Clusters and exotic structures in light nuclei probed through reactions and decay

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Exploring low-energy nuclear properties:
latest advances on reaction mechanisms with light nuclei

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Reactions and Decay

Transition Rate

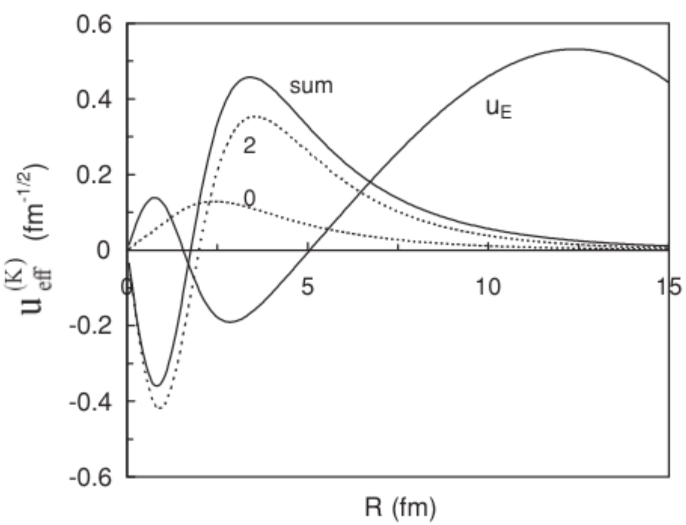
$$\lambda = \frac{2\pi}{\hbar} \left| \langle \Psi_f | V | \Psi_i \rangle \right|^2 \rho(E_f)$$

- Matrix element $\langle \Psi_f | V | \Psi_i \rangle$ contains nuclear structure and interaction potential
- Reactions: either…
  - consistent approach for the two
  - focus on reaction mechanism
  - focus on structure
- If focus on structure
  → use "simple/well-known" processes:
  resonant elastic, nucleon transfer… or decay!

Exotic decay modes: β-delayed charged-particle emission

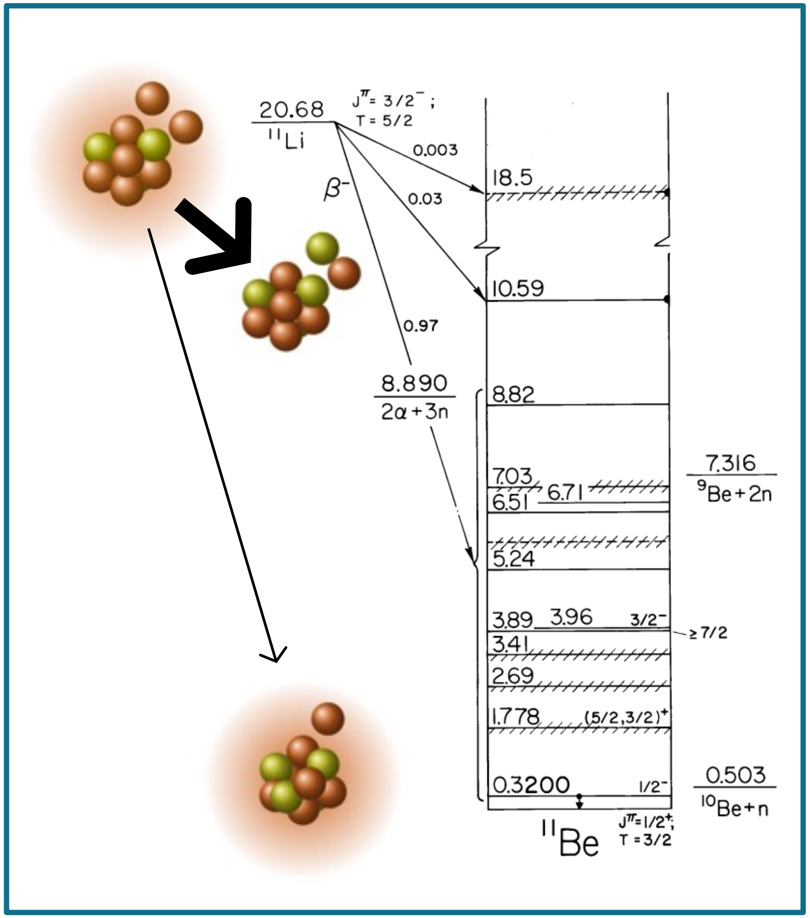
Decay of halo states

- Poor overlap
  → decreased decay probability
- Patterns: decay of the halo (cluster)
- Contribution of different regions
  of the wave function,
  possible cancellation effects



^{6}He

E. M. Tursunov, D. Baye,
and P. Descouvemont, PRC 73 (2006) 014303

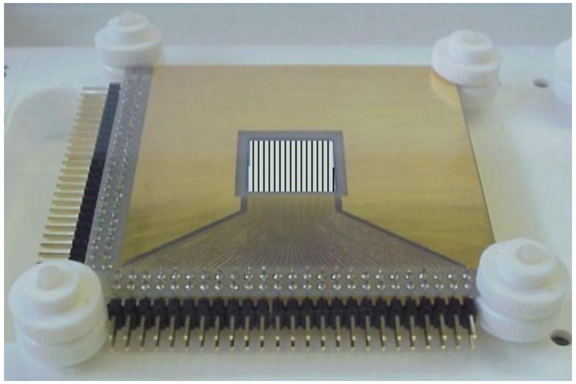


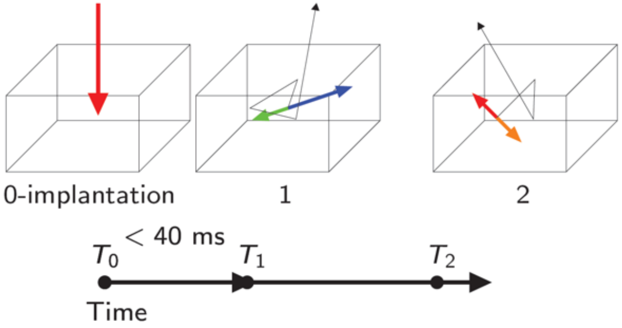
Exotic decay modes: techniques

β-delayed charged-particle emission

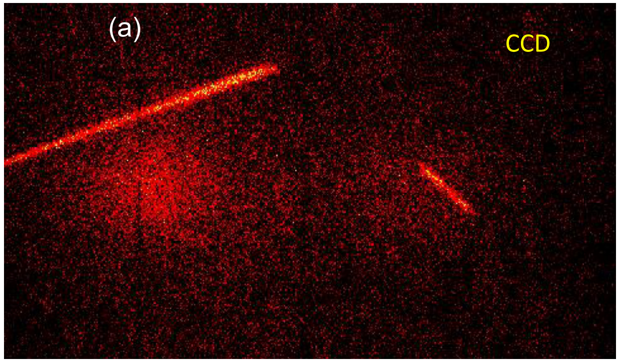
- Method: implantation and decay in the detector
- Advantages
  - suppression of β-particles background
  - high efficiency
  - high precision
  - high accuracy
  - “history” of each decay
- Measured: ^{6}He, ^{11}Li, ^{11}Be, ^{8}B, ^{12}N, ^{12}B, ^{16}N

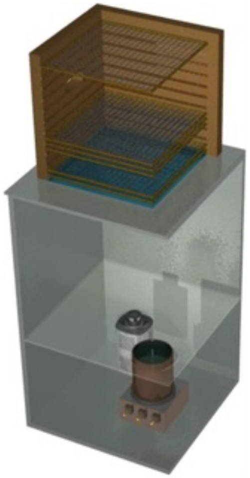
Pixelated Si detector (Leuven)





Optical TPC (Krakow group)





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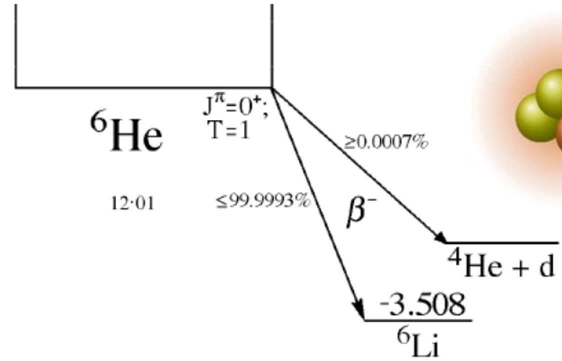
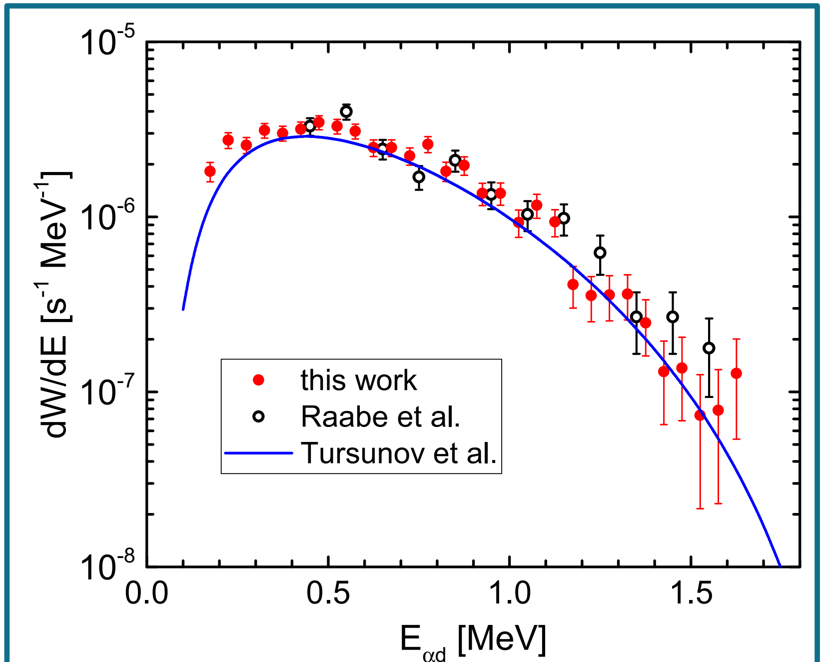
Exotic decay modes: $^6He \rightarrow \alpha + d$

Decay into the continuum

- Small decay channel (≈10^{-6}) into α+d
- Measurement in Louvain-la-Neuve
  315 α+d decay events in ≈4 days
- Branching ratio:
  1.65(10) x 10^{-6} ($E_{c.m.}$ > 525 keV)
- Measurement at ISOLDE
  Spectrum extended to $E_{c.m.}$ ≈ 150 keV
- Very small B.R. explained by the <u>cancellation</u> between the internal and halo components of the matrix element
- Branching ratio sensitive to halo wave function at large distances



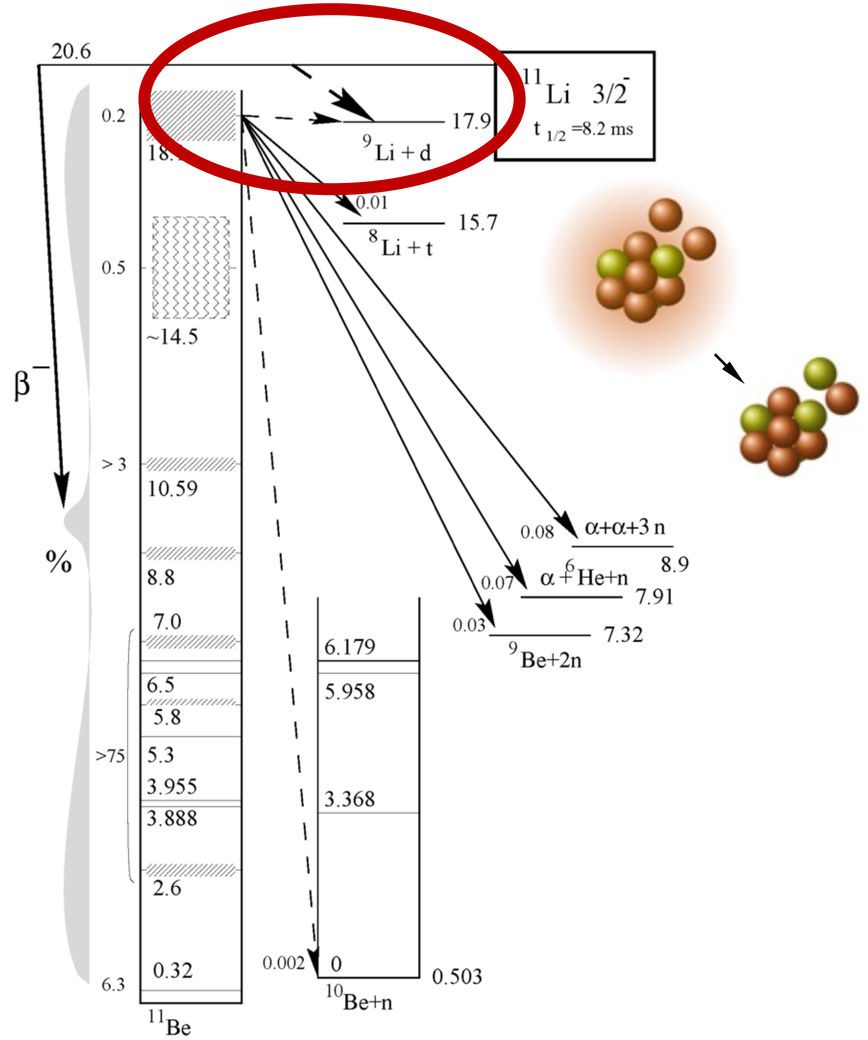


M. Pfützner at al., PRC 92 (2015) 014316
R. Raabe et al., PRC 80 (2009) 054307
E.M. Tursunov et al., PRC 73 (2006) 014303

Exotic decay modes: $^{11}Li \rightarrow {}^{9}Li + d$

Decay into continuum+resonance(?)

- Many different decay channels
  → identification is crucial
- Use of daughter-decay
  (time and spatial correlation)



K. Riisager, NPA 616 (1997) 169c

Exotic decay modes: $^{11}Li \rightarrow {}^{9}Li + d$

Decay into continuum+resonance(?)

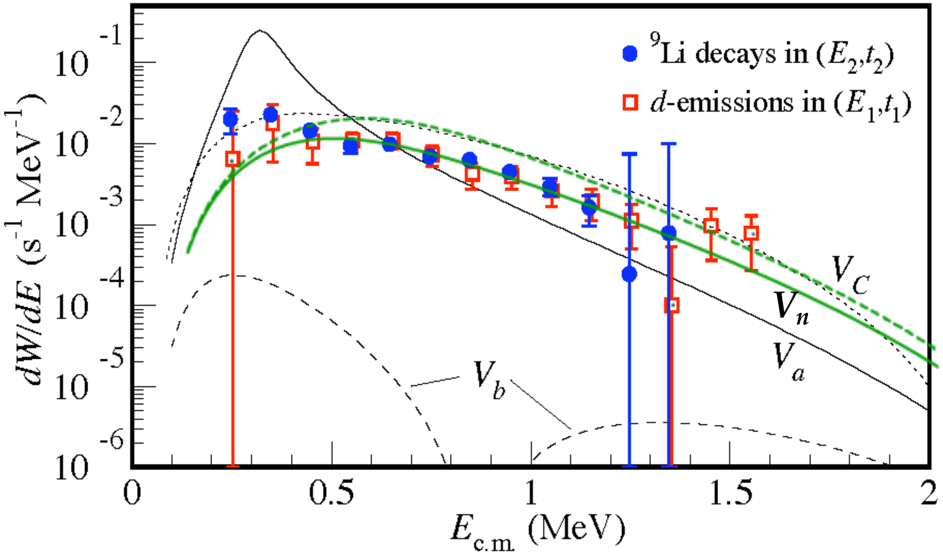
- Branching ratio:
  $1.30(13) \times 10^{-4}$ (E_{cm} > 200 keV)
- Calculations: optical potentials for 9Li+d

  V_c : ^{9}Li+d: Coulomb only (reference)
  M.V. Zhukov et al., PRC 52 (1995) 2461

  V_a : ^{9}Li+d resonance at 0.33 MeV
  V_b : ^{9}Li+d resonance at –0.18 MeV
  D. Baye, E. M. Tursunov, and P. Descouvemont, PRC 74 (2006) 064302

  V_n : ^{9}Li+d: broad resonance at 0.8 MeV (with weak absorption)
  E. M. Tursunov, D. Baye, and P. Descouvemont, IJMPE 20 (2011) 803

R.R. et al., PRL 101 (2008) 212501



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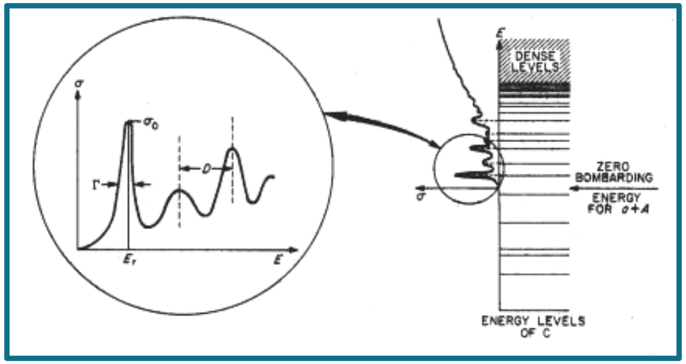
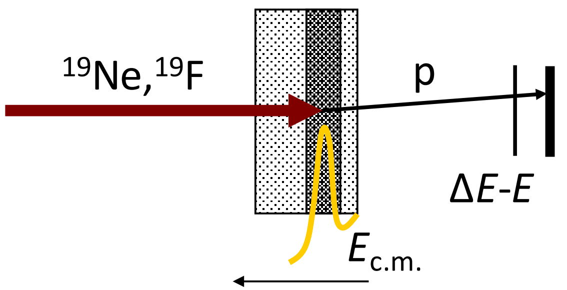
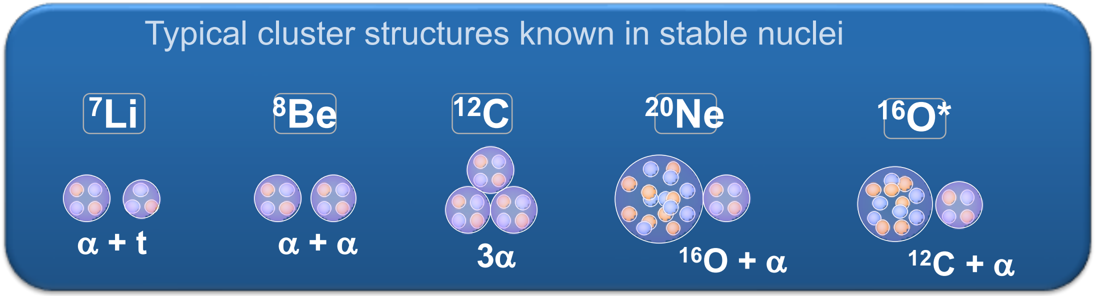
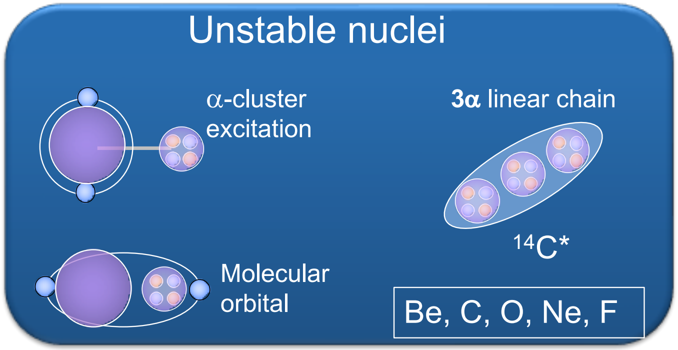
Reactions: resonant scattering

- Very well suited to study cluster structures (in unbound states)
- Important: measure spatial correlations
- With radioactive ion beams:
  inverse kinematics, detection at forward angles, energy loss of the beam in the target









Y. Kanada-En'yo, Varenna 2017

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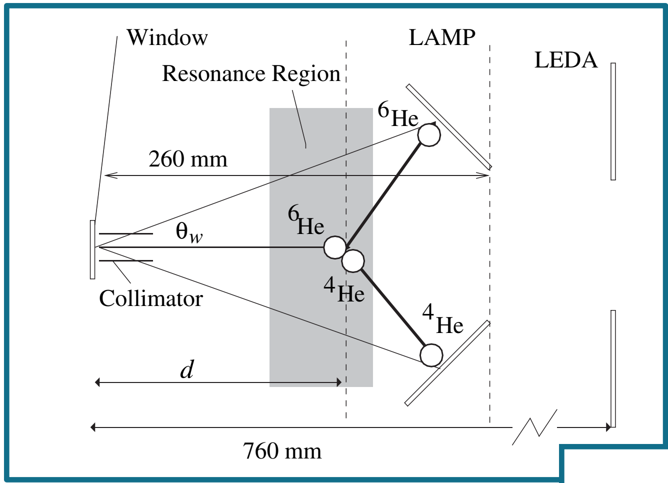
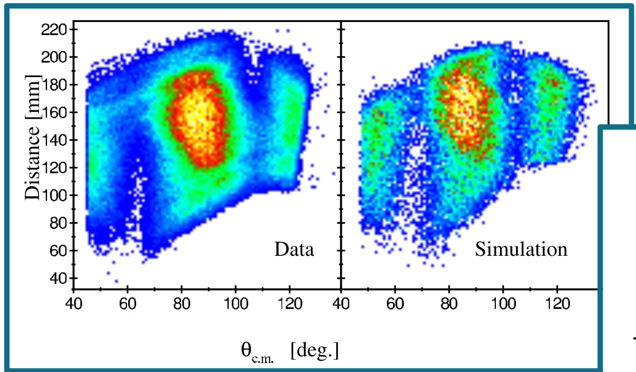
Molecular states in ^{10}Be

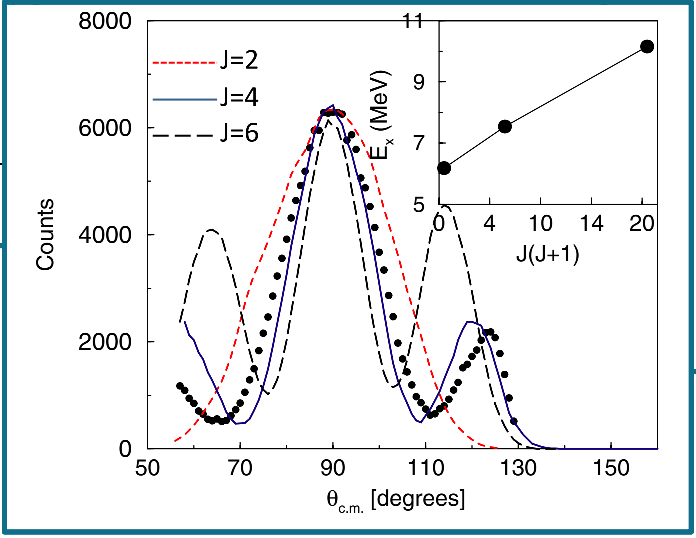
^{6}He + ^{4}He → ^{10}Be in LLN

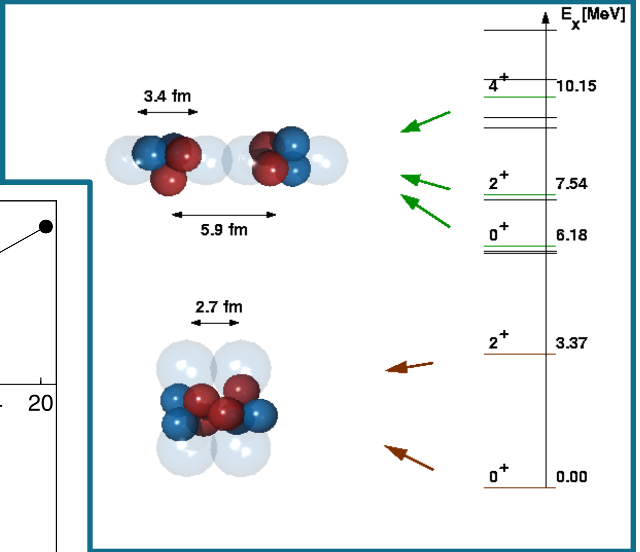
- Coincident detection in ^{4}He gas
- Measured spin, α spectroscopic factor
- "Dumbbell" structure confirmed



M. Freer et al,
PRL 96 (2006) 042501





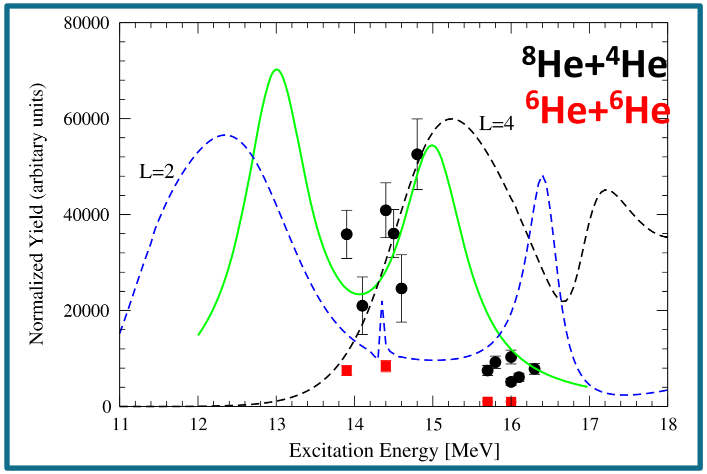


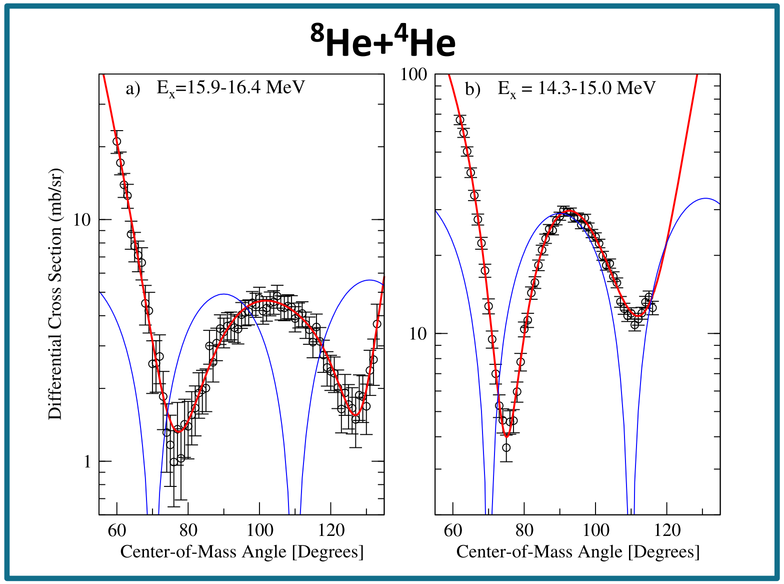
Cluster/Molecular states in ^{12}Be

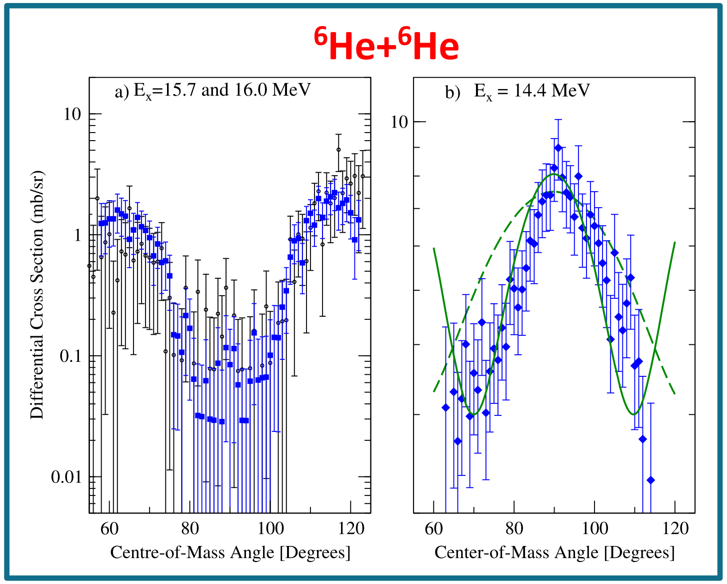
^{8}He + ^{4}He → ^{12}Be in GANIL

- Measured elastic channel and ^{6}He+^{6}He channel
- Possible *L*=4 resonance at *E**≈14-15 MeV
- Cluster/molecular structure predicted in this range

M. Freer et al, PLB 775 (2017) 58



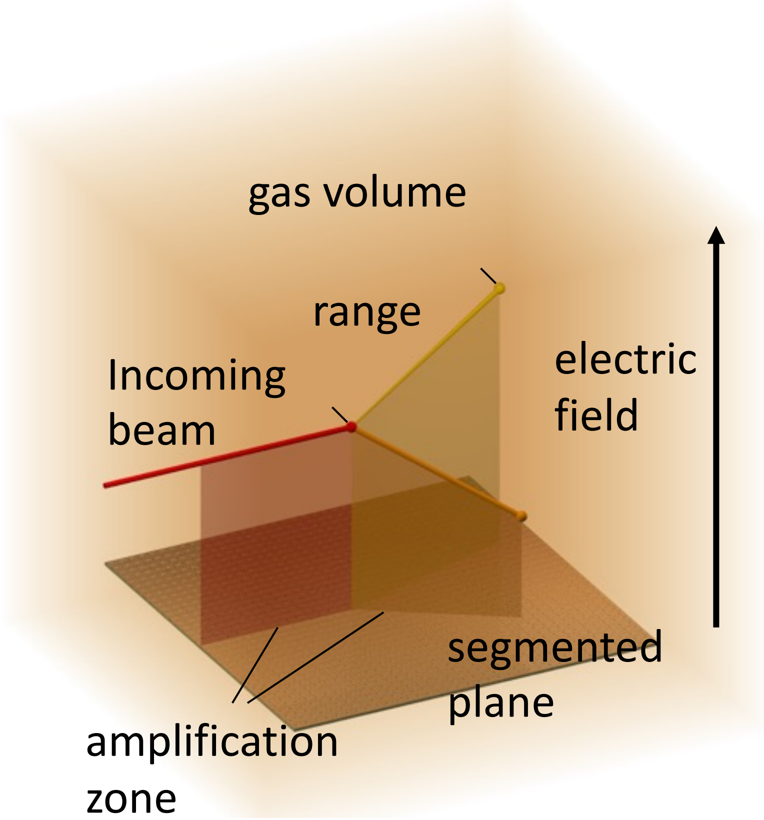




Active targets

Time-Projection Chamber (TPC)
+ gas is the target

- Electrons produced by ionization drift to an amplification zone
- Signals collected on a segmented "pad" plane ⇒ 2d-image of the track
- 3rd dimension from the drift time of the electrons
- Information:
  - angles
  - energy (from range or charge)
  - particle identification

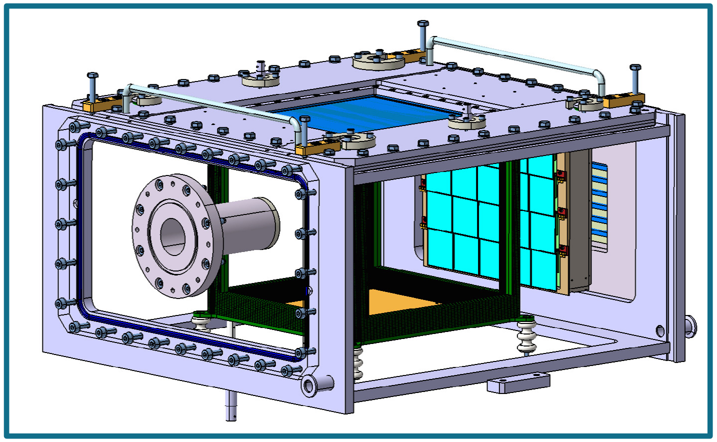


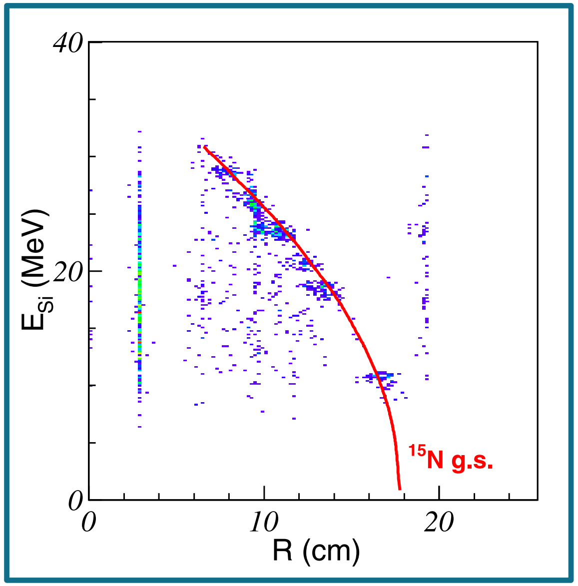
New frontiers with ACTAR TPC

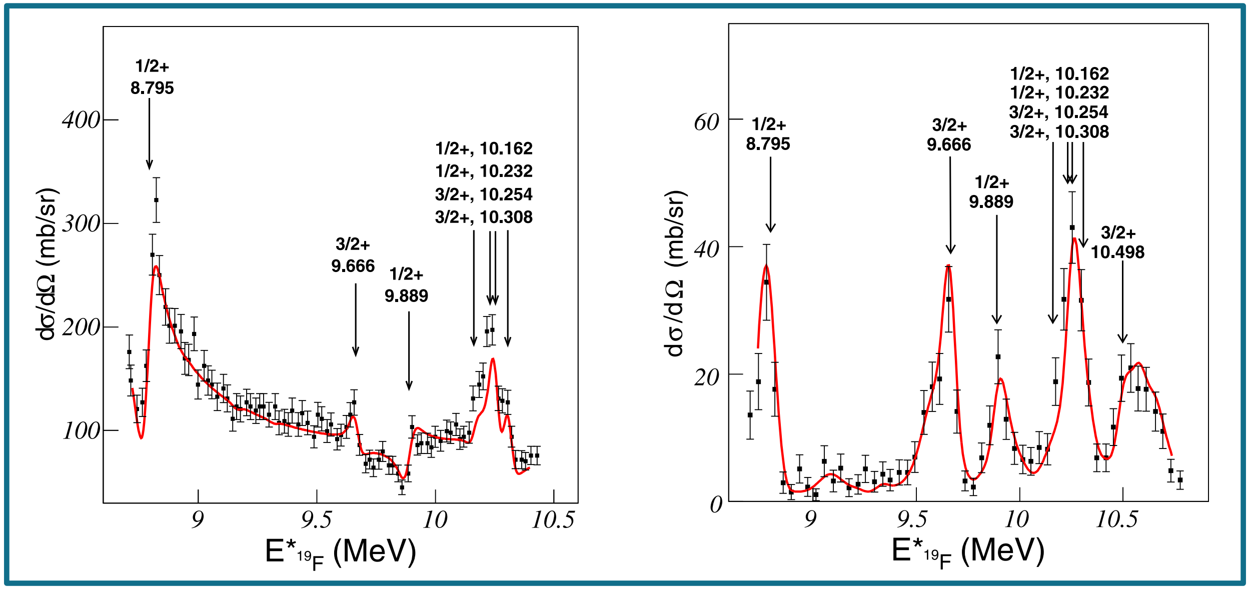
^{18}O + p in ACTAR TPC

- Micro-pattern gaseous detector: Micromegas
- High granularity of the pad plane → very good spatial resolution
- p and α channels measured Resolution 38 keV and 54 keV

B. Mauss et al, NIMA 940 (2019) 498





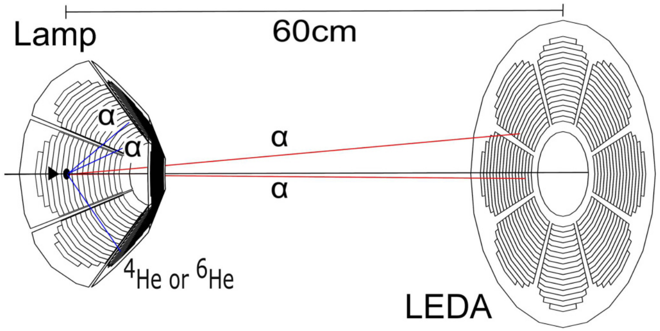


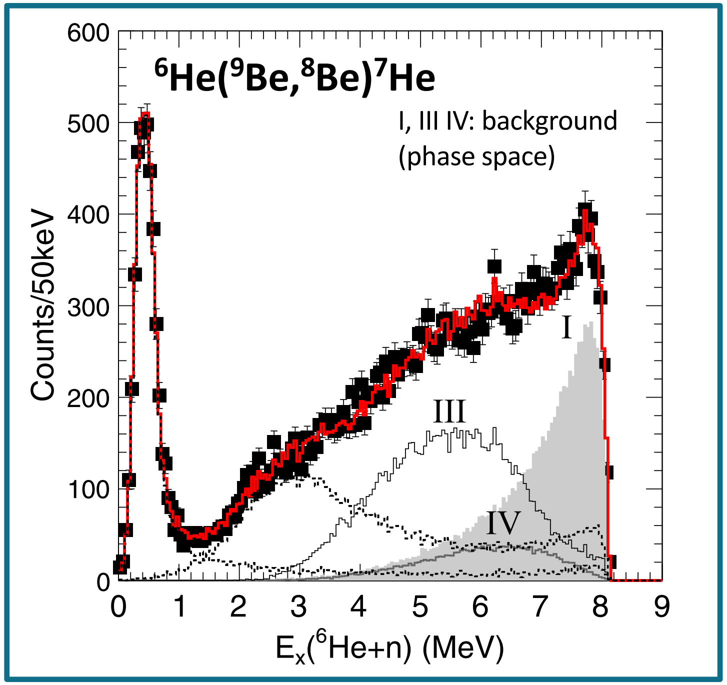
Transfer reactions: low-lying states in ^{7}He

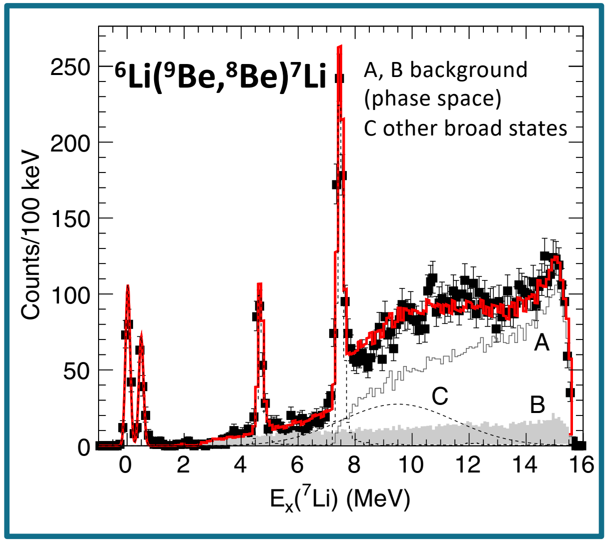
$^{6}He(^{9}Be,^{8}Be)^{7}He$ in LLN

F. Renzi et al, PRC 94 (2016) 024619

- Very clean identification from the characteristic $^{8}Be \rightarrow 2\alpha$ signal
- Identification of low-lying resonances in ^{7}He: First excited at ≈2.6 MeV







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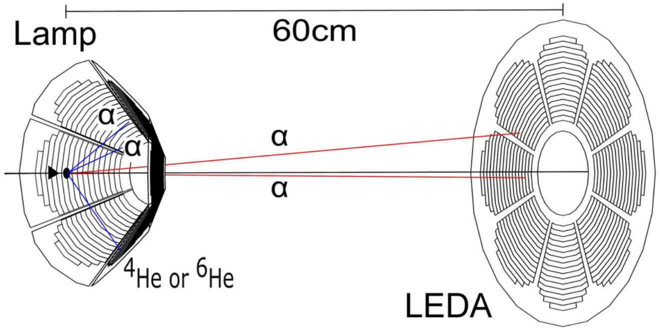

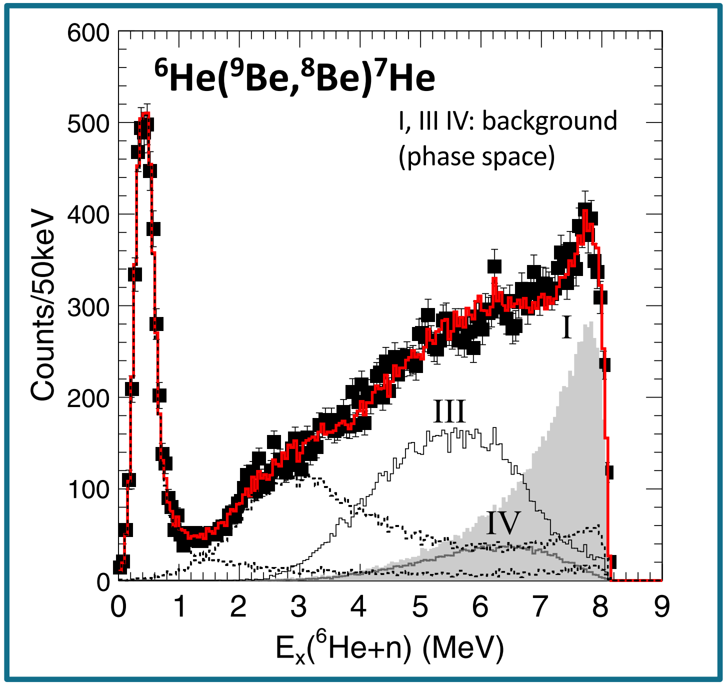

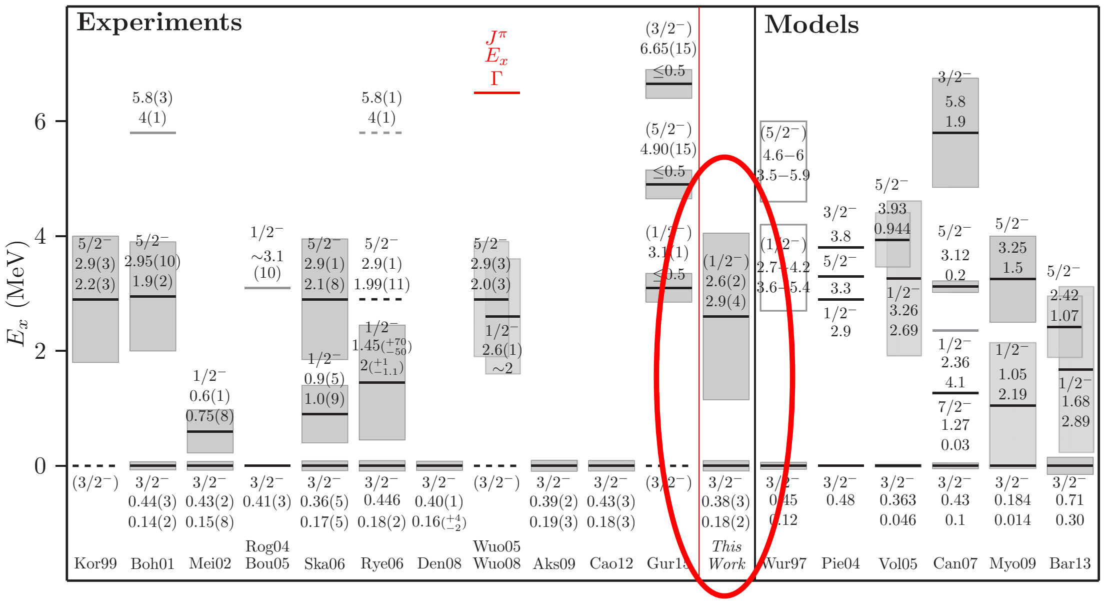

^{7}H in the Maya active target

$^{8}He + ^{12}C, ^{19}F$ in Maya at GANIL

M. Caamaño et al, PLB 829 (2022) 137067
M. Caamaño et al, PRL 99 (2007) 062502

- ^{8}He 15.4 MeV/nucleon onto He(90%)-CF_4(10%) gas at 176 mbar
- Detection of heavy recoil in the gas and ^{3}H (from ^{7}H decay) in Si+CsI detectors
- Energy of ^{7}H from Missing Mass+conditions
- **Peak at ≈0.7 MeV above $^{3}H+4n$, width ≈0.2 MeV**
- More than 200 events → angular distribution!