^{11}Li structural information from inclusive break-up measurements

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1 Introduction

Exotic nuclei are systems rich in neutrons or protons. They are unstable nuclei with short half-life. Due to the fact that they are far away from the stability valley, the way they interact with other nuclei and their structure can be very different from that of stable nuclei. In this work, we study the ^{11}Li reactions with ^{208}Pb at laboratory energies around the Coulomb barrier (E_{lab}=24.3 and 29.8 MeV). This experiment was performed at the TRIUMF radioactive ions beams facility in Vancouver (Canada).

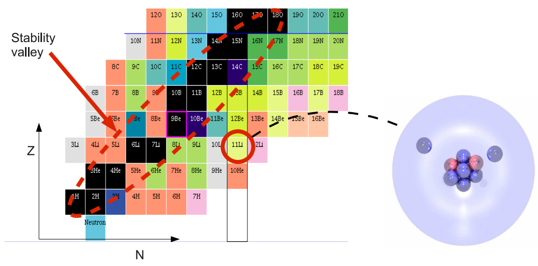

Figure 1. Chart of nuclides.

The ^{11}Li nucleus is composed by a core of ^{9}Li and two weakly bound neutrons (S_{2n}=369.15(65) keV [1]). This system is an example of Borromean nucleus because the binary subsystems, n+^{9}Li and n+n, are unbound. Due to the weakly bound structure of the nucleus, the dipolar Coulomb polarizability, produced by the lead target, affects the elastic scattering at energies around the Coulomb barrier, producing a reduction of the elastic cross section with respect to the Rutherford formula. Furthermore, this effect increases the breakup probability of the nucleus.
Experimental data of the ^{9}Li+^{208}Pb reaction are presented and compared with semiclassical and CDCC calculations.

2 Experimental Setup

The experiment was performed at the ISAC-II line of the radioactive beams facility of TRIUMF (Canada). The detection system consisted of 4 silicon telescopes (ΔE-E) covering a wide angular range, from 10° to 140°. This set-up allowed us to separate ^{9}Li fragments coming from the breakup of the ^{11}Li projectile.

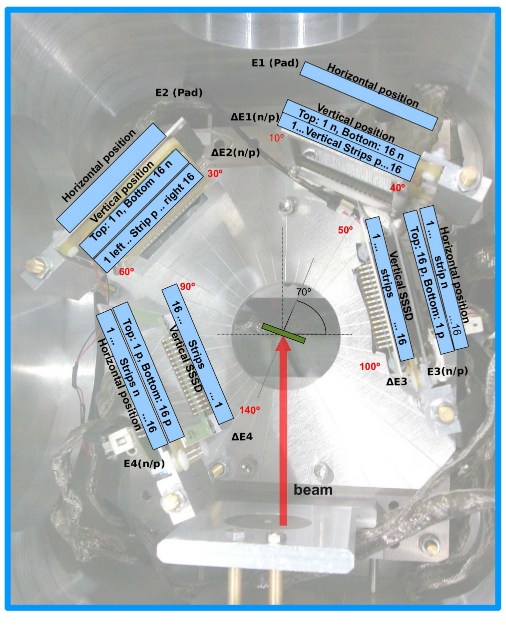

Figure 2. Scheme of the experimental set-up.

The set-up is illustrated in figure 2. In the forward angles we set install two telescopes, each one consisting of a DSSSD of 16x16 strips with 40 μm thick ΔE detector and 500 μm thick PAD E detector. These detectors covered different angles: 10°-40° and 30°-60°, respectively. The backward telescopes consisted of a 20 μm thick ΔE SSSD of 16 strips in front of a 60 μm thick E DSSSD and covered the angles 50°-100° and 90°-140°, respectively.

3 ΔE vs E Diagrams

Figure 3 shows two-dimensional diagrams (ΔE vs E) of the total events acquired through detectors 1 at two different incident energies (24.3 and 29.8 MeV), integrated for the pixels corresponding to the angular bins of 33(1.5)°.

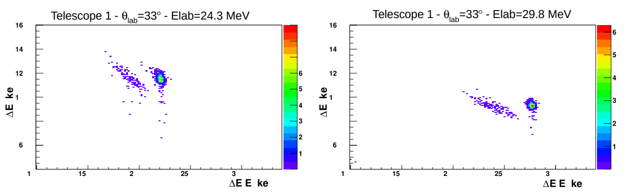

Figure 3. Diagrams ΔE vs E of detector 1 at 24.3 and 29.8 MeV.

4 Experimental data

Figure 4 (left) shows the elastic scattering angular distribution of the ^{11}Li+^{208}Pb reaction [2] and the corresponding 3b-CDCC calculations at 24.3 and 29.8 MeV. 3b-CDCC calculations are based on a simple two-body model of ^{11}Li (^{9}Li + 2n). An impressive suppression of the ^{11}Li elastic cross section with respect to the Rutherford prediction is observed.

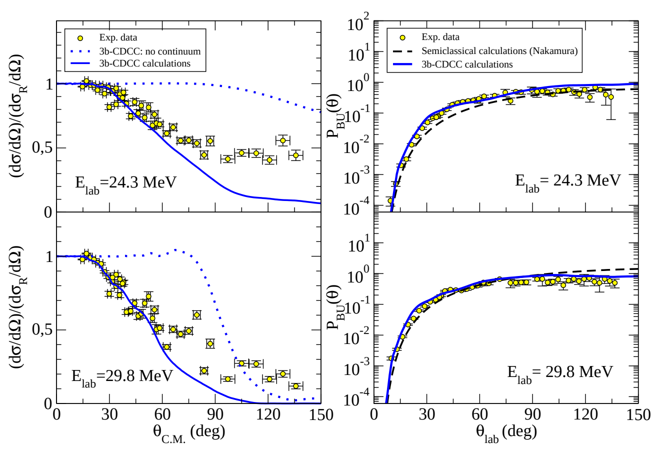

Figure 4. Elastic scattering (left side) and break-up probability (right side) angular distribution for the reaction ^{11}Li+^{208}Pb at 24.3 and 29.8 MeV.

In figure 4 (right) we present the experimental data of the ^{11}Li breakup probability (ratio between ^{9}Li and ^{9}Li+^{11}Li events) at different energies resulting from the two-neutron removal process in the ^{11}Li+^{208}Pb reaction [3]. We compare the experimental data with semiclassical and CDCC calculations. The semiclassical calculations include only the first order Coulomb excitation (E1) and the breakup probability is given by equation (1). The CDCC calculations include both Coulomb and nuclear couplings to all orders.

$$P_{BU}(E1,\Omega)=\left(\frac{Z_T e}{\hbar v a_0}\right)^2\frac{2\pi}{9}\int_{\varepsilon_b}^{\infty}d\varepsilon\frac{dB(E1)}{d\varepsilon}[I_{1,\,1}^2+I_{1,\,-1}^2]. \quad (1)$$

5 Reduced Breakup Probability

It is useful to define the *reduced breakup probability* given by equation:

$$P_r(t)=P_{BU}(E1,\Omega)\frac{9t^2(\hbar v)^3 a_0\epsilon}{16\pi^2(Z_A e)^2}, \quad (2)$$

where t is the collision time: $t=\frac{(2sin^{-1}(\theta_{CM}/2)+\pi)a_0}{\hbar v}$.
When dipole Coulomb excitation is dominant, the reduced breakup probability becomes an universal function of the collision time, independent on the collision energy:

$$P_r(t)=\int_{\varepsilon_b}^{\infty}\varepsilon d\varepsilon\frac{dB(E1)}{d\varepsilon}e^{(-\varepsilon t)}t^2\simeq be^{-\varepsilon_b t}, \quad (3)$$

where, for large collision times, the B(E1) distribution is approximated by, $\varepsilon\frac{dB(E1)}{d\varepsilon}\simeq b(\varepsilon-\varepsilon_b)$.

5 Reduced Breakup Probability

In figure 6 we can see that the reduced break-up probability, for collision times larger than 5 MeV^{-1}, is indeed independent on the collision energy.

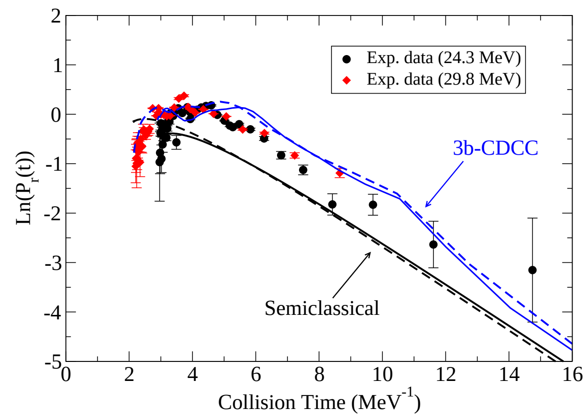

Figure 6. Reduced breakup probability.

From the linear fit of this magnitude, we can obtain the effective break-up energy (ε_b=0.35(4) MeV) and the parameter b, which is associated with the slope of the B(E1) distribution.

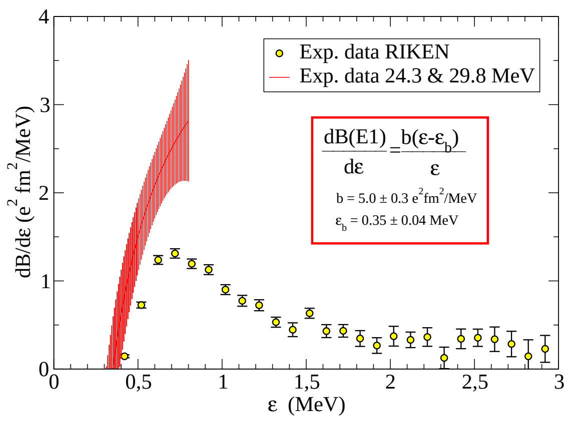

Figure 7. B(E1) distribution.

The interpretation of our data indicates that the large breakup probabilities found at forward angles, might be due to a large B(E1) probability just above the breakup threshold, which might be even larger than the values previously mentioned in the literature [4].

6 Summary and Conclusions

- We have presented the experimental set-up used to measure the breakup of ^{11}Li on ^{208}Pb at energies around the Coulomb barrier at TRIUMF facility (Canada).
- The set-up allowed us to separate elastically scattered ^{11}Li from ^{9}Li breakup fragments in ^{11}Li+ ^{208}Pb reaction.
- A **strong reduction** of the σ_{elast} with respect to σ_{Ruth} have been observed.
- We have defined a new magnitude referred to as **reduced break-up probability.** This magnitude is a function of the collision time and is **independent of the collision parameters.**
- From the experimental reduced break-up probability, we have obtained a value of the **effective break-up energy** of ε_b=0.35(4) MeV and **the behaviour of the** $B(E1)$ **distribution** at low excitation energies.
- The experimental data suggest **more strength of the** $B(E1)$ **distribution** than the distribution obtained by Nakamura [4].

References

[1] M. Smith *et al.*, Phys. Rev. Lett. 101, 202501 (2008).

[2] M. Cubero *et al.*, Phys. Rev. Lett. 109, 262701 (2012).

[3] J. P. Fernández-García *et al.*, Phys. Rev. Lett. 110, 142701 (2013).

[4] T. Nakamura *et al.*, Phys. Rev. Lett. 96, 252502 (2006).