Low energy nuclear reactions with RIBRAS, Radioactive Ion Beam in Brasil, system.

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Abstract. RIBRAS, Radioactive Ion beam in Brasil, is a system based on superconducting solenoids which can produce low energy RNB (Radioactive Nuclear Beams) at the University of São Paulo, Brazil. Secondary radioactive beams of light particles such as $^6$He, $^7$Be and $^8$Li have been produced and low energy elastic scattering and transfer reaction experiments have been performed. The recent scientific program using this facility includes elastic scattering and transfer reactions of $^6$He halo nucleus on $^9$Be, $^{27}$Al, $^{51}$V and $^{120}$Sn targets and $^8$Li on $^9$Be, $^{12}$C and $^{51}$V targets. The total reaction cross section as a function of energy has been extracted from the elastic scattering data and the role of breakup of weakly bound or exotic nuclei is discussed. Also spectroscopic factors have been obtained from the transfer reactions.

1. Introduction

Many new facilities have been installed or upgraded to produce beams of radioactive nuclei. The main purpose of these facilities is to investigate nuclei at extreme conditions in terms of density, temperature, angular momentum and isospin. The possibility of using radioactive (exotic) nuclear beams has opened an exciting field of investigation in nuclear physics with strong implications in areas such as nuclear astrophysics. To produce low energy RNB (Radioactive Nuclear Beams), the University of São Paulo, Brazil installed a system based on superconducting solenoids, the RIBRAS system \cite{1}. This facility is the first and only of such device in the southern hemisphere. In this contribution we present the recent scientific program using radioactive light particle beams such as $^6$He, $^7$Be and $^8$Li to investigate low energy elastic scattering and transfer reactions, which can provide useful information on the structure of light nuclei near the dripline and astrophysics. Total reaction cross sections have been also extracted from the elastic scattering data and breakup effect has been discussed.
2. Production of low energy RNB.

To produce low energy RNB, the University of São Paulo, Brazil, adopted a similar system as the one installed at University of Notre Dame, USA [2] based on superconducting solenoids to select and focus secondary low energy radioactive beams. The RIBRAS at São Paulo consist of two large air-core (30 cm clear warm bore), superconducting solenoid with 6.5T maximum central field. With the large bore of the solenoids it is possible to reach a large angular acceptance, \(2^\circ < \theta < 15^\circ\), i.e., about 30 msr in solid angle, in comparison with about 5 msr which can be obtained from dipoles based system. The magnets are immersed in LHe Dewar with LN and vacuum shields to minimize LHe consumption to 0.1 liter/h per magnet. The superconducting solenoids in these systems act as thick lenses to collect, select, and focus the secondary beam into a scattering chamber. The production target consists of a gas cell, mounted in an ISO chamber with a thin foil for entrance and exit windows. The windows can be the production target itself as the 12 \(\mu\)m thick \(^9\text{Be}\) vacuum tight foil, and in this case the gas would work as a cooling, or it can be just Havar foil and the gas inside the cell, as \(^3\text{He}\), would be the production target. A picture of this system can be seen in Figure-1.

![Figure 1. Picture of the RIBRAS system installed in University of São Paulo.](image)

At low energies \((E < 5 \text{ MeV/A})\) transfer reactions are the best option to produce radioactive nuclear beams. Cross sections for these reactions are not as high as for fragmentation reaction at higher energies, and thus, the large angular acceptance for the RIBRAS system is very useful. For this particular system based on solenoid separator it is recommended the use of transfer reactions with broad forward-peaked cross-sections angular distribution. Reactions with very sharp forward-peak angular distribution such as light projectiles induced transfer reactions, \((d,p)\) and \((^3\text{He},d)\), are better for dipole based on-line separator. We have been used \(^9\text{Be}(^7\text{Li},^8\text{Li})\), \(^9\text{Be}(^7\text{Li},^6\text{He})\) and \(^3\text{He}(^6\text{Li},^7\text{Be})d\) transfer reactions, where the \(^6\text{Li}\) and \(^7\text{Li}\) primary beams are obtained from a 8 MV Tandem accelerator, to produce reasonably intense \(^8\text{Li}\) \((10^6 \text{ pps})\), \(^6\text{He}\) \((10^5 \text{ pps})\) and \(^7\text{Be}\) \((10^5 \text{ pps})\) beams for 1\(\mu\)A of primary beam.

After crossing the production target, the primary beam is suppressed in a tungsten Faraday cup which measures its intensity and a current integrator measures the total incident charge during a run. The first magnet selects the produced ions and only particles with the same magnetic rigidity, i.e., the same \(ME/Q^2\) ratio, where \(M\), \(E\) and \(Q\) stand for mass, energy and charge state of the ion, are transmitted. The purity of the secondary radioactive beam is determined by a system of blocking apertures. With two solenoids it is possible to use differential energy loss in a energy degrader foil, located at the crossover point between the magnets, to
select the ion of interest and move the contaminant ions out of the bandpass of the second solenoids. This method does not provide a good separation for isotopes. An additional cleaning of the secondary beam can be obtained by using time of flight (TOF) technique, for which a pulsed primary beam would be very useful.

3. Elastic scattering measurements.

The low energy RNB produced by the RIBRAS system has been used to investigate low energy elastic scattering. A good number of experiments related to elastic scattering of radioactive nucleus on several targets have been performed. In general, elastic scattering can be an interesting measurement especially when one of the interacting particles is a loosely bound nucleus. Using the RIBRAS system we have investigated elastic scattering of $^6$He on $^9$Be [3], $^{27}$Al [4], $^{120}$Sn [5] targets and $^8$Li on $^9$Be [6], $^{12}$C [7] and $^{51}$V [6] targets. Elastic scattering can be considered an effective tool for revealing unusual features in nuclei such as extended halos or neutron skins for loosely bound nuclei. Some of these features can be present in the elastic scattering as influence of competing mechanisms and coupled-channel analysis would be required. For instance, due to the lower binding energy of the weakly bound nuclei either direct or sequential breakup can become an important competing mechanism, even at relatively low incident energies. In the analysis of elastic scattering measurements, breakup effect can be responsible, for instance, for a strong enhancement of the imaginary part of the optical potential giving rise, sometimes, to what is called breakup threshold anomaly [8]. The importance of these couplings is well known in the investigation of elastic scattering of the neutron rich nuclei $^6$He on different targets such as $^{209}$Bi [9], $^{64}$Zn [10] or less extensively in light target as $^{27}$Al [4] and $^{12}$C [11]. This effect is also present in the recent measurement of low energy $^8$B elastic scattering on $^{58}$Ni [12]. The role of the breakup can be investigated by plotting total reaction cross sections, derived from the elastic angular distribution, for weakly, and tightly bound nuclei, where different breakup threshold energies are involved, on the same target nucleus as a function of energy. To better compare the total reaction cross sections for the different systems we used the procedure suggested in Ref. [13]. In this proposed receipt, $\sigma_{\text{reduced}} = \sigma_R/(A_p^{1/3} + A_T^{1/3})^2$, where $\sigma_R$ is the total reaction cross section and the $E_{\text{reduced}} = E_{\text{C.M.}} \times (A_p^{1/3} + A_T^{1/3})/Z_P Z_T$, with $Z_P(Z_T)$ and $A_P(A_T)$ standing for the charge and mass of the projectile (target), respectively. In this way, the geometrical effects are, in principle, removed and the eventual anomalous values of the reduced radii $r_0$, which should be related to the physical processes to be investigated, are not washed out. Figure-2 shows the results of the reduced total reaction cross sections, $\sigma_{\text{reduced}}$, for many systems plotted as a function of the reduced energy. As one can see, the systems with halo ($^8$B + $^{58}$Ni [12] and two-neutron Borromean nucleus $^6$He + $^{209}$Bi, $^{64}$Zn, $^{27}$Al [14, 10, 4]) systems have reduced cross sections which lie above those for the weakly-bound normal nuclei (Li and Be isotopes projectiles [15, 16]) and much above then for the tightly bound projectile $^{16}$O. For the $^6$He+$^{27}$Al system the reduction cross sections are just a little above to the other weakly bound stable systems, indicating that for light target system the effect of breakup due to the halo on the reaction cross sections could be much smaller than the effect observed for heavier target. More recently, we have performed elastic scattering measurement of radioactive $^8$Li beam on $^{12}$C [7]. The total reaction cross section has been extracted from the optical model analysis and compared the results with the other $^6,^7$Li isotopes on also $^{12}$C. In Figure-3 we present the reduced cross section as a function of reduced energy for lithium isotopes $^6,^7,^8$Li as well as for the halo Borromean $^6$He nucleus and tightly bound $^4$He and $^{11}$B on the light target $^{12}$C. As one can see they all have the same behavior, indicating that for light target the effects of the binding energy of the projectile through the breakup on the reaction cross sections is very small. A similar plot for systems with heavier targets can be seen in Figure-4 of the reference.
[5]. For heavier target the total reaction cross sections for the exotic projectile $^6$He is higher than for the weakly-bound or tightly bound nuclei.

![Graph](image1.jpg)

**Figure 2.** The reduced reaction cross sections for many systems with weakly bound and tightly bound projectiles on medium mass target. The references for the data are in the text. The curves are just to guide the eye joining sets of data with similar behavior.

![Graph](image2.jpg)

**Figure 3.** Similar reduced reaction cross sections plot for systems with $^{12}$C target and weakly bound and tightly bound projectiles. The figure has been extracted from [7] and the references for the data are cited therein.

### 4. Transfer reactions measurement

Transfer reactions have also been performed using $^{8}$Li radioactive secondary beam produced by the RIBRAS system. The $^{8}$Li nucleus has some interest related to primordial nucleosynthesis since it could help to bridge the $A=8$ gap. For this the important reactions would be the $^{8}$Li($^4$He,n)$^{11}$B, $^{8}$Li(n,γ)$^{9}$Li and $^{8}$Li(p,γ)$^{9}$Be reactions. Moreover the $^{8}$Li(p,$^4$He)$^5$He reaction, with high positive Q-value=+14.42 MeV, would be the main path to avoid the synthesis of heavier elements. Thus, the comparison of the reaction rates for these reactions at
the astrophysical energies can be an important issue. To obtain the neutron and proton capture reaction cross sections by the $^8$Li we have applied the potential model [20]. One of the ingredient for these calculation is exactly spectroscopic factors. Thus, to obtain the angular distributions have been analyzed in terms of FR-DWBA (Finite-Range Distorted Wave Born Approximation) calculations using the code FRESCO [17] and SP potential [18]. The obtained spectroscopic factor for the $^8$Be($^8$Li+$p$) and $^8$Li($^8$Be+n) system, extracted from the angular distributions, were then used to calculate the capture cross-sections for the $^8$Li(p,γ)$^9$Be and $^8$Li(n,γ)$^9$Li capture reactions using the potential model [20, 21]. Also, we have measured the excitation function for the $^8$Li(p,$^4$He)$^5$He reaction between Ecm = 0.2 - 2.5 MeV in inverse kinematics. We impinged $^8$Li secondary beam on a polyethylene target (CH2) and detected the energetic α-particles at forward angles [3]. The reaction populates high lying resonances in the compound nucleus $^5$Be and R-matrix calculations are in progress.

5. Future plans

The many experiments performed so far with the RIBRAS system have shown that low-energy radioactive nuclear beams can be very suitable not only for spectroscopic investigations but also to study many reactions mechanisms. There are already on-going plans to keep performing experiments with $^4$He, $^7$Be, $^8$Li and $^8$B beams. There are also future plans to perform measurements of (α,p) and (p,α) reactions using radioactive beam in reverse kinematics and cooled gas target. These experiments are of strong interest for nuclear astrophysics. The future plan for this facility is to couple this system to a LINAC post-accelerator, which will deliver a higher energy primary beam. That should multiply by a factor 2 to 3 the actual maximum energy and should also deliver heavier beams. To inject a primary pulsed beam into LINAC a buncher system is under development.

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