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Spectroscopy of high lying resonances in ^{9}Be produced with radioactive ^{8}Li beams

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Abstract. We present the results of the ^{8}Li(p,α)^{5}He and ^{8}Li(p,p)^{8}Li reactions measured at the RIBRAS (Radioactive Ion Beams in Brazil) system. The experiment was realized in inverse kinematics using a thick $[CH_2]_n$ polyethylene target and an incident ^{8}Li beam, produced by RIBRAS. Using the thick target method, the complete excitation function could be measured between $E_{cm} = 0.2 - 2.1$ MeV, which includes the Gamow peak energy region. The excitation function of the ^{8}Li(p,α)^{5}He reaction, populating resonances between 16.888 and 19.0 MeV in ^{9}Be, was obtained[1] and the resonances were fitted using R-matrix calculations. This study shed light on spins, parities, partial widths and isospin values of high lying resonances in ^{9}Be. The measurement of the resonant elastic scattering ^{8}Li(p,p)^{8}Li populating resonances in the same energy region can constrain the resonance parameters. Preliminary results of the elastic scattering are also presented.

1 Introduction

Reactions induced by radioactive nuclei are one of the subjects in nuclear physics with great activity and investments, with interest in nuclear structure, reactions, astrophysics and production of superheavy elements. Measurements of elastic, inelastic and transfer cross sections of unstable projectiles are possible nowadays due to new Radioactive Nuclear Beam (RNB) facilities[2]. Recent experiments involving radioactive beams have been quite successful in nuclear astrophysics [3], where many stellar

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scenarios involve short-lived nuclei [4]. Also, radioactive beams provide a probe of the nuclear structure, in unusual conditions of excitation energy and isospin. Many experiments have been performed in recent decades with various beams of halo nuclei such as ^{6}He, ^{11}Be, ^{8}He or ^{11}Li (see references in Ref. [2]). At energies near the Coulomb barrier or above, these experiments provide valuable information on the structure of exotic nuclei.

In this work, we present our recently published results [1] of the ^{8}Li(p,α)^{5}He reaction, together with preliminary results of the ^{8}Li(p,p)^{8}Li cross sections at low energies. These experiments have been performed at RIBRAS (Radioactive Ion Beams in Brazil) [5, 6] with a ^{8}Li radioactive beam ($\tau_{1/2} \approx 0.8$ s).

The first goal of our work was to investigate the ^{9}Be structure near the proton threshold (16.89 MeV) through the ^{8}Li(p,α)^{5}He reaction. The ^{9}Be level scheme is well known at low excitation energies [7, 8], but the high-energy region is still uncertain. The ^{8}Li(p,α)^{5}He reaction [1] allows the precise determination of several resonance parameters: energies, spins, proton and alpha widths. A transfer reaction offers several advantages. In particular, the isospin of the exit channel limits the population of $T = 1/2$ states in ^{9}Be, and interference with the Coulomb interaction, which are dominant in elastic-scattering experiments, are absent in a transfer reaction. The recent measurement of the elastic scattering ^{8}Li(p,p)^{8}Li intends to constrain the resonance parameters, since the resonance energies and proton partial widths are the same in the calculations.

Reactions associated with ^{8}Li can also play an important role in nuclear astrophysics [9]. In particular, the ^{8}Li(α,n)^{11}B reaction could affect the non-standard Big-Bang nucleosynthesis (see Ref. [10] and references therein), and was investigated by various groups (see, for example, Ref. [11] and references therein). More recently, it was also suggested that this reaction could be the seed for r-process nucleosynthesis [12]. Consequently, the role of other reactions involving ^{8}Li is an important issue which is addressed by the present experiment. In particular, the ^{8}Li(p,α)^{5}He reaction is important as it not only depletes the ^{8}Li, but feeds back to lower masses, preventing the production of high Z nuclei. The ^{8}Li(p,α)^{5}He reaction was previously measured at E_{cm} = 1.5 MeV [13]. Here we provide the experimental cross section over a wide energy range (from 0.2 MeV to 2.1 MeV), which allows us to determine a reliable reaction rate.

The measurement of the ^{8}Li(p,p)^{8}Li reaction was realized recently and we could detect simultaneously the protons and the α-particles coming from the ^{8}Li(p,p)^{8}Li and ^{8}Li(p,α)^{5}He reactions. The simultaneous measurement of both reactions was possible due to the use of both solenoids, with a degrader between them, and a large scattering chamber located behind the second solenoid. The use of both solenoids could clean considerably the radioactive ^{8}Li beam.

2 Experimental method and results of the ^{8}Li(p,α)^{5}He reaction

This work was performed at the RIBRAS facility, installed at the 8-UD Pelletron Tandem Laboratory of the University of São Paulo. A short description of the experimental equipments is given here and more detail can be found in Refs. [5, 6].

The most important components of this facility are two superconducting solenoids with 6.5 T maximum central field and a 30 cm clear warm bore. The solenoids are installed in the experimental area on the 45B beam line of of the Pelletron Tandem. The presence of the two magnets is very important to produce pure secondary beams.

In the first experiment[1], only the first solenoid was used. When using only one solenoid, the secondary beam still has some contaminants easily identified in elastic scattering experiments. The ^{7}Li^{3+} primary beam was accelerated by the Pelletron Tandem to energies between 16 and 22 MeV and its intensity was typically 300 nAe. We have used a ^{9}Be foil of 16 μm thickness as the production target. The $^{8}Li^{3+}$ secondary beam was produced by the $^{9}Be(^{7}Li,^{8}Li)^{8}Be$ transfer reaction (Q = 0.367 MeV). The primary beam is stopped in a Faraday cup, constituted by an isolated tungsten rod which stops all particles in the angular region from 0 to 2 degrees and where the primary beam intensities were integrated. The stopper and a collimator at the entrance of the solenoid bore define the angular acceptance of the system which, in the present experiment, was respectively $2^\circ - 6^\circ$ in the entrance and $1.5^\circ - 3.5^\circ$ at the end of the solenoid. The solenoid selects and focuses the chosen radioactive beam on the secondary target, located in a central scattering chamber between the two solenoids.

The ^{8}Li production rate was maximized at each energy by varying the solenoid current and measured through the Rutherford elastic scattering on a ^{197}Au secondary target. The measurement with the gold target was performed several times during the experiment and the production rate was quite constant. The production rate depended on the incident energy and varied between 10^5 and 5×10^5 pps at the secondary target position. The secondary targets were a $[CH_2]_n$ polyethylene foil of 6.8 mg/cm^2 thickness and a gold target of 5 mg/cm^2 thickness. According to the high Q-value of the reaction (+14.42 MeV), the α particles had high kinetic energy and were detected at forward angles using four $\Delta E - E$ Si telescopes. The ΔE and E detectors had thicknesses of 20 μm and 1000 μm, respectively, with geometrical solid angles of 18 msr. The secondary beam was not pure, as remnants of the primary beam were detected at zero degrees in the 2+ charge state, as well as ^{4}He, ^{3}H and protons transmitted with the appropriate energy through the first solenoid.

The maximum incident energy in the laboratory frame was $E(^{8}Li)$ = 19.0 ± 0.4 MeV, which corresponds to $E_{c.m.}$ = 2.11 ± 0.04 MeV for the p+ ^{8}Li system, thus all resonances in ^{9}Be below $E_{c.m.}$ = 2.15 MeV could be populated while the ^{8}Li projectile is slowing down in the thick target. Whenever a resonance is populated, a larger number of α-particles are produced and detected in the Si telescopes, producing a peak in the α-energy spectrum. Thus, the energy spectrum of the α-particles represents the excitation function of the reaction, and peaks in the energy spectrum correspond to resonances in the excitation function.

In the $^{8}Li(p,\alpha)^{5}He$ reaction, the recoiling ^{5}He is unbound and disintegrates into an α-particle and a neutron. Similarly, in the $^{1}H(^{8}Li,^{8}Be)n$ reaction, the ^{8}Be is unbound breaking into two α-particles. The contribution of these α-particles, as well as the continuous energy distributions of α-particles resulting from the 3-body break-up, were calculated and subtracted from the energy spectra. All details of these calculations can be obtained in the reference of Mendes et al. [1]. We performed measurements at four different incident energies, the ^{8}Li secondary beam energies incident on the thick $[CH_2]_n$ secondary target were, respectively 13.2, 14.5, 17.0 and 19.0 MeV.

The final results of these measurements are presented in Fig. 1, which contains two spectra. The spectrum located on the left side represents the complete excitation function of the reaction $^{8}Li(p,\alpha)^{5}He$ with the R-matrix fit. In the spectrum located on the right side, we present this same reaction, performing a zoom on the low energy resonances and their R-matrix-fit. The present data show evidence of a broad peak near $E_{c.m.} \approx 1.7$ MeV. Owing to its large amplitude, this peak can be fitted only by assuming two overlapping resonances. The energies (1.69 and 1.76 MeV) are consistent with known spectroscopic properties of ^{9}Be. The existence of a broad structure near E_x = 18.6 MeV in ^{9}Be has been already suggested by a previous $^{7}Li(d,\alpha)^{5}He$ experiment [14], and is consistent with the overlapping states observed in the present experiment.

From the cross section, the astrophysical S-factor and the reaction rate of the $^{8}Li(p,\alpha)^{5}He$ reaction could be calculated . In Fig. 2 we present the $^{8}Li(p,\alpha)^{5}He$ and $^{8}Li(\alpha,n)^{11}B$ reaction rates multiplied by the proton and α mass fractions. This comparison shows that the depletion of ^{8}Li is faster than the (α,n) reaction which could bridge the A=8 gap.

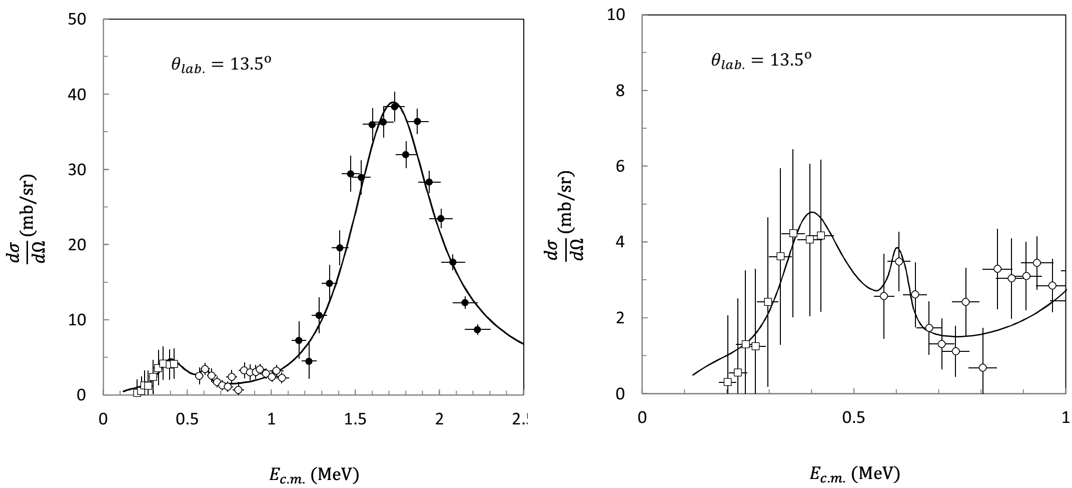

Figure 1. The spectrum on the left shows the ^{8}Li(p,α)^{5}He differential cross sections at $\theta_{\rm lab} = 13.5°$, with the *R*-matrix fit (solid line.) In the spectrum on the right we present the same reaction, performing a zoom on the low energy resonances and their R-matrix-fit.

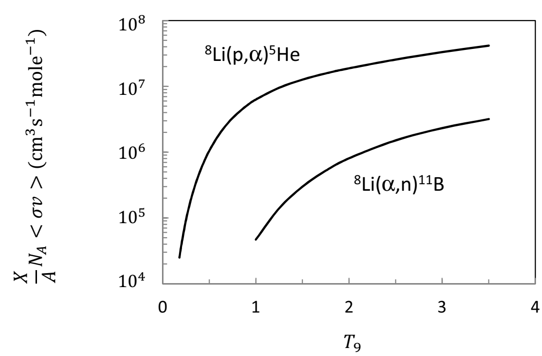

Figure 2. The ^{8}Li(p,α)^{5}He and ^{8}Li(α,n)^{11}B reaction rates multiplied by the proton and α mass fractions.

3 Experimental method and results of the ^{8}Li(p,p)^{8}Li reaction

The measurement of the elastic scattering (p,p) in inverse kinematics is more difficult than the corresponding (p,α) reaction, for several reasons: (i) the (p,α) reaction has a large positive Q-value (+14.42 MeV) thus, the α particles from the reaction are more energetic than the contaminant α-beam, which is focused by the solenoid. The elastic scattering has Q=0 and the protons from the reaction have lower energy than the contaminant proton beam. (ii) The protons lose less energy in the detectors and are more difficult to be detected with good energy resolution. (iii) The low energy protons stop in the ΔE Si detector and cannot be detected, limiting the excitation function at low energies.

The measurements of the ^{8}Li(p,p)^{8}Li reaction had to be performed with a clean radioactive ^{8}Li beam. With two solenoids, it is possible to produce pure secondary beams by using a degrader at the crossover point between them, where the different ions have different energy losses and their magnetic rigidities change. Choosing the magnetic field in the second solenoid to focus only the secondary beam of interest, the contaminant ions are no longer focused. The secondary targets were a $[CH_2]_n$ polyethylene foil of 7.7 mg/cm^2 thickness and a gold target of 5 mg/cm^2 thickness.

The particles produced by the secondary beam on the secondary targets were detected at $\theta_{\text{lab}} = 10°$ using a $\Delta E - E$ Si telescope. The ΔE and E detectors had thicknesses of 50 μm and 1000 μm, respectively, with geometrical solid angles of 13 msr. Bidimensional spectra of the Si telescope, presented in Fig. 3, show that the purity of the ^{8}Li beams after the second solenoid was about 99%, to be compared with a purity of 65%, without the use of a degrader.

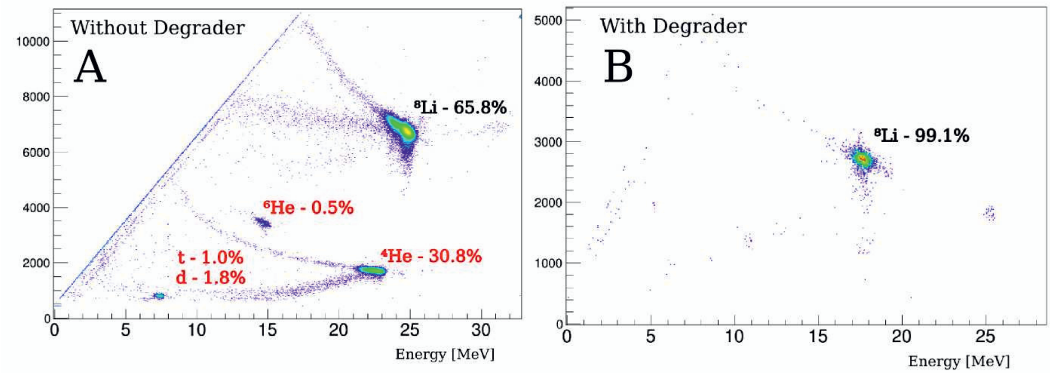

Figure 3. Bidimensional energy spectra obtained using a Si telescope at Θ_{lab}=10^o, in the large chamber after the second solenoid, with the secondary beams focused on a gold target. Spectrum A was obtained without a degrader and spectrum B with a degrader.

The energy spectra measured by the $\Delta E - E$ Si telescope had very good energy resolution and the protons resulting from the ^{8}Li(p,p)^{8}Li reaction were well separated from other light particles. In Fig. 4 we can see the bidimensional energy spectrum obtained using the thick $[CH_2]_n$ target.

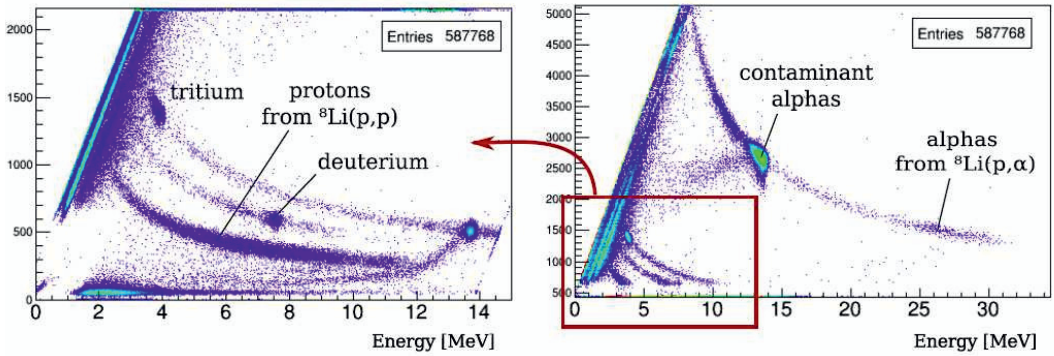

Figure 4. Bidimensional energy spectra obtained using a Si telescope at Θ_{lab}=10^o, in the large chamber after the second solenoid, with the secondary beams focused on a $[CH_2]_n$ target. The spectrum on the left is a zoom of the spectrum on the right.

The presence of contaminant α-particles, as well as deuterons and tritons can be observed in the energy spectra of Fig. 4 despite the important purification of the secondary beam. These contaminations should not depend on the target and they can be measured in the runs with the gold target. The precise normalization of the spectra obtained with different targets is essential before the subtraction, however it is not straightforward, since the secondary beam ^{8}Li stops in the thick $[CH_2]_n$ target and is not detected.

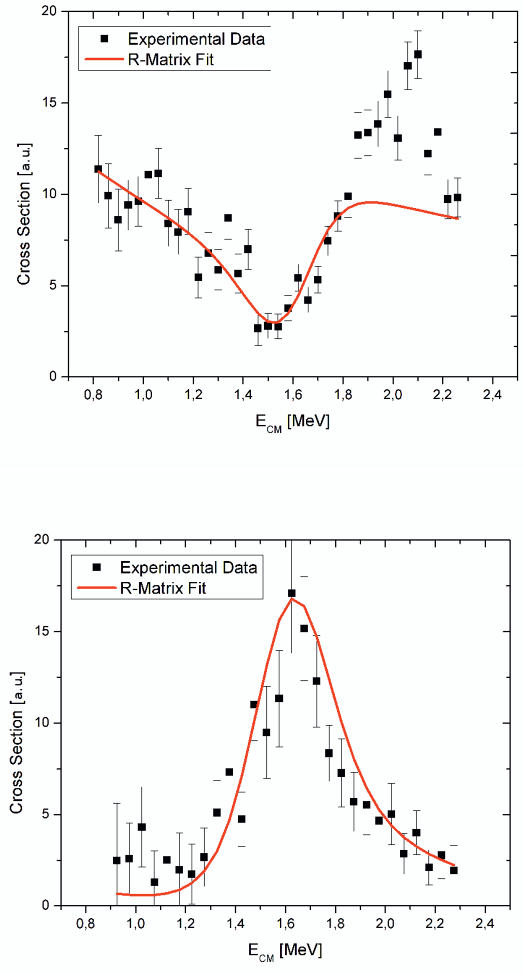

Figure 5. The excitation function of the ^{8}Li(p,p)^{8}Li reaction, together with a fit by the R-matrix calculation is shown on the top. On the bottom is the excitation function of the ^{8}Li(p,α)^{5}He reaction, together with a fit by the R-matrix calculation.

Two incident energies were used in this experiment, $E_{lab}(^8\mathrm{Li})$=18.4 and 15.8 MeV, and the resulting excitation function is obtained from the superposition of these measurements. In Fig. 5 we present the excitation function of the ^{8}Li(p,p)^{8}Li reaction, together with a fit by the R-matrix calculation. These results are preliminary since the subtraction of contaminations was not properly performed and there are contributions from the contamination in the higher energy part.

As we can observe in Fig. 4, the α-particles from the ^{8}Li(p,α)^{5}He reaction could be also detected simultaneously with the protons; however, due to a much lower cross section, the statistics were fairly poor for this reaction. The resulting excitation function is presented in the lower part of Fig. 5 together with the R-matrix fit, with the same parameters used in the calculation for the ^{8}Li(p,p)^{8}Li reaction.

4 Conclusions

The use of two solenoids with a degrader between them has allowed the purification of the ^{8}Li secondary beam and detection with good resolution of protons and α-particles from the reactions ^{8}Li(p,p)^{8}Li and ^{8}Li(p,α)^{5}He. The simultaneous detection and measurement of both excitation functions will help to constrain the resonance parameters in the R-matrix calculations. Measurements will be performed in the near future with the use of gaseous ΔE detectors to extend the detection threshold of the protons to lower energies and to accumulate better statistics for the ^{8}Li(p,α)^{5}He reaction.

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