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

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

- Matrix element $\langle \Psi_f | V | \Psi_i \rangle$ contains <u>nuclear structure</u> and <u>interaction potential</u>
- 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!

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Exotic decay modes: β-delayed charged-particle emission

Decay of halo states

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





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: ⁶He, ¹¹Li, ¹¹Be, ⁸B, ¹²N, ¹²B, ¹⁶N



Pixelated Si detector (Leuven)



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

Decay into the continuum

- Small decay channel ($\approx 10^{-6}$) into α +d
- Measurement in Louvain-la-Neuve
 315 α+d decay events in ≈4 days
- Branching ratio:

1.65(10) x 10⁻⁶ ($E_{\rm c.m.} > 525 \text{ keV}$)

- 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: ¹¹Li \rightarrow ⁹Li + 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)x10⁻⁴ (E_{cm} > 200 keV)
- Calculations: optical potentials for 9Li+d
 - V_c: ⁹Li+d: Coulomb only (reference) M.V. Zhukov et al., PRC 52 (1995) 2461
 - V_a : ⁹Li+d resonance at 0.33 MeV V_b : ⁹Li+d resonance at -0.18 MeV D. Baye, E. M. Tursunov, and P. Descouvemont, PRC 74 (2006) 064302

V_n: ⁹Li+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)

nel radius R = 4.5 fm (this point will be discussed later

on), by means of the regular and irregular Coulomb wave

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functions. In Fig. 1, which presents a $^{19}Ne+p$ spectrum taken at 0°, the two prominent structures seen around $E_{\rm c.m.} \sim 800$ and 900 keV are broad resonances. The difference between the maximum and minimum cross sections around the resonance energy reflects the statistical weight factor $\omega = (2J+1)/(2I+1)(2i+1)(J, I, \text{ and } i \text{ are})$ the spins of the resonance, target, and projectile, respectively). A good fit to the data over the whole angular range was obtained with an angular momentum l = 0 for both resonances, and $\omega = \frac{3}{4}$ and $\frac{1}{4}$, respectively, indicating J^{π} values of 1^+ and 0^+ , respectively. The former J^{π} value could be reached by an l = 0 + 2 mixing in principle; adding an l = 2 component did not improve the fit. Figure 2 presents BW fits of the energy distributions at several angles. In order to estimate the importance of the experimental effects introduced in Sec. II B, pure BW calculations ($\Delta = 0$) and convoluted ones are compared

in Fig. 3. The *R*-matrix and *K*-matrix formalisms are detailed elsewhere [16,17]. Let us just recall here their main differences and their relation with the BW approximation. As long as the *R*-matrix parametrization is restricted to a single pole and the Thomas approximation is assumed (that the shift factor is a linear function of energy), there is no difference between this method and the extended

 $\frac{d\sigma}{d\Omega} \xrightarrow{\pi} \Theta_{L} = 0^{\circ} \xrightarrow{\Theta_{L} = 7^{\circ}} \Theta_{L} = 7^{\circ}$ $\frac{d\sigma}{400} \xrightarrow{J^{\pi}} = 1^{+} \xrightarrow{\pi} = 0^{+} \xrightarrow{\Phi_{L} = 16.3^{\circ}} \Theta_{L} = 10^{\circ}$ $\frac{d\sigma}{d\Omega} \xrightarrow{\Theta_{L} = 16.3^{\circ}} \Theta_{L} = 10^{\circ}$ $\frac{d\sigma}{d\Omega} \xrightarrow{\Theta_{L} = 32^{\circ}} \Theta_{L} = 13^{\circ}$

R. COSZACH et al.

BW formula. Note that the so-called "observed" width, and not the better known "formal" *R*-matrix width Γ_F , must be employed. The only difference with the BW formula comes from a nonlinearity in the energy dependence of the shift factor. The *R* matrix allows an introduction of further poles, either physical or simulating a background. Therefore, it offers the possibility of improving the description of off-resonance cross sections. In the limited energy range considered here, such refinements





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Molecular states in ¹⁰Be



Cluster/Molecular states in ¹²Be

⁸He + ⁴He \rightarrow ¹²Be in GANIL

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











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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



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Introduction

New frontiers with ACT

Decay Studies

(MeV)

¹⁸O + p in ACTAR TPC

- Micro-pattern gaseous detector
 Micromegas
- High granularity of the pad plan \rightarrow very good spatial resolution ρ_0
- p and α channels measured
 Resolution 38 keV and 54 keV







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Transfer reactions: low-lying states in ⁷He

⁶He(⁹Be,⁸Be)⁷He in LLN F. Renzi et al, PRC 94 (2016) 024619

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







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Transfer reactions: low-lying states in ⁷He

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⁷H in the Maya active target

⁸He + ¹²C,¹⁹F in Maya at GANIL

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

- ⁸He 15.4 MeV/nucleon onto He(90%)-CF₄(10%) gas at 176 mbar
- Detection of heavy recoil in the gas and ³H (from ⁷H decay) in Si+CsI detectors
- Energy of ⁷H from Missing Mass+conditions
- Peak at ≈0.7 MeV above ³H+4n, width ≈0.2 MeV
- More than 200 events → angular distribution!







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