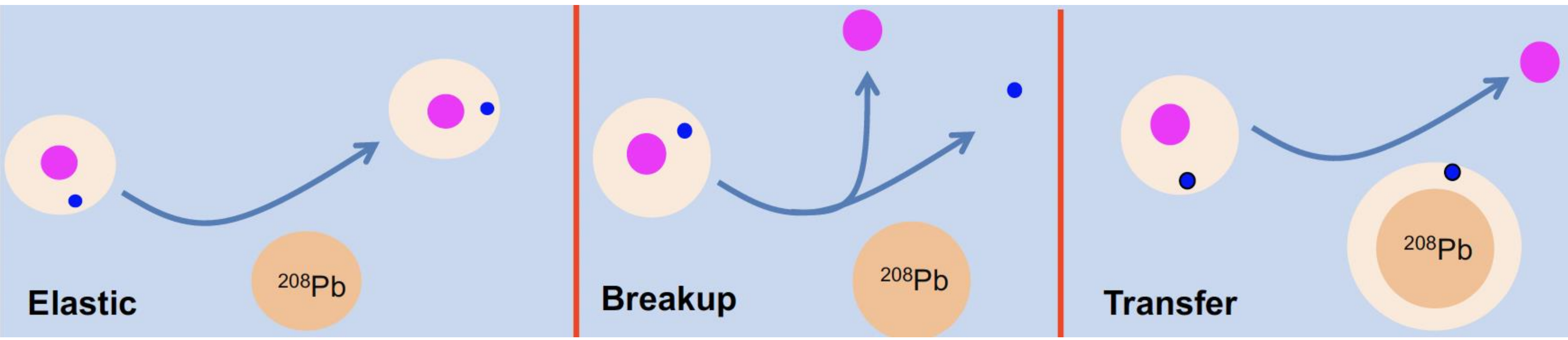
Neutron Haloes

Provide an ideal test bench to study few-body correlations by measuring elastic, nucleon transfer and breakup

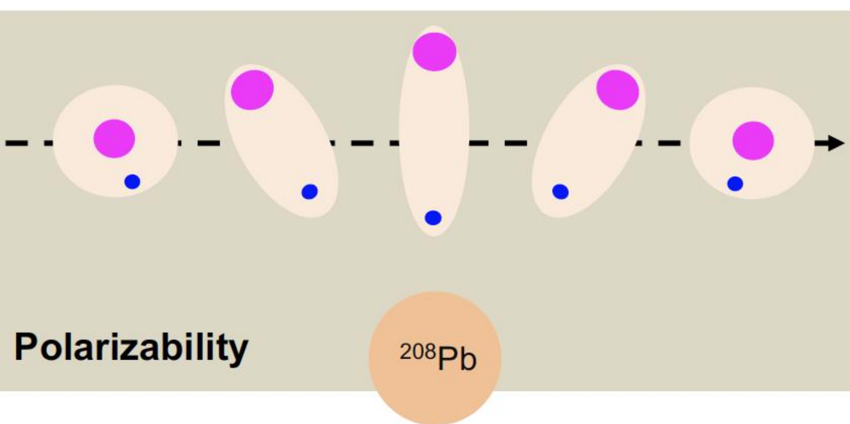
Tanihata, PRL 55 (1985)2676

Scattering of Halo Nuclei @ Coulomb Barrier

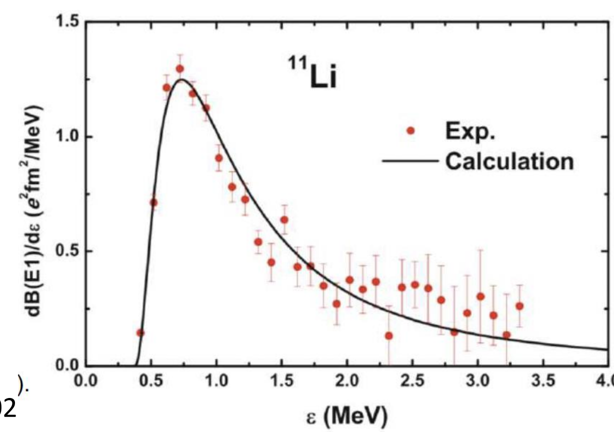
- Coupling between relative motion and internal degrees of freedom
  - Elastic – inelastic – transfer – breakup – fusión + effects of the continuum
- Strong absorption in elastic channel
- Large cross section for fragmentation



Easy polarizable: distorsion of structure in vecinity of heavy target→ Coulomb dipole polarizability



Nakamura et al, PRL 96 (2006) 252502
Kim et al., J Kor Phys Soc 73 (2018)553

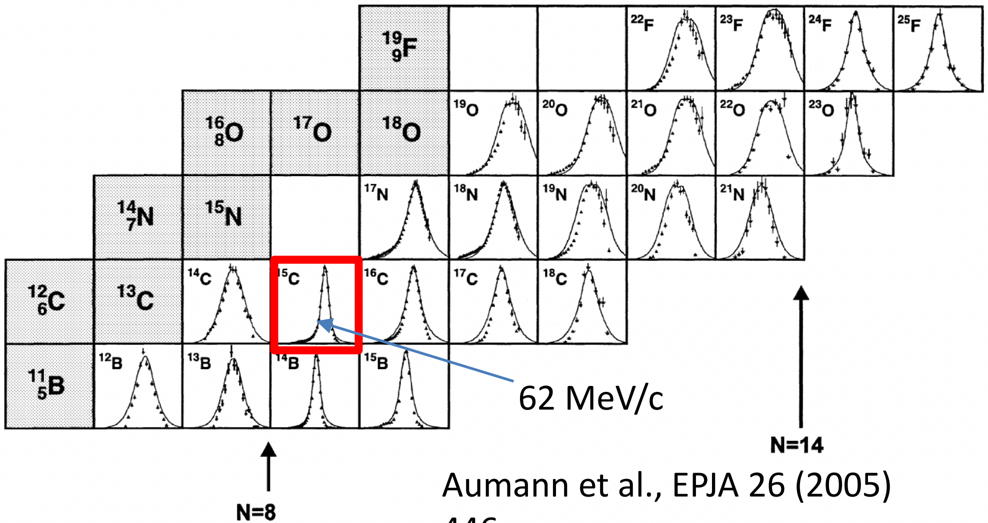


What makes ^{15}C ($T_{1/2}$ = 2.45s) Interesting ?

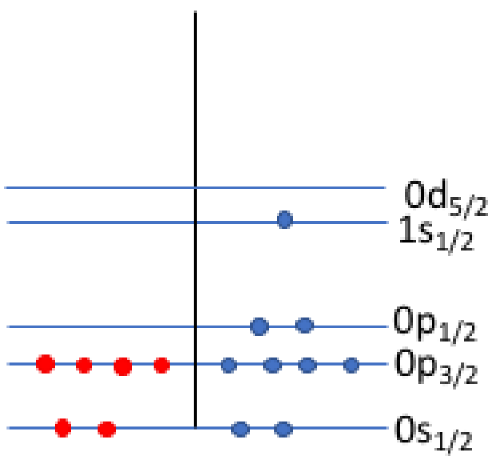
- Realively weakly bound

  $S_n = 1.2\ MeV;\ S_{2n} = 9.4\ MeV$
- Relatively narrow longitudinal momentum distribution
- First excited state (E = 740 keV)
- Ground state $2s_{1/2}$ →

a s-wave 1n-halo coupled to ^{14}C could explains these features,

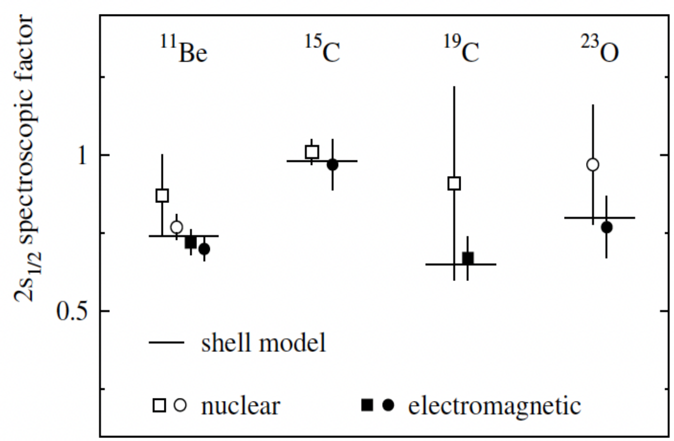


Aumann et al., EPJA 26 (2005) 446



$^{15}C\ I^{\pi} = ½+$

Spectroscopic Factor



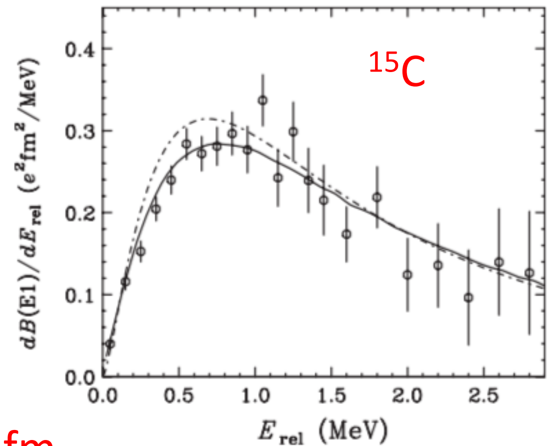
Aumann et al., EPJA 26 (2005) 446

^{15}C: Controversial 1n-halo

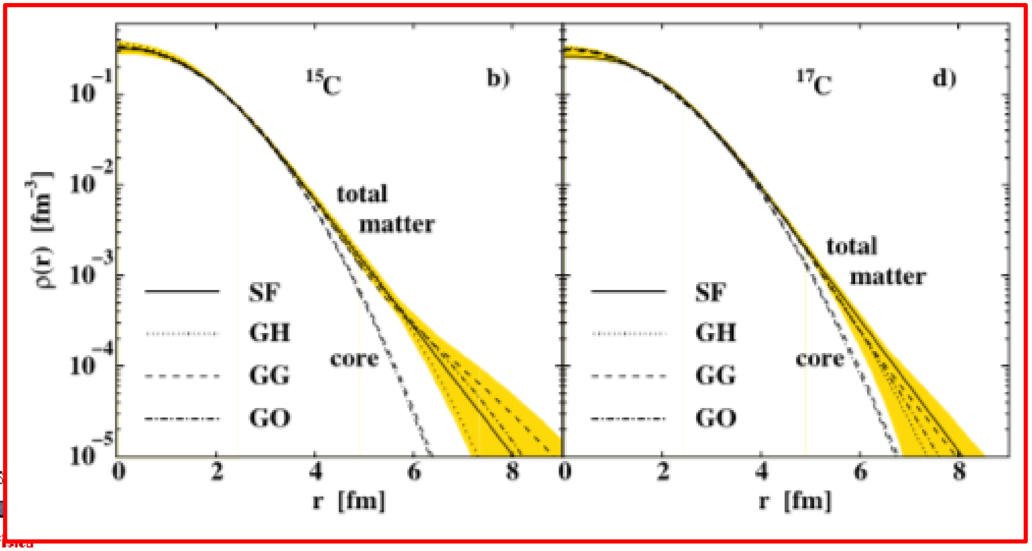
- Reaction cross section larger than $^{14,16}C$ at intermediate energies, but not at higher energies
  - ➢ It seems that coupling increases when energy decreases
- B(E1) deduced from coulomb breakup of ^{15}C on Pb longer tail than ^{11}Be and smaller value of mean square radius.
- Nuclear matter radii and density recently revisited

R_m = 2.59(5) fm ; R_p = 2,37(3) fm R_n = 2,73(8) fm → δ_{np} = 0.36(9) fm

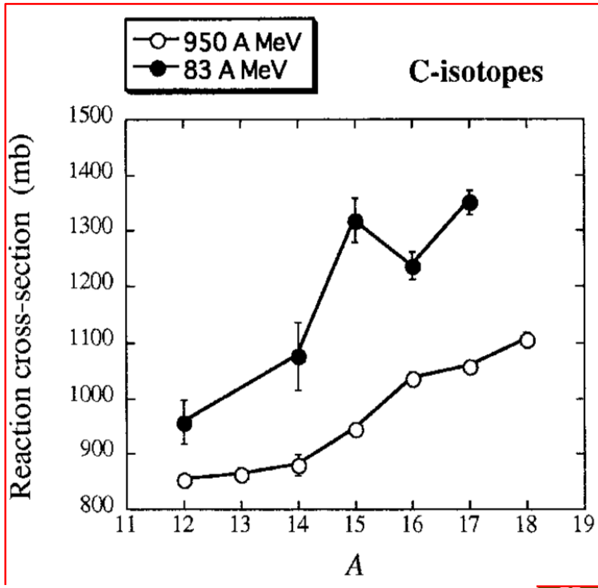
R_c = 2,41(5) fm ; R_ν = 4.36 (38) fm → $\kappa = R_\nu / R_c$ = 1.81 (halo κ > 2)



Nakamura et al., PRC 79 (2009) 035805



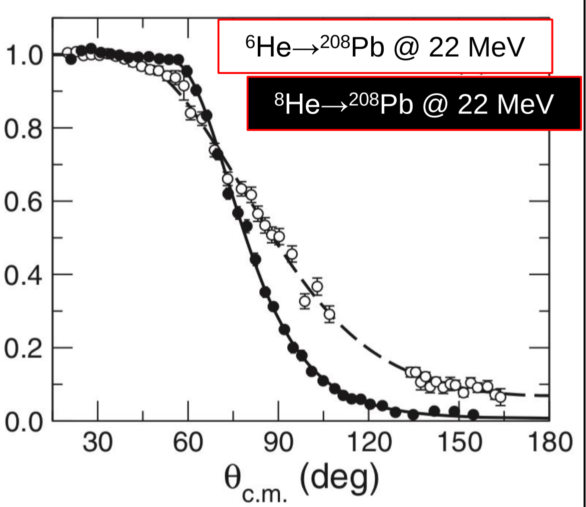
Dobrovolsky et al., NP A 1008 (2021) 122154

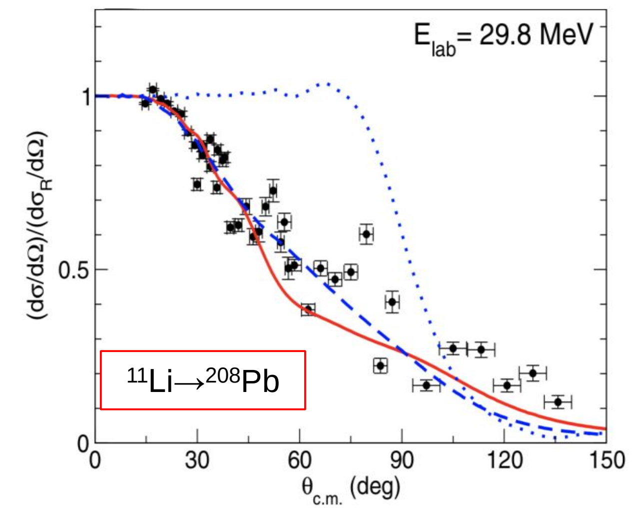


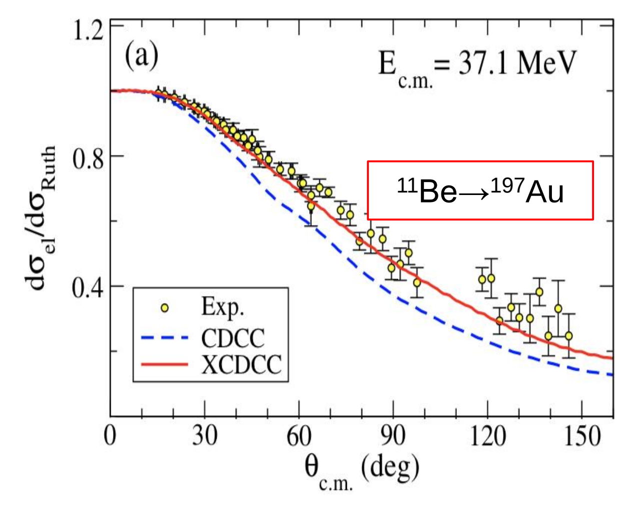
Ozawa et al., NP A738 (2004) 38

Elastic Scattering of halo/skin Nuclei @ Coulomb Barrier

- We have studied the halo effects on the elastic scattering on heavy targets at energies close to the Coulomb barrier
- The scattering of loosely bound n-rich system in the strong electromagnetic field of the reaction target induces a dipole polarization in the projectile.
- A strong absorption in the elastic channel and the suppression of the rainbow arising from the Fresnel interference in the Optical Model is found.
- The structure effects manifest on the angular distribution of the elastic cross section.







Marquinez-Duran et al. P RC 94 064618 (2016)

Cubero et al. PRL109 (2012) 262701

Pesudo, PRL118 (2017)152502

Grupo de Física Nuclear Experimental

IEM

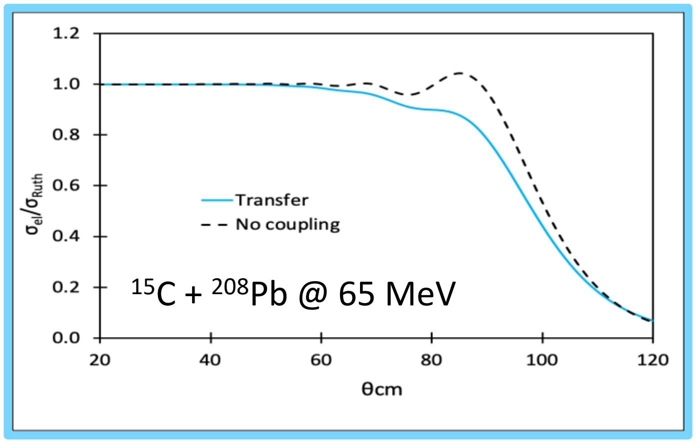
Coulomb Barrier Scattering of ^{15}C + ^{208}Pb

- Reaction studies done at high energies all agree with a moderate halo structure for ^{15}C → Which is the diferential elastic cross near Coulomb Barrier

- Theoretical studies of ^{15}C+^{208}Pb at Coulomb Barrier exist for E = 65 MeV

- 1n-stripping:

Couple reaction channel (CRC)

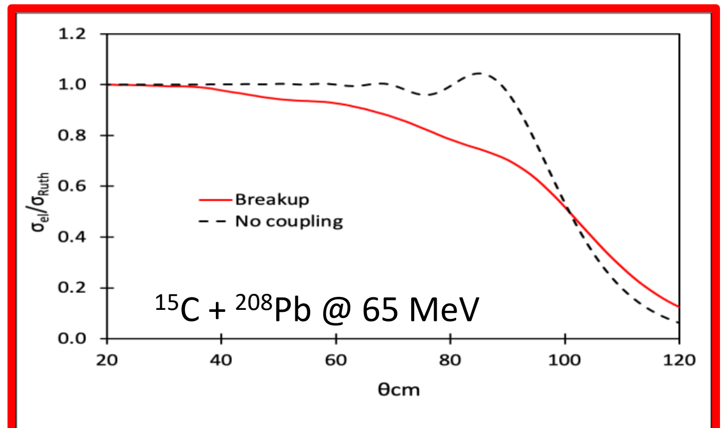


N. Keenley et al., PRC 75 (2007) 056610; EPJA 50 (2014) 145

- 1n-breakup:

Continuum discretized couple channel (CDCC)

- Inelastic (1st excited @ 740 keV)



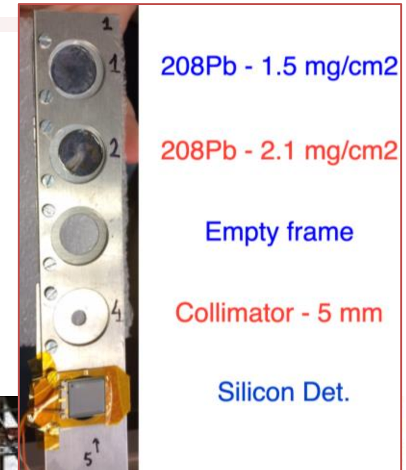
Scattering dominated by the competition of 1n-stripping and breakup

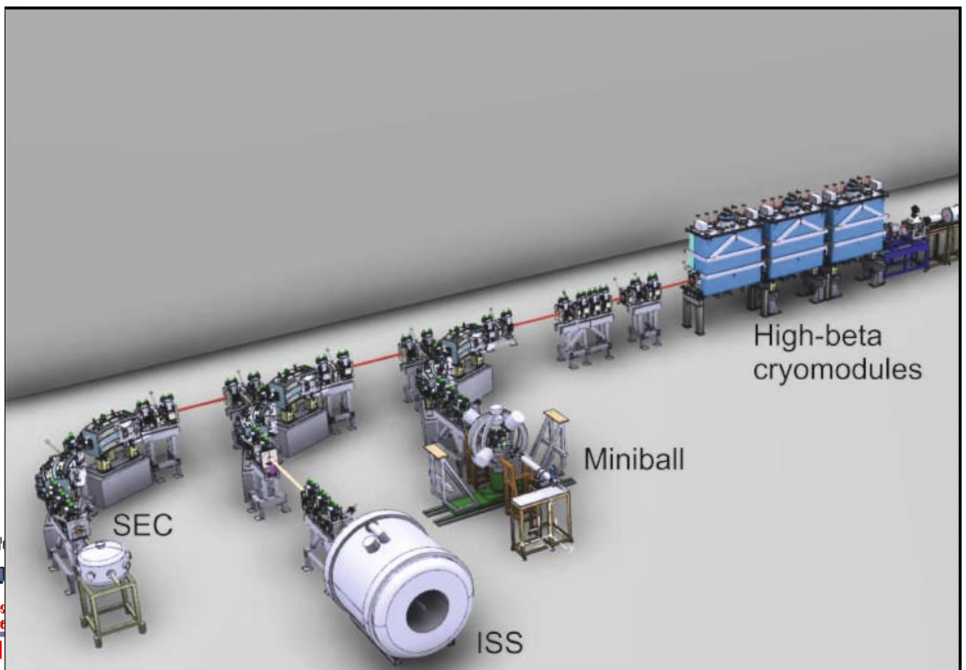
CRC/ 1n stripping		CDCC/ direct breakup	
Total reaction (mb)	927	Total reaction (mb)	1379
1-n stripping (mb)	265	Breakup (mb)	462
		Excitation(5/2+,740keV) (mb)	45

Coulomb barrier scattering of $^{15}C + ^{208}Pb$

Experiment IS699 @ HIE-ISOLDE (CERN)

- **1 x 10^3 pps average ^{15}C at reaction point**
- E = 4.37 MeV/u incoming ^{15}C (FWHM = 225 keV)
  - 65,43 MeV, after 75 μg/cm^2 stripping C-foil; 64,56(23) MeV in the middle of the ^{208}Pb-foil Vc ~ 66,34 MeV
- Cocktail beam of $^{15}N + ^{15}C$: $^{15}C/^{15}N \approx$ 1-3%
  - ✓ ^{15}N tightly bound @ this energy → use for monitoring and normalization





SEC: Scattering chamber

Experimental setup

- Gobal Reaction Array **GLORIA**
  - (*NIM A 755 69-77 [2014]*).

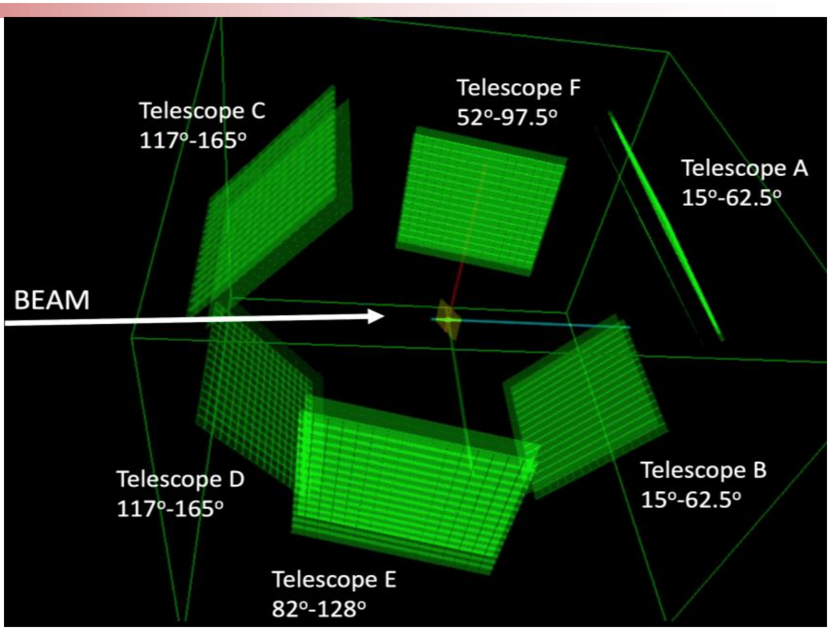
- 6 Si telescopes tangent to a 6 cm radius sphere.

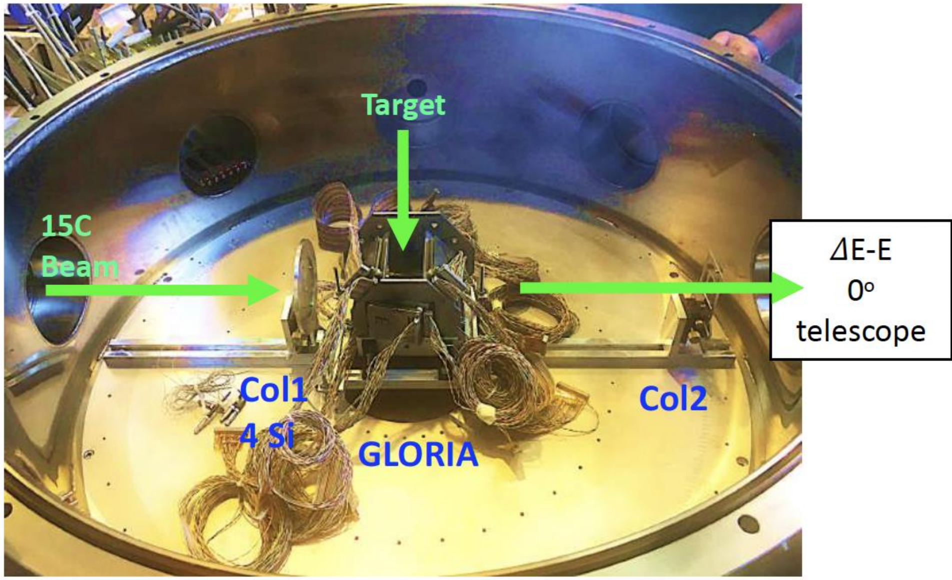
- 40 µm (ΔE) + 1 mm (E) DSSDs in 256 pixels of 3x3 mm^2
  - 2-3º angular ressolution

- 25% geometric eff.

- Full angular coverage θ_{LAB} =15º -165º

- ^{208}Pb **targets** 2.1 and 1.2 mg/cm^2.

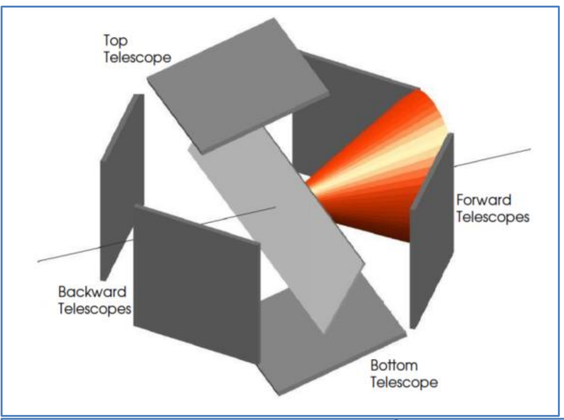


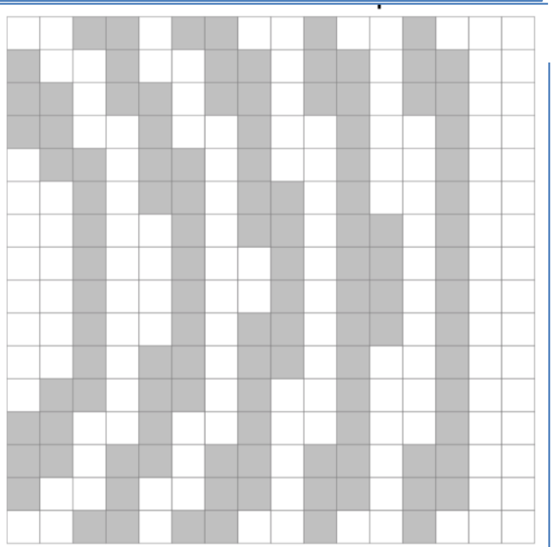


CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

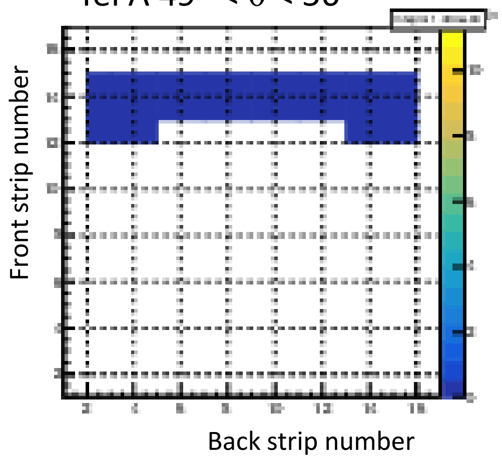
Data Analysis

- Telescope configuration allows for particle identification from 2D (ΔE-E_{TOT}) plots.
- High granularity of DSSDs allows for grouping together pixels within a $\Delta\theta$ range.
- In the $\Delta\theta$ sectors the same physics are expected (non-polarized beam) and minor effects of different energy losses happen, maximizing the statistics and reducing the errorbars.

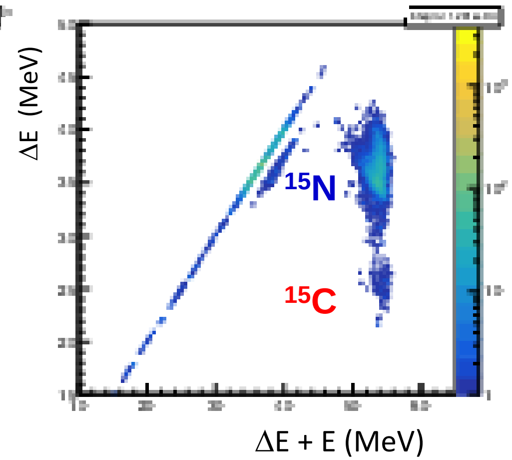




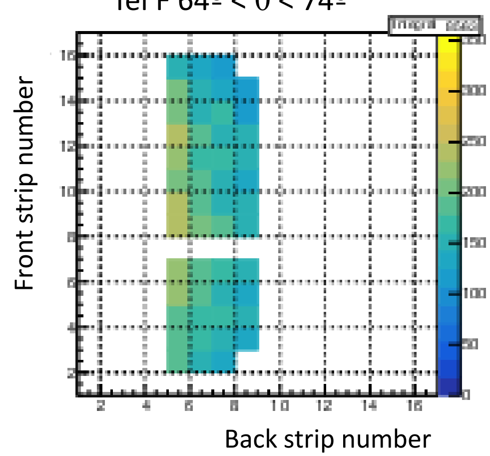
Tel A 49º < θ < 56º



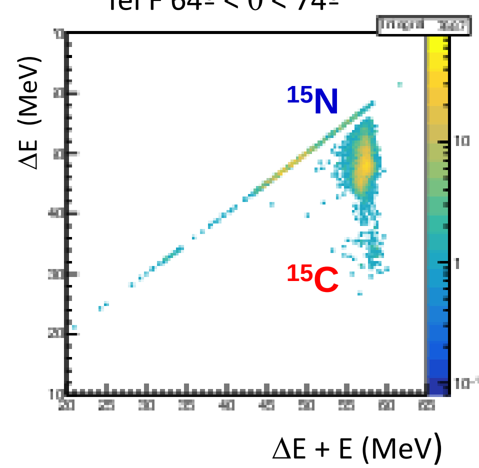
Tel A 49º < θ < 56º



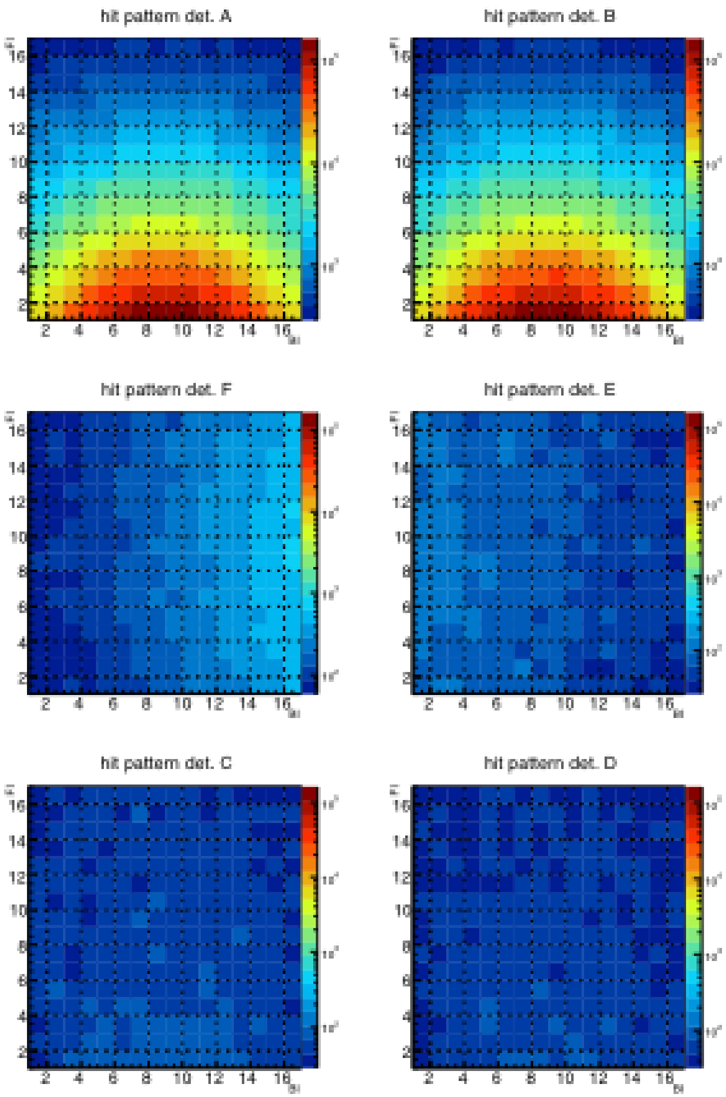
Tel F 64º < θ < 74º

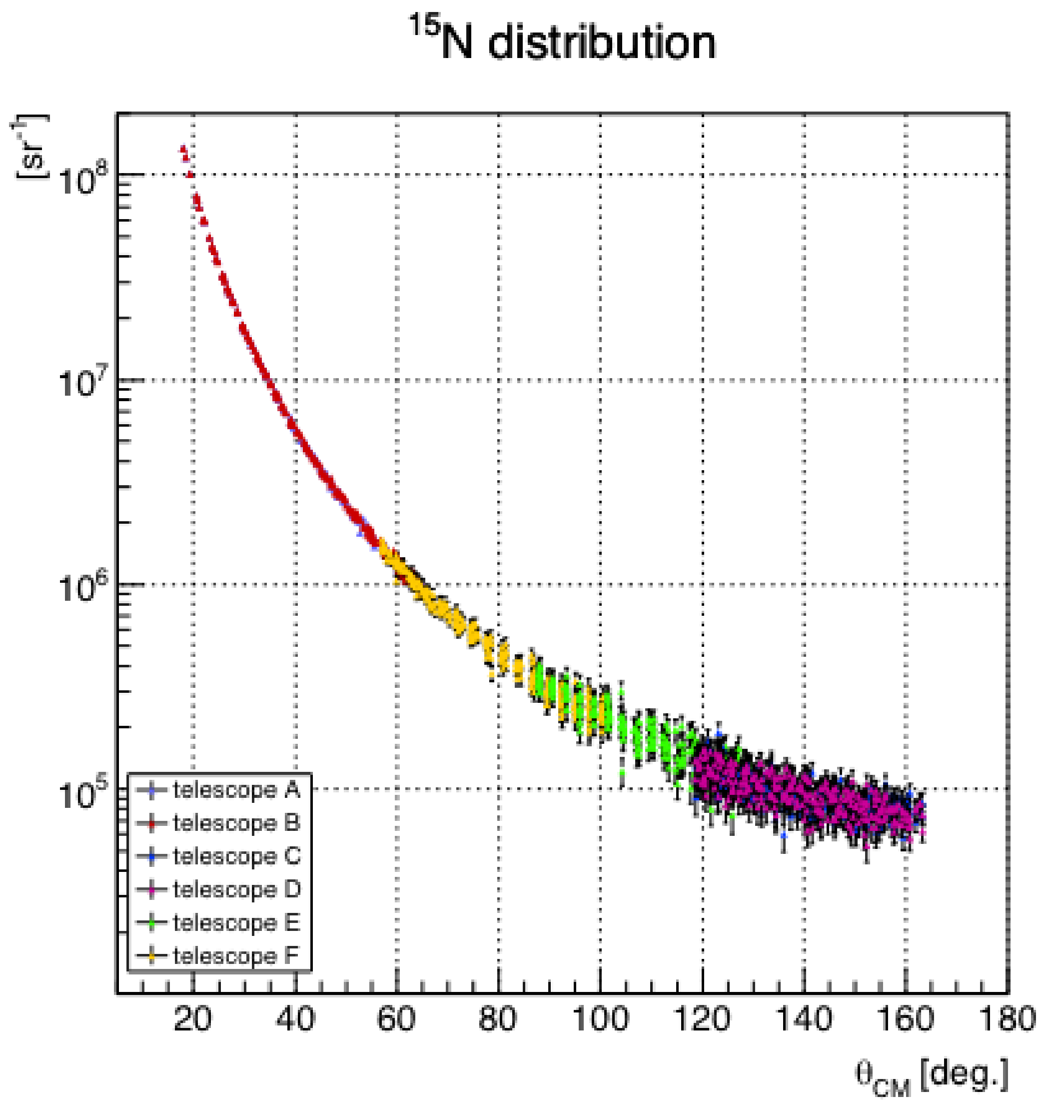


Tel F 64º < θ < 74º



Angle and solid Angle Optimization





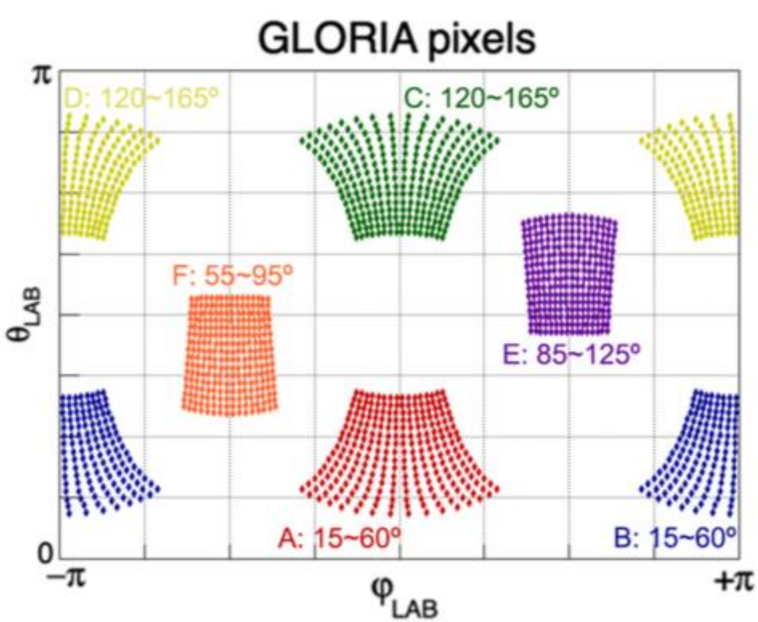
CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

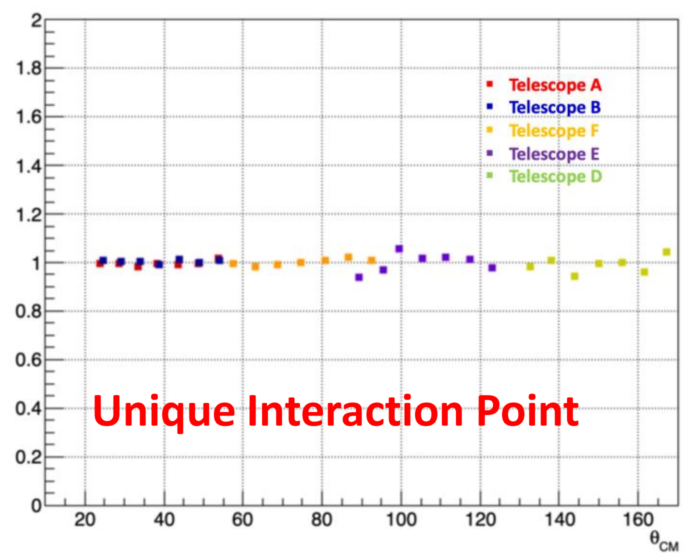
Solid Angle Optimization

- **Angle/solid angle determination** is, determine geometrically for every pixel. Then the data from ^{15}N is used as at the present energy the behaviour is Rutherford and it is optimized with a χ^2 test.
- Optimal θ, φ and ΔΩ are chosen from the set of free parameters $(\overrightarrow{r_{RP}}, I_N) = (x_{RP}, y_{RP}, z_{RP}, I_N)$ minimizing the χ^2/ndf when compared to the theoretical Rutherford cross section distribution.
- The loop happens to converge for several sets (z_{RP}, I_N), so the most feasible one is chosen according to the geometry and the intensity estimation by the ISOLDE beam team.

$$N_{Obs} = I_{beam} \cdot t \cdot \sigma_{Pb} \cdot \frac{d\sigma_{Ruth}}{d\Omega} \cdot \Delta\Omega$$

^{15}N + ^{208}Pb → ^{15}N + ^{208}Pb





$$\left(\frac{Z_2\alpha\hbar c}{E_{CM}}\right)^2 \frac{1}{\sin^4(\theta_{CM}/2)}$$

$$\sum_{i=1}^{n} \frac{(O_i - E_i)^2}{E_i}$$

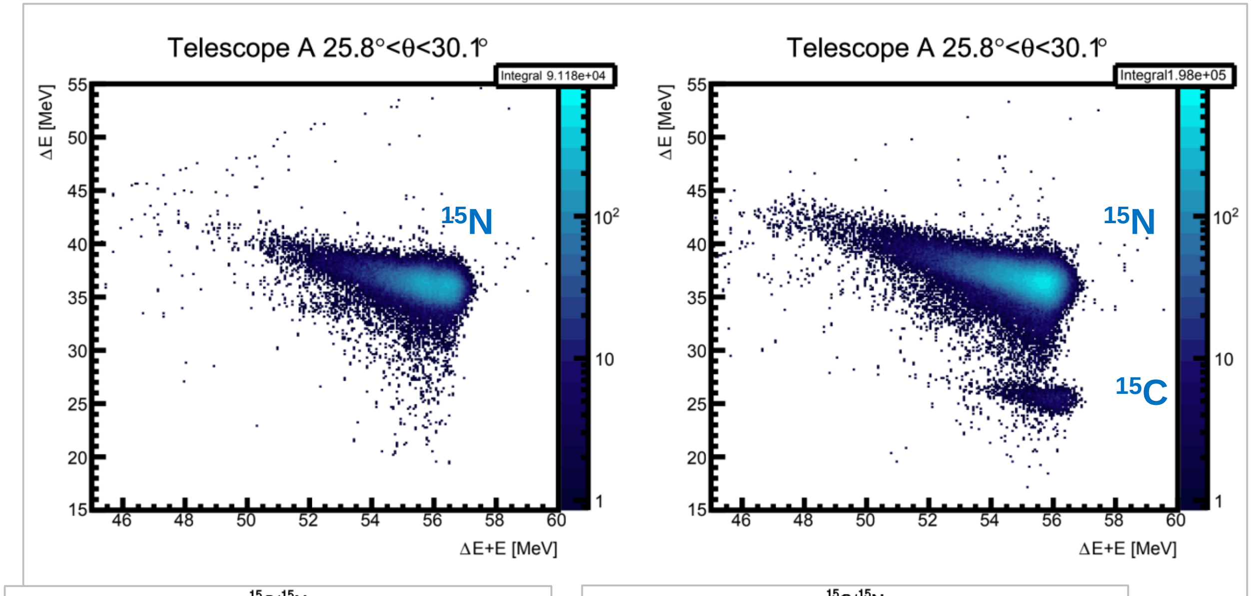
$$\sum_i \frac{(N_i^{obs} - N_i^{exp})^2}{N_i^{obs}}$$

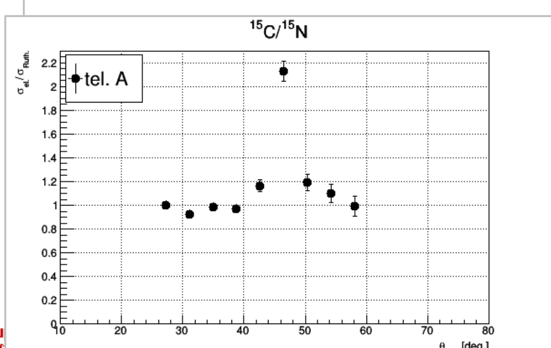
IEM

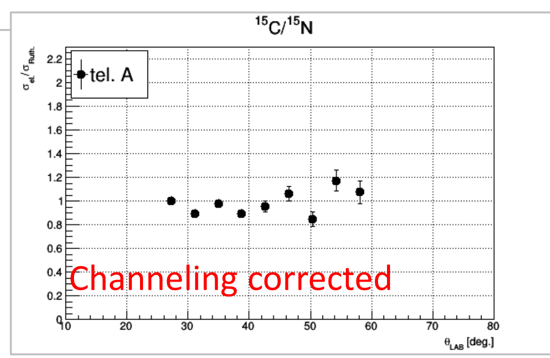
IEM

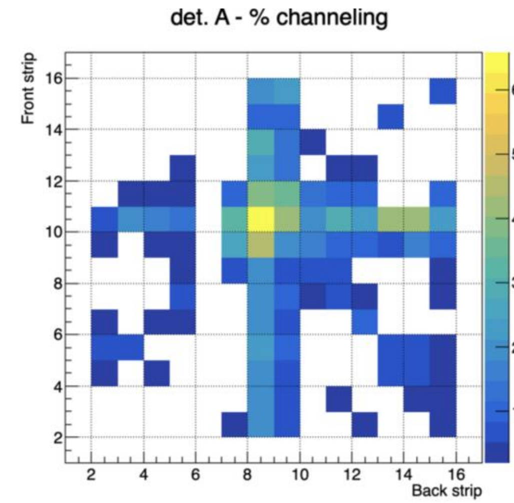
Channeling Effects

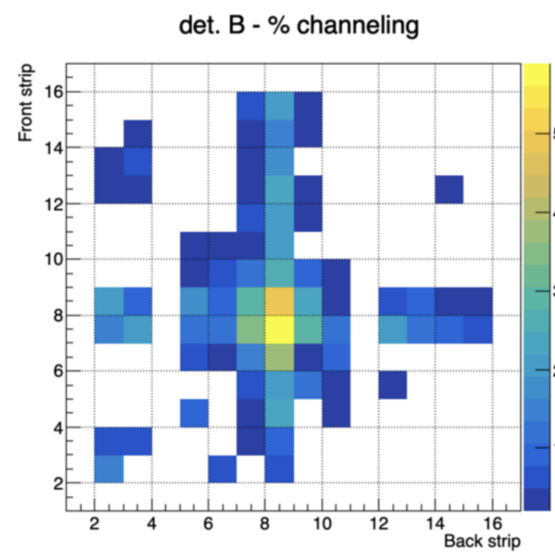
- **Channeling** through **Si lattice** in ΔE detectors leads to a smaller energy deposition.
- It happens in specific regions where the trajectory of the incident particle coincides with a channel of the detector wafer.
- The channeling of ^{15}N overlap with elastic of site of ^{15}C





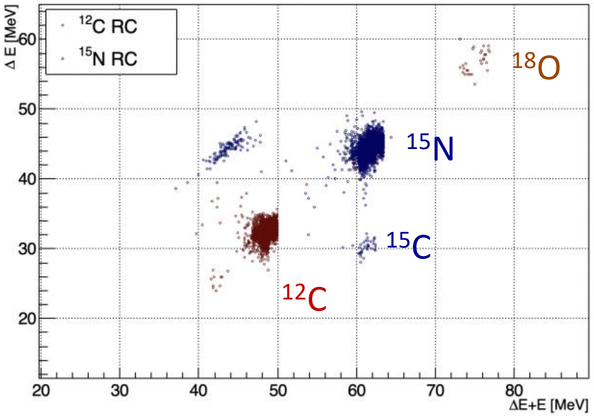






Calibration with α and heavy ions

Telescope A , pixel F2B2 = 26,7º



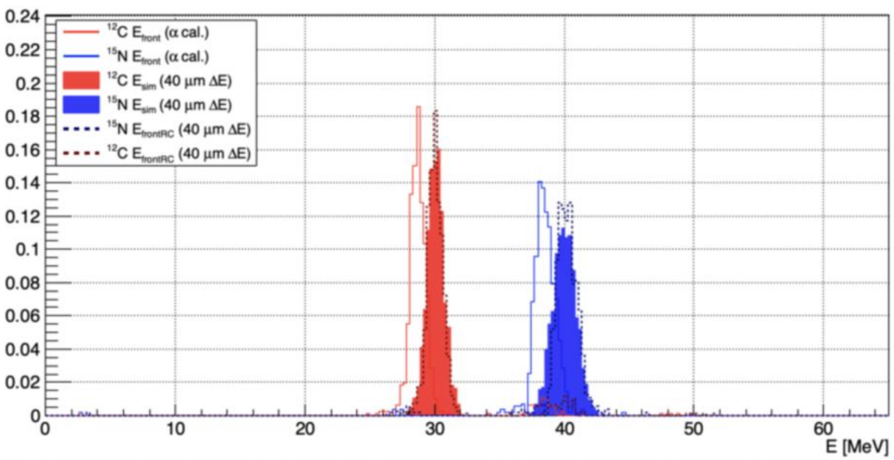
$$\boxed{(dE+E)_{RC} = a\cdot(dE_\alpha + E_\alpha) + b}$$

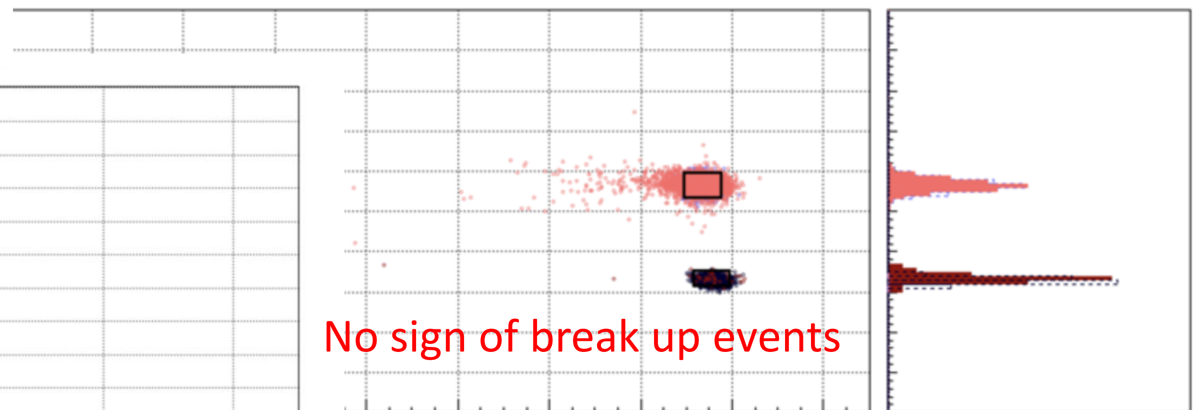
$$a = (E_{Nsim} - E_{Csim})/(E_{Nexp} - E_{Cexp})$$

$$b = -(E_{Cexp}\cdot a - E_{Csim}) = -(E_{Nexp}\cdot a - E_{Nsim})$$

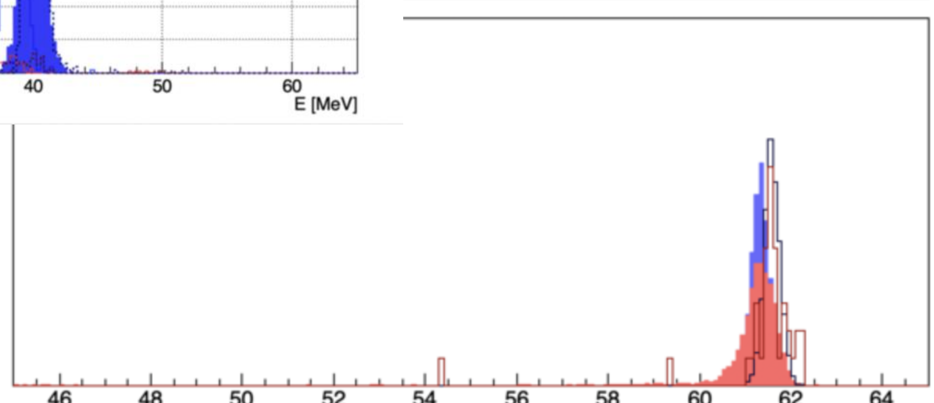
-> The slope ‘a’ will reproduce the separation between the two used peaks.

-> The offset ‘b’ will shift the spectra to make the sim-exp centroids coincide.

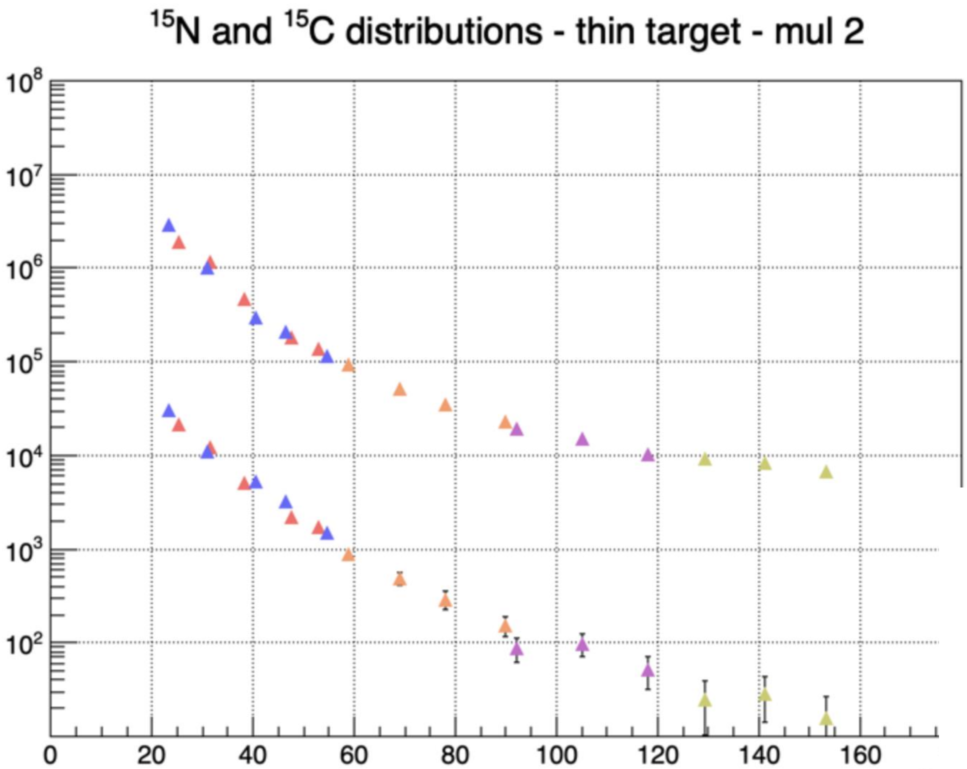




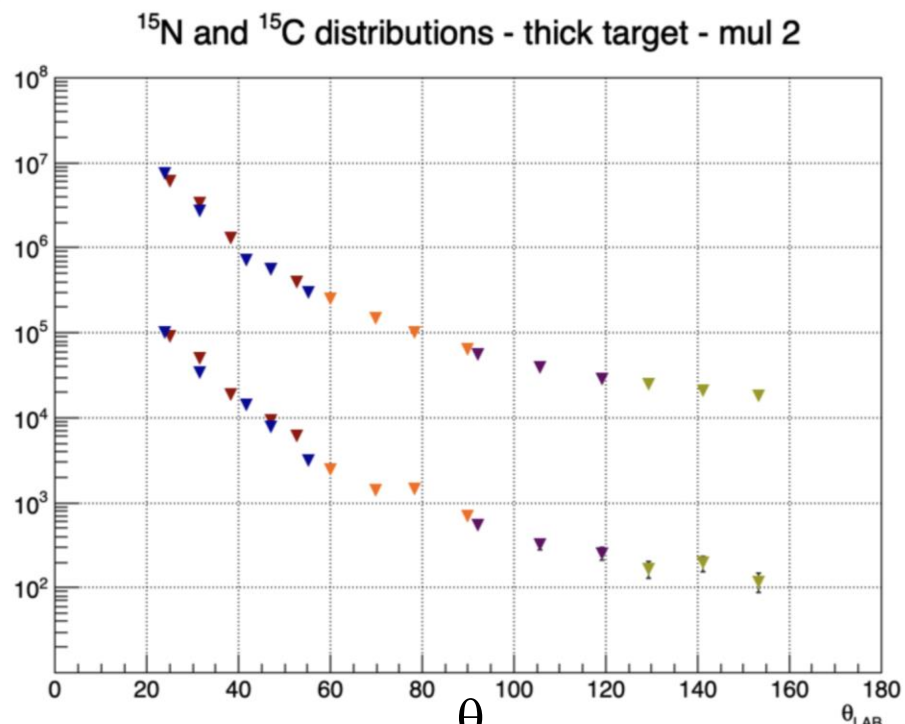
No sign of break up events



^{15}N / ^{15}C Distributions

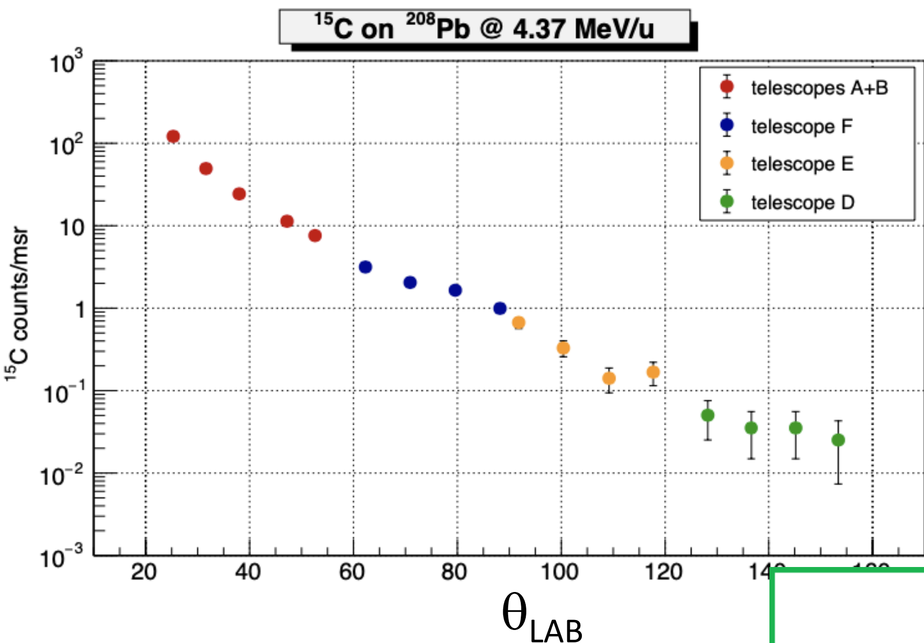


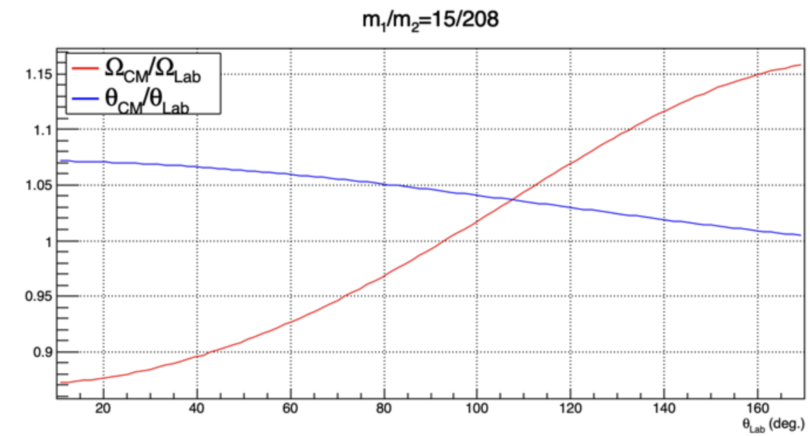
θ_{LAB}



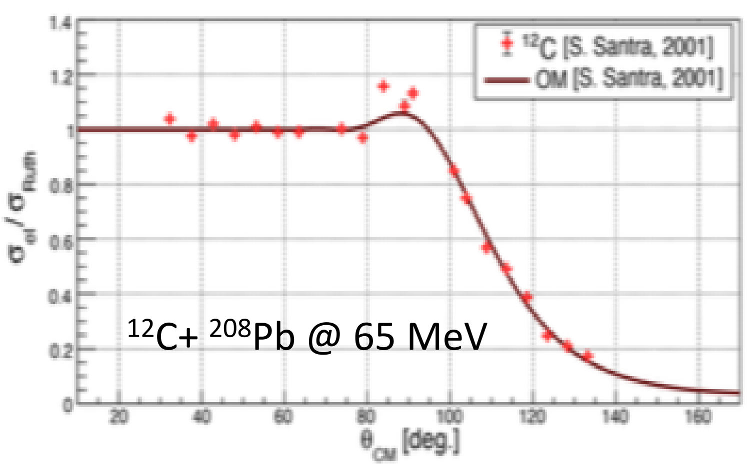
θ_{LAB}

^{15}C + ^{208}Pb Cross Section

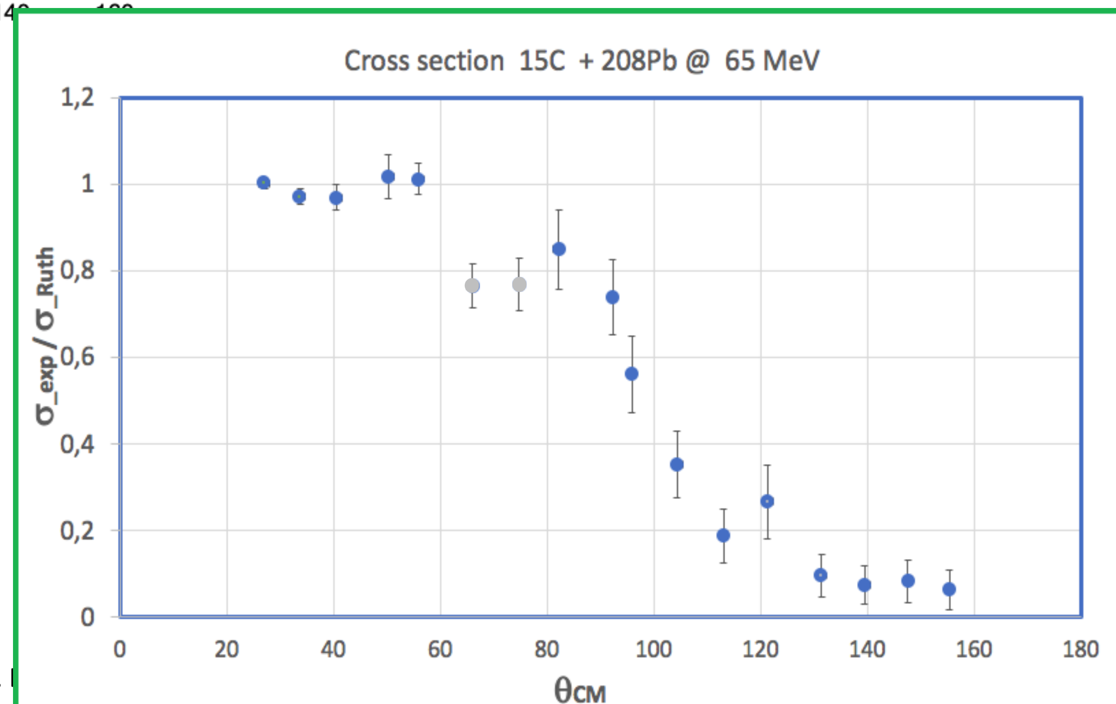




Santra et al., PRC 64 (2001) 024602

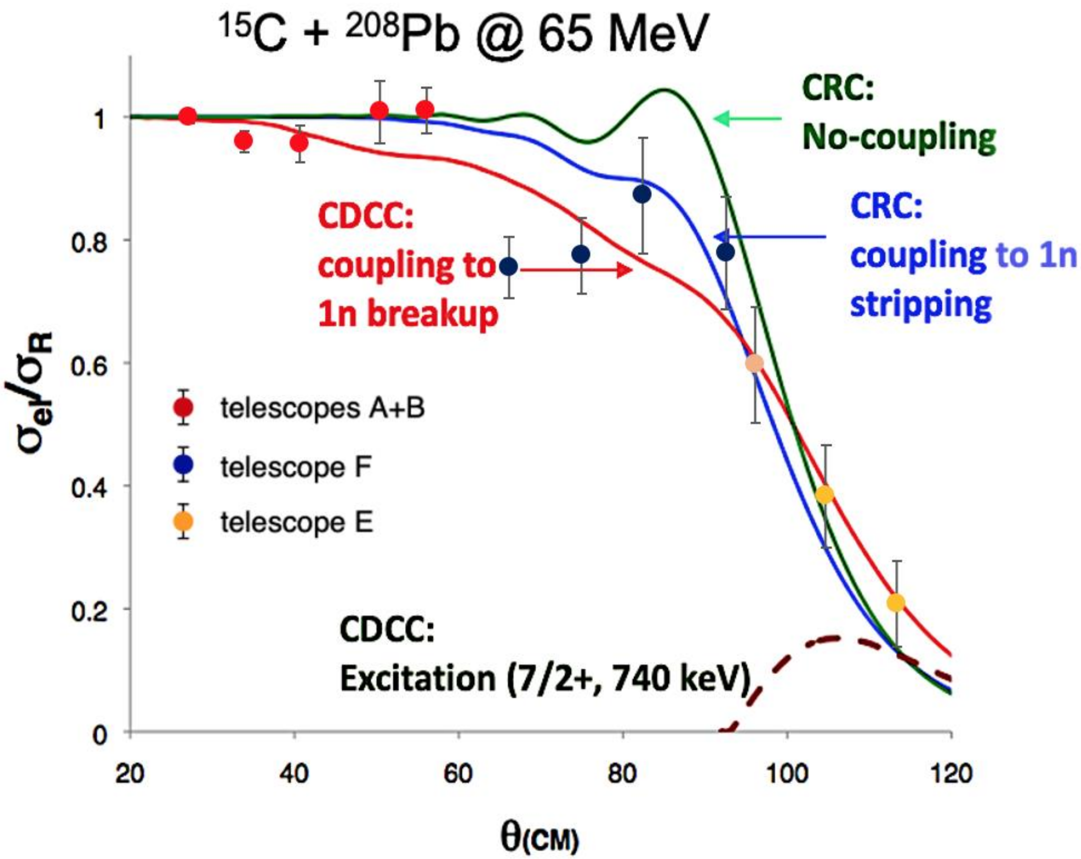


.G. I



Comparison of Experimental results with Theory

The experimental angular distribution cross section of $^{15}C + ^{208}Pb$ @ 65 MeV are compared with the calculations done by Keenley et al., for the extreme case of no coupling and 1n-stripping within the coupled reaction channel and CDCC for no coupling and 1n breakup.



N. Keenley et al., PRC 75 (2007) 056610; EPJA 50 (2014) 145

Summary & Outlook

- We have performed the first study of the angular distribution of the elastic cross section of $^{15}C + ^{208}Pb$ @ 65 MeV at HIE-ISOLDE (CERN).
- ^{15}C nucleus is a border line halo case with relatively low binding energy, a moderate halo case,
- It constitutes a unique case where the last neutron sits mainly in a $1S_{1/2}$–wave state.
- Predictions on the scattering of $^{15}C + ^{208}Pb$ @ 65 MeV were done by Keenley, Alamanos and Rusek in the framework of CRC including 1n-stripping and CDCC including breakup. 1n-stripping contribution wasexpected to be prominent as well as 1n-breakup
- The experimental angular distribution of the elastic scattering near the Coulomb Barrier (~ 60 MeV) shows strong couplings. The distribution favours the presence of 1n-stripping channel. Both the nuclear and Coulomb couplings as important as it the case of ^{11}Be and at difference of ^{6}He and ^{11}Li where the Coulomb coupling dominates.
- Hopefully the total cross section will support these conclusions

The IS699 collaboration

J.D. Ovejas , V.G. Tavora, O. Tengblad

Instituto de Estructura de la Materia, CSIC, Serrano 113-bis, E-28006 Madrid, Spain

I. Martel, A.M. Sánchez-Benítez

Departamento de Física Aplicada, Universidad de Huelva, E-21071, Huelva, Spain

A. Di Pietro, P. Figuera

INFN, Laboratori Nazionali del Sud, via S. Sofia 62, 1-95123, Catania, Italy

N. Keeley, K. Rusek

National Center for Nuclear Research, ul Andrzeja Soltana 7, 05-400 Otwock, Poland

L. Acosta

Dpto Física Experimental, Instituto de Física , UNAM (Mexico)

J. P. Fernández

Departamento de FAMN, Universidad de Sevilla, Seville, Spain

D. Galaviz

Faculty of Sciences, LIP, Lisbonne, Portugal

Thanks for Your Attention

CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

Geometry Optimization / Hit pattern