Understanding the scattering of ^{6}He and ^{11}Li at energies around the Coulomb barrier.

Antonio M. Moro

University of Seville (Spain)

On behalf of the E-1104 Collaboration:
U. Sevilla , IEM-CSIC (Madrid), U. Lisboa, Chalmers, U. Huelva, U. York,
U. Aarhus, TRIUMF

Outline

1. Motivation of the experiment.
2. ^{6}He+^{208}Pb at LLN.
3. The ^{11}Li+^{208}Pb experiment at TRIUMF.
   - Experimental setup
   - Comparison with semiclassical and CDCC calculations
   - Scaling in breakup probability for Coulomb dominated reactions.
4. Conclusions and forthcoming projects

How does a weakly bound nucleus behaves in the field of a heavy target?

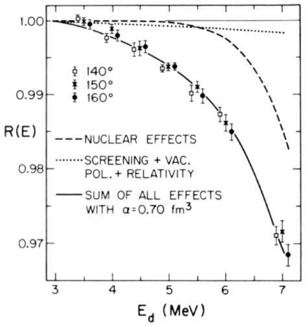
1. The strong Coulomb field will produce a polarization ("stretching") of the projectile, giving rise to a dipole contribution on the real potential:

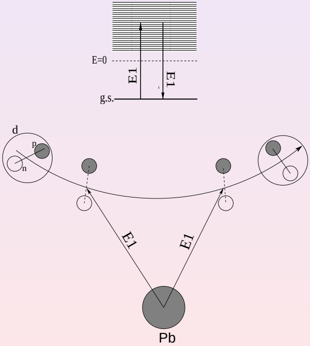
$$V_{\mathrm{dip}} \approx -\alpha \frac{Z_1 Z_2 e^2}{2R^4}$$

2. The weakly bound nucleus can eventually break up, leading to a loss of flux of the elastic channel ⇒ imaginary polarization potential.

Eg: deuteron polarizability from d+^{208}Pb:

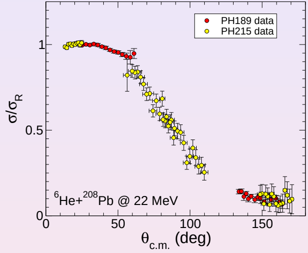
☞ Adiabatic limit ($E_x \gg$): $V_{\rm dip} = -\alpha \frac{Z_1 Z_2 e^2}{2R^4}$





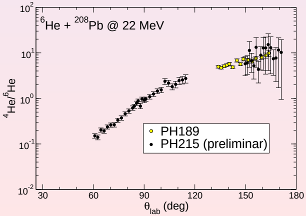
Rodning et al, PRL49, 909 (1982) ⇒ $\alpha = 0.70 \pm 0.05$ fm^3

The ^{6}He+^{208}Pb experiments at LLN



ELASTIC

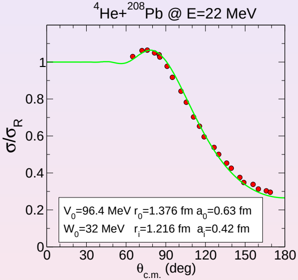
- Significant deviation from Rutherford.
- Suppression of Fresnel peak.
- Expected strong Coulomb and nuclear couplings.

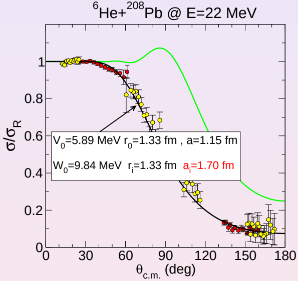


INCLUSIVE BREAKUP

- Large α yield
- $E_\alpha \approx E_{^6\mathrm{He}}$
  (suggests a transfer-like mechanism)

How does the halo structure affect the elastic scattering?

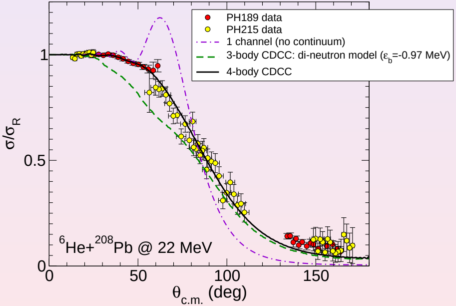


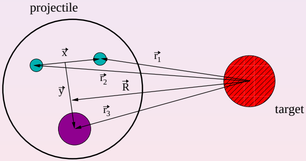


- ^{4}He+^{208}Pb: typical Fresnel pattern well reproduced by a “standard” optical potential $\Rightarrow$ *strong absorption*
- ^{6}He+^{208}Pb: requires optical potentials with a very large diffuseness parameter ($a_i \approx 2$ fm). $\Rightarrow$ *long-range absorption*

Four-body CDCC calculations for ^{6}He+^{208}Pb

Elastic scattering can be explained by 4-body CDCC calculations, but not by “simple” 3-body CDCC calculations.

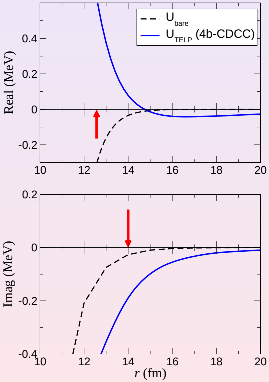




M. Rodríguez-Gallardo et al, Phys.Rev. C 77, 064609 (2008); Phys.Rev. C 80, 051601 (2009)

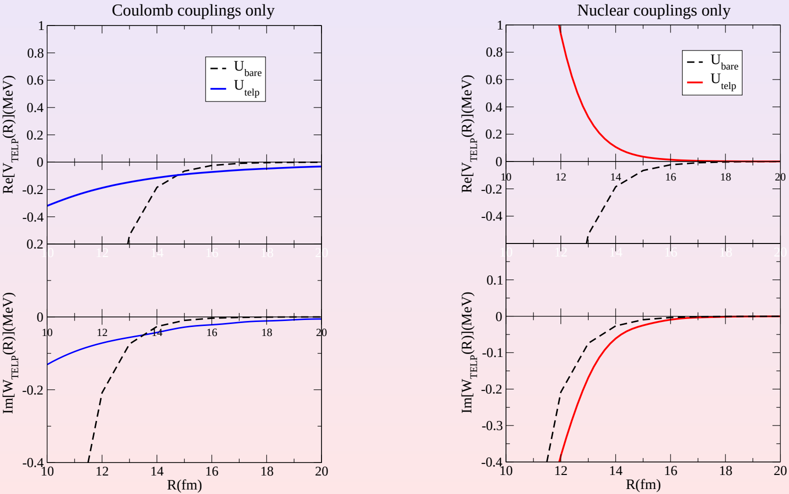
Trivial equivalent local polarization potential

CDCC solution $\Rightarrow U_{\rm eff}(r) = U_{\rm bare}(r) + U_{\rm TELP}(r)$



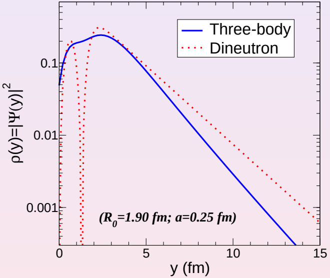
☞$U_{\rm TELP}$ exhibits the expected long-range attractive real part and absorptive imaginary part.

Trivial equivalent local polarization potential



The dineutron model for ^{6}He revisited

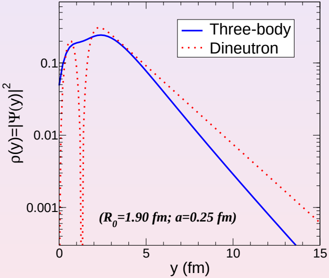
Density distribution for α-2n relative motion:

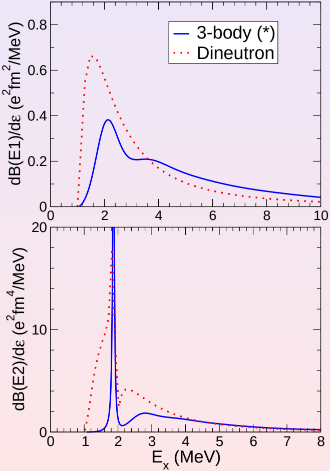


- 3-body: $\langle r_{\alpha-2\mathrm{n}} \rangle = 3.25$ fm
- 2-body: $\langle r_{\alpha-2\mathrm{n}} \rangle = 4.10$ fm

The dineutron model for ^{6}He revisited

Density distribution for α-2n relative motion:

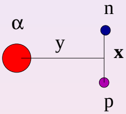




- 3-body: $\langle r_{\alpha-2n} \rangle = 3.25$ fm
- 2-body: $\langle r_{\alpha-2n} \rangle = 4.10$ fm

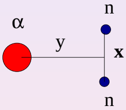
An improved dineutron model for ^{6}He

^{6}Li



- ^{6}Li=α + d
- $\varepsilon_{\alpha-d} = -1.47$ MeV
- $\varepsilon_{n-p} = \varepsilon_{d} = -2.22$ MeV

^{6}He

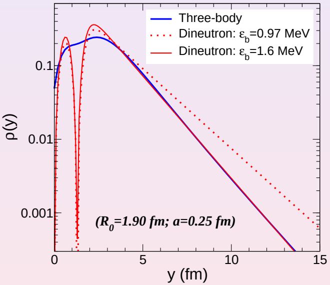


- ^{6}He=α + ^{2}n
- $\varepsilon_{\alpha-2n} = S_{2n} = -0.97$ MeV
- $\varepsilon_{n-n} \sim 0$?

In reality, we expect $\varepsilon_{n-n} > 0$

An improved dineutron model for ^{6}He

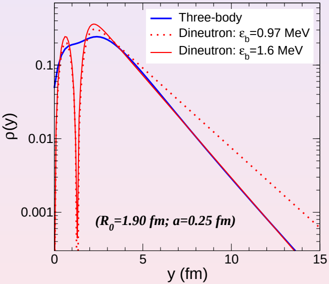
Define an effective α*-2n relative energy*: $\varepsilon_{2n-\alpha} \simeq -1.6$ MeV

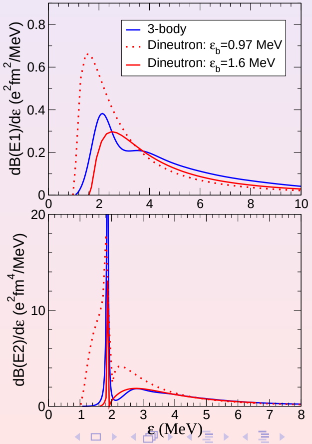


- 3-body: $\langle r_{\alpha-2n} \rangle = 3.25$ fm
- 2-body: $\langle r_{\alpha-2n} \rangle = 3.45$ fm

An improved dineutron model for ^{6}He

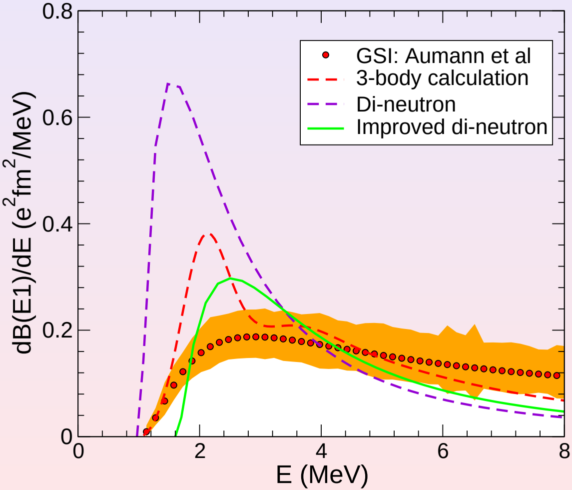
Define an effective α-2n relative energy: $\varepsilon_{2n-\alpha} \simeq -1.6$ MeV





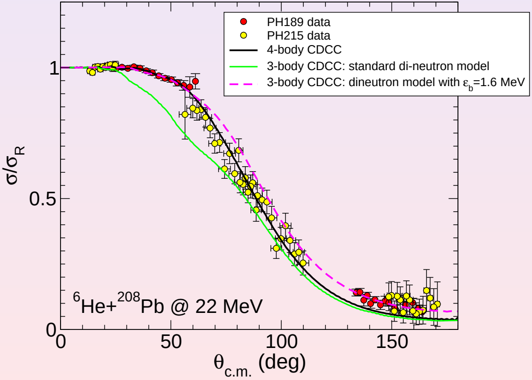
- 3-body: $\langle r_{\alpha-2n}\rangle = 3.25$ fm
- 2-body: $\langle r_{\alpha-2n}\rangle = 3.45$ fm

Theoretical vs experimental B(E1) distributions for ^{6}He

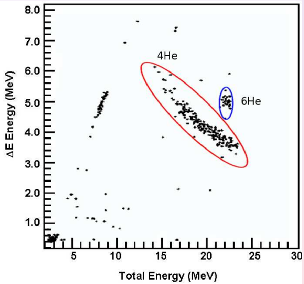


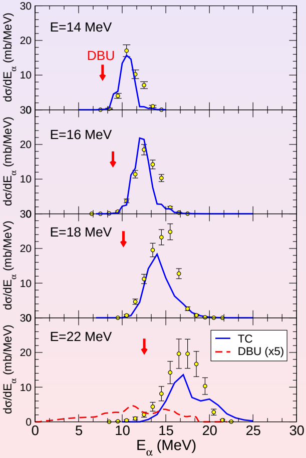
^{6}He+^{208}Pb at LLN: elastic scattering

CDCC calculations based on the “improved” dineutron model reproduce well the data:



^{6}He+^{208}Pb at LLN: α production channel



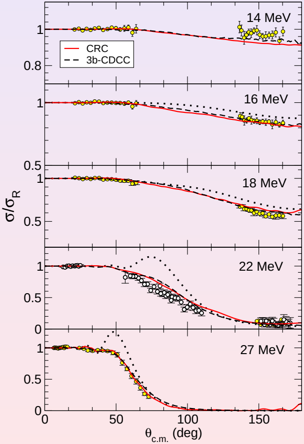


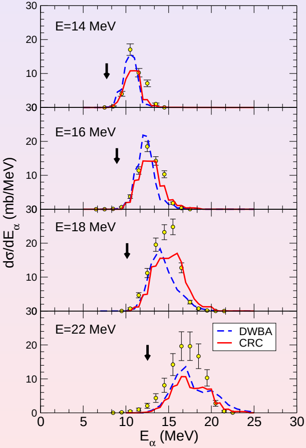
^{6}He+^{208}Pb at LLN: CRC calculations

- CDCC calculations reproduce the elastic scattering, and hence the long-range absorption effect, but not the α channel.
- TC calculations (2n-transfer) reproduce the α channel.

Can the 2n-transfer channel explain also the long-range absorption effect on the elastic channel?

^{6}He+^{208}Pb at LLN: CRC calculations

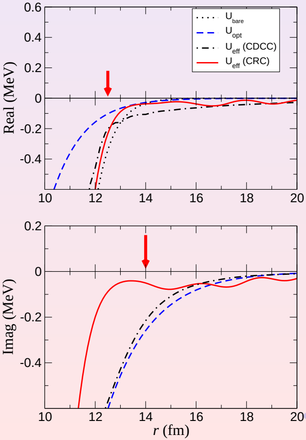




^{6}He+^{208}Pb at LLN: trivial polarization potential

From the CDCC or CRC calculations we determine the TELP, sucht that:

$$U_{\text{eff}}(R) = U_{\text{bare}}(R) + U_{\text{TELP}}$$



Motivation of the ^{11}Li+^{208}Pb experiment

- ^{11}Li weakly bound ($S_{2n} = 378$ keV) $\Rightarrow$ expected interesting phenomena:
  - Strong polarization due to Coulomb and nuclear fields.
  - Predicted significant departure from Rutherford scattering, even below the barrier.
- Large $B(E1)$ at low excitation energy:

  ☞ *Indirect tool to extract information on the $B(E1)$.*
- 3-body Borromean structure $\Rightarrow$ complicated 4-body problem not yet fully understood.

The ^{11}Li+^{208}Pb experiment @ TRIUMF

- Experiment performed at the ISAC-II facility (2008)
- RIB beams around the Coulomb barrier ($V_b \sim 28$ MeV):

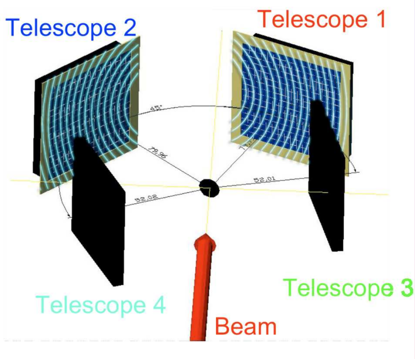
Beam	**Energy (MeV)**	**Pb target**	**Intensity**
^{9}Li	24.0	1.45 mg/cm^2	$\sim 10^5$ pps
	29.4	1.45, 1.90 mg/cm^2	
	33.0	1.90 mg/cm^2	
^{11}Li	24.2 , 29.4	1.45 mg/cm^2	4300 pps

- Inclusive measurements (only charged fragments detected).

Experimental setup

☞ 4 DSSSD telescopes

- T1: (10°-40°)
- T2: (30°-60°)
- T3: (50°-100°)
- T4: (90°-140°)

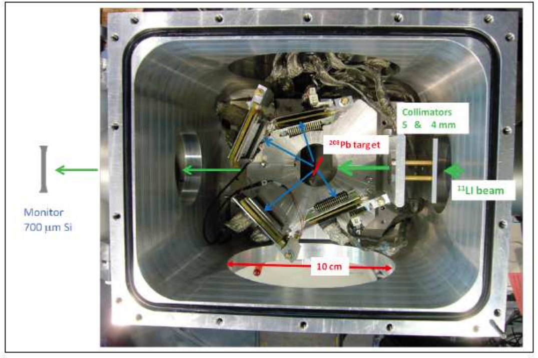


☞ Pixeled detectors. Good angular resolution but difficult analysis.

Experimental setup

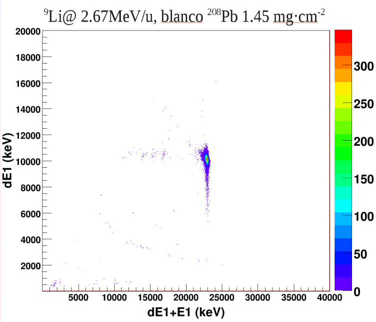
☞ 4 DSSSD telescopes

- T1: (10°-40°)
- T2: (30°-60°)
- T3: (50°-100°)
- T4: (90°-140°)



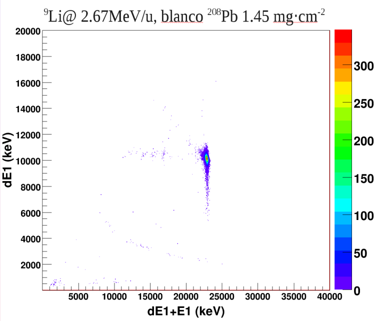
☞ Pixeled detectors. Good angular resolution but difficult analysis.

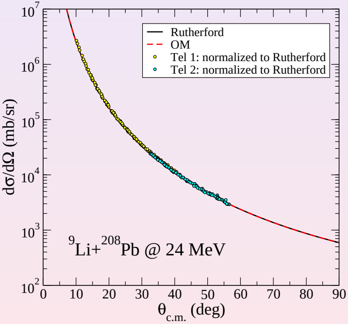
Particle identification for ^{9}Li+^{208}Pb @ 24 MeV



☞ Only elastic group observed

Particle identification for ^{9}Li+^{208}Pb @ 24 MeV



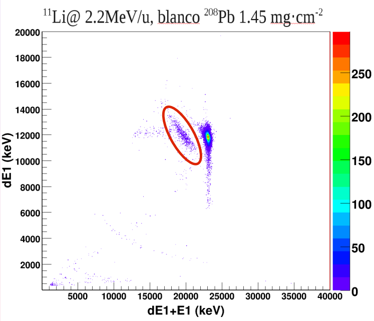


☞ Only elastic group observed

☞ Follows Rutherford formula

Particle identification for ^{11}Li+^{208}Pb @ 24 MeV

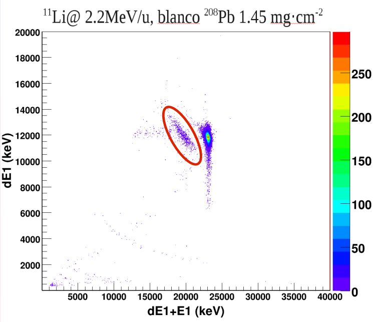
$$\Delta E \propto \frac{mZ^2}{\Delta E + E}\Delta x = \frac{2Z^2}{v^2}\Delta x$$

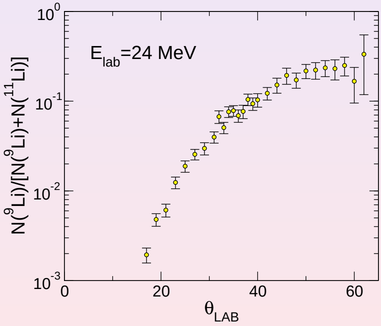


☞ ^{9}Li group with $v_{^9\mathrm{Li}} \approx v_{^{11}\mathrm{Li}}$ ($E_{^9\mathrm{Li}} \approx \frac{9}{11}E_{^{11}\mathrm{Li}}$)

Particle identification for ^{11}Li+^{208}Pb @ 24 MeV

$$\Delta E \propto \frac{mZ^2}{\Delta E + E}\Delta x = \frac{2Z^2}{v^2}\Delta x$$





☞ ^{9}Li group with $v_{^9\text{Li}} \approx v_{^{11}\text{Li}}$ $(E_{^9\text{Li}} \approx \frac{9}{11} E_{^{11}\text{Li}})$

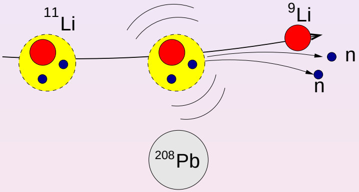
☞ Large ^{9}Li yield, even below the barrier!

What can we learn from the ^{11}Li data?

- What is the reaction mechanism responsible for the production of ^{9}Li?
- Can we relate the measured breakup observables to some property of the structure of ^{11}Li?

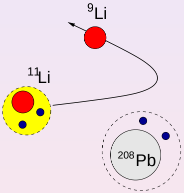
Direct breakup vs transfer models

DIRECT BREAKUP



$$v_{^9\text{Li}} \approx v_{^{11}\text{Li}} \Rightarrow E_{^9\text{Li}} \approx \frac{9}{11} E_{^{11}\text{Li}}$$

2n TRANSFER



$$E_{^9\text{Li}} \approx E_{^{11}\text{Li}}$$

☞ *Present data consistent with a direct breakup mechanism.*

Theoretical frameworks for direct breakup

1. 1^{st} order semiclassical Coulomb excitation.
    - Only $E1$ excitation.
    - Neglect higher order effects.
    - Numerically simple.
2. Continuum-Discretized Coupled-Channels (CDCC) method:
    - Includes both nuclear and Coulomb to all orders.
    - Includes $\lambda \neq 1$ excitations
    - Numerically demanding.

☞ *Both methods require a structure model for ^{11}Li.*

Theoretical frameworks for direct breakup

1. 1^{st} order semiclassical Coulomb excitation.
    - Only $E1$ excitation.
    - Neglect higher order effects.
    - Numerically simple.
2. Continuum-Discretized Coupled-Channels (CDCC) method:
    - Includes both nuclear and Coulomb to all orders.
    - Includes $\lambda \neq 1$ excitations
    - Numerically demanding.

☞ *Both methods require a structure model for ^{11}Li.*

Theoretical frameworks for direct breakup

1. 1^{st} order semiclassical Coulomb excitation.
    - Only $E1$ excitation.
    - Neglect higher order effects.
    - Numerically simple.
2. Continuum-Discretized Coupled-Channels (CDCC) method:
    - Includes both nuclear and Coulomb to all orders.
    - Includes $\lambda \neq 1$ excitations
    - Numerically demanding.

☞ *Both methods require a structure model for* ^{11}*Li.*

Breakup probability in a semiclassical approach

First order (dipole) Coulomb excitation probability:

$$\boxed{P_{\rm bu}(\theta) = \frac{\pi}{9}\left(\frac{Ze}{\hbar v a_0}\right)^2 \int d\varepsilon \frac{dB(E1)}{d\varepsilon} f_{\rm E1}(\xi,\varepsilon)}$$

- $f_{\rm E1}(\xi,\varepsilon)$ analytical function given by Alder and Winther theory of Coulomb excitation.
- The structure of ^{11}Li enters through the $B(E1)$ distribution.

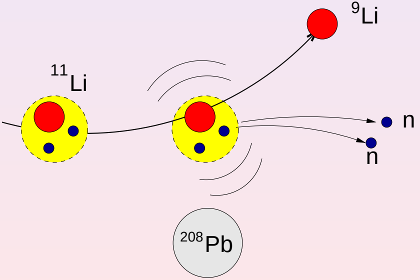
CDCC calculations

- Breakup treated as coupling due to nuclear and Coulomb couplings to 3-body continuum (^{9}Li+n+n)
- Requires a 4-body CDCC calculation. Available for ^{6}He scattering but not yet for ^{11}Li:
  - Pauli blocking in both *s* and *p* orbitals.
  - Smaller binding energy ⇒ stronger continuum couplings.
  - Core excitation is expected to be more important.
- At this stage, a simple di-neutron model can provide a first useful insight on the data (3-body CDCC)

^{11}Li+^{208}Pb using a di-neutron model

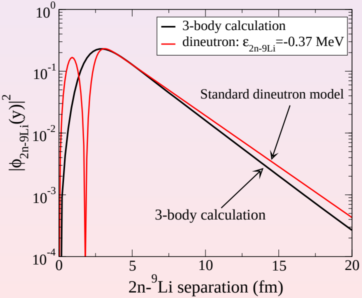
Justification:

- the strong Coulomb force tends to act mainly on the 2n-^{9}Li degree of freedom.



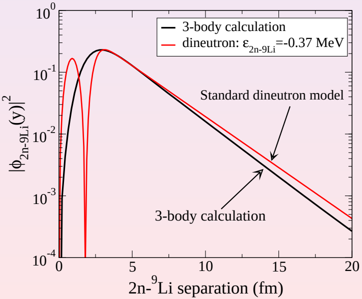
Standard di-neutron model for ^{11}Li

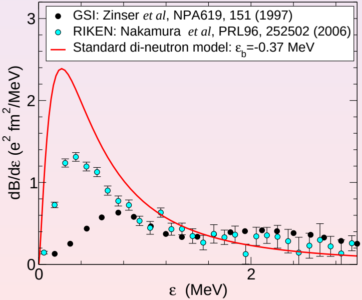
- Ignore *n*-*n* dynamics.
- 2n-^{9}Li motion in 2S configuration in ^{11}Li g.s.
- Assume $\varepsilon_{2\mathrm{n}-^{9}\mathrm{Li}} = -|S_{2n}| =$-0.378 MeV $\Rightarrow \varepsilon_{\mathrm{n-n}} = 0$!!



Standard di-neutron model for ^{11}Li

- Ignore *n*-*n* dynamics.
- 2n-^{9}Li motion in 2S configuration in ^{11}Li g.s.
- Assume $\varepsilon_{2\mathrm{n}-^{9}\mathrm{Li}} = -|S_{2n}|$ =-0.378 MeV $\Rightarrow \varepsilon_{\mathrm{n}-\mathrm{n}} = 0$!!

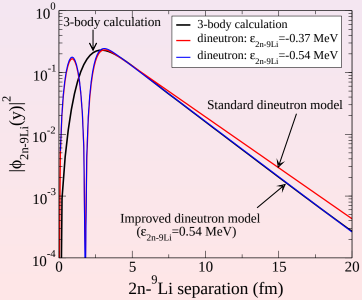


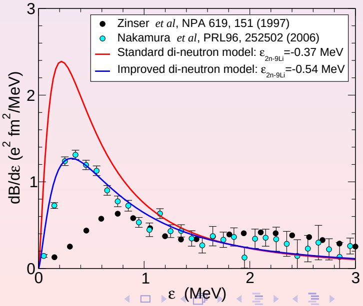


An improved di-neutron model

- Also neglect *n-n* degree of freedom.
- Define an effective $\varepsilon_{2n-{}^9\mathrm{Li}}$ in order to reproduce the g.s. rms.

☞ $\varepsilon_{2n-{}^9\mathrm{Li}} \simeq -0.54$ MeV $\xrightarrow{?}$ $\varepsilon_{n-n} \approx 0.2$ MeV

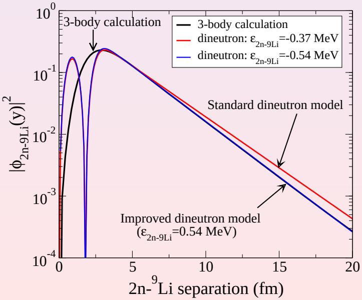


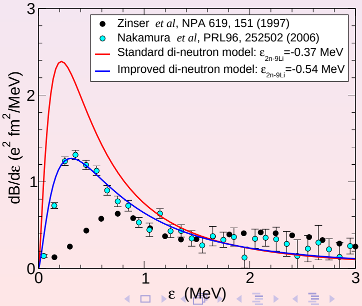


An improved di-neutron model

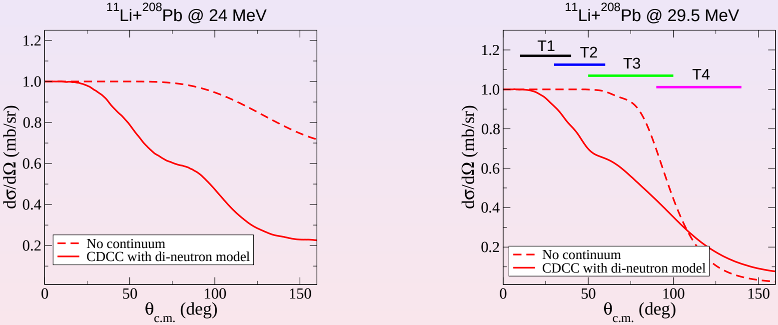
- Also neglect *n-n* degree of freedom.
- Define an effective $\varepsilon_{2\mathrm{n}-{}^9\mathrm{Li}}$ in order to reproduce the g.s. rms.

☞ $\varepsilon_{2\mathrm{n}-{}^9\mathrm{Li}} \simeq -0.54$ MeV $\xrightarrow{?}$ $\varepsilon_{\mathrm{n}-\mathrm{n}} \approx 0.2$ MeV



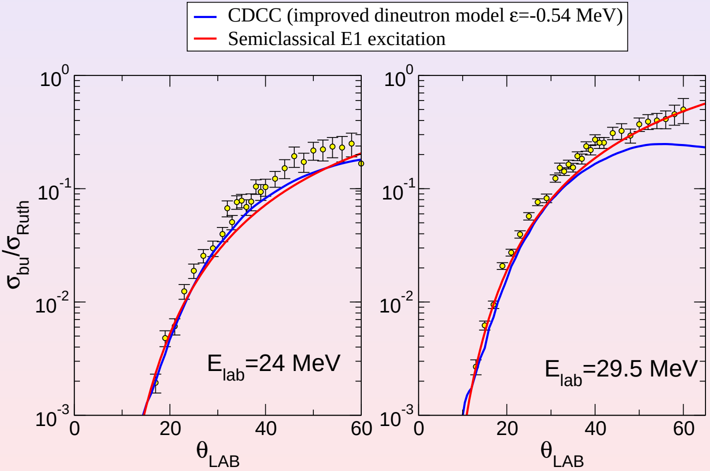


Elastic scattering

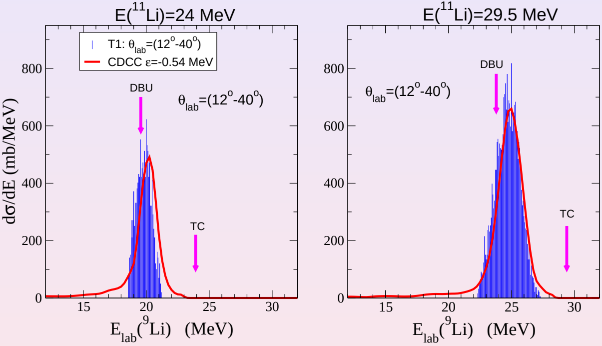


- 3-body CDCC calculations predict large reduction with respect to Rutherford.
- Data analysis and 4-body CDCC calculations still in progress.

Breakup probability



Energy distribution of ^{9}Li fragments following breakup



- DBU: Kinematical estimate for a breakup process with $Q \approx -|\epsilon_b|$
- TC: Kinematical estimate for a 2n-transfer process with $Q \approx 0$

☞ **Energy distribution consistent with a direct breakup picture**

Extracting structure information from the reaction data

Assuming that we have a reliable description of the reaction mechanism, what structure information can be extracted from the measured elastic / breakup data?

Breakup probability in terms of collision time

- Semiclassical breakup probability:

$$P_{\rm bu}(\theta) = \frac{\pi}{9}\left(\frac{Ze}{\hbar v a_0}\right)^2 \int d\varepsilon \frac{dB(E1)}{d\varepsilon} f_{\rm E1}(\xi,\varepsilon)$$

- Collision time:

$$t = \left(\pi + \frac{2}{\sin(\theta/2)}\right)\frac{a_0}{\hbar v}$$

- For small θ (large t):

$$P_{\rm bu}(t) \approx \left[\frac{16\pi^2}{9}\frac{(Ze)^2}{(\hbar v)^4\left(t - \frac{\pi a_0}{\hbar v}\right)}\right]\int d\varepsilon \frac{dB(E1)}{d\varepsilon}\varepsilon e^{-t\varepsilon}$$

Breakup probability in terms of collision time

- Semiclassical breakup probability:

$$P_{\mathrm{bu}}(\theta) = \frac{\pi}{9}\left(\frac{Ze}{\hbar v a_0}\right)^2 \int d\varepsilon \frac{dB(E1)}{d\varepsilon} f_{\mathrm{E1}}(\xi, \varepsilon)$$

- Collision time:

$$t = \left(\pi + \frac{2}{\sin(\theta/2)}\right)\frac{a_0}{\hbar v}$$

- For small θ (large t):

$$P_{\mathrm{bu}}(t) \approx \left[\frac{16\pi^2}{9}\frac{(Ze)^2}{(\hbar v)^4\left(t - \frac{\pi a_0}{\hbar v}\right)}\right] \int d\varepsilon \frac{dB(E1)}{d\varepsilon} \varepsilon e^{-t\varepsilon}$$

Breakup probability in terms of collision time

- Semiclassical breakup probability:

$$P_{\rm bu}(\theta) = \frac{\pi}{9}\left(\frac{Ze}{\hbar v a_0}\right)^2 \int d\varepsilon \frac{dB(E1)}{d\varepsilon} f_{\rm E1}(\xi,\varepsilon)$$

- Collision time:

$$t = \left(\pi + \frac{2}{\sin(\theta/2)}\right)\frac{a_0}{\hbar v}$$

- For small θ (large t):

$$P_{\rm bu}(t) \approx \left[\frac{16\pi^2}{9}\frac{(Ze)^2}{(\hbar v)^4(t-\frac{\pi a_0}{\hbar v})}\right]\int d\varepsilon \frac{dB(E1)}{d\varepsilon}\varepsilon e^{-t\varepsilon}$$

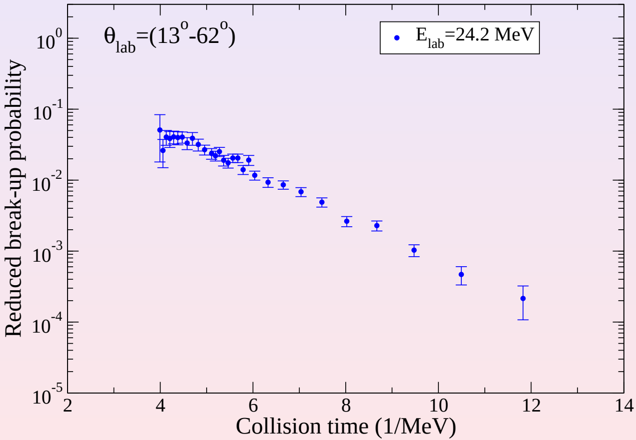
Reduced breakup probability

Define:

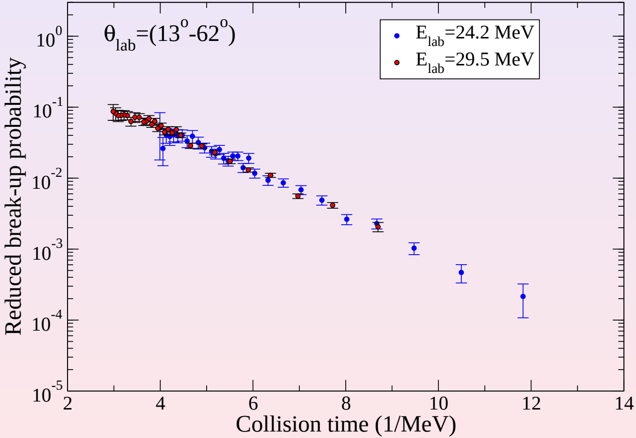
$$\boxed{B(t) \equiv \frac{P_{\rm bu}(t)}{\frac{16\pi^2}{9}\frac{(Ze)^2}{(\hbar v)^4 (t - \frac{\pi a_0}{\hbar v})}} = \int d\varepsilon \frac{dB(E1)}{d\varepsilon} \varepsilon e^{-t\varepsilon} \equiv \mathcal{L}\left[\frac{dB(E1)}{d\varepsilon}\varepsilon\right]}$$

- ☞ $B(t)$ is the Laplace transform of $\varepsilon dB(E1;\varepsilon)/d\varepsilon$.
- ☞ $B(t)$ independent of v and on the target charge Z.
- ☞ $\ln[B(t)]$ linear dependence with t for large t (small θ).
- ☞ The logarithmic derivative of $B(t)$ is just the average breakup energy.

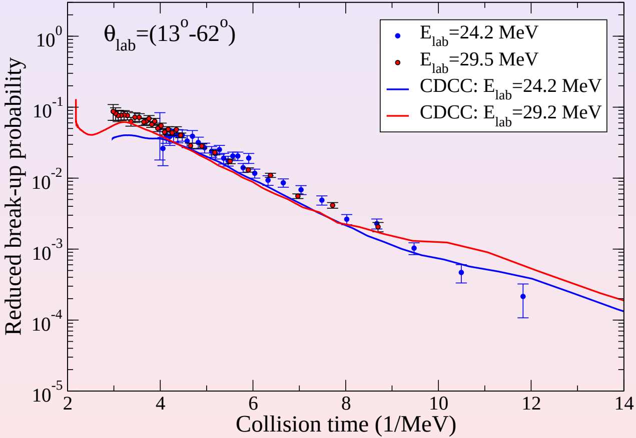
How well does the “scaling law” work for the ^{11}Li+^{208}Pb data?



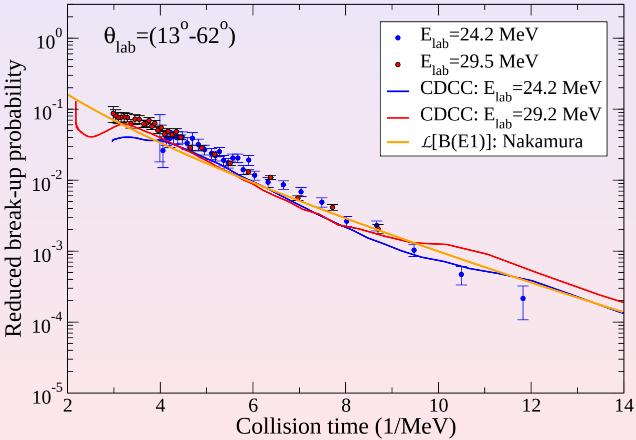
How well does the “scaling law” work for the ^{11}Li+^{208}Pb data?



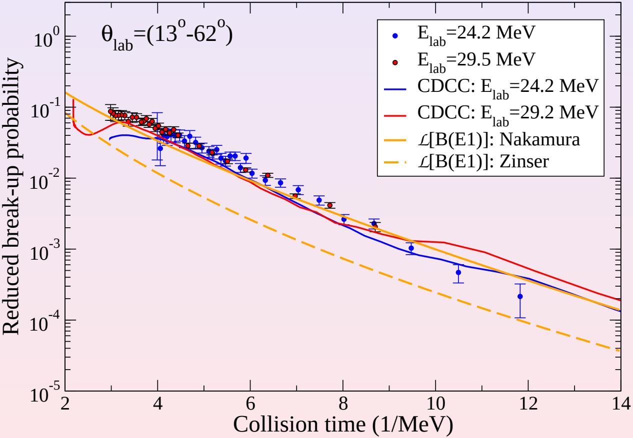
How well does the “scaling law” work for the ^{11}Li+^{208}Pb data?



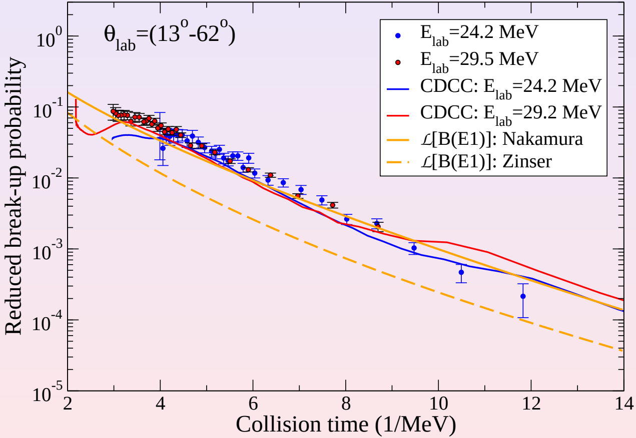
How well does the “scaling law” work for the ^{11}Li+^{208}Pb data?



How well does the “scaling law” work for the ^{11}Li+^{208}Pb data?



How well does the “scaling law” work for the ^{11}Li+^{208}Pb data?



☞ From the slope of this curve $\langle \varepsilon \rangle = 0.75$ MeV ⇒ signature for halo nuclei!

Conclusions

- Following our previous ^{6}He+^{208}Pb experiments, the elastic and breakup of ^{11}Li+^{208}Pb has been measured for the first time at Coulomb barrier energies, using the TRIUMF facility.
- Break-up cross sections are very large (larger than for ^{6}He)
- Angular/energy distribution of ^{9}Li fragments consistent with CDCC and semiclassical calculations $\Rightarrow$ direct breakup mechanism.
- Measured reduced breakup probability exhibits a nice scaling behaviour in terms of the collision time, consistent with dominance of $E1$ excitation.
- Measured breakup probability consistent with $B(E1)$ data from RIKEN (T. Nakamura *et al.*, PRL96, 252502 (2006)).

List of collaborators

- University of Sevilla (Spain) / Centro Nacional de Aceleradores:
  M. A. G. Alvarez, J.A. Lay, J.P. Fernández-García, J. Gómez-Camacho, I. Mukha, M. Rodríguez-Gallardo.
- University of Huelva (Spain):
  L. Acosta, I. Martel, A. M. Sánchez-Benítez.
- CSIC/Madrid (Spain):
  M. Alcorta, M. J. G. Borge, M. Cubero, M. Madurga, O. Tengblad.
- University of Lisbon (Portugal): D. Galaviz.
- Aarhus University (Denmark): H.O.U. Fynbo.
- University of York (UK): C.G. Diget, B. Fulton.
- TRIUMF (Canada): L. Buchmann, A. Shotter, P. Walden.

Ongoing work

1. Data analysis:
   - Extract elastic cross sections.
   - Extend the analysis to larger scattering angles.
2. Theory:
   - Develop four-body CDCC calculations using a three-body description of ^{11}Li
   - Study the effect of 1n and 2n transfer.

^{9}Li+^{208}Pb elastic data

- ^{9}Li is a “normal nucleus” well described by “standard” optical potentials.
- Follows Rutherford formula for energies below the barrier in the full angular range.
- Deviations from Rutherford expected for $\theta > 100°$.