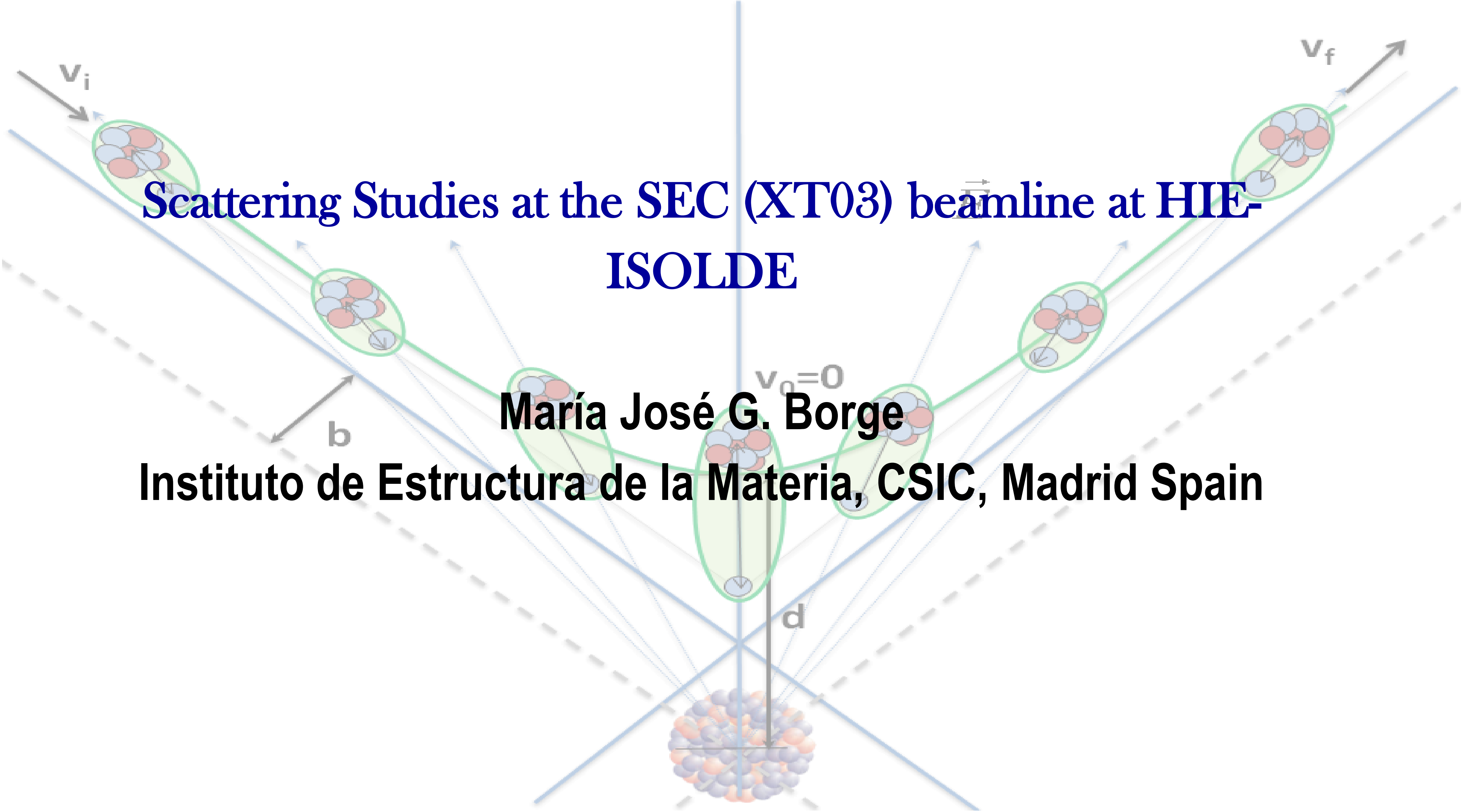
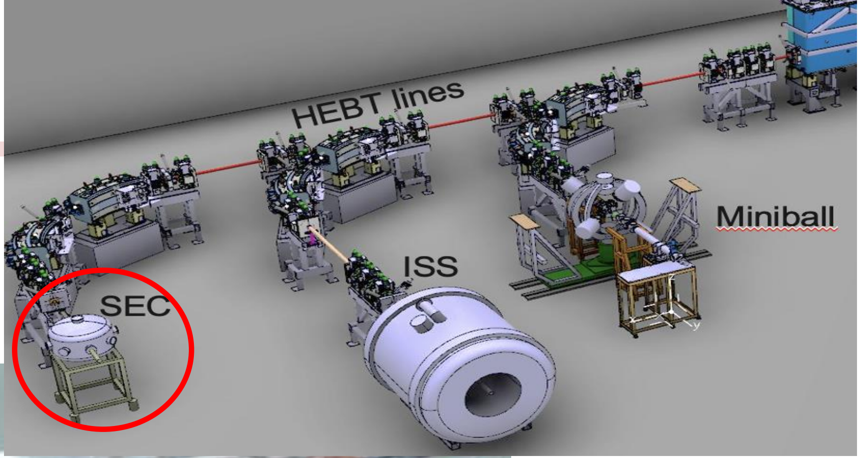


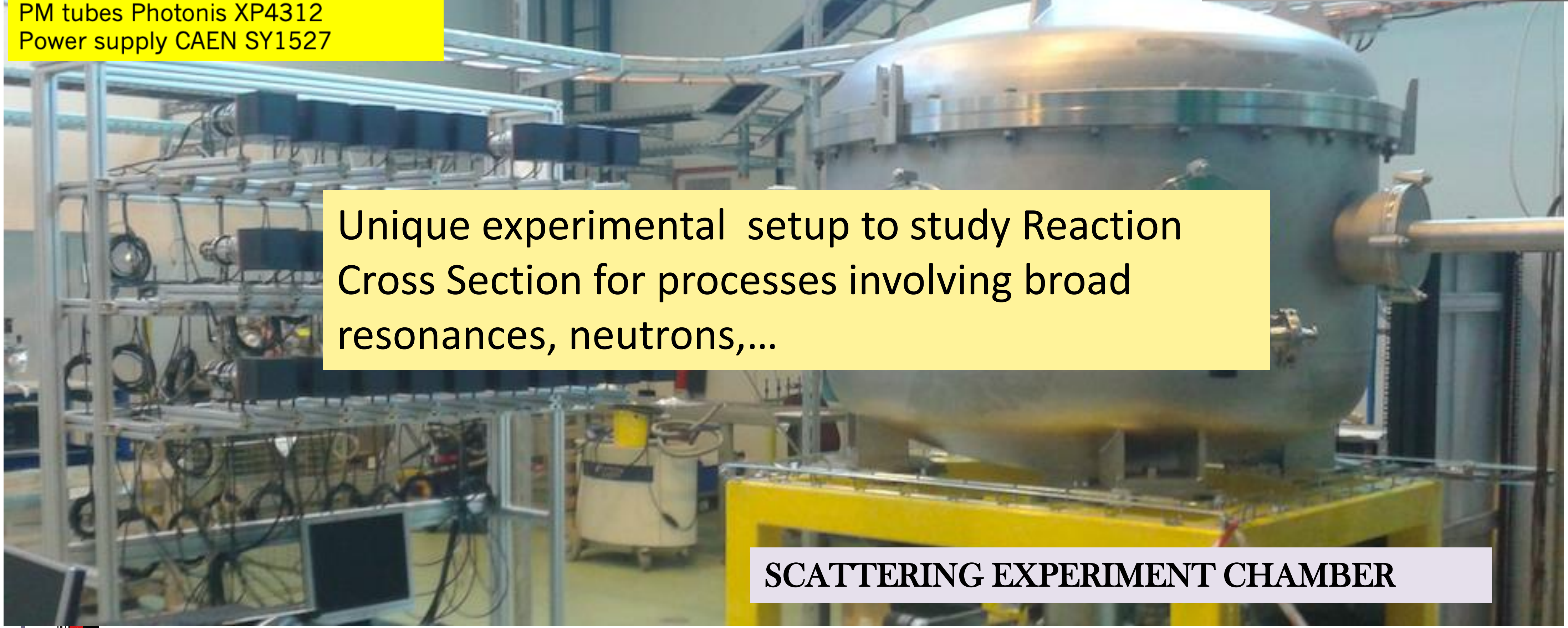
Scattering Studies at the SEC (XT03) beamline at HIE-ISOLDE

María José G. Borge
Instituto de Estructura de la Materia, CSIC, Madrid Spain

SEC @ XT03 HIE-ISOLDE



SAND n-Array
30x 10x10x10cm^3 Plastic TPS-1000
PM tubes Photonis XP4312
Power supply CAEN SY1527



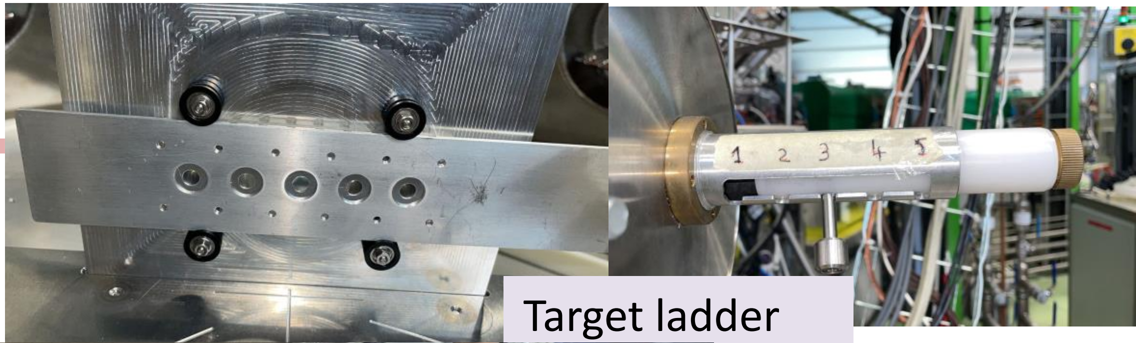
Unique experimental setup to study Reaction Cross Section for processes involving broad resonances, neutrons,…

SCATTERING EXPERIMENT CHAMBER

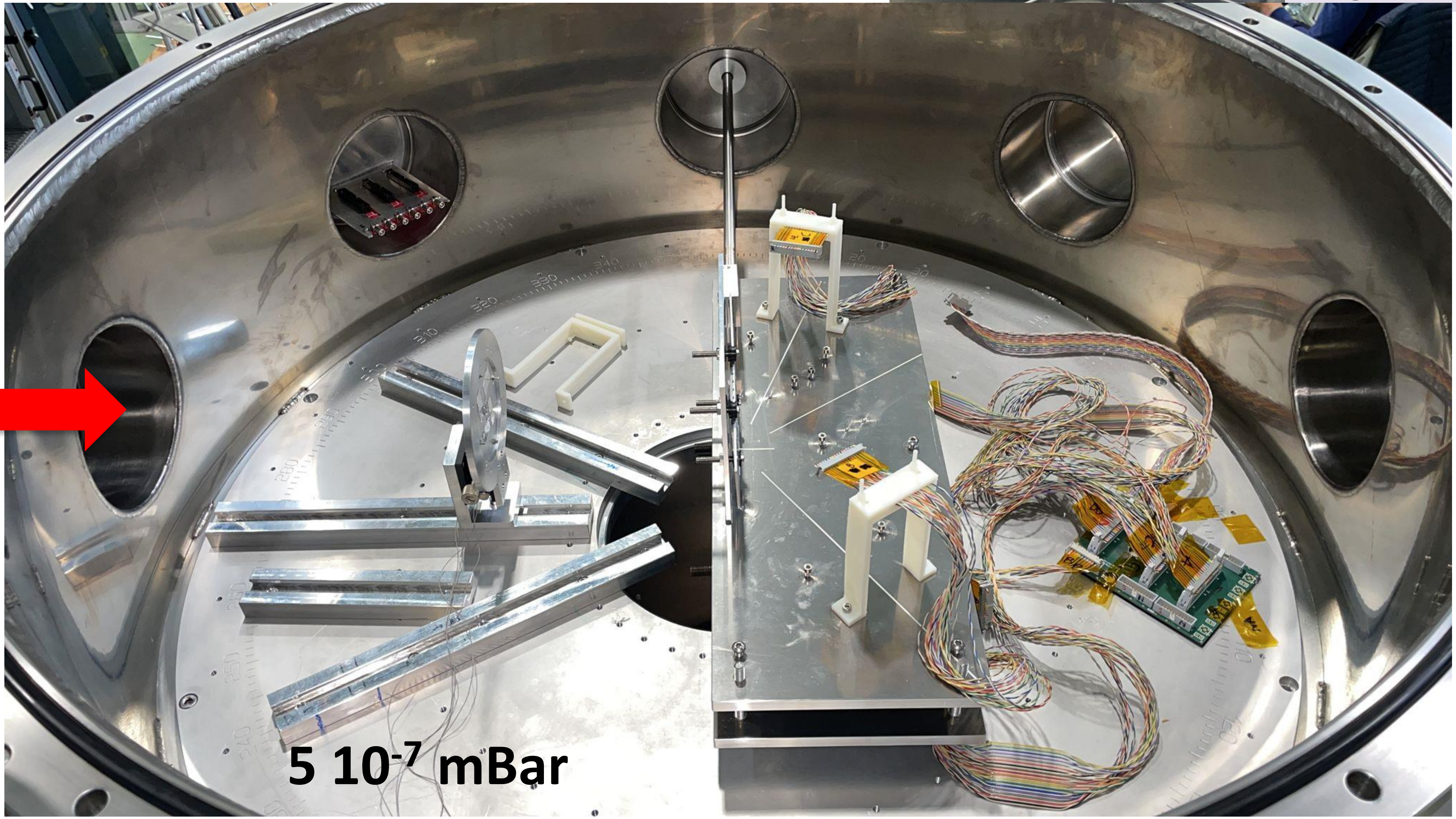
J. Cederkall joakim.cederkall@nuclear.lu.se O. TENGBLAD olof.tengblad@csic.es

SEC chamber

- Multipurpose chamber of 1m diameter built by U Lund (J Cederkall)
- Very good Vaccum!



Target ladder



$5\ 10^{-7}$ mBar

Experiments @ SEC (Run 2)

- **2016, IS561 @ XT02**. K. Riisager Study of ^{9}**Li** Transfer reactions at the neutron dripline on deuteron target. HIE-ISOLDE comissioning year
- **2017, IS619** I. Martel O. Tengblad Effects of the neutron halo in ^{15}**C** scattering at energies

IS581 M. Veselsky, R. Raabe Determination of the fission barrier height in fission of heavy radioactive beams induced by the (d,p)-transfer using the ACTAR TPC

- **IS607** C. Lederer The ^{59}**Cu**(p,α) cross section and its implications for nucleosynthesis in core collapse supernovae.

8 experiments during Run 2

Light nuclei.:

Structure
Halo structure and decay modes (OTPC).
Exploring the dynamics of halo nuclei in scattering near the Coulomb Barrier
Reaction addressing the ^{7}Li abundance anomaly

Intermediate Nuclei

Reaction (p,α) with implication in core collapse supernovae
Fission barrier determination of heavy beams by (d,p) reactions

Experiments Approved @ SEC (Run 3)

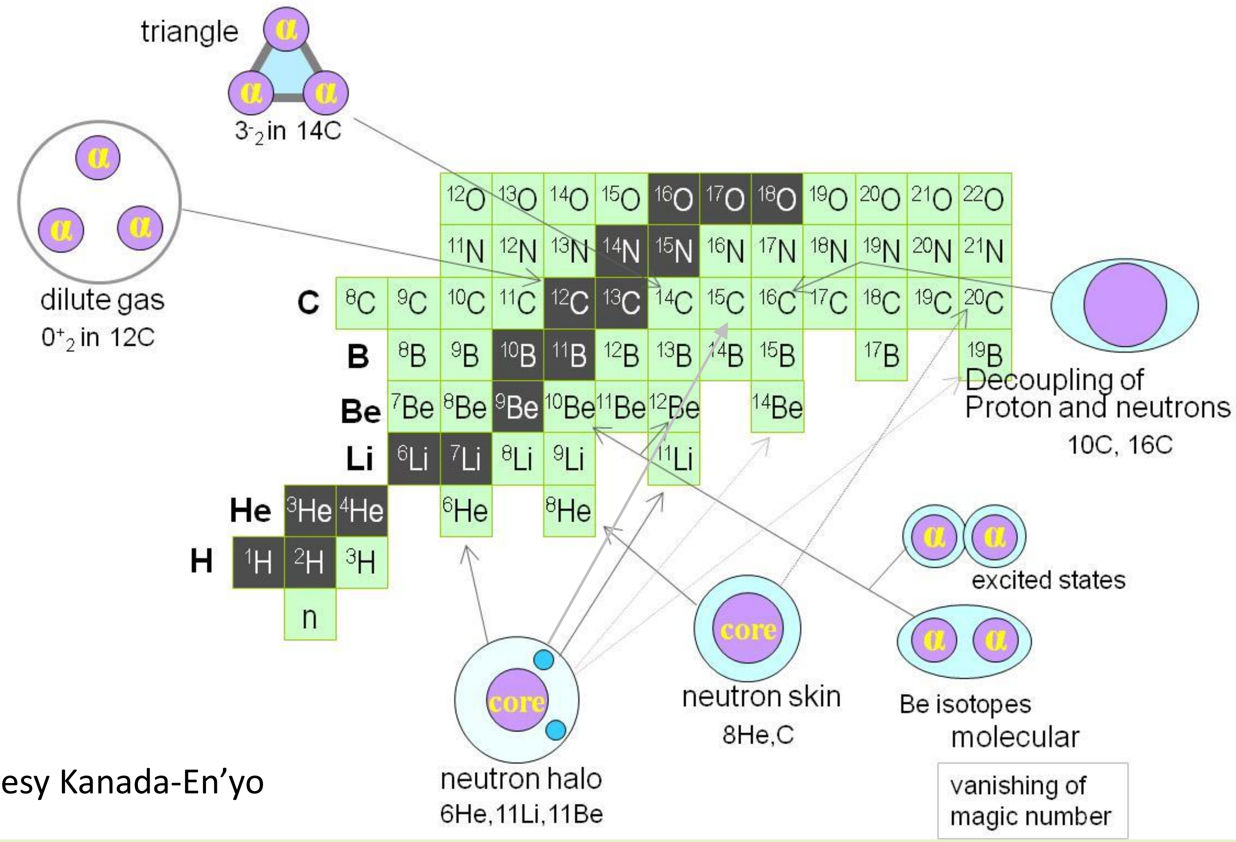
2022

- **IS698** D. Galaviz IP-Lisbon α-scattering on unstable proton-rich tin isotopes in inverse kinematics for the astrophysical p-process. ^{112}Sn+^{4}He

2024

- **IS690** M J G. Borge MAGISOL Reaction studies with neutron-rich light nuclei at the upgraded SEC Device
- **IS716** Y. Ayyad Determination of the α decay width of a near-threshold proton-emitting resonance in ^{11}B
- **IS550** S. Heinz & E. Kozulin GSI/Dubna Study of the Dinuclear System ^{A}Rb + ^{209}Bi (Z1 + Z2 = 120).

Why to study Light Nuclei ?

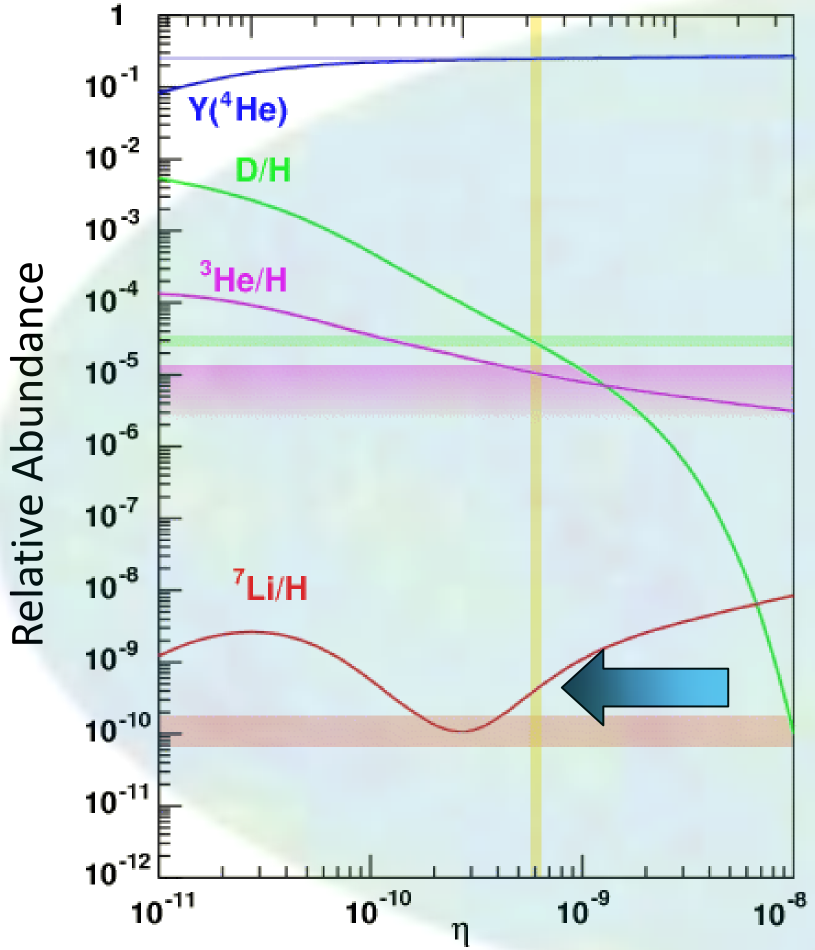


Courtesy Kanada-En’yo

Light nuclei: a laboratory of quantum mechanics

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
As well as the determination of these exotic structures and their reaction dynamics

The Cosmological ^{7}Li problem



Observed (predicted) values: bands (lines) for H/D; ^{3,4}He; ^{7}Li

The standard **Big Bang** model of the Primordial Universe is very successful in accounting for the observed relative abundance of the light elements.

The only astrophysical input to the Big Bang Nucleosynthesis (BBN) calculation is the **baryon density** of the Universe, which is now known precisely.

However, BBN theory fails to predict correctly the **observed abundance of ^{7}Li.**

BBN theory using η : $\frac{^7\mathrm{Li}}{\mathrm{H}} = 5.12^{+0.71}_{-0.62} \times 10^{-10}$

Observationally extracted: $\frac{^7\mathrm{Li}}{\mathrm{H}} = 1.58^{+0.35}_{-0.20} \times 10^{-10}$

Solutions:

Astrophysical solutions: Hidrodynamics *Korn, Nature (2006);*

Physics Beyond the standard BBN Model

NP of primordial Problem: ^{7}Li is mainly from EC of ^{7}Be

Production of ^{7}Be @ T=0.3-0.6 GK : **^{3}He(α,γ)^{7}Be**

Destruction: **^{7}Be(n,p)^{7}Li**, **^{7}Be(n,α)^{4}He** and **^{7}Be(d,p)2α**.

Incomplete nuclear physics input for BBN calculations ?

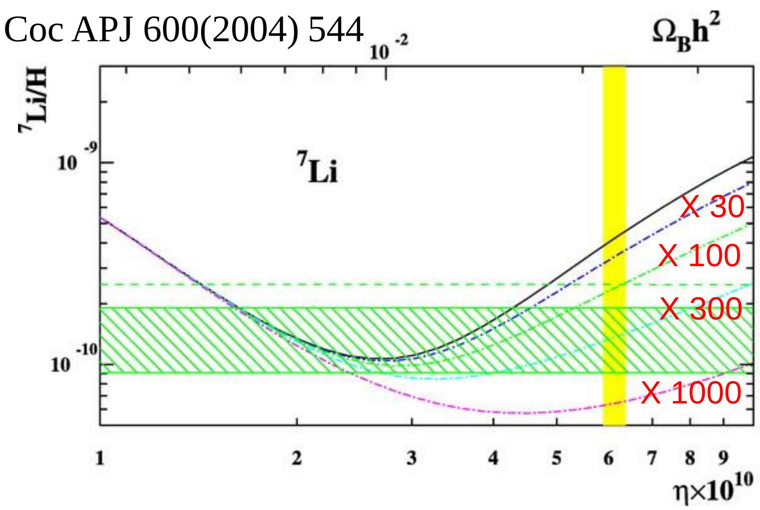
The production reaction **^{3}He(α,γ)^{7}Be** has an uncertainty of < 5%

^{7}Be(n,p)^{7}Li, **^{7}Be(n,α)^{4}He** have failed to solve the Li anomaly (n_ToF *Damone PRL 121(2018)042701; Barbagallo PRL117(2016) 152701)*

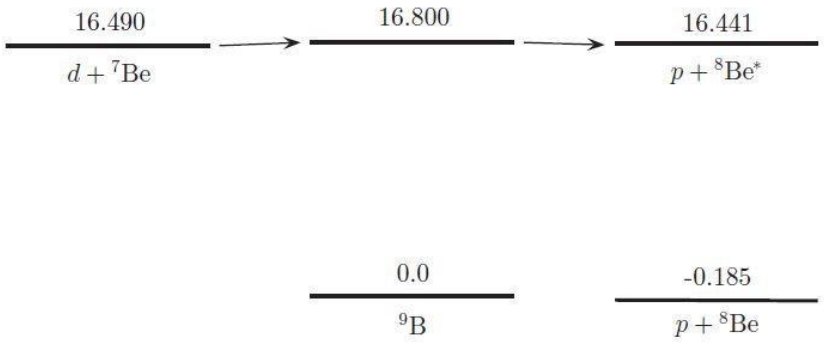
Increased mass-7 destruction by novel reaction pathways or by resonant enhancement of minor channels.

The ^{7}Li discrepancy resolved, if the **^{7}Be(d,p)^{8}Be*(2α)** Q = 16.674 MeV reaction rate larger by a factor **~ 100,**
Resonant enhancement in ^{7}Be + d?

Coc APJ 600(2004) 544



Proposed alternative ^{7}Be destruction mechanism d + ^{7}Be → ^{9}B* → p + ^{8}Be*



Kirseboom & Davis PRC 84 (2011)058801

The ^{7}Be + d reaction leads to the 16.8 MeV state in ^{9}B, which decays by proton emission to a **highly excited state in ^{8}Be**, **16.626 MeV** above the ground state, which subsequently breaks up into two α particles.

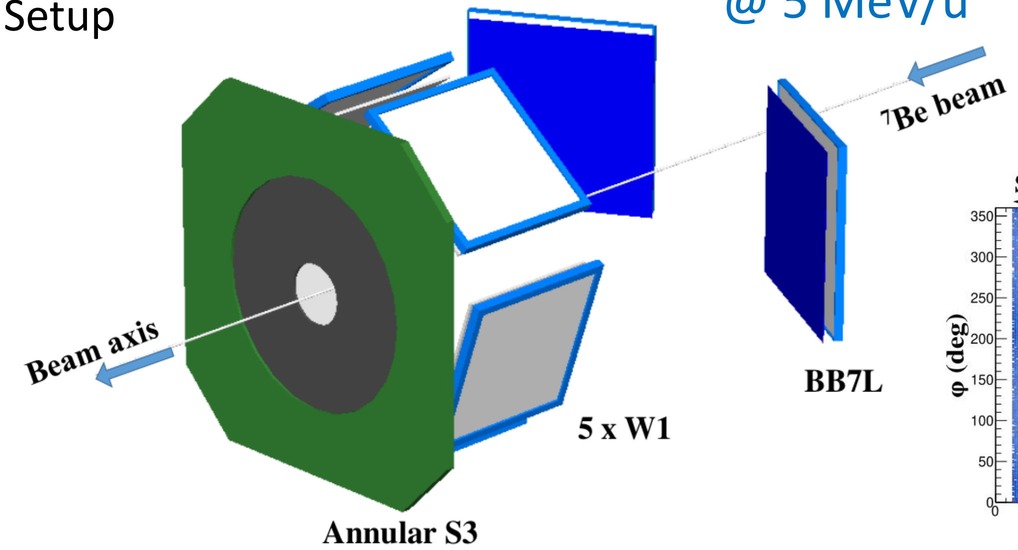
Study ^{7}Be(d,p)^{8}Be*(2α) at high energy

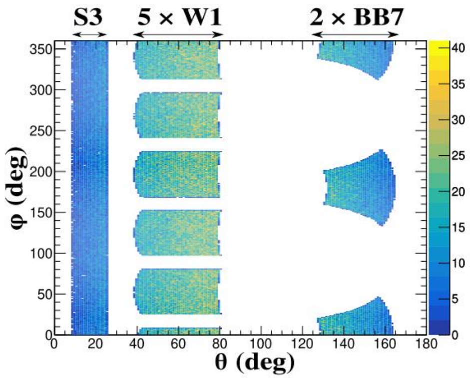
Study of ^{7}Be(d,p)^{8}Be* at (IS554) at 0-22 MeV (Winter Physics)

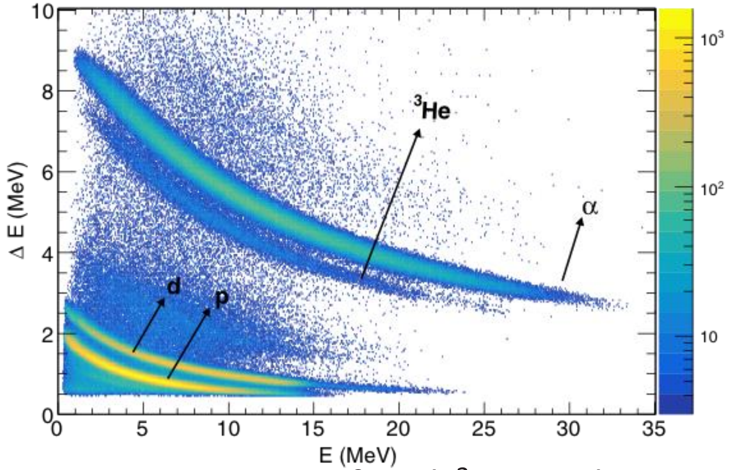
MAGISOL
Setup

^{7}Be^{4+} beam (5x105pps)
@ 5 MeV/u

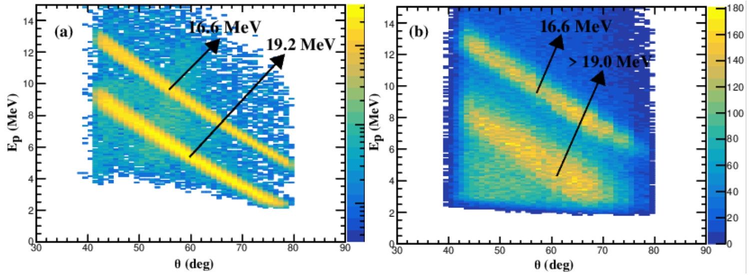
Targets:
15μm CD$_2$; 15μm CH$_2$







ΔE-E spectrum of p, d, ^{3}He, and α, detected at W1 + BB7 telescopes



The total solid angle coverage of the detectors is **~32% of 4π.**

Charge particle detector setup

1 x S3 annular DSSD (24 x 32 strips, 1000 μm) covering front angles 8° – 25°
5 x W1 DSSD (16 x 16 strips, 60 μm) in pentagon geometry covering angles 40° – 80°
2 x BB7 DSSD (32 x 32 strips, 60 μm and 140 μm) at backward angles 127° – 165°
The W1 and BB7 DSSDs are backed by 1500 μm thick unsegmented pads MSX25/MSX40

Two bands for higher excitations of ^{8}Be, one corresponds to states 16.63 + 16.922 MeV (E resolution~ 660 keV), other to states in 17-22 MeV. Protons identified in W1 and BB7 in coincidences a in S3

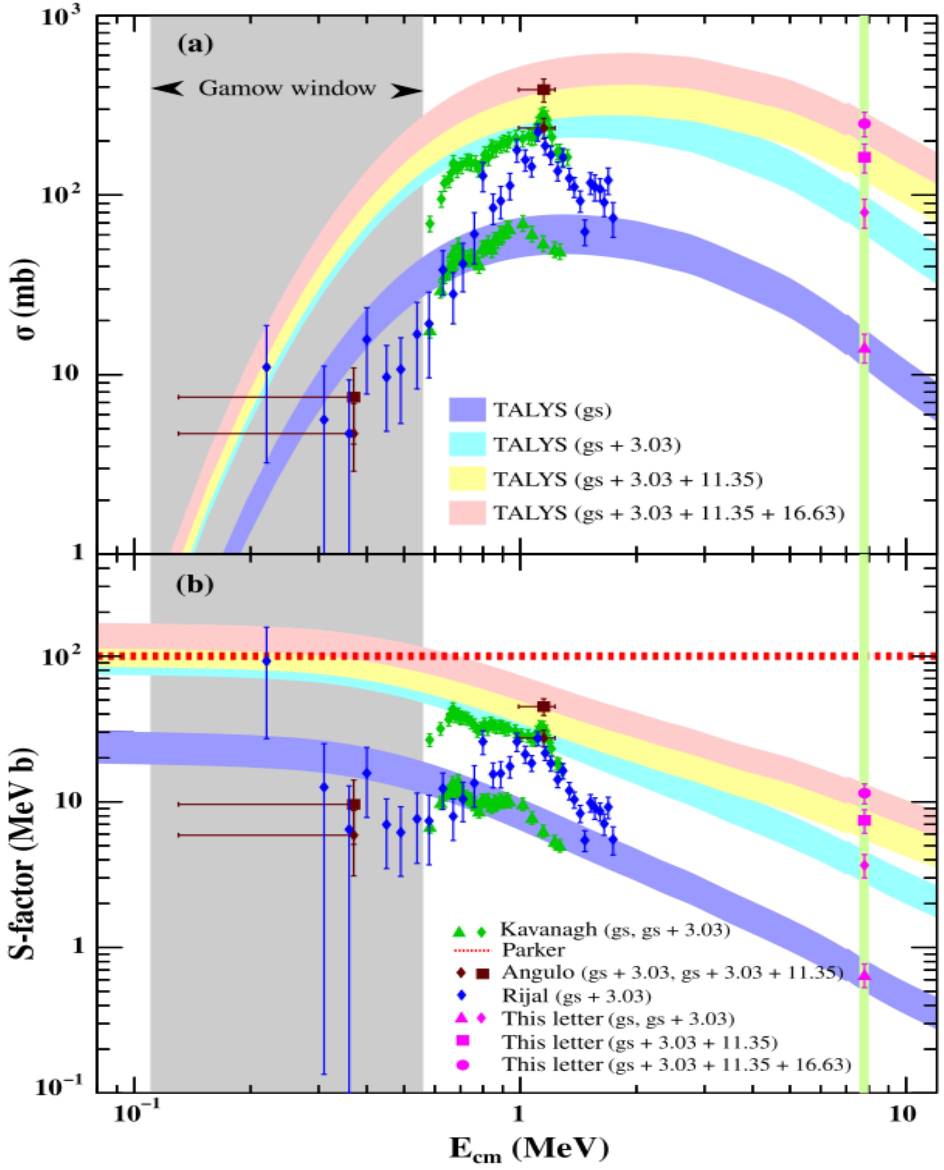
Results of the $^{7}Be(d,p)^{8}Be^{*}$ Study

Excitation function of the different levels is calculated with the nuclear reaction code TALYS. The bands are TALYS calculations normalized to the measured cross section, giving an estimate of contributions of individual states of ^{8}Be up to the 16.6 MeV state for the **first time.**

The existing data within Gamow window (T = 0.5–1 GK, $E_{c.m.}$ = 0.11–0.56 MeV) has **large error bars**. Good agreement with data outside Gamow window. The ***S* factor** due to contribution of gs+3.03+11.35 MeV state agrees with Parker's estimate of 100 MeV b.

Addition of the **16.63** (+ 16.922) **MeV** state leads to a **maximum value of S factor within the Gamow window increase to 167 MeV b** but it cannot help solving the Lithium anomaly. The **Li abundance is reduced by < 1%**.

Contribution of higher excited states in $^{7}Be(d,p)^{8}Be^{*}$ do not solve the Cosmological lithium problem

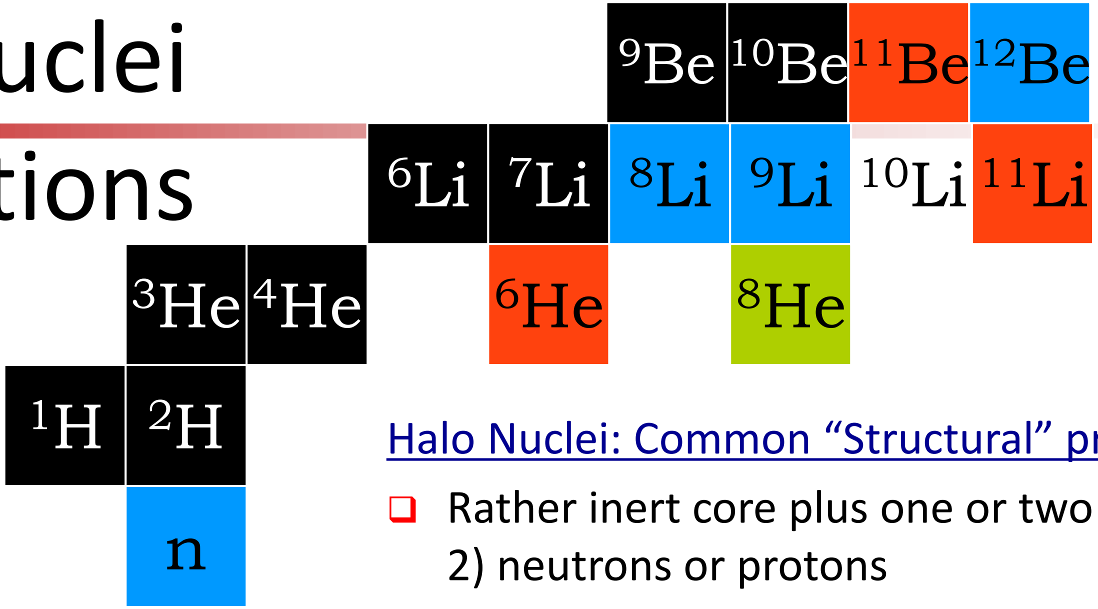


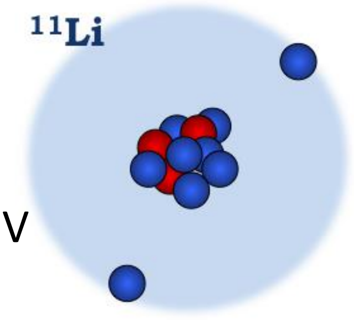
Ali, et al PRL 128 (2022) 252701

Courtesy of Dhruba Gupta

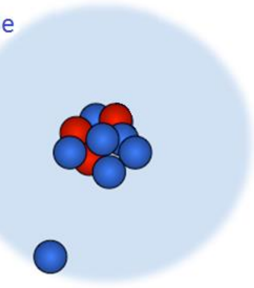
For Inelastic scattering of ^{7}Be+^{12}C see poster

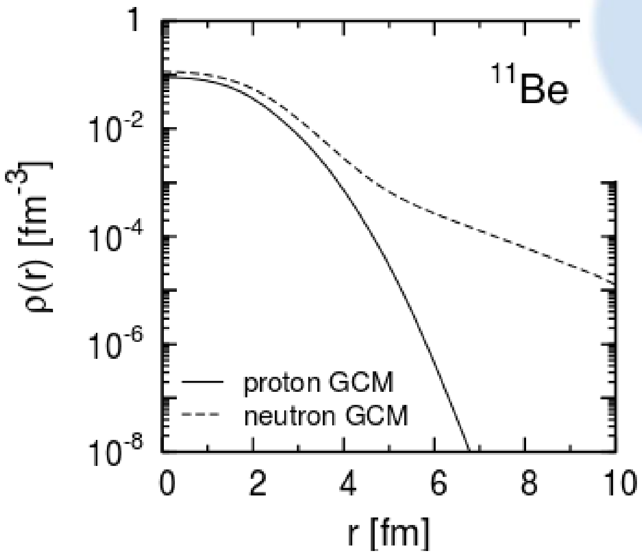
Halo nuclei & reactions





S_{2n} = 0.265 MeV





S_n = 0.5 MeV

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

<u>Halo Nuclei: Common “Structural” properties</u>

- ❑ 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 structure: Insight into slow degrees of freedom (Sn=0.5 MeV, t = 10^{-21}S; For S_n = 8 MeV t = 10^{-23}s

<u>Reaction properties at near-barrier energies:</u>

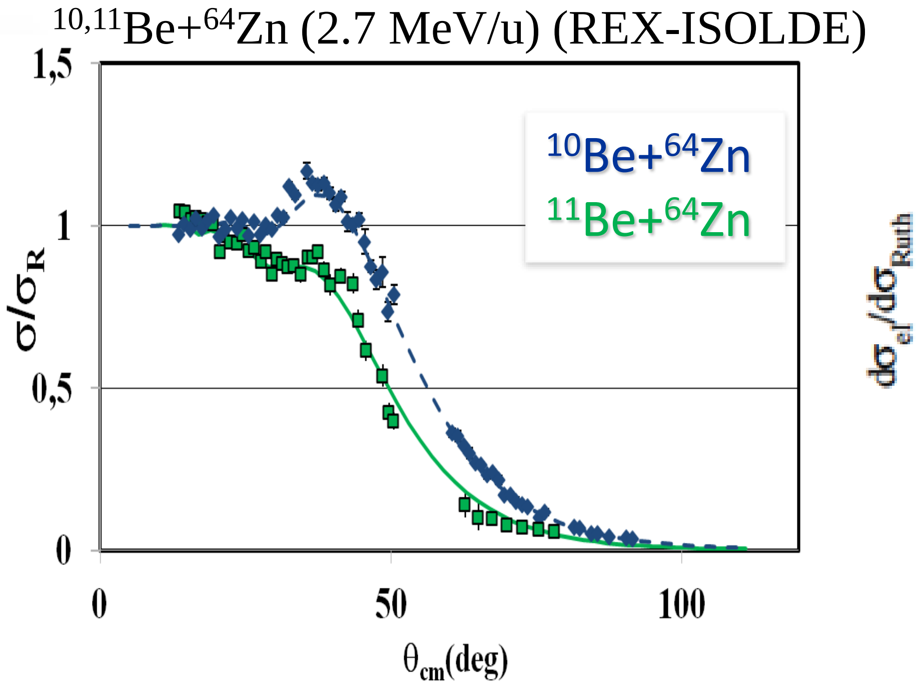
→ Strong absorption in elastic channel: suppression of rainbow

→ Large cross section for fragmentation

→ They are easily polarizable.

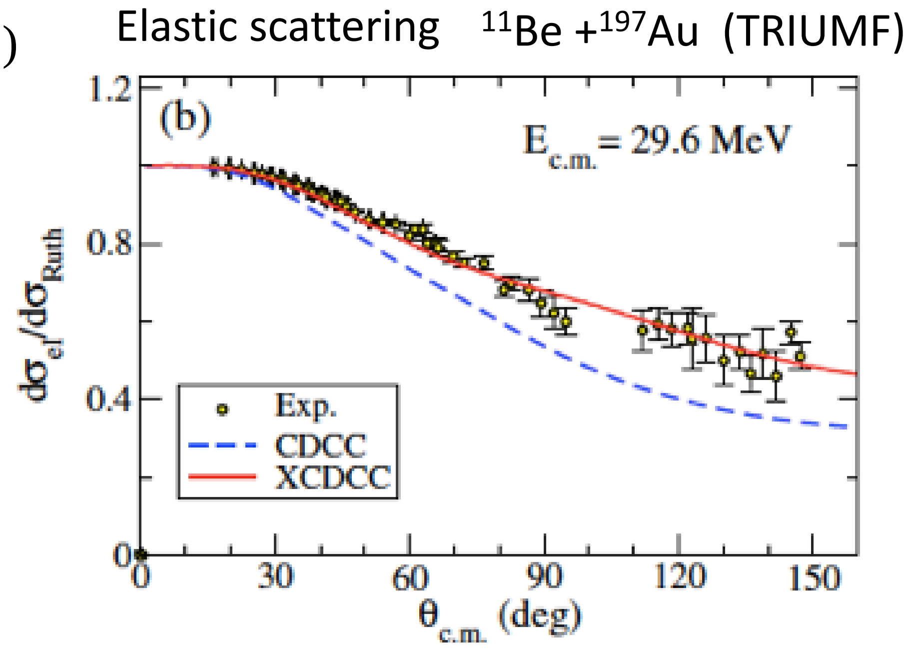
Interplay between Nuclear Structure & Reaction Mechanism

Elastic Scattering of the 1n-halo nucleus ^{11}Be+ ^{64}Zn /^{197}Au



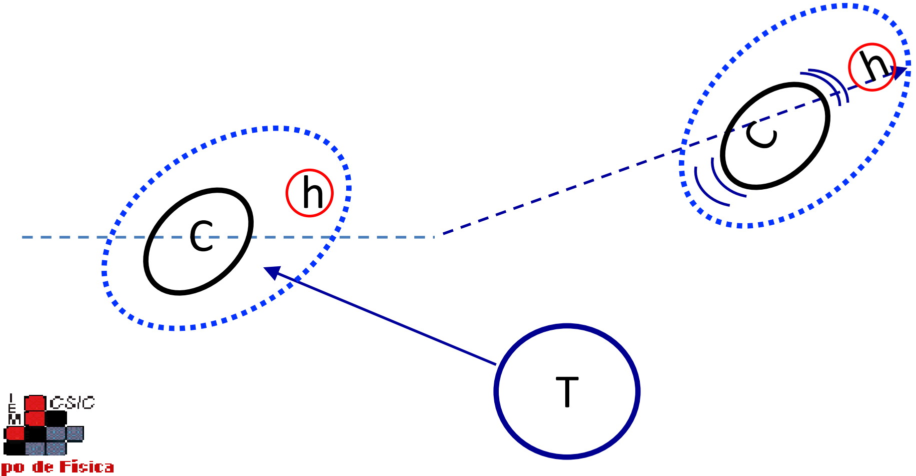
^{10,11}Be+^{64}Zn (2.7 MeV/u) (REX-ISOLDE)

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



Elastic scattering ^{11}Be +^{197}Au (TRIUMF)

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



CDCC accounts of halo degrees of freedom. Coupling to continuum effects insufficient to reproduce the experimental data.

XCDCC accounts for both the halo and core degrees of freedom. The structure model accounts for the appropriate admixture of 0$^+$ and 2$^+$ components in the ^{10}Be core.

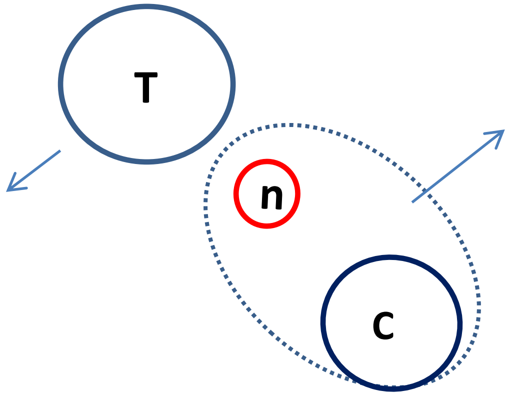
p-halo vs n-halo behaviour in Coulomb interaction dynamics

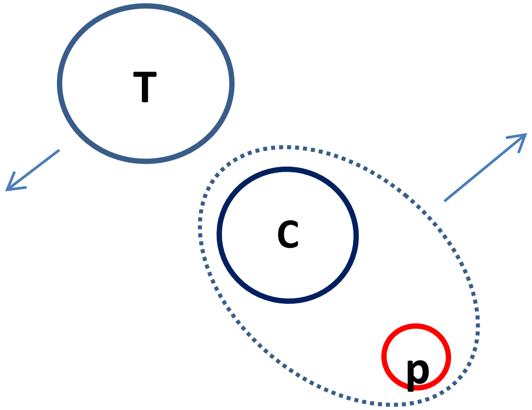
The p in the halo feels Coulomb interaction, **expected dynamics different from n-halo**

The proton in the halo feels the e.m. field and interacts with core and target

These additional interactions create an “effective barrier” making the halo dynamically more bound [e.g. Kucuc & Moro PRC86 (2012) 034601; A.Bonaccorso et al.: PRC69 (2004) 024615]

Possible semiclassical picture





Due to a dynamic polarization effect, the valence proton is expected to be displaced behind the nuclear core and shielded from the target; **this effect causes a reduction of break-up probability** compared to first-order perturbation theory predictions

Scattering of ^{8}B on a ^{64}Zn Target (IS616)

First ^{8}B beam @ HIE-ISOLDE

Carbon Nanotube primary target

Beam $^{8}BF_2$

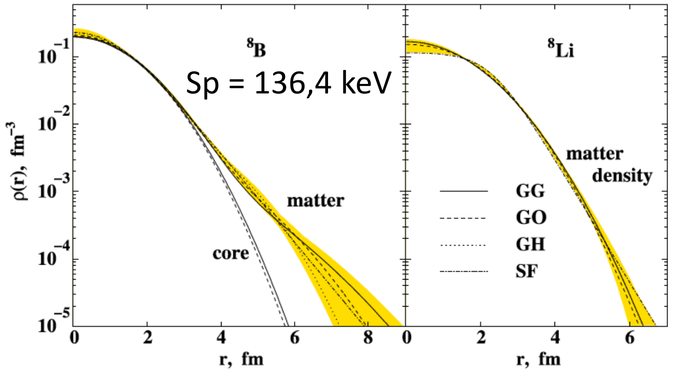
Yield ~ 400 pps

E = 4.9 MeV/u (1.5 V_B ~ 30 MeV)

1,05 mg/cm^2 ^{64}Zn-target

Aim

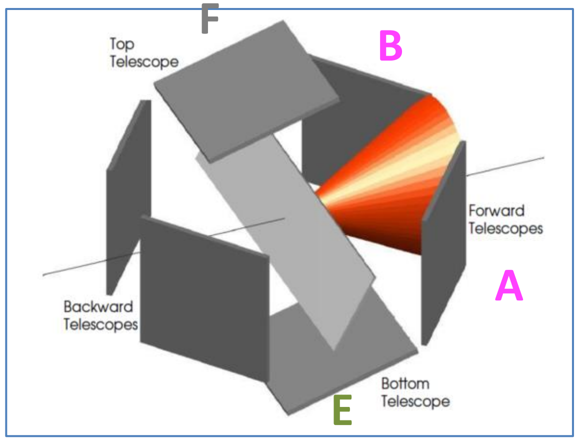
- Measure Diff Elastic Cross Section
- Measure Break-up & Transfer Distributions
- Total Cross Section
- Deduce the Nuclear & Coulomb Contributions

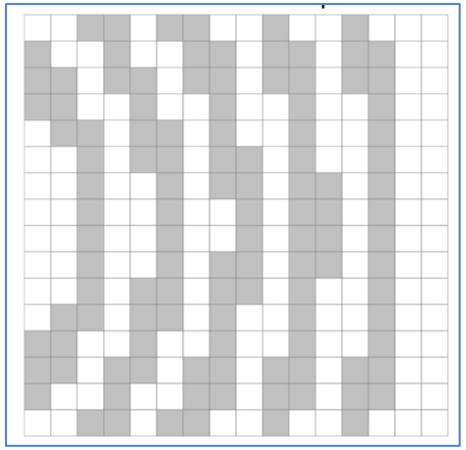


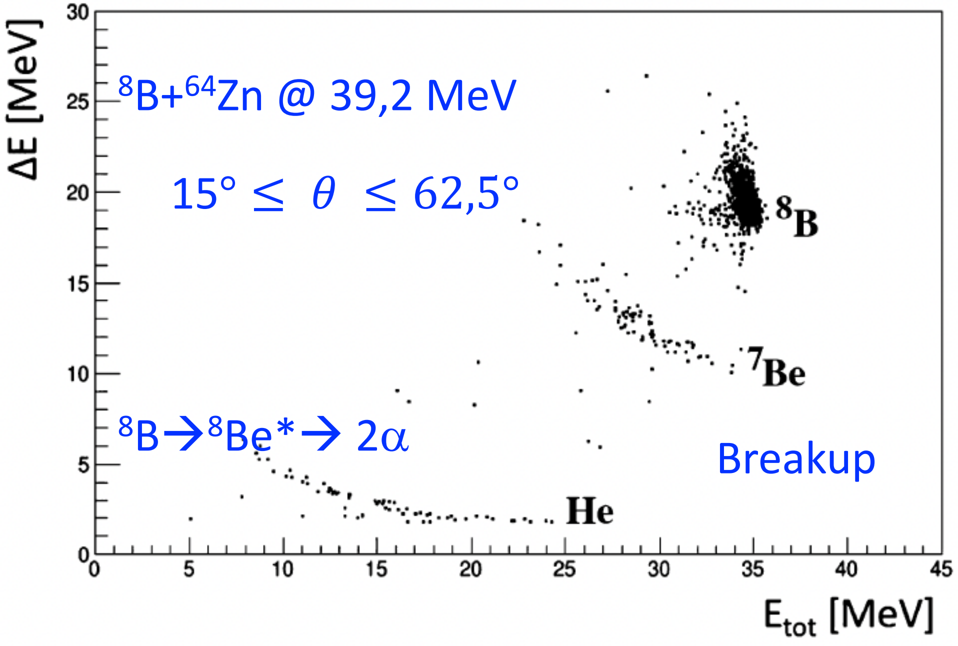
^{8}B *vs* ^{8}Li density distribution

G.A. Korolev et al.
Phys.Lett. B 780 (2018) 200

Large angular range-
high granularity GLORIA detector chamber
NIM A 755 (2014) 69



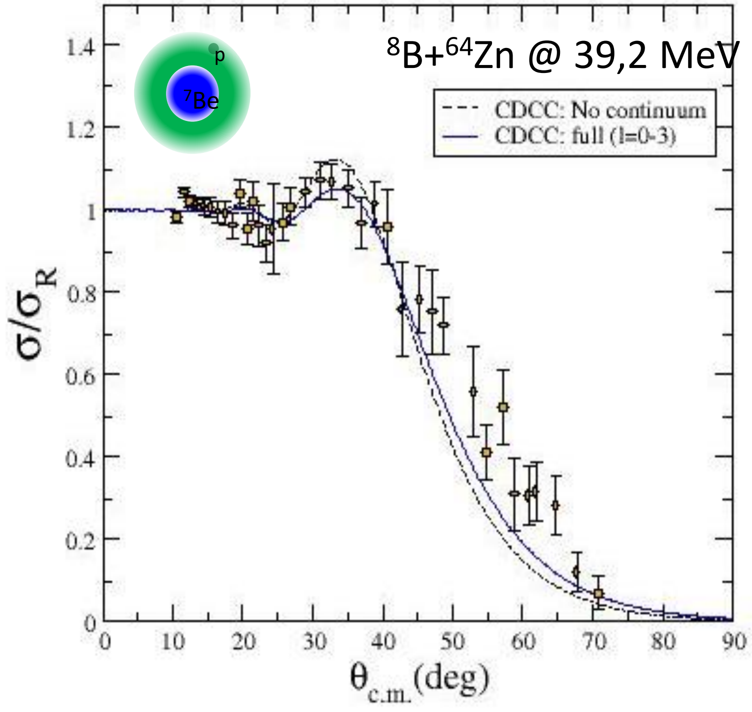




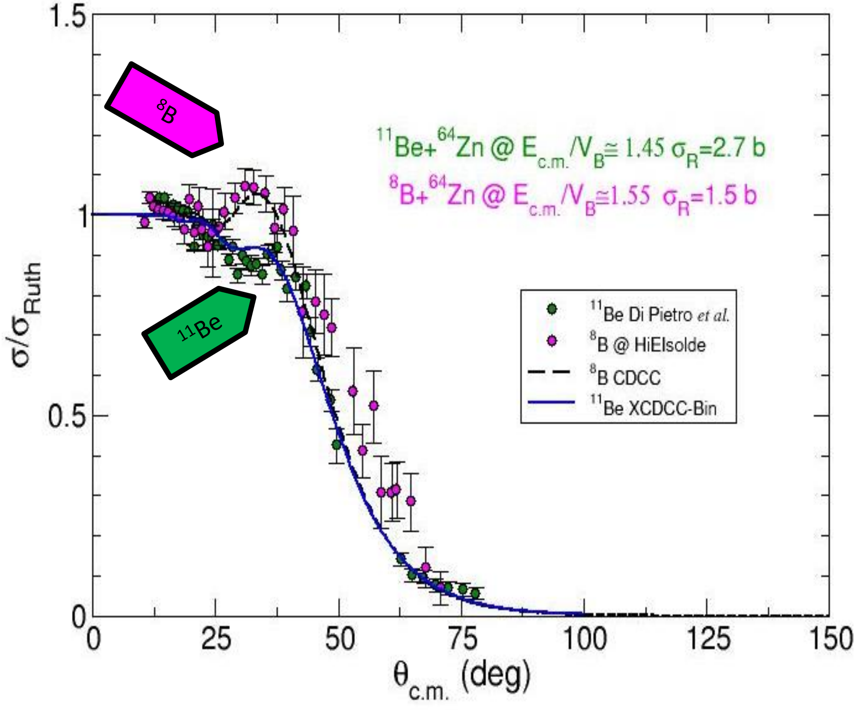
Scattering of ^{8}B on a ^{64}Zn Target (IS616)

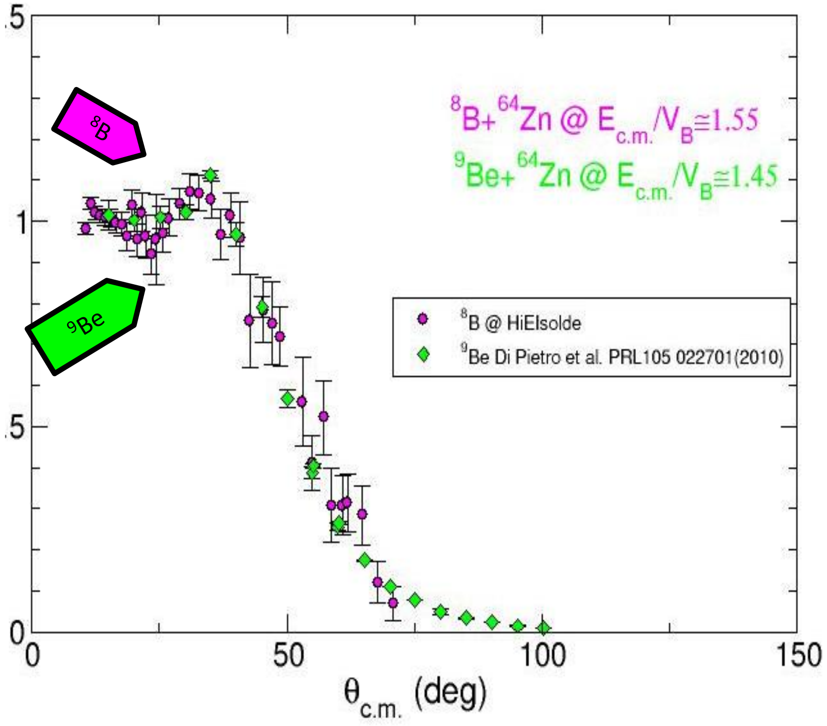
^{8}B,^{11}Be+^{64}Zn: p-halo *vs* n-halo

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



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

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

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)

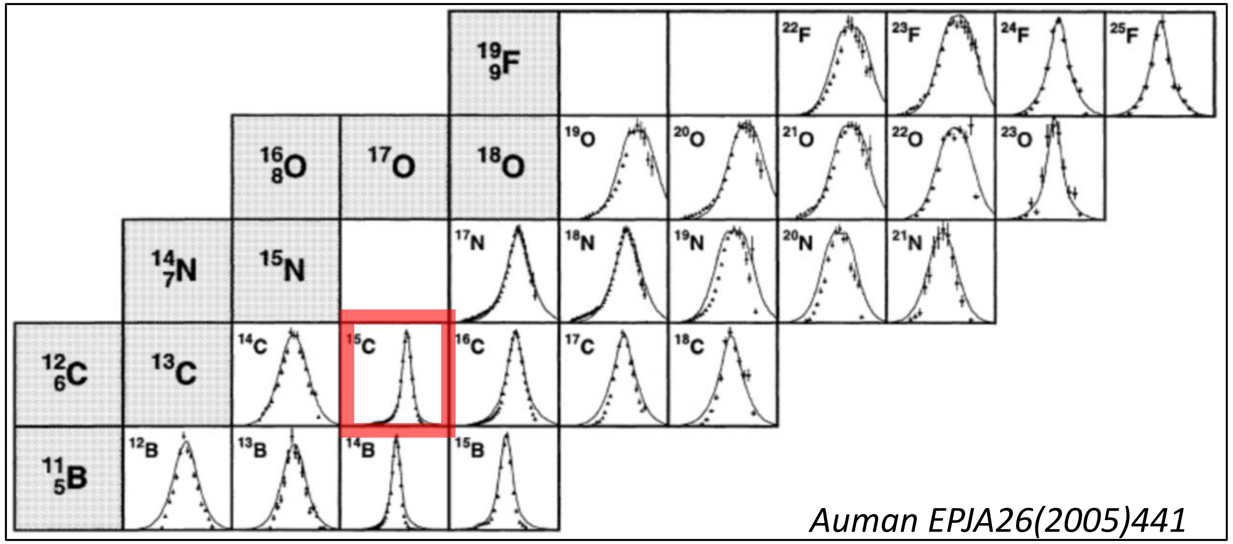
CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

Elastic Scattering of ^{15}C on a ^{208}Pb target: Elucidating the 1n-halo character

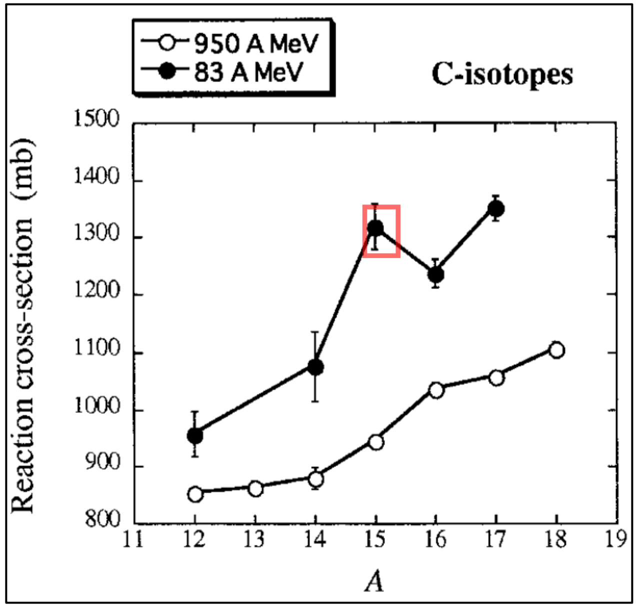
- The halo structure of ^{15}C has been debated
- For **^{15}C**, a high reaction cross section & a narrow longitudinal momentum distribution is found at relativistic energies (Γ = 67(3) MeV/c) although no as narrow as for the ^{11}Be or ^{11}Li cases ($\Gamma = 40$ MeV/c).
- A halo structure with a **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.

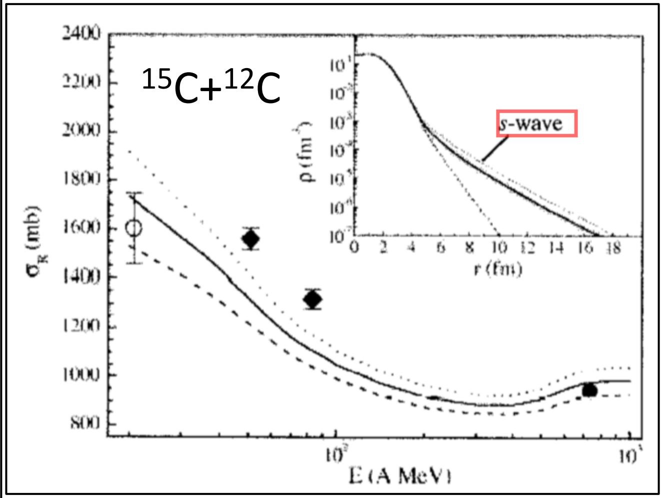
S_n = 1218 keV ; S_{2n} = 9394 keV

- 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.



Auman EPJA26(2005)441





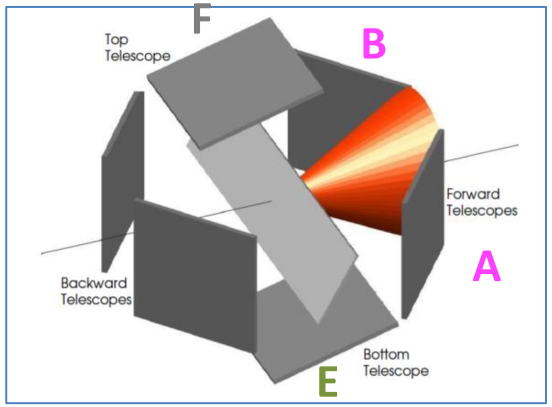
Ozawa. Nuc Phys A 738 (2004) 38

Grupo de Física Nuclear Experimental
IEM

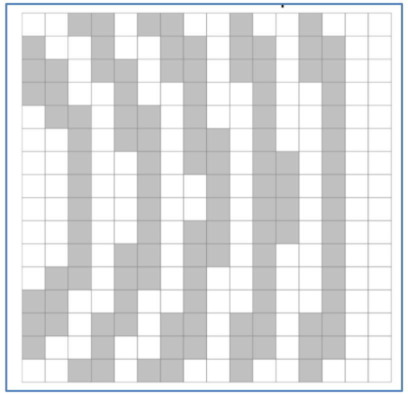
IEM

$^{15}C+^{208}Pb$ analysis and results

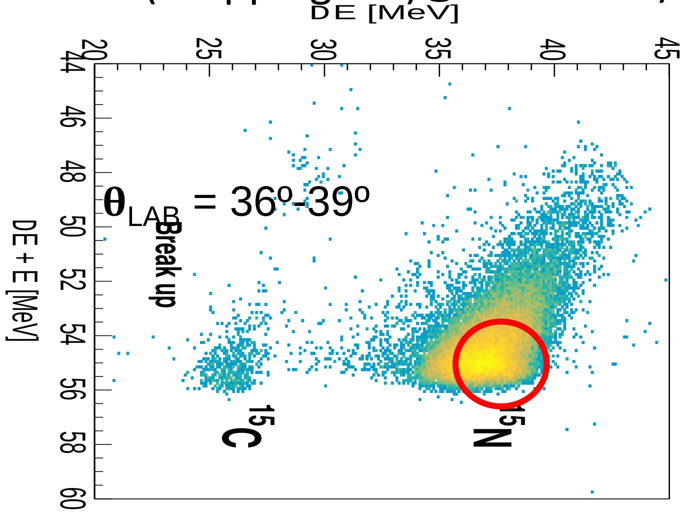
From 2D pixel to angular sectors



GLORIA Setup

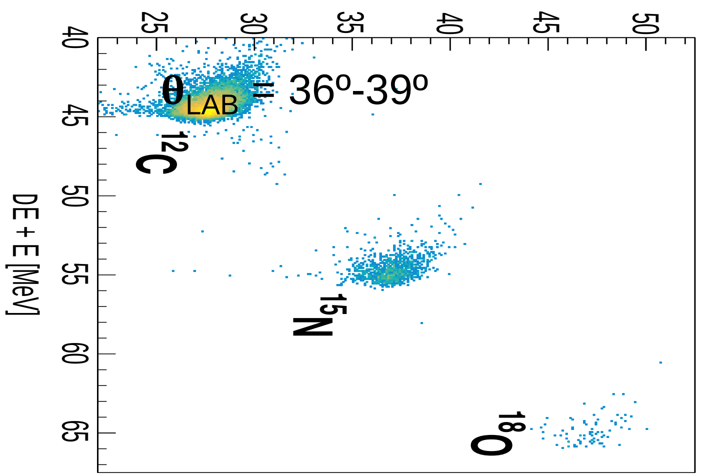


beam (Stripping foil)@ 4.37 MeV/u



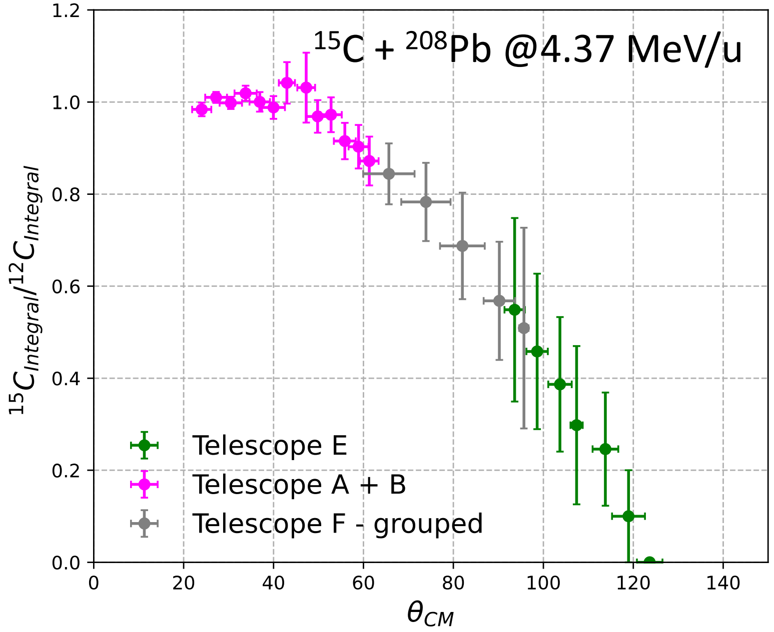
Cocktail beam A/q = 3

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

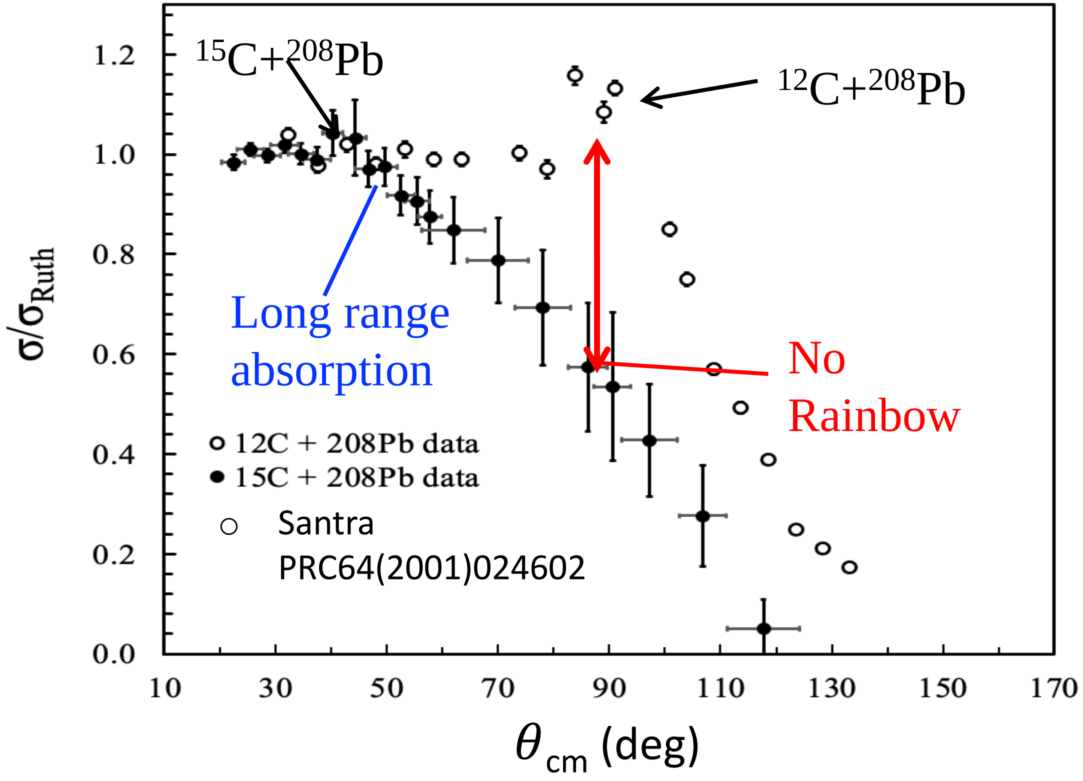


Unexpected Difficulties

- 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 have to used for normalization the ^{12}C + ^{208}Pb
- The scattered ^{15}N beam produced channelling effects that force to disregard central pixels



Comparison of ^{15}C+^{208}Pb Scattering @ 65 MeV with ^{12}C and Theory



Calculations by Nick Keeley for the proposal

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

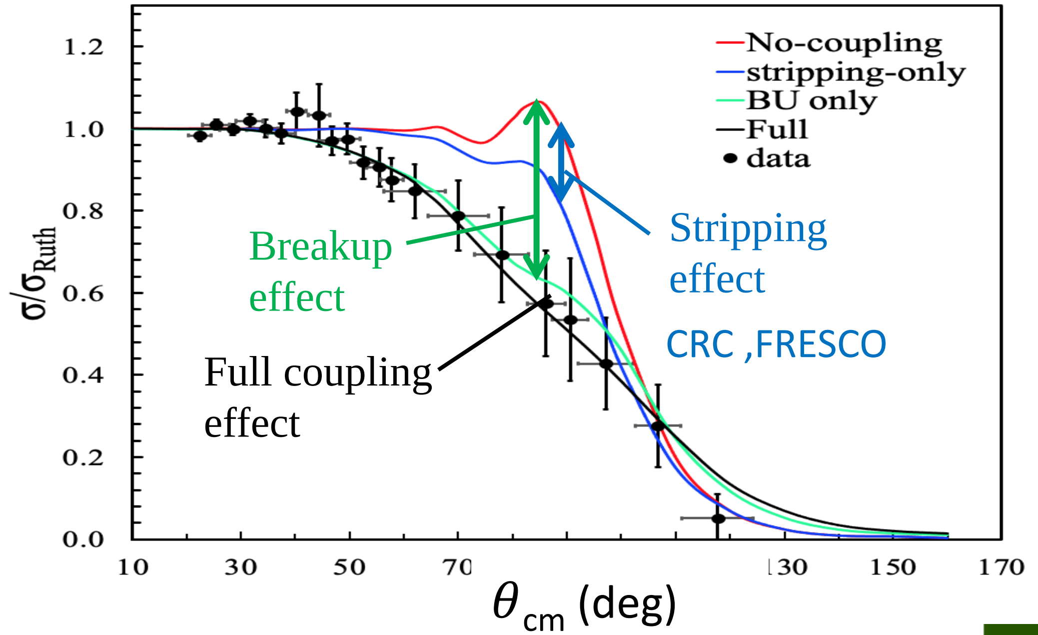
- ✓ ^{14}C inert core – 1st level (1^-) lies at 6.09 MeV
- ✓ 0.74-MeV $5/2^+$ level in ^{15}C omitted
- ✓ Optical Model potentials
  - ❖ n + ^{208}Pb – Koning & Delaroche, NPA713 (2003) 231
  - ❖ ^{14}C + ^{208}Pb – ^{12}C data S. Santra, PRC64, 024602 (2001)

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]

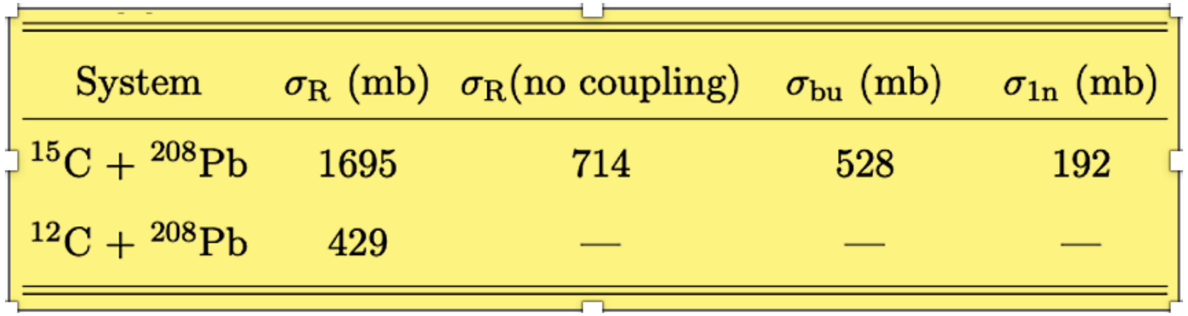
Halo effects in ^{15}C are clearly demonstrated:

- 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).

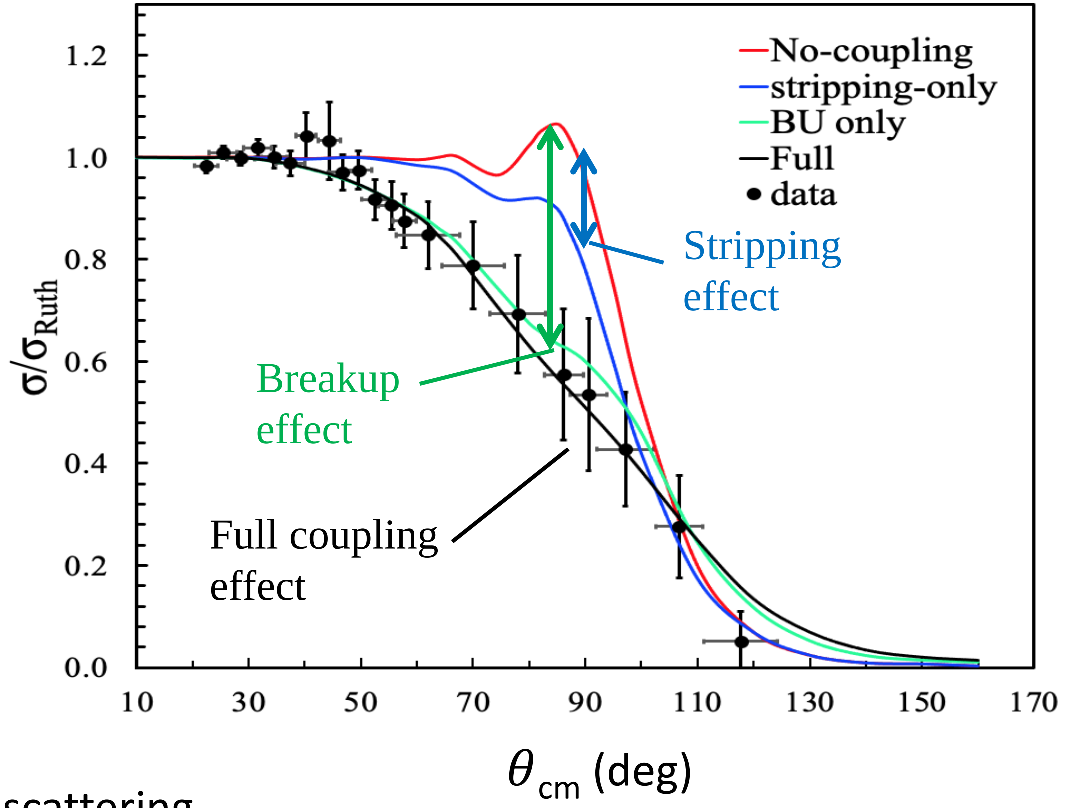


Results of the ^{15}C + ^{208}Pb @ 65 MeV (IS619)

- 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,
- The effects due to the halo are clearly seen as compared to ^{12}C



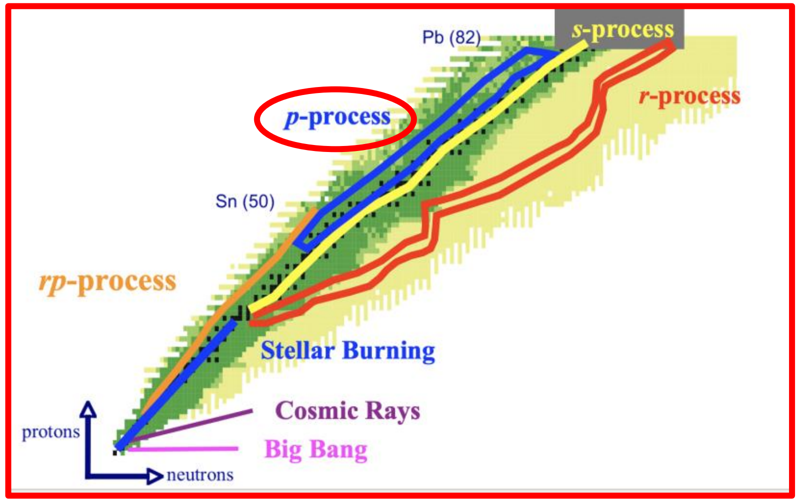
System	σ_R (mb)	σ_R(no coupling)	σ_{bu} (mb)	σ_{1n} (mb)
^{15}C + ^{208}Pb	1695	714	528	192
^{12}C + ^{208}Pb	429	—	—	—



- The reaction cross sections is a factor of 4 larger than the ^{12}C scattering

V.G. Távora, J.D. Ovejas ; paper in preparation

α-scattering of light tin-isotopes (IS698) /p-process

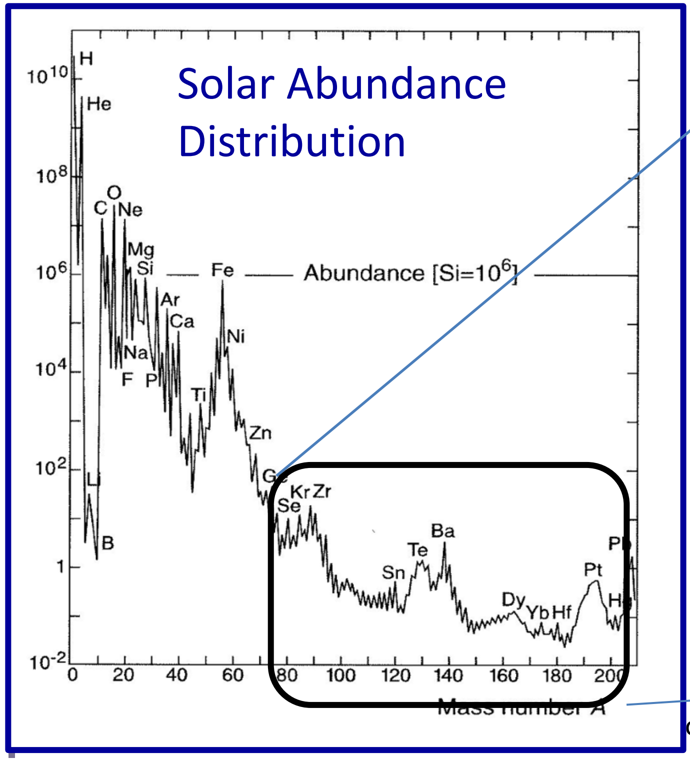


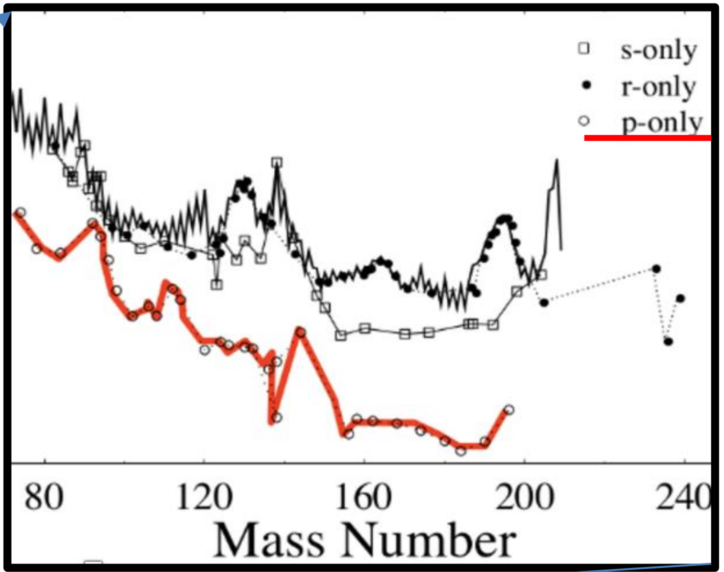
- The 38 most proton rich stable isotopes between Se and Hg are produced in the p-process
- Contrary to nuclei produced by s- and r-process they mainly occur via **photon induced reactions.**

For 140<A<240 The (γ,n) and (γ,α) reactions dominate

However, scarce (γ,α) cross section are experimentally known at astrophysically interesting energies. Further **these reactions are very sensitive to the α-nucleus potential.**

These potentials are poorly known and the calculations often differ up to a factor of 2.





Aim (IS698):

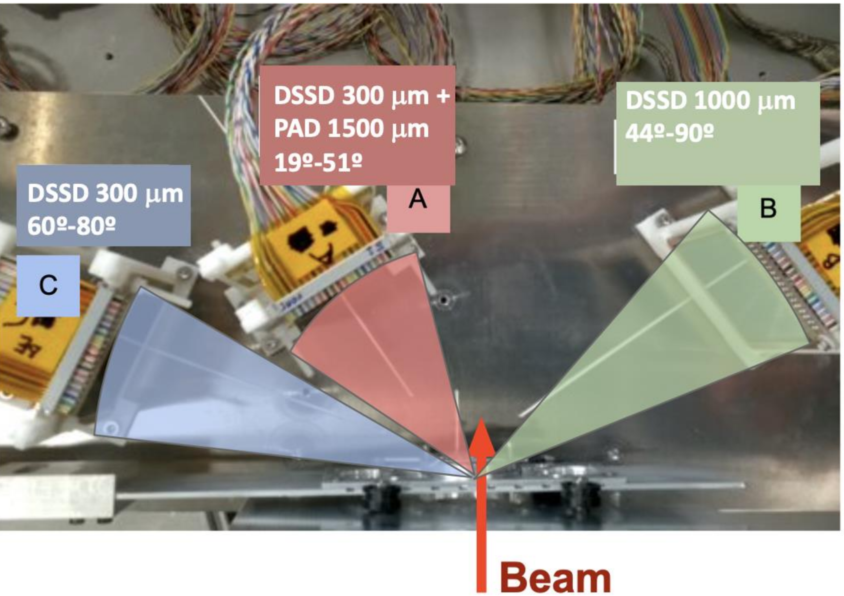
Determination for first time of complete angular distributions of the elastic α scattering process on exotic Sn nuclei at energies around the Coulomb barrier, close to the energy region of astrophysical interest.

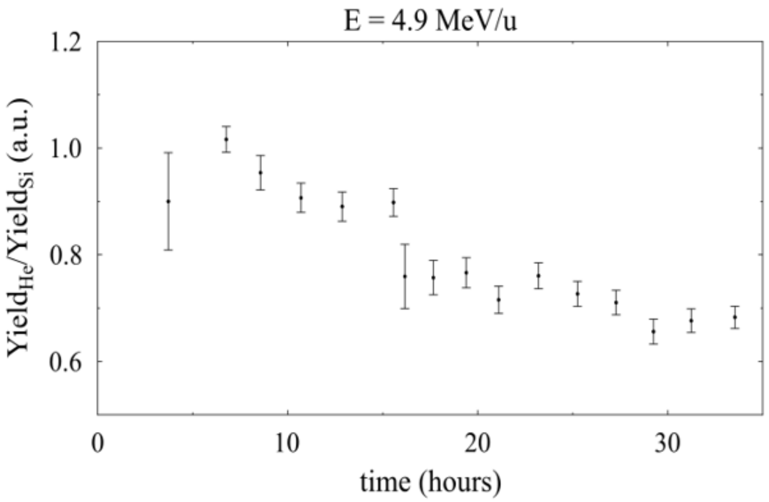
Preliminary results of IS698

Targets:

- ^{4}He in Si Matrix $\approx 2x1018\ at/cm^{2}$
- ^{197}Au ≈ 300 mg/cm^{2}

Nucleus	Yield @ SEC
^{108}Sn	50 pA
^{109}Sn	90 pA
^{110}Sn	80 pA
^{112}Sn	30 PA

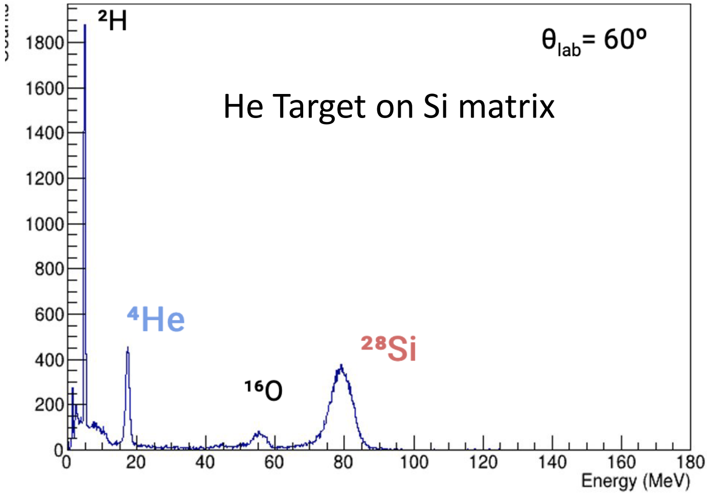


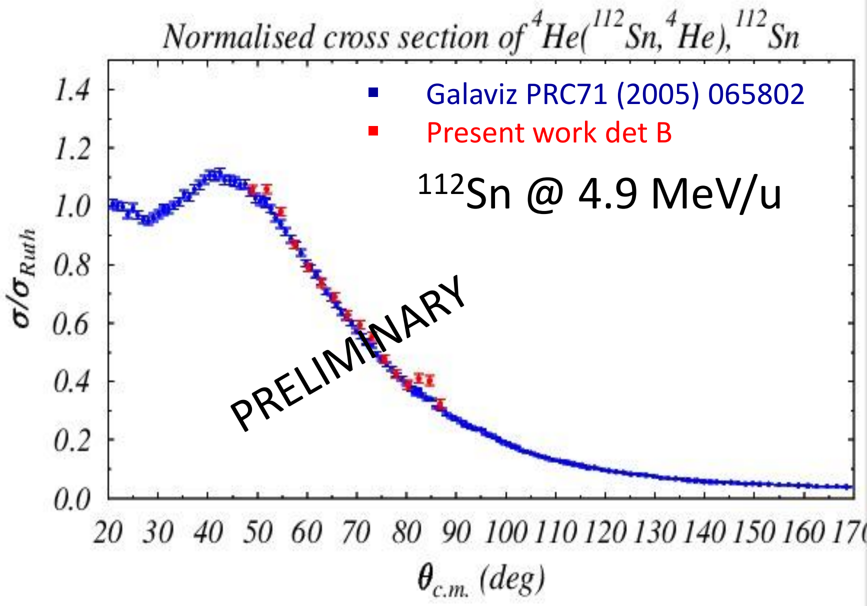


The ratio He/Si decreases with time
→ Analyse data run by run

The good agreement between the direct and inverse kinematic reactions for the stable ^{112}Sn → confidence for the study of the more exotic cases

^{4}He (^{112}Sn, ^{112}Sn) ^{4}He @ 4.9 MeV/u

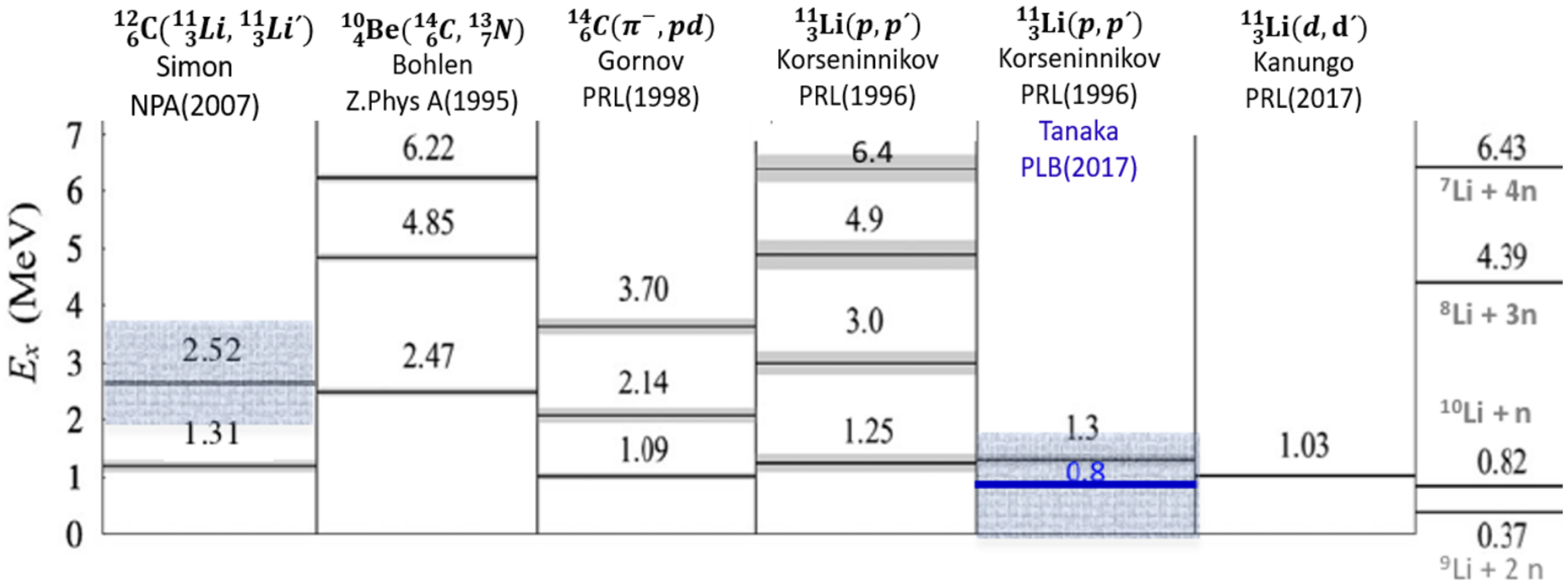




Next Experiments / SEC Upgrade

Excited Structure of ^{11}Li

- The archetype of 2n-halo nucleus ^{11}Li provides a good ground to study di-neutron correlations.
- In spite of the efforts the excited structure of ^{11}Li is not well known.



- Diversity in energy of excited structure of ^{11}Li. No firm spin assignments.
- Identification of resonances without incorporating reaction dynamics.
- Very narrow states suggested at high energies of 3-6 MeV.
- Many studies done from ^{11}Li which gs has a very complex structure.

2n-halo at the surface with 35(4)%$(1s)^2$ + 59(1)%$(0p)^2$ + 6(4)%$(0d)^2$

Kubota et al PRL 125, 252501 (2020).

Excited states of ^{11}Li populated by t(^{9}Li,^{11}Li)p reaction

The nature of the 1.2 MeV resonance in ^{11}Li can be due to dipole excitation → Not be populated from ^{9}Li

We propose a reaction starting from the simpler g.s. of ${}^{9}_{3}Li$ using the t(${}^{9}_{3}Li$, ${}^{11}_{3}Li^{*}$)p reaction

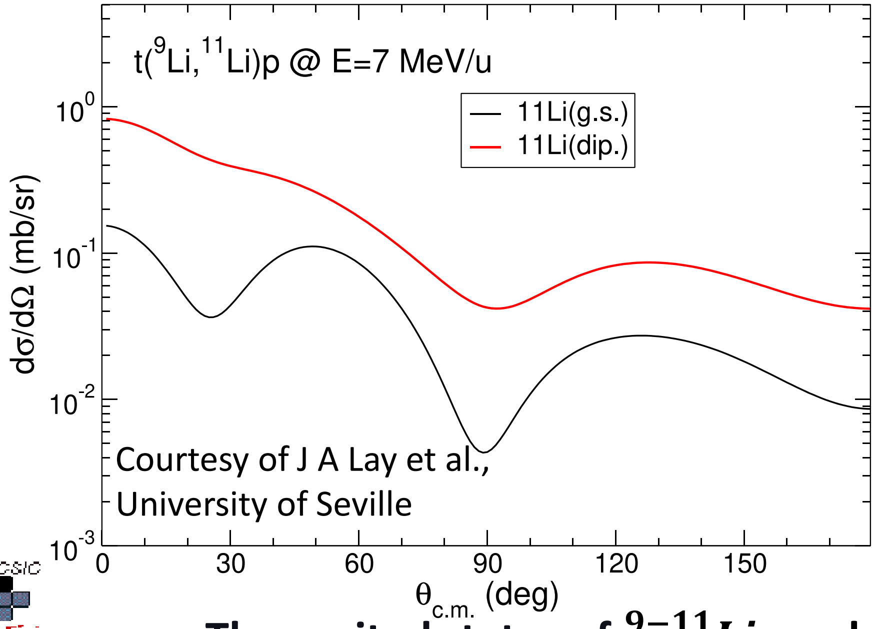
(t,p) reaction with direct and sequential decay → Dominating the direct channel.

Complement the results of p(^{11}Li,^{9}Li)t reaction @ TRIUMF at 3MeV/u using MAYA.

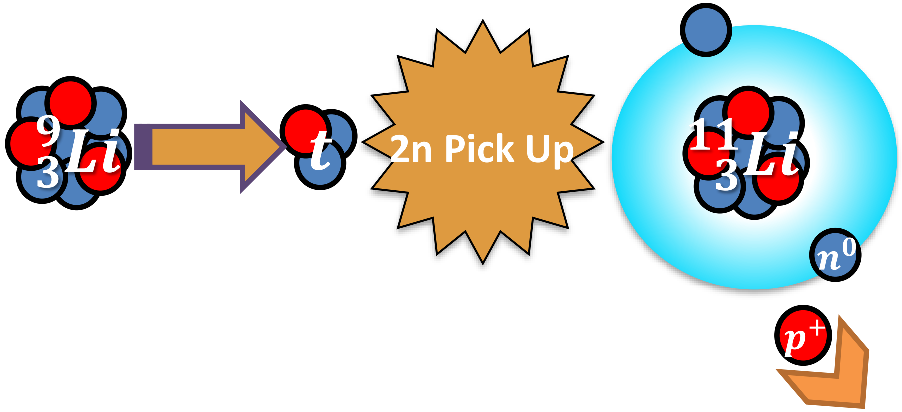
The 2nd-order DWBA calculation using (FRESCO) gives three reactions channels

I. Thompson, *50 Years of Nuclear BCS* Ed by R. A. Broglia and V. Zelevinsky (World Scientific, 2013), chap. 34

t + ^{9}Li: Xi. Li et al, Phys. A789 (2007)1
d + ^{10}Li : H. An and Ch. Cai, PRC 73, 054605(2006)
p + ^{11}Li: A.J. Koning & J.P. Delaroche NPA 713, 231 (2003)
^{11}Li w.f assumed 31% $(s_{1/2})^2$ + 64% $(p_{1/2})^2$
(P2) of Thompson & Zhukov, PRC 49 (1994), 1904



Courtesy of J A Lay et al., University of Seville



The excited states of ${}^{9-11}_{3}Li$ can be studied via the emitted tritons, deuterons and protons.

Improvements in the SEC MAGISOL setup

The particle + gamma detection system developed for IS690 @ SEC

Detectors

DAQ

Gamma Detection
↓
Scintillator detectors
8 GAGG Array
15x15x30 mm3

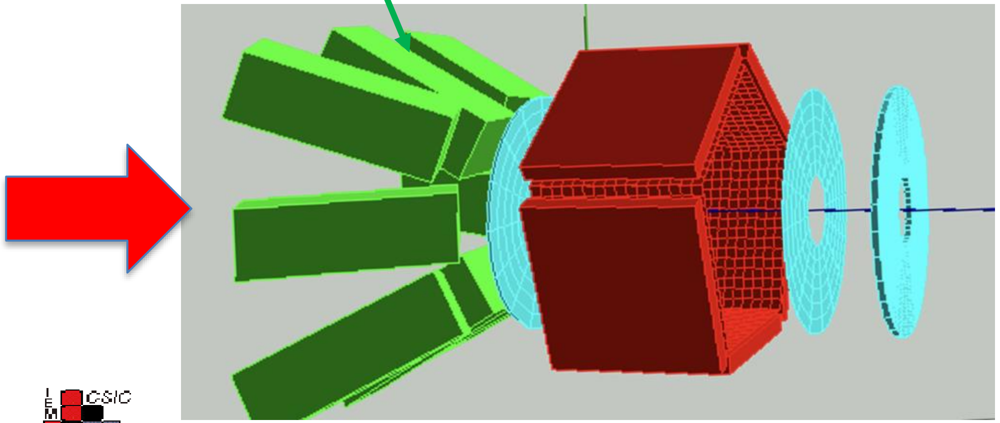
16 % of 4π

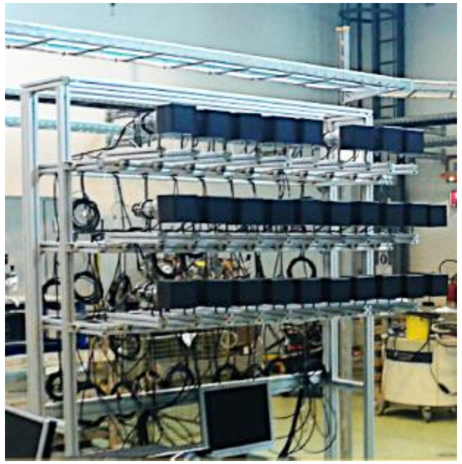
Particle Identification
↓
Silicium detectors
5 DSSD+PAD (Central Body)
3 CD (Caps)

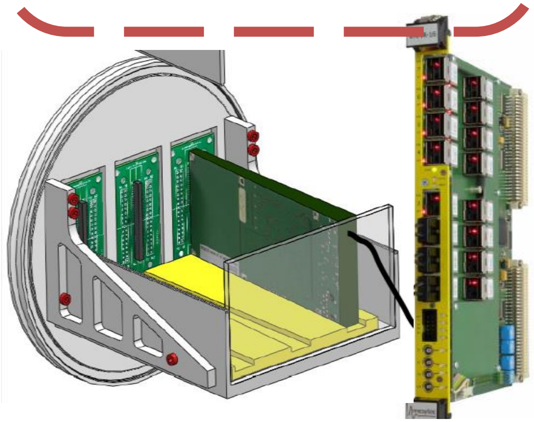
54 % of 4π

Neutron Detection
↓
SAND detectors

- ✓ **MVLC (Controler)**
- ✓ **6 x MMR-64 (DSSD+CD)**
- ✓ **VMMR-8 (Optical link)**
- ✓ **3xMPP16-QDC (GAGG+SAND)**
- ✓ **MDPP 32**







More compact Electronics
Faster
Less source of Noise

Summary & Outlook

❑ The SEC scattering chamber play the role of the general purpose device for reaction studies

❑ Unique device to study reaction dynamic and resonant states.

❑ Eight experiments were done during Run2 including different devices: GLORIA, MAGISOL,…

❑ Characterization of Halo nuclei their dynamic at low energy, and decay: ^{8}B, ^{11}Be, ^{15}C

❑ Reaction studies addressing important astrophysical problem such us the ^{7}Li anomaly and the p-process.

✓ The MAGISOL setup has been upgraded allowing for the detection of charged particle with larger angular coverage with mass determination, neutron and gamma (GAGG).

✓ More compact electronics has been implemented allowing for faster DAQ and less noise.

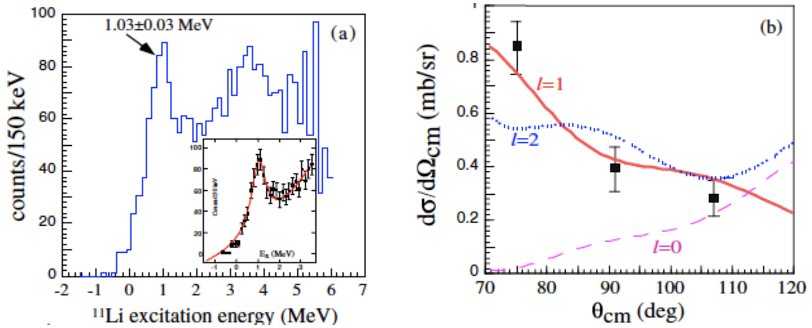
✓ The ^{3}H/Ti target for (t,p) studies is already available at reduced ^{3}H rate (0.5 ^{3}H/T)

Thanks to Alessia Di Pietro, Daniel Galaviz, Dhruba Gupta, Ismael Martel, Marek Pfützner and Olof Tengblad for the materials, and you for your attention

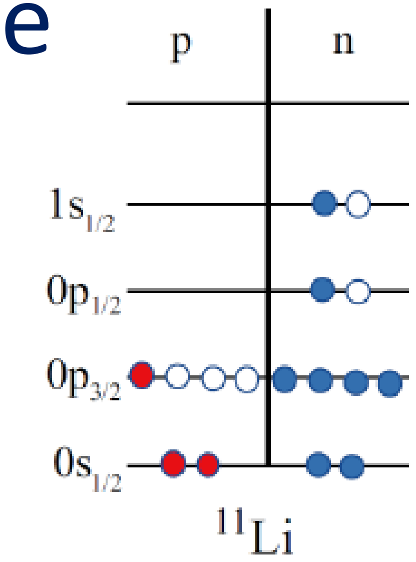
Soft Dipole Resonance

E* = 1.03 MeV
Γ = 0.51 MeV

TRIUMF @66 MeV



$^{11}\mathrm{Li}(d,d')$ R. Kanungo *et al.*, PRL**114,** 192502 (2015)

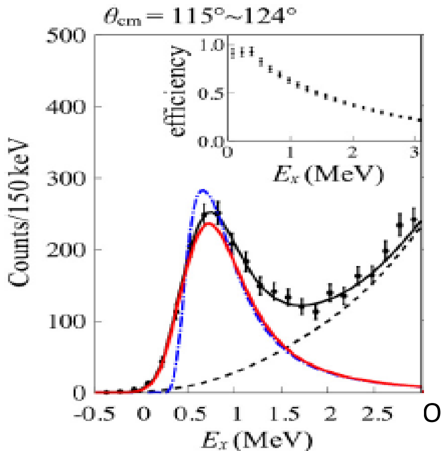


35(4)%$(1s)^2$ + 59(1)%$(0p)^2$ + 6(4)%$(0d)^2$

Kubota et al PRL 125, 252501 (2020)

$^{11}\mathrm{Li}(p,p')$ J. Tanaka *et al.*, PLB **774, 268** (2017)

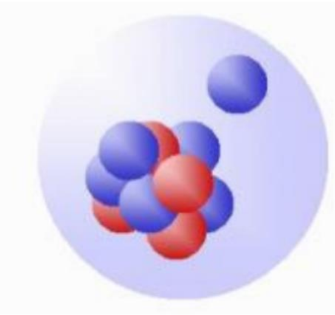
E*=0.8 MeV,
Γ=1.15 MeV



- With the discovery of halo in ^{11}Li→ **Soft Dipole Resonance** due to halo-core **oscillations** could lead to the appearance of a **low-energy branch of a giant dipole resonance** with an excitation energy of less than **1 MeV**
- Spectrum taken with the same device by the same group. The different energies could be due to overwhelming contribution of Coulomb excitation

Rare decays measured at HIE-ISOLDE with the Warsaw Optical Time Projection Chamber

Study of neutron halo via charged particle emission following β-decay
Unique technique: CCD images of nuclear decay

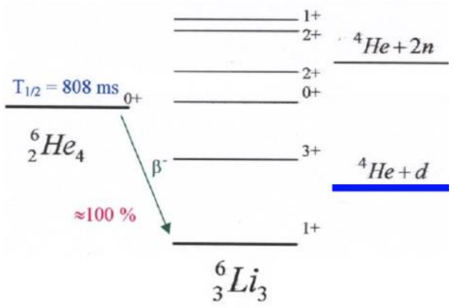


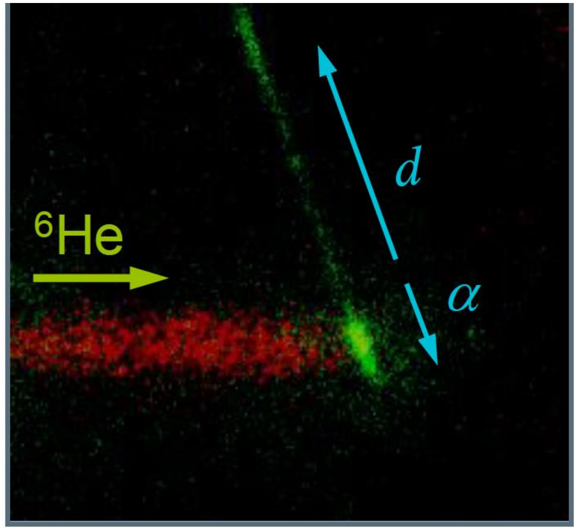
^{6}He @ REX (2012) IS505

- 2n halo nucleus; S_{2n} = 975,45 (5) keV
- The $\beta^{-}d$ decay possible $^{6}He \rightarrow \alpha + d$

$Q_{\beta d}$ (keV)= 3007- S_{2n} = 2033 keV,

Predicted branching: 10^{-4}





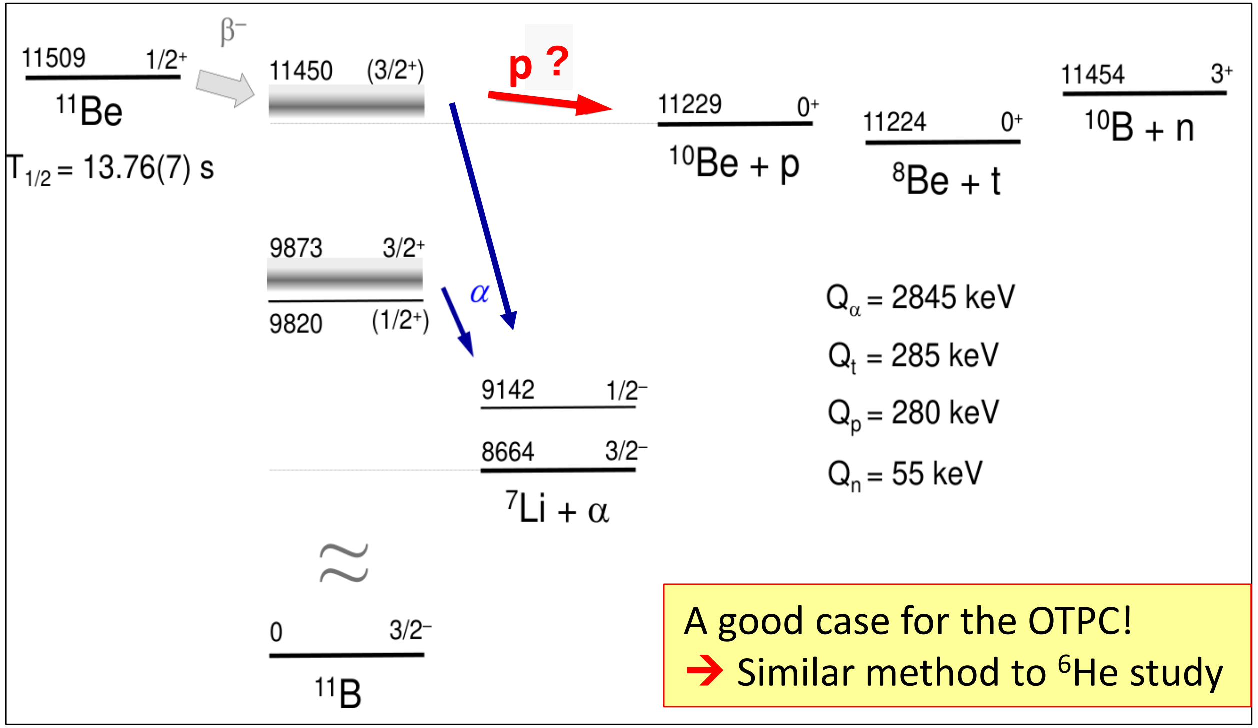
Very weak decay branch
2,78(18)x10^{-6} $^{6}He \rightarrow \alpha + d$
2000 events measured ⇨ insight into the 2n halo of ^{6}He (3-body Model)

Pfützner et al., PRC92(2015) 014316

^{11}Be @ HIE-ISOLDE (2018) (IS629)

- 1n halo nucleus, Sn = 501,64 (25) keV
- The $\beta^{-}\alpha$ emission observed
- The $\beta^{-}p$ decay possible

Q_p = 280 keV, the predicted branching: $b_p < 10^{-6}$

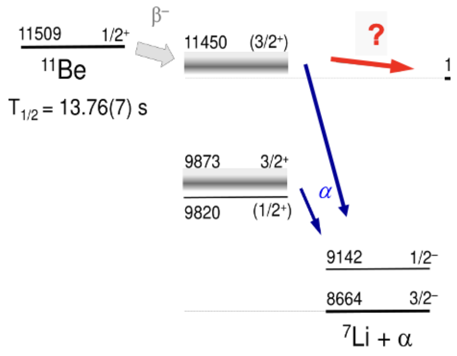


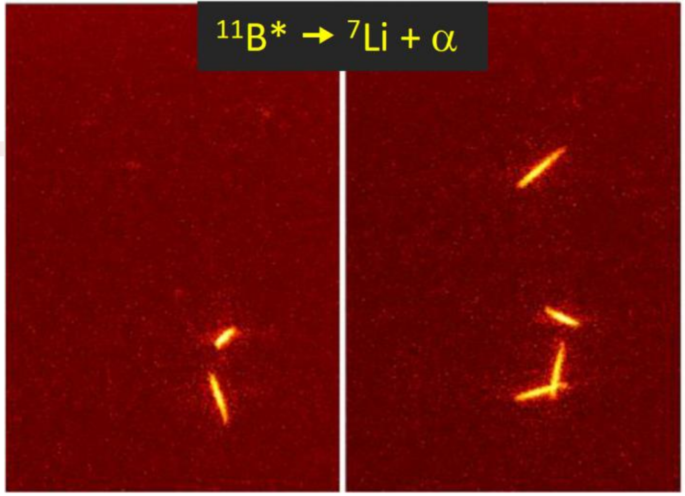
A good case for the OTPC!
→ Similar method to ^{6}He study

βα decay of ^{11}Be(IS629)

- Bunches of about 10^4 ions of ^{11}Be (T1/2 = 13.7(6)s)
- accelerated 7.5 MeV/u & implanted into the OTPC every 1 min.
- ☐ βα branch, 3.3(1)%, provides normalization
  but it is a source of low-energy background
- Previous results: 2 level contribution;

  lack of info below 500 keV
- Search for βp Branch



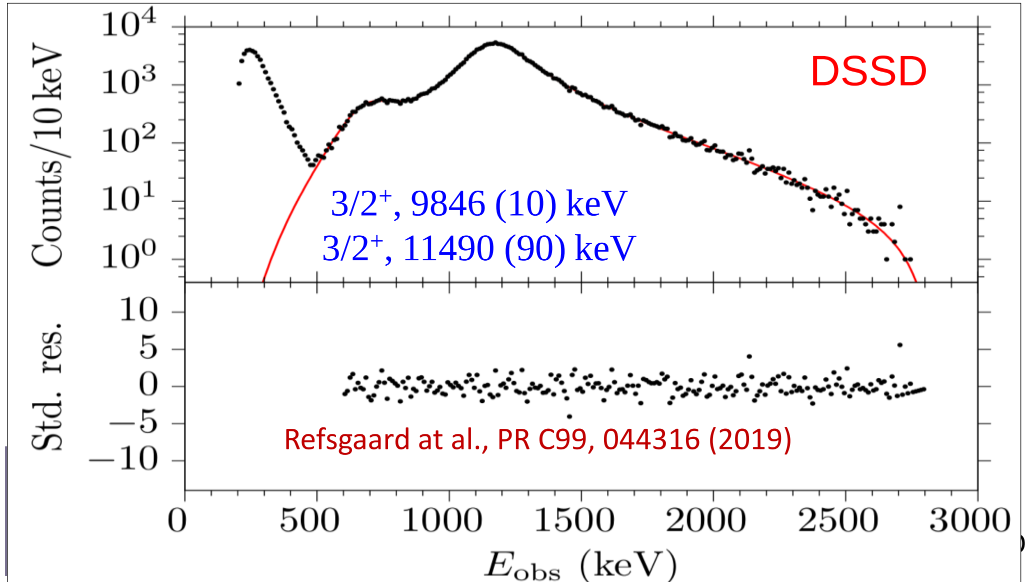


βα = 3.27(46)%

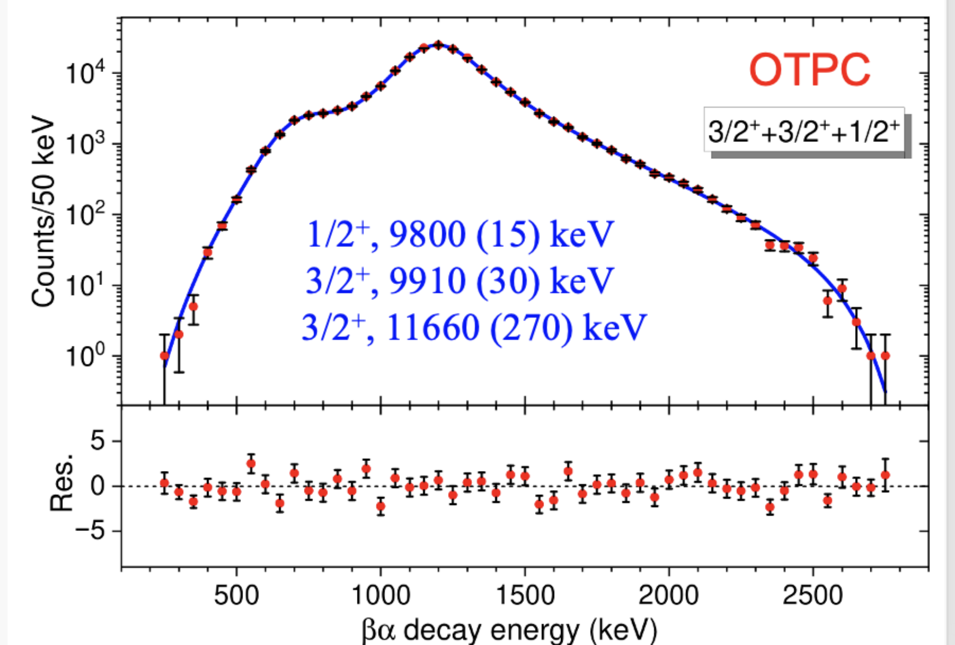
Better fit with 3 levels contribution;

βp < $2x10^{-6}$ Contrary to recent results (PRL123 (2019) 082501)

N. Sokołowska et al., PhD Thesis, U. of Warsaw, 2023
and submitted to Phys. Rev. C

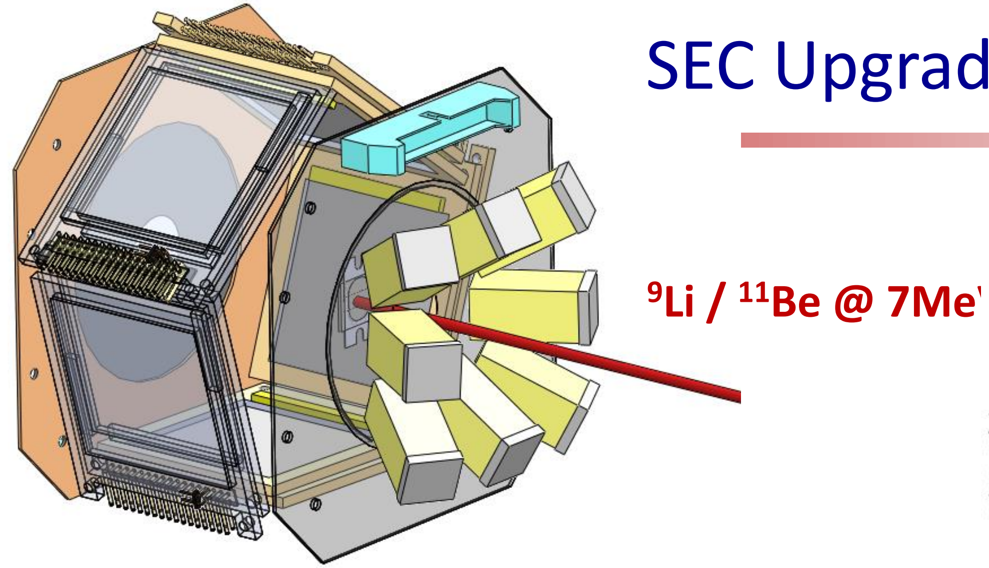


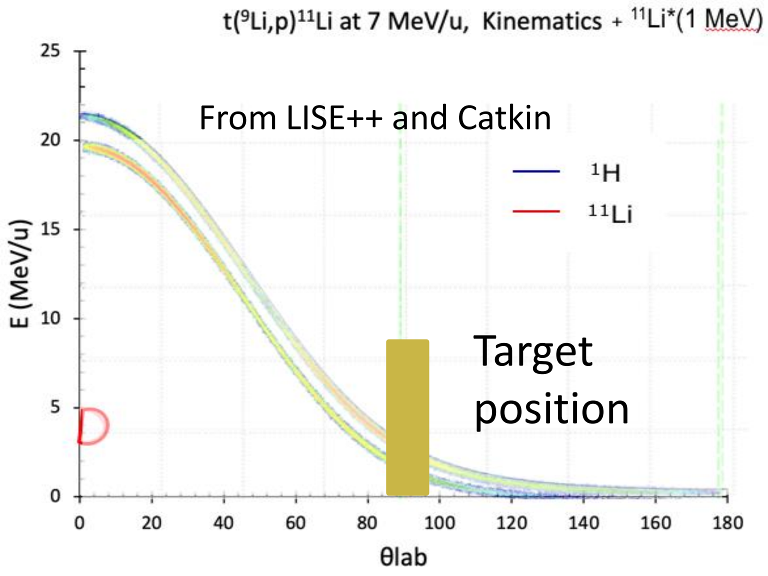
Refsgaard at al., PR C99, 044316 (2019)



Courtesy of
C. Mazzochi
M.. Pfützner

SEC Upgrade Experimental Setup





- Tritium Target from Sodern Co (France)
- 450mg/cm^2 of ^{3}H/ Ti of 1 x 0.5 cm^2

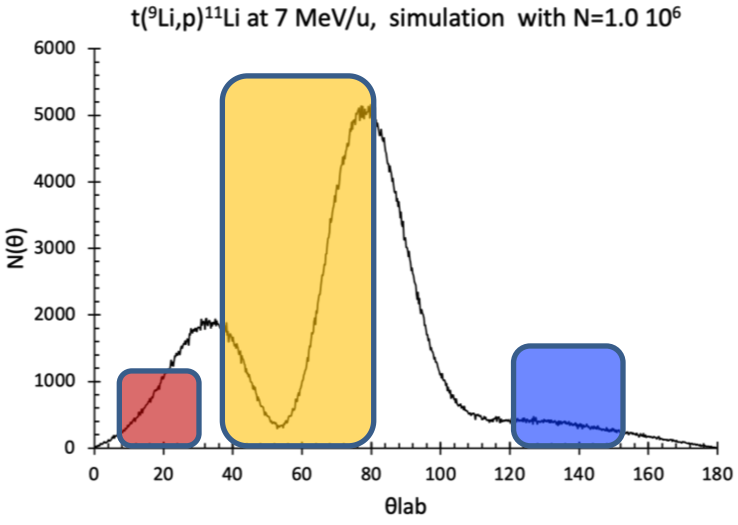
•Upgraded SEC setup

Forward S3 6º -20º →
Forward S5 8º - 27º → 5% of 4π
Pentagon 38º - 79º → 29 % of 4π
Backward S5 115º - 148º → 19 % of 4π

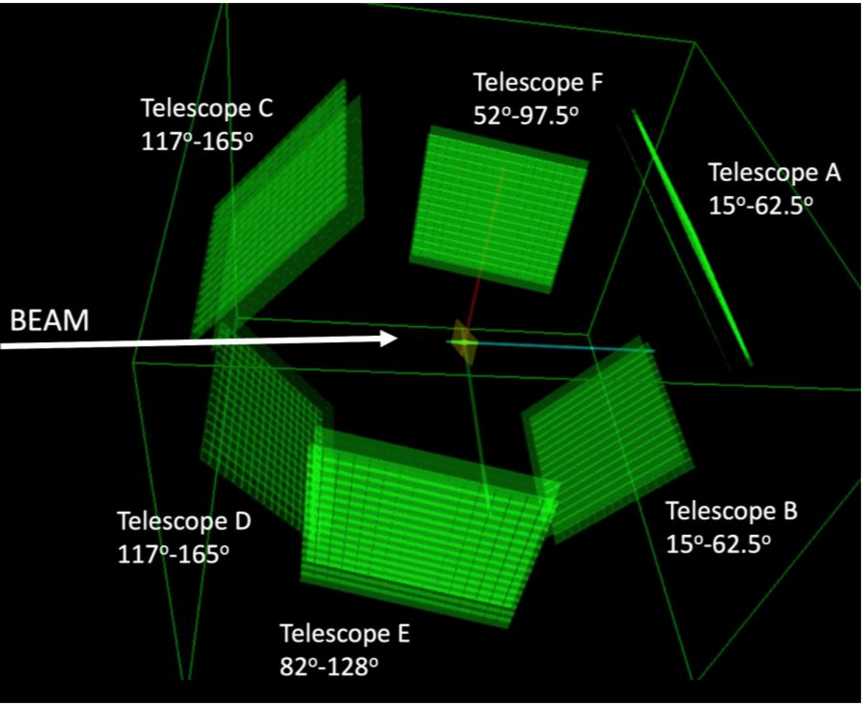
8 15x15x30 mm^3 GAGG scintillators 16% of 4π

SAND for neutron detection

More compact electronics and updated DAQ.



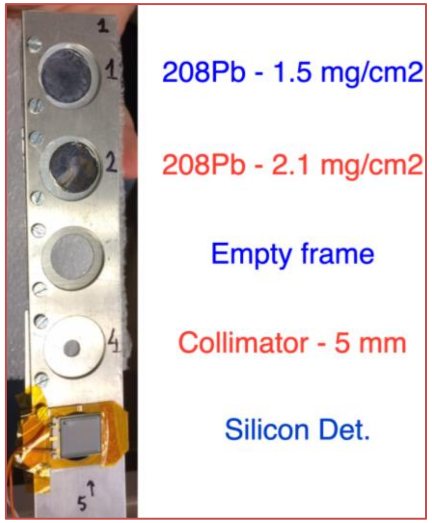
Effects of the 1n-halo in ^{15}C scattering on ^{208}Pb at energies around the Coulomb barrier



Global Reaction Array **GLORIA**
NIM A 755 (2014) 69
6 telescopes (40+1000 μm)
θ_{LAB} from 15º to 165º
$$\Omega = 25\ \%\ of\ 4\pi$$

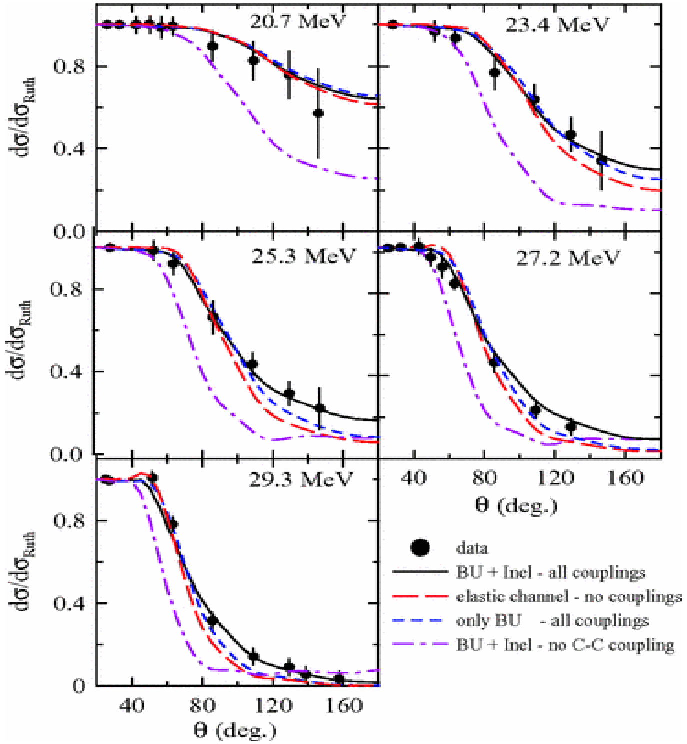
- Post-accelerated ^{15}C with A/q=3 up to 4.37 MeV/u,
- $T_{1/2}$ (^{15}C) = 2,449(5) s;
- **J^p (gs) = ½$^+$($s_{1/2}$) ; 1st @ 740keV J^p = 5/2$^+$ ($d_{5/2}$),**
- 2nd @3103(4) keV J^p = ½-
- Cocktail beam ^{12}C + ^{15}N + ^{18}O at the same energy provides useful information for geometric / energetic calibration.
- ^{15}N present after a 75 μg/cm² stripping foil **$^{15}C/^{15}N$ ≈ 1-3%**
- Estimated ^{15}C yield ~ 10^3 pps
  (1.1· 10^4 pps requested)
- ^{208}Pb **targets** 2.1 and 1.2 mg/cm². Purity ≈ 98%
- 30º tilted target to beam direction → no shadowing at 90º

Target Ladder



Previous result on the Scattering of ^{8}B

^{8}B + ^{58}Ni. @ 20.7 – 29.3 MeV



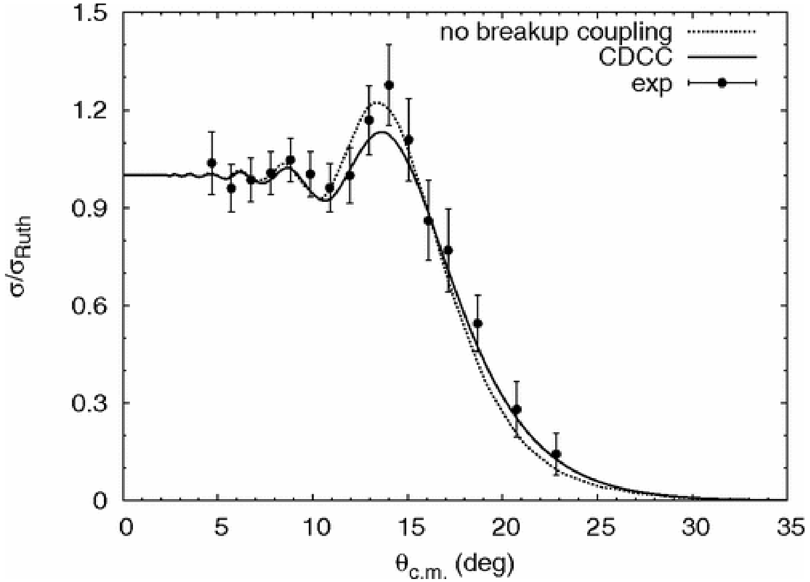
- Data from cocktail beam
- Low angular resolution
- The CDCC shows that continuum-continuum coupling is essential to describe the elastic angular distribution near the V_B = 28,6 MeV

J. Lubian et al PRC 79 (2009) 064605
data from E.F. Aguilera et al. PRC 79, (2009) 021601(R)

Proton-halo structure of ^{8}B debated

- ✓ Very low binding for last proton S_p =136.4(10) keV
- ✓ Interaction cross section @ E > 100 AMeV no enhancement
- ✓ Large enhancement at low energies → long tail deduced
- ✓ Large 1p-removal cross section → Important to deduced whether this p-removal is due to elastic breakup

^{8}B + ^{nat}Pb @170 MeV



Y. Y. Yang *et al.* PRC **87 (2013)** 044613

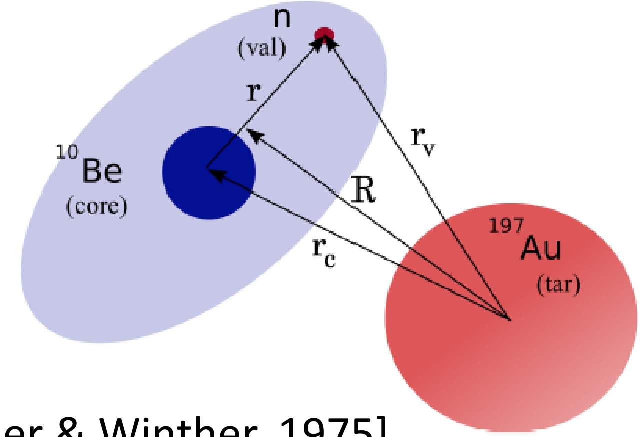
The CDCC does not need coupling to the continuum

Theoretical Interpretation

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

What can we learn of the ^{11}Be structure?

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]

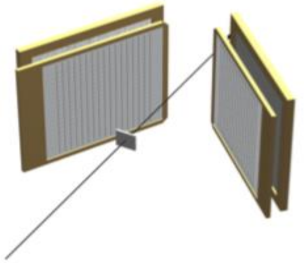
Structure of ^{11}Be
P. Capel et al, PRC70 (2004) 064605

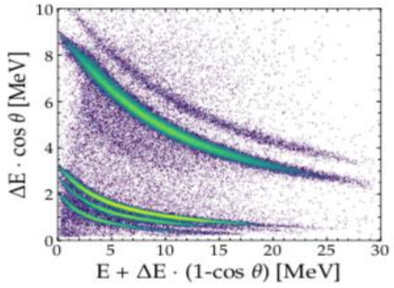
Koning & Delaroche
NPA713 (2003) 231

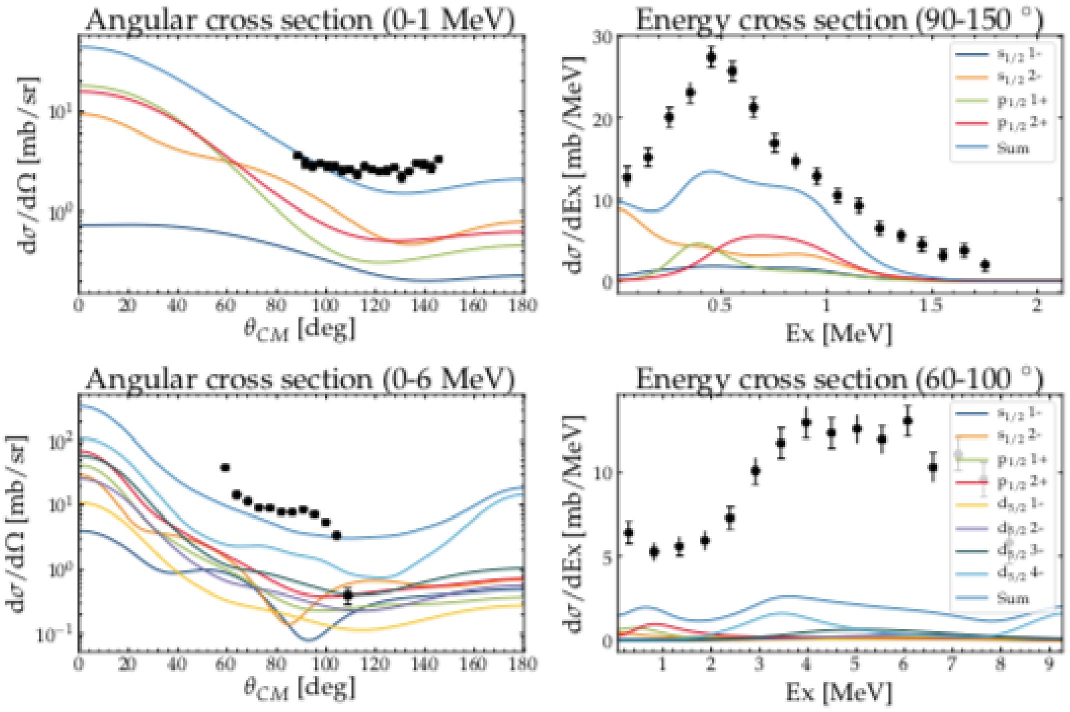
From ^{10}Be + ^{208}Pb data
Kolata et al., PRC69(2007)047601

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

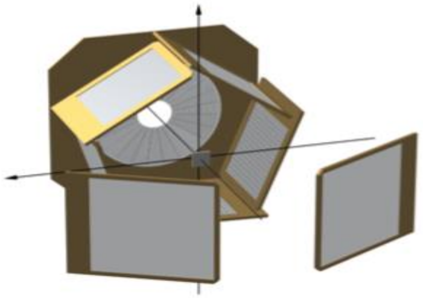
Study of ^{10}Li structure

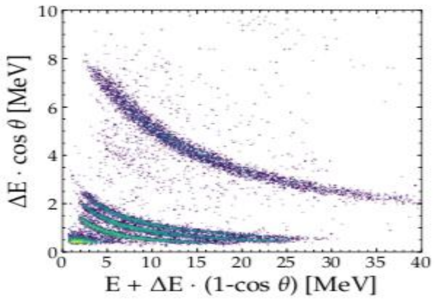






d (^{9}Li,^{10}Li)p @ 2.65 MeV/u (2006)





d (^{9}Li,^{10}Li)p @ 8 MeV/u (2018)

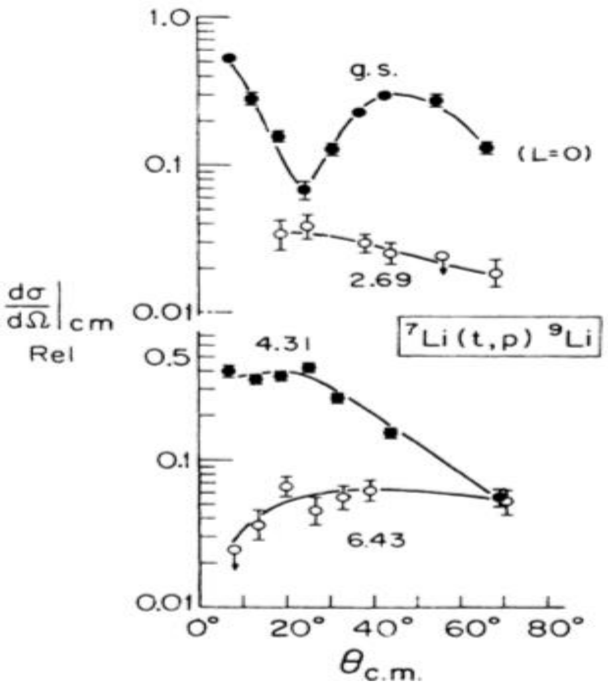
- Evidence for reaction mechanism based on kinematics
- Evidence of s-wave and p-wave contribution in ^{10}Li at low energy
- Indication of dominating d-breakup at higher energies

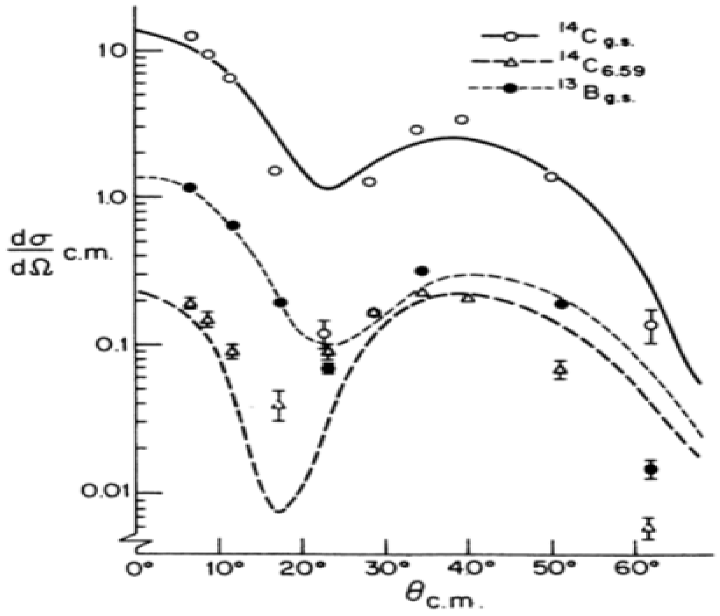
[Taken from Ph.D. Jesper H Jensen, 19 October 2019]

Old (t,p) reactions

The ^{7}Li(t,p)^{9}Li was studied at triton energies of 15MeV (PRC4(1970)1592) y by Ajzenberg-Selove PRC17(1978) at t=22 MeV

The ^{11}B(t,p)^{13}B was studied together by Ajzenberg-Selove PRC17(1978) For ^{9}Be(t,p)^{11}Be a more recent work PRC42(1990)167.

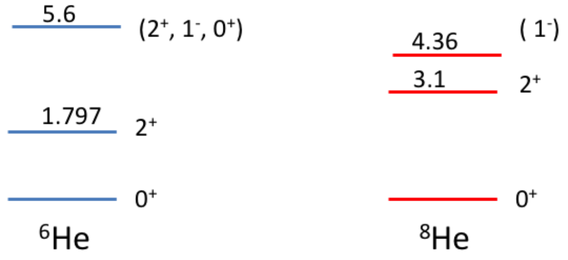




Additional Channels of Interest

- The elastic scattering channel is essential to fix the optical potential in the theoretical models.

- The ^{9}Li(t,α)^{8}He has not been been observed so far . The corresponding reaction ^{7}Li(t,α)^{6}He is known to populate both the ground state and several excited states.



- The ^{11}Be(t,α)^{10}Li and ^{11}Be(t,d)^{12}Be channels will be available simultaneously.

In particular it will be interesting to fix the first unbound state in ^{12}Be.

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