Halo effects in the Scattering of $^{7}$Li on heavy targets at energies around the Coulomb barrier

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Halo Nuclei

**Common “Structural” properties**
- Rather inert core plus one or two barely unbound extra neutrons
- Extended neutron distribution, large “radius”.$\rightarrow$ “halo”
- Low binding energy
- Very few excited states –if any.

**Reaction properties at near-barrier energies:**
- Strong absorption in elastic channel
- Large cross section for fragmentation
- They are easily polarizable:
  - In the scattering process the forces between target and core/ halo are different $\rightarrow$ distortion effects $\rightarrow$ e.g. Coulomb dipole polarizability

Diagram: Direct Breakup \( { }^{208}\text{Pb} \), Transfer to the continuum, 1n-Transfer. Reaction: \( ^{11}\text{Li} \rightarrow \text{Borromean Halo} \).
Previous Study results on $^6$He (CRC@Louvain-la-Neuve)

- One channel calculations (---) unable to describe the scattering data
  
  - Coupling to the continuum needed (---):
    - Dipole polarizability
    - Nuclear { contribution
What did we learn from the $^6$He experiments?

- Long range absorption dominant in elastic scattering of $^6$He $\Rightarrow$ Suppress the rainbow in elastic cross sections.

- Long range absorption is produced by nuclear and Coulomb coupling to the continuum ($^4$He + 2n)

- Breakup mechanism is dominated by neutron transfer to the continuum

- Energy dependence in the optical potentials consistent with Threshold Anomaly

Do these features occur in other halo nuclei?
What makes $^7\text{Li}$ special

- $^7\text{Li}$ is the archetype of halo nuclei. Its structure is not yet fully known. Extremely weakly bound nucleus ($B_{\text{2n}} = 369.15(65)\text{ keV}$).

- Dipole polarizability:
  
  Huge E1 strength at low break-up energy.

- The elastic cross sections around the Coulomb barrier are sensitive to the B(E1) values close to the break-up threshold. A measurement of elastic scattering can confirm the presence of the large dipole polarizability.

- Reaction mechanisms and Nuclear effects of halo nuclei need to be understood. Elastic scattering and break-up effects should be described by means of scattering calculations that consider explicitly the coupling to the continuum.

Realistic 3-body calculation of $^7\text{Li}$ using an effective separation energy for the 2n-$^9\text{Li}$ system given by the experimental 2n binding energy, but this effective energy:

- Do not describe the B(E1) at low excitation energy
- RMS too large
- Non realistic model to describe $^7\text{Li}$ scattering

Zinser et al., NPA619(1997)151
Nakamura et al., PRL 96 (2006) 252502
Li elastic scattering around the Coulomb barrier

Coupled Channel calculations including Coulomb and nuclear coupling to the continuum states

- Strong reduction of the elastic cross section at forward angles associated to Coulomb dipole polarizability.
- Reduction of the cross sections at backward angles related to Coulomb and nuclear break-up.
- Arrows: experimental coverage planned, compromise between physics and statistics.
$^{11}\text{Li}$ break-up ($^{9}\text{Li}$ events)

Energy distribution for $^{9}\text{Li}$ in the transfer to the continuum mechanism at backward angles.
Experiment 1104 @ TRIUMF

- Measure the elastic scattering of $^{11}$Li on $^{208}$Pb at energies below and above the Coulomb barrier (≈ 27 MeV).
  - Energies chosen: 2.2 MeV/u = 24.2 MeV
    2.7 MeV/u = 29.7 MeV

- Measure the inclusive break-up cross section by detecting $^9$Li and α fragments.

- Compare with the elastic scattering of the core $^9$Li isotope measured with the same setup and the same central of mass energies.
  - $^9$Li on $^{208}$Pb at energies of 2.67 MeV/u and 3.27 MeV/u
  - For a more detailed knowledge of the potential describing the core system
    Extra measurement of $^9$Li at 3.27 MeV/u performed
Set-up for $^{11}\text{Li} \@ \text{SEBT2 at ISACII Hall}$
Set-up of $^{911}$Li

4 Telescopes

- $10^\circ-40^\circ$ 40 (16x16) +500 $\mu$m
- $30^\circ-60^\circ$ 40 (16x16) +500 $\mu$m
- $50^\circ-100^\circ$ 20(16)+60 (16x16) $\mu$m
- $90^\circ-140^\circ$ 20(16)+60 (16x16) $\mu$m
The Experiment 1104: Data Taken July & Oct 2008

The use of Square DSSSD complicate the analisis:
- Lack of cylindrical symmetry
- Allows to get much closer
- Use the existing 20 µm thick One side Si strip det.

- The full setup consisted of:
  - Angles: 10º-40º telescope of 40 µm (16x16 strips) + 500 µm E
  - Angles: 30º-60º telescope of 40 µm (16x16 strips) + 500 µm E
  - Angles: 50º-100º telescope of 20 µm (16 strips) + E of 60 µm(16x16)
  - Angles: 90º-140º telescope of 20 µm (16 strips) + E of 60 µm(16x16)
  - Downstream a Si-barrier monitor detector.

Total number electronic channels = 163 of energy and 128 of TDC signals.

- Beams used in the experiment:
  - Stable beams of $^3$Ne,$^{18}$O and $^2$Ne.
  - $^9$Li @ 2.67 MeV/u, target $^{208}$Pb of 1.45 mg/cm$^2$ during 11h 45 min.
  - $^9$Li @ 3.27 MeV/u, target $^{208}$Pb of 1.45 mg/cm$^2$ during 7h 35 min.
  - $^9$Li @ 3.27 MeV/u, target $^{208}$Pb of 1.90 mg/cm$^2$ during 17h 38 min.
  - $^9$Li @ 3.67 MeV/u, target $^{208}$Pb of 1.90 mg/cm$^2$ during 23h 30 min.

- $^{11}$Li @ 2.2 MeV/u, target $^{208}$Pb of 1.45 mg/cm2 during 82h.
- $^{11}$Li @ 2.7 MeV/u, target $^{208}$Pb of 1.45 mg/cm2 during 119h.

Up to 7000 $^{11}$Li/s!!
Average 5000/s!!
$^9$Li & $^{11}$Li data for the same CM energy, below Coulomb barrier / Detector 1

Conditions:

$|E_f - E_b| \leq 70$ keV (dynamic choice)

$\Sigma$ Pixels (3x3mm$^2$)
Li & Li data for the same CM energy, above Coulomb barrier

Conditions:
\[ |E_f - E_b| \leq 70 \text{ keV (dynamic choice)} \]
\[ \sum \text{ Pixels (3x3 mm}^2) \]
$^9$Li & $^{11}$Li data for the same CM energy, below Coulomb barrier / Detector 2

Clear separation of the elastic and the inclusive $^9$Li breakup
Theoretical Approach

- Two choices for the Optical Model

- C1 ($^9$Be$+^{208}$Pb): $V_b \approx 27.5$ MeV
  
  Woolliscroft et al, PRC68 (2003) 014611

- C3 ($^7$Li$+^{208}$Pb): $V_b \approx 28.5$ MeV

\[ ^9 \text{Li} + ^{208} \text{Pb} @ E_{lab} = 29.5 \text{ MeV} \]

-Above the barrier deviation from Rutherford at angles larger than 75°

-C1, the imaginary part of the optical potential has long range

Cross section divided by Rutherford do not show any rainbow, while the OM C3 thus show it!!.
Comparison of Theory and Data from $^9$Li

$^9$Li+$^{208}$Pb @ 24 MeV

- $^9$Li is a “normal nucleus” well describe by the optical model.
- Following Rutherford for energies below the barrier in the full angular range.
- For energies above the barrier deviations expected of the OM versus Rutherford at large polar angles, beyond 100º.

$^9$Li+$^{208}$Pb @ 29.5 MeV

- Preliminary!
The Comparison of the breakup/elastic cross sections allows to decide which of the 3-body model of $^{11}\text{Li}$ is more realistic.
Tunning of the Calculations to reproduce the data. Good agreement for energies below and above the barrier for the binding energy of the di-neutron.

$^{11}\text{Li} + ^{208}\text{Pb} @ \text{TRIUMF}$

$E_{\text{lab}} = 29$ MeV
The energy distribution of the breakup products indicates that the dominant process at forward angle is DIRECT BREAK UP.

- Comparison of data without dead-layers correction
- CDCC calculation using $\varepsilon_b = 0.46$ MeV.

→ Shows kinematic value for 9/11 of $E_{rc}$
A linear behaviour of \( \ln \left( \frac{\sigma_b}{\sigma_d} \right) \) versus \( r_{\text{min}} \) indicates in a semi-classical approach that the dominant interaction at large distance is the Dipole interaction.

\[
T_{\text{adison}} \propto r_{\text{min}}
\]

- The slope is proportional to the excitation energy of the relevant states of the system (\(^9\text{Li} + 2\text{n}\)).
- Small slope \( \Rightarrow \) relevance of states of low excitation energy.
- The value of \( \ln \left( \frac{\sigma_b}{\sigma_d} \right) \) at a certain \( r_{\text{min}} \) is related to the B(E1) to the relevant BU states.

Which states of the \(^9\text{Li}+2\text{n}\) continuum are explored?
B(E1) Values

Realistic 3-body calculation of $^7$Li using an effective separation energy for the 2n-$^9$Li system.

Black line: Relative energy = $S_{2n}$
Over estimate

B(E1)
The square mass radius

Redline: improved 3-body model to reproduce the density probability and square mass radius of the ground state of $^7$Li.

Gives a good account of the B(E1) and of our scattering data.

Zinser et al, NPA619(1997)151
Nakamura et al., PRL 96 (2006) 252502
Summary & outlook

Physics learned so far

- $^9$Li: alpha reaction channel is very strong, even at subbarrier energies and forward angles.
- $^9$Li: Accurate elastic differential cross sections will be obtained. $^9$Li+$^{208}$Pb Optical potential can be determined.
- $^{11}$Li: Strong break-up is seen at forward angles (coulomb break-up)
- $^{11}$Li: Strong reduction of elastic cross sections at forward angles, below and above the coulomb barrier, is seen.

- Halo effect in $^{11}$Li has been seen, and is stronger than expected
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$E = 2.2 \text{ MeV/u}$

$\theta_{\text{lab}} = (12^\circ - 60^\circ)$

- Black line: CDCC
- Green line: T2 ($\theta_L = 12^\circ - 40^\circ$)
- Blue line: T2 ($\theta_L = 32^\circ - 60^\circ$)

$E = 2.7 \text{ MeV/u}$

$d\sigma/dE$ (mb/MeV) vs. $E_{\text{lab}}(\beta\text{Li})$ (MeV)
- Two choices for the Optical Model

- $C_1$ ($^9$Be$^{+208}$Pb): $V_b \sim 27.5$ MeV
- $C_3$ ($^7$Li$^{+208}$Pb): $V_b \sim 28.5$ MeV

$-V_{\text{eff}}(r) = V_{\text{coul}}(r) + W_{\text{nuc}}(r)$

$^9$Li$^{+209}$Pb effective potential

- The $C_3$ has real part positive because the potential is very shallow about 13.7 MeV.
- But both potentials have the same behaviour in the tail.
- This is the sensitive part in reactions at low energy.

- $C_1$, the imaginary part of the optical potential has long range. This explains that the cross section divided by Rutherford do not show any rainbow, while the OM $C_3$ thus show it.
$^9$Li @ 2.67 MeV/u @ 1.43 mg/cm² $^{208}$Pb
RESULTS on $^{11}$Be

Elastic Xsections
- Strong absorption effect.
- CDCC (solid line) follow the trend of the data

`Breakup probability` (Nbu/Nqe) →
- Large yields
- CDCC results consistent with the trend of the data
- Do not fully account for the experimental results
- Energy distribution shows possible component due to other reaction channels

→ transfer to continuum should be investigated

PRELIMINARY RESULTS SUGGEST A COMPETITION BETWEEN DBU + TC (possibly) AT FORWARD ANGLES
What did we learn from the $^6$He experiments?

- Long range absorption dominant in elastic scattering of $^6$He ⇒ Suppress the rainbow in elastic cross sections.
- Long range absorption is produced by nuclear and Coulomb coupling to the continuum ($^4$He + 2n)
- Breakup mechanism is dominated by neutron transfer to the continuum
- Energy dependence in the optical potentials consistent with Threshold Anomaly

Do these features occur in other halo nuclei?
Break-up data: $^6\text{He} + ^{208}\text{Pb} @ 22 \text{ MeV}$

Angular distribution of elastic and break-up event at backward angles

- $\alpha$-particles from $^6\text{He}$ break-up carry large fraction of the energy
- Neutrons are transferred to low energy continuum states in the target
Direct Breakup

Transfer to the continuum

1n-Transfer