Scattering of $^9\text{Li}$ on $^{208}\text{Pb}$ at energies around the Coulomb barrier


$^1$ Instituto de Estructura de la Materia, CSIC, E-28006 Madrid, Spain.
$^2$ CICANUM, Universidad de Costa Rica, Apdo. 2060, San José, Costa Rica.
$^3$ Dpto Física Atómica Molecular y Nuclear, Facultad CC Físicas, Universidad de Sevilla, Aptdo. 1065, 41080 Spain.
$^4$ Dpto de Física Aplicada, Universidad de Huelva, E-21071 Huelva, Spain.
$^5$ Centro Nacional de Aceleradores, E-41092-Sevilla, Spain.
$^6$ TRIUMF, V6T2A3 Vancouver B.C., Canada.
$^7$ Department of Physics, University of York, YO10 5DD Heslington, York, U.K.
$^8$ Department of Physics and Astronomy, University of Aarhus, DK-8000, Árhus, Denmark.
$^9$ Centro de Física Nuclear da Universidade de Lisboa, 1649-003 Lisboa, Portugal.
$^{10}$ Instituto de Física Corpuscular, CSIC-Universidad de Valencia, Spain.
$^{11}$ Fundamental Physics, Chalmers University of Technology, S-41296 Göteborg, Sweden.

Abstract. In order to study the dynamics of $^{11}\text{Li}$ and $^9\text{Li}$ beams in a strong electric field at energies around the Coulomb barrier, we measured at the ISACH-TRIUMF Facility the angular distribution of elastic and inelastic scattering of $^{11}\text{Li}+^{208}\text{Pb}$ at 24.2 and 29.7 MeV and $^9\text{Li}+^{208}\text{Pb}$ at 24, 29.5 and 33 MeV laboratory energies. We present here the first determination of the angular distribution of the cross section of $^9\text{Li}+^{208}\text{Pb}$. The results are compared with theoretical calculations using the double-folding São Paulo Potential (SPP) for the real part and for the imaginary part a Woods-Saxon potential. A good overall agreement is obtained.

1 Introduction

The neutron-rich lithium isotope $^{11}\text{Li}$ is the archetype of a boronaceous halo nucleus with a half-live of 8.5(2) ms [1], and structurally is composed of a $^7\text{Li}$ core and two weakly bound neutrons with $S_{2\nu}=369.15(65)$ keV [2]. Due to the loosely bound structure, the neutron halo should be easily polarizable in the strong electric field of a heavy target such as $^{208}\text{Pb}$.

The size of $^{11}\text{Li}$ is abnormally big. The rms matter radius for the $^9\text{Li}$ isotopes with $A$ from 6 to 9 is around 2.45 fm, but for $A=11$ the rms radius is 3.71(2) fm [3]. Therefore it is interesting to study the dynamic of the halo nucleus $^{11}\text{Li}$ at Coulomb barrier energies on the intense electric field created by a $^{208}\text{Pb}$ target. This process can reveal new features of halo nuclei as predicted by [4]. For halo nuclei it is expected that collisions with heavy targets, in our case $^{208}\text{Pb}$, at energies below the Coulomb barrier will depart from Rutherford scattering. This deviation are explored: First, the distortion of the wave function generated by the displacement of the charged core with respect to the center of mass of the nucleus should reduce the Coulomb repulsion, and thus the elastic cross sections [4].

$^9\text{Li}$ is an exotic nucleus with a half-live of 178.3(4) ms [5], a ground state with a spin-parity $J^\pi=\frac{1}{2}^-$ and a matter radius of 2.45(3) fm [3]. The magnetic and quadrupole moments were reported in [5, 6]. The most recent values for the ground state are $\mu=+3.43678(6)\mu_N$ and $Q_{exp}=-30.6(2)$ mb [6].

The first known excited state of $^9\text{Li}$ is $J^\pi=\frac{1}{2}^-$ with an excitation energy of 2691(5) keV. The next known state is a $(\frac{3}{2}^+)$ resonance at 4296(15) keV excitation energy. There are experimental evidences of two more states with excitation energies of 5380(60) and 6430(15) keV [5]. Theoretical calculations for $^9\text{Li}$ states have been presented [7–10]. The recently ab initio no-core shell model (NCSM) calculations [10] provide E2 transition matrix elements for states with $J^\pi=\frac{3}{2}^+$ and $\frac{5}{2}^-$, but these transition probabilities have not been measured yet. For the reaction $^9\text{Li}+^{208}\text{Pb}$ there are two breakup/transfer channels [11]. The first, produces $^7\text{Li}+^{210}\text{Pb}$ ($Q=+3.0$ MeV). The second, $^9\text{Li}+^{209}\text{Pb}$ ($Q=-0.1$ MeV). Another possibility [11] is the breakup of $^9\text{Li}$ on two charged fragments $^4\text{He}+^5\text{He}$ ($Q=-2.4$ MeV).

In order to disentangle the contribution of the loosely bound structure of $^9\text{Li}$ to the reaction process, one should know the behavior of the core, $^9\text{Li}$, in the same conditions. Previously, the cross section of $^9\text{Li}$ on a 0.3 mg·cm$^{-2}$

This is an Open Access article distributed under the terms of the Creative Commons Attribution-Noncommercial License 3.0, which permits unrestricted use, distribution, and reproduction in any noncommercial medium, provided the original work is properly cited.
thickness of 208Pb target has been measured at 86 MeV and the results have been compared to different calculations [12]. This energy is high compared with the Coulomb barrier at CM (\(V_g \sim 30\) MeV) for the 9Li + 208Pb system. Near the Coulomb barrier, the fusion cross section of 9Li + 208Pb has been measured at CM energies from 23.9 to 43.0 MeV, the “reduced” fusion excitation function was found to be equivalent for the A\(=\)7-9 Li isotopes [11]. Due to the lack of information on the 9Li scattering on lead around the Coulomb barrier we decided to study this process in detail to characterize the potential parameters describing the dynamic behavior of the 11Li core, 9Li. The results of this work are presented herein.

2 Experiment

The experiment was performed in ISAC-II facility at TRIUMF. The cross section of 11Li on 208Pb at laboratory energies of 24.2 and 29.7 MeV was measured. Further, in order to characterize the Optical Potential (OP) parameters for this system we measured the 9Li + 208Pb scattering, at the same center of mass energies as well as at an energy well beyond the Coulomb barrier.

Both secondary beams of 9Li and 11Li were produced with a primary 100 \(\mu\)A proton beam of 500 MeV [13] from the cyclotron TRIUMF and Ta primary target. The secondary beams were transported to the ISAC-II facility for post acceleration. The time duration of each measurement is given in Table 1. The average yield with the 11Li beam as detected in our circular Si monitor detector (thickness of 700 \(\mu\)m and active area of 300 mm²) placed in the beam axis after the 208Pb scattering target was 4.300 \(11\) Li/s with a maximum yield approaching 6.000 pps.

In order to identify all the fragments in the relevant angular range, we designed and optimized the configuration of the setup by calculating the losses of energy on \(|E|\) and \(|E|\) sensitive parts of the telescopes for both the 9Li (breakup) and 11Li (elastic) for different incoming energies. Our setup consisted of four telescopes as illustrated in Fig. 1. In the forward direction we put two telescopes, T1 and T2, each one consisting of a Double-Sided Silicon Strips Detector (DSSSD) [14,15] of 16 strips in front of a 60 \(\mu\)m thick E DSSSD.

For the T3 and T4 telescopes the detector center was chosen at a distance of 52 mm from the beam-target intersection, covering the following angles, T3:50-100° and T4:90-140°.

The segmentation of each detector system gave rise to 256 pixels (16x16 strips) by matching front and back strips of the DSSSD, resulting in a high angular resolution. Due to the different distances between telescope and target the angular resolution is 2-3° for T1 and T2 and for the rear detectors (T3 and T4) between 3-4°.

The choice of the angles covered by the telescopes was made considering the behavior expected for the differential cross section for the elastic scattering of the halo nucleus 11Li, according to the coupled-channels calculation developed by us which includes both nuclear and Coulomb couplings to the continuum. We used two targets of 208Pb with thicknesses of 1.45 and 1.9 mg·cm⁻², both tilted at 75° with respect to the beam axis. The kinematic channels for the elastic, transfer and break-up fragments of 11Li on a 1.45 mg·cm⁻² thick 208Pb tilted target is shown in Fig. 2.

Table 1. Summary of the experimental conditions used at TRIUMF to study the dynamics of the 11Li + 208Pb and 9Li + 208Pb systems. The different energies, target thicknesses and time duration are indicated.

<table>
<thead>
<tr>
<th>Beam</th>
<th>Energy (MeV)</th>
<th>Target Thickness (mg·cm⁻²)</th>
<th>Energy (MeV) @ Mid-Target</th>
<th>Time (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9Li</td>
<td>2.67</td>
<td>1.45</td>
<td>23.77</td>
<td>11.75</td>
</tr>
<tr>
<td>9Li</td>
<td>3.27</td>
<td>1.45</td>
<td>29.20</td>
<td>7.63</td>
</tr>
<tr>
<td>9Li</td>
<td>3.27</td>
<td>1.90</td>
<td>29.12</td>
<td>9.95</td>
</tr>
<tr>
<td>9Li</td>
<td>3.67</td>
<td>1.90</td>
<td>32.77</td>
<td>31.05</td>
</tr>
<tr>
<td>11Li</td>
<td>2.2</td>
<td>1.45</td>
<td>24.18</td>
<td>82.20</td>
</tr>
<tr>
<td>11Li</td>
<td>2.7</td>
<td>1.45</td>
<td>29.68</td>
<td>118.12</td>
</tr>
</tbody>
</table>

![Fig. 1.](image1.png) (Color online). Schematic view of the experimental setup. The positions of the Pb, monitor detector, forward (T1, T2) and backward (T3, T4) telescopes are shown. The shadow of the target in is gray color.

![Fig. 2.](image2.png) (Color online). Expected energy for elastic and break-up reaction fragments in the four telescopes for a 11Li beam at 24.7 MeV on a target of 1.45 mg·cm⁻².
3 Experimental Analysis

We present here the first determination of the angular distribution for the $^9$Li cross section on lead at energies around the Coulomb barrier. The experimental results are analyzed in the framework of the optical model (OM) and also using a coupled channel (CC) analysis.

Due to the long duration of the data taking, the stability of the electronics was checked by looking at the centroid of the peaks obtained with the calibration alpha-sources as well as those of the pulse signal. The dead time of the system and the possible differences between telescopes were studied by integrating the pulser peak area in different files. We confirmed that no electronic change occurred during the data taking. In the experimental analysis the relevant events were selected in the following way. We included an individual threshold for each strip. Furthermore, when two neighbor strips were fired the event was disregarded to avoid charge sharing [14, 15]. The strip energy calibrations were performed using $^{148}$Gd and the triple-$\alpha$ source ($^{239}$Pu + $^{241}$Am + $^{244}$Cm). To separate well the signal from heavy ions and avoid beta contributions, a condition in the energy deposited in the front and back strips forming the pixel was applied, $\Delta E_{diff} \leq 70$ keV. There was a small percentage of events of multiplicity two that hit the same front or back strip. These events do not pass the energy matching condition although they were good physical events, so they were rescued and treated individually.

Elastic events were selected in the two-dimensional plot of $\Delta E$ versus total E mass spectra. A clear identification of the elastic peaks, both in the $^9$Li and in the $^{11}$Li scattering data were achieved. A preliminary data analysis was done assuming that the detectors T1 and T2 were at the position determined by the geometrical measurements, and the optical beam axis determined by the geometrical measurements, and the optical beam axis centered in the $^{208}$Pb target. The solid angle was calculated for each pixel, considering that it depends on the laboratory angle and the projection of the pixel area (3x3 mm$^2$) over a tangent sphere centered in the target. Due to the close geometry of the setup, a refined study of the angle subtended by each pixel was done based on the expected flat behavior of the ratio of the elastic cross section divided by Rutherford at forward angles. This correction includes the losses for the events arriving in between strips. The optimization for the position of the T1 and T2 telescopes was performed by the $\chi^2$ minimization of the Rutherford angular dependence for the $^9$Li data at 2.67 MeV/u$^{-1}$. The differential cross section with optimized position vectors for each detector was calculated by the weighted average of the pixels corresponding to a certain angle. The angles covered by the T3 and T4 telescopes were determined only by geometrical considerations as angular dependence of the cross section get flatter. For angles larger than 60° the pixels of one strip corresponds to the same angular interval. Three strips of $\Delta E$ SSD detector were not working. Furthermore the target frame shadowed a bit the larger angles in the telescopes T2 and T3, reduced the overlap between T2 and T3 and contributed to a region without angular coverage between T3 and T4, Fig. 3.

4 Interpretation of the Results

The measured elastic data have been analyzed within the framework of the optical model, using the FRESCO code [16, 17]. The $^9$Li scattering data at 24 MeV were excluded from this analysis since these data are very close to Rutherford cross section and hence showed very little sensitivity with respect to the parameters of the nuclear potential. In this analysis, the real part of the $^9$Li+$^{208}$Pb interaction was described in terms of the double-folding São Paulo potential (SPP) [18] with the $^9$Li matter radius of $R_m=2.45(3)$ fm from Ref. [3] and matter radius for $^{208}$Pb obtained from a Hartree-Fock calculation, giving $R_m=5.53$ fm. The imaginary part was parametrized using a Woods-Saxon potential. The three parameters ($W_r$, $r_i$ and $a_i$) of the Woods-Saxon potential as well as the normalization of the real part ($N_r$) were taken as adjustable parameters in order to reproduce the experimental data. In a first approach, we searched for a set of parameters that gave the best overall fit to the $^9$Li scattering data at 29.5 and 33 MeV. For the former case, we considered the data for the 1.45 and 1.9 mg·cm$^{-2}$ targets together. This provided the geometry parameters $r_i=1.35$ fm and $a_i=0.51$ fm. Then, we kept the geometry fixed and readjusted the normalization $N_r$ and the imaginary depth $W_r$ at each energy. The resulting parameters are listed in Table 2 and the corresponding angular distributions are compared with the data in Fig. 3. We can see that it is possible to describe the

![Fig. 3. Differential cross section divided by Rutherford is shown for $^9$Li on $^{208}$Pb at 29.5 and 33 MeV beam energies. Experimental data at 29.5 MeV is given for the two measured targets of 1.45 mg·cm$^{-2}$ (black up triangles) and 1.9 mg·cm$^{-2}$ (green down triangles). The OM calculations correspond to the dashed lines. Solid lines represent the CC calculations. The fitting parameters are shown in Table 2. Both, the OM and CC calculations reproduce similarly well the data.](image-url)

Table 2. The parameters used in the OM and CC calculations are listed. The parameters $r_i=1.35$ fm and $a_i=0.51$ fm are equal in all cases.

<table>
<thead>
<tr>
<th>Model</th>
<th>Energy (MeV/u)</th>
<th>$N_r$</th>
<th>$W_r$ (MeV)</th>
<th>$\chi^2/n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>OM</td>
<td>3.27</td>
<td>0.883</td>
<td>6.01</td>
<td>4.1</td>
</tr>
<tr>
<td>OM</td>
<td>3.67</td>
<td>0.798</td>
<td>17.6</td>
<td>6.4</td>
</tr>
<tr>
<td>CC</td>
<td>3.27</td>
<td>0.85</td>
<td>6.50</td>
<td>4.2</td>
</tr>
<tr>
<td>CC</td>
<td>3.67</td>
<td>0.95</td>
<td>17.18</td>
<td>6.2</td>
</tr>
</tbody>
</table>
data at both energies using a fixed geometry. The real normalization constants are slightly smaller than unity, what would indicate some attractive polarization effect due to the coupling with non-elastic channels. From the values quoted in Table 2 we can see also that the data at 29.5 MeV requires a significantly smaller imaginary potential depth, which is an expected result due to the progressive closure of non-elastic channels when the incident energy decreases into the region of sub-Coulomb energies.

In addition, we have studied the effect of the coupling to the first excited state of 9Li on the elastic cross section. For this purpose, we have performed CC calculations in which the ground and first excited states of 9Li are coupled. We assume a collective model for these states. Since the 9Li has a sizable quadrupole moment, we have also taken into account the reorientation term for the ground state. The strength of the quadrupole coupling potential arising from the Coulomb interaction is given by the reduced matrix element of the electric operator, M(E2; J → Jf).

For the 3/2− → 1/2− coupling, we used the reduced matrix element M(E2; 3/2− → 1/2−) = 3.55 e·fm², which was obtained from the transition probability B(E2; 3/2− → 1/2−) = 3.15 e²·fm⁴ given in [7]. For the reorientation term, the reduced matrix element, M(E2), was obtained from the experimental quadrupole moment, Qexp = −27.4(1) mb [5], giving M(E2; 3/2− → 3/2−) = −3.86 e·fm². The radial part of the nuclear coupling was obtained as the derivative of the central potential multiplied by the reorientation term for the ground state. The resulting potential provides a reasonably good overall agreement of the angular distribution for energies at 29.5 and 33 MeV. Although a more refined analysis is still to be done, this kind of potentials will be an essential ingredient for the few-body calculations that will be eventually performed for the 11Li+208Pb elastic and breakup data measured in the same experiment.

5 Summary and Outlook

The elastic scattering of a exotic 9Li beam on a 208Pb target has been measured at three energies: 24, 29.5 and 33 MeV. For the lowest energy, which is below the nominal Coulomb barrier, the extracted cross section is consistent with an almost pure Rutherford scattering. For the two other energies, the measured angular distribution follows the Rutherford formula for scattering angles up to 45°. The data for these two energies have been compared with OM calculations.

A previous OM analysis of these data [19] was performed with an optical potential derived from the elastic scattering of 9Li by 208Pb at Coulomb barrier energies in [21]. This potential proved to be inadequate to describe the present data in spite of the trend indicated by the recent fusion results [11].

With the idea of extracting a global optical potential for the measured energies, we performed a best-fit analysis of the data starting from the above mentioned potential, fixing the geometry but allowing for the normalization of the real part and the potential depth of the imaginary part to vary.

The resulting potential provides a reasonably good overall agreement of the angular distribution for energies at 29.5 and 33 MeV. Although a more refined analysis is still to be done, this kind of potentials will be an essential ingredient for the few-body calculations that will be eventually performed for the 11Li+208Pb elastic and breakup data measured in the same experiment.

Acknowledgments

We thank the TRIUMF and, in particular, the accelerator staff for their support during the experiment. We acknowledge support from CICYT via contract FPA2009-07387, FPA2009-08848, FPA2010-22131-C02-01 and FPA2009-07653. One of us (M.C.) acknowledges the support of the CSIC-Costa Rica fellowship program.

References

17. I. Thompson, Nuclear Reactions for Astrophysics (Cambridge, 2009) 1-466.
19. M. Cubero et al., AIP proceedings (to be published).