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# The Scientific program with RIBRAS (Radioactive Ion Beams in Brasil)

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**Abstract.** The Radioactive Ion Beams Facility (RIBRAS) is in operation since 2004 at the Pelletron Accelerator Laboratory of the University of São Paulo and consists of two superconducting solenoids capable of producing low energy secondary beams of light exotic nuclei. Measurements of the elastic scattering, breakup and transfer reactions with radioactive projectiles such as $^{6}$He, $^{8}$Li, $^{7}$Be on several targets have been performed. A review of the research program carried on along the last four years using the RIBRAS facility is presented.

**Keywords:** radioactive beams, elastic scattering
**PACS:** 25.60.Bx, 29.38.-c

## INTRODUCTION

The possibility of producing secondary beams of unstable nuclei opened a huge field of research in Nuclear Physics. There are 283 stable nuclei and thousands of nuclides out of the line of stability with half lifes long enough to allow the production of secondary beams. Nuclei very far from the line of the stability and close to the drip lines, the so called exotic nuclei, present very interesting new features as the "neutron halo" observed in neutron rich nuclei such as $^{11}$Li [1], $^{11}$Be, $^{6}$He and others. The very low binding energy and low angular momentum of the valence neutrons in these nuclei favours the formation of a halo of neutrons which extends over large distances from the stable core [2] and has densities much lower than the normal nuclear density. The $^{11}$Li and $^{6}$He nuclei are examples of Borromean nuclei consisting of two neutrons loosely bound to a core $(n+n+c)$ forming a bound three body system. The study of the nuclear structure of the exotic nuclei is very motivating since it represents a challenge for the nuclear theorists who developed their models for the nuclei around the line of the stability. The modification or even the disappearance of the magic numbers observed for nuclei

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near to the neutron drip line is an example of this challenge. The presence of a very difuse nuclear surface due to the halo could have an effect on the spin-orbit interaction of the surface nucleons causing modifications in the shell structure. The existence of the exotic nuclei, on the other side, has certainly consequences in other fields as the astrophysics. The nucleosynthesis and the energy production in massive stars, where the temperatures and densities are sufficiently high to produce exotic species, can be affected by its presence in the stellar enviroment. For instance, the presence in massive stars of light neutron rich nuclei as the $^{6}$He and $^{8}$Li can play a role in the nucleosynthesis of heavy elements helping to bridge the mass $A = 5$ and $A = 8$ gaps [3].

In order to explore some of these new interesting subjects a group of physicists decided to install the Radioactive Ion Beams Facility (RIBRAS) in the São Paulo Pelletron Accelerator Laboratory. The 8MV São Paulo Pelletron is a low energy Tandem accelerator, capable of producing primary beams of stable elements in the energy range of 3-5 MeV/A and intensities of $1\mu Ae$ maximum. At these low energies the transfer reactions available for producing unstable nuclei have cross sections of about $10-20$ mb to be compared to the larger cross sections of fragmentation reactions of $\approx 100-200$mb at higher energies. For this reason a system of large acceptance is required to obtain useful secondary beam intensities. Solenoids are selectors with acceptance of about 30 msr in comparison to 5 msr of dipoles. For this reason a system of solenoids was considered to be the best option for our accelerator. The decision of using superconductors solenoids was taken in the perspective of the installation of a 10 MeV/A superconducting LINAC post accelerator in the future.

Since 2004 we are operating with RIBRAS in one of the Pelletron beam lines. We are performing measurements of elastic scattering angular distributions of $^{6}$He, $^{8}$Li and $^{7}$Be on several targets. These measurements allow a systematic study of the interacting potential of these exotic projetiles and the determination of the total reaction cross sections at low energies. Reaction channels other than the elastic, as the projectile breakup, neutron transfer reactions, the $p(^{8}Li,\alpha)$ and $^{12}C(^{8}Li,^{9}Be)^{11}B$ transfer reactions are also being investigated.

In this paper we present a description of the RIBRAS system and a review of the most important measurements performed until now.

## THE RIBRAS SYSTEM

The system consists of two superconducting solenoids [4, 5] of maximum field of 6.5T each and maximum $B\rho \approx 2$T.m. The criostats have 1 meter long per 1 meter diameter and are mounted on an aluminum bench of 7.5m length total. The bore of the criostats has 30cm diameter The primary target is mounted on a ISO chamber just before the first solenoid and consists of a gas cell with two windows. To produce the $^{6}$He and $^{8}$Li beams we use a $^{9}$Be exit window which is the primary target itself. As the entrance window we use a havar foil of $2\mu$m. Helium gas can be pressurized into the cell to cool down the Berilum foil which is heated by the high intensity primary beam. At primary beam currents above 500nAe the cooling is necessary to prevent the primary target breakdown, however, below this intensities, the cooling is not necessary and one can operate without gas in the cell. High pressure gas targets of a few bars are possible by using two havar windows in the cell. The usual production reaction at RIBRAS are $^{9}Be(^{7}Li,^{8}Li^{6}He)$, and $^{3}He(^{7,6}Li,^{7}Be)$ [6] and the intensities of secondary beams are of the order of $10^{5}$pps.

After crossing the primary target the primary beam is supressed in a tungsten Faraday cup which measures its intensity. A current integrator measures the total charge incident on the primary target during a run. The secondary particles produced in the forward direction are collected by the first solenoid within an angular acceptance of $2 \leq \Theta \leq 6$ deg. The magnetic field of the first solenoid is adjusted to focus the secondary beam of interest in an ISO-250 scattering chamber located in the middle between the solenoids. Due to the low energy of the machine we are presently using only the first solenoid and performing the experiments in the secondary scattering chamber in the midway between the two solenoids. The secondary targets are mounted in the center of the mid scattering chamber in a mounting which permits the change of up to 4 targets from the outside of the chamber without breaking the vacuum. The detectors are mounted in the scattering chamber on a rotating plate which allows the measurement of angular distributions. A systems of 4 Silicon telescopes $E(500-1000\mu m)-\Delta E(20\mu m)$ are normally used as the detector system and are mounted separated by 30 deg. A fixed detector can be mounted on the top of the scattering chamber to be used as a monitor. The area of the silicon detectores are between $150-300mm^{2}$ and the typical solid angles of the telescopes are in the range from 10 msr at the forward angles up to 50 msr at the backward angles. The secondary targets have typical thickness in the range of a few $mg/cm^{2}$ and its thickness are measured off-line by the energy loss of alpha particles from a $^{241}$Am source. Usually a heavy element target as gold is mounted and runs are performed during the experiment. In many cases at our energies the scattering in gold is pure Rutherford and it can be used for normalization of the cross sections and monitoring the secondary beam production rate. The energy resolution of the secondary beams is tipically in the range $0.5-1$ MeV and is determined mainly by the straggling on the primary target and the kinematics of the production reactions. The straggling in the primary target is calculated by the difference in energy of the reaction products coming from a reaction taking place at the beginning or at the end of the primary target.

## THE $^{8}Li$, $^{6}He+^{51}V$ SYSTEMS

The first experiment at RIBRAS has been performed in 2004 during the XIII J.A. Swieca Summer School in São Paulo. $^{8}$Li and $^{6}$He secondary beams have been produced at $E_{lab}=26$ MeV and $E_{lab}=23$ MeV respectively. The difference in energy of the secondary beams is due to the Q-values of the production reactions. Quasi-elastic angular distributions of $^{6}$He and $^{8}$Li on natural $^{51}$V have been measured and are presented in Fig.1. By a coincidence of energies between the alpha contaminant and the $^{6}$He beam we were able to measure two angular distributions at comparable energies for the $^{6}He,\alpha+^{51}$V systems. It allows a comparision between the halo $^{6}$He and the double magic $\alpha$ projetiles. One can see in Fig. 1 that the halo $^{6}$He is more absorptive.

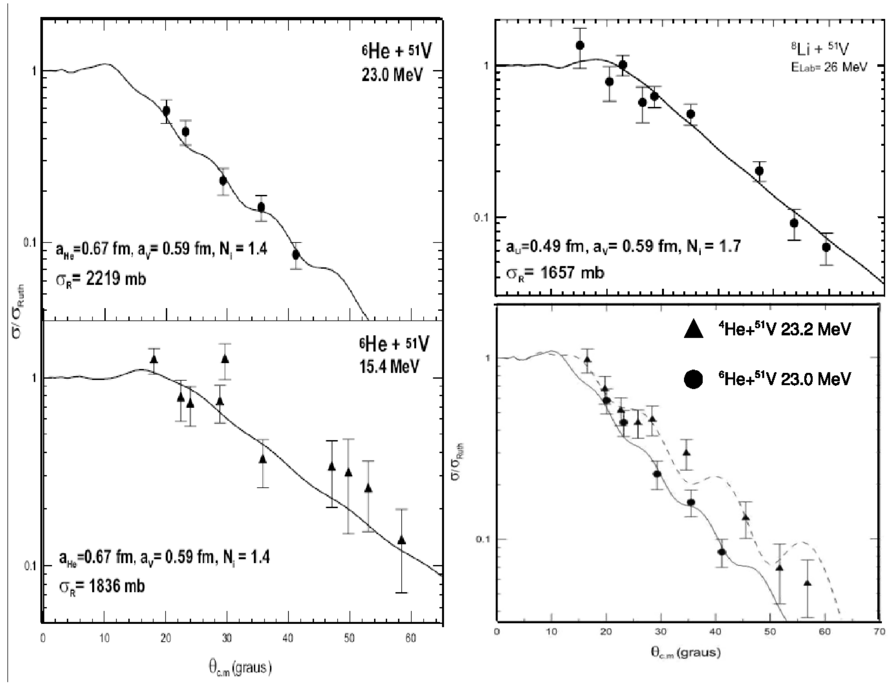


**FIGURE 1.** $^{8}$Li,$^{6}$He+$^{51}$V scattering angular distributions. Comparison between $^{6}$He and $^{4}$He+$^{51}$V at the same energy (right down). The solid curves are optical model calculations.

## THE $^{6}He+^{27}Al$ SYSTEM

Previous studies [7, 8, 9] of the elastic scattering of $^{6}$He and other stable weakly bound projectiles as on several medium mass targets have shown that there is a large enhancement of the total reaction cross section of the halo projectile in comparison to the weakly bound nuclei. The reaction channels causing this enhancement are not yet well identified and the first guess was that the projectile breakup could be responsible for the extra reaction cross section. As the $^{6}$He is a weakly bound halo nucleus it is expected that it will easily break into an alpha particle and two neutrons giving rise to this extra reaction cross section observed as an absorption in the elastic scattering. The idea was to extend the measurements of medium mass targets to lighter targets as the $^{27}$Al. In lighter targets the Coulomb breakup is less important compared to the nuclear breakup which becomes dominant. The $^{27}$Al was chosen due to the existence in the literature of previous measurements [7] of elastic angular distributions using several projectiles that would allow a systematic analysis of the reaction cross sections data. Four elastic scattering angular distributions $^{6}$He $+^{27}$Al have been measured at low energies and the results are presented in [5]. The data have been analysed by the Optical Model adjusting the normalization of the imaginary part and the difuseness of the density distribution to

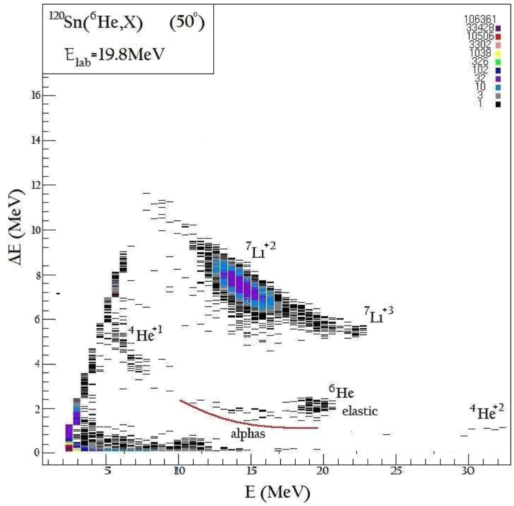


**FIGURE 2.** $E-\Delta E$ spectrum of the $^6$He+$^{120}$Sn collision

fit the angular distributions. The reduced reaction cross sections have been compared to other systems and apparently no enhancement with respect to the weakly bound projetiles is observed.

## THE $^6He+^{120}Sn$ SYSTEM

As the enhancement observed in the total reaction cross section for the $^6$He projectile apparently disappears for lighter targets, the next step is to extend the measurements to heavier targets. The $^{120}$Sn is an interesting candidate since it is not a very deformed nucleus, magic in protons, with its first excited state at 1.171 MeV which would be easily separated from the elastic peak. We measured elastic angular distributions of $^6$He $+^{120}$Sn at four energies ($E_{lab} = 17.4, 18.1, 19.8, 20.5$ MeV) a little above the Coulomb barrier. We used an isotopically enriched (98.29%), $3.8 mg/cm^2$, $^{120}$Sn target. Four $E-\Delta E(20\mu m)$ silicon telescopes have been mounted in the scattering chamber and angular distributions have been measured from 20 deg up to 75 deg in steps of 5 deg in the laboratory. We performed normalization runs with gold target in the begin and at the end of each $^{120}$Sn run. In Fig. 3 we present an $E-\Delta E$ spectrum of the particles emerging from the $^{120}$Sn target. The elastic peak is clearly separated of the $^7$Li$^{2+}$ contamination. In the alpha particle line there is a group of counts with a broad distribution of energies centered a little below the energy of the elastic peak. Further we will discuss in more detail the energy spectrum of the alpha particles and present some possible reaction mechanisms which could produce them.

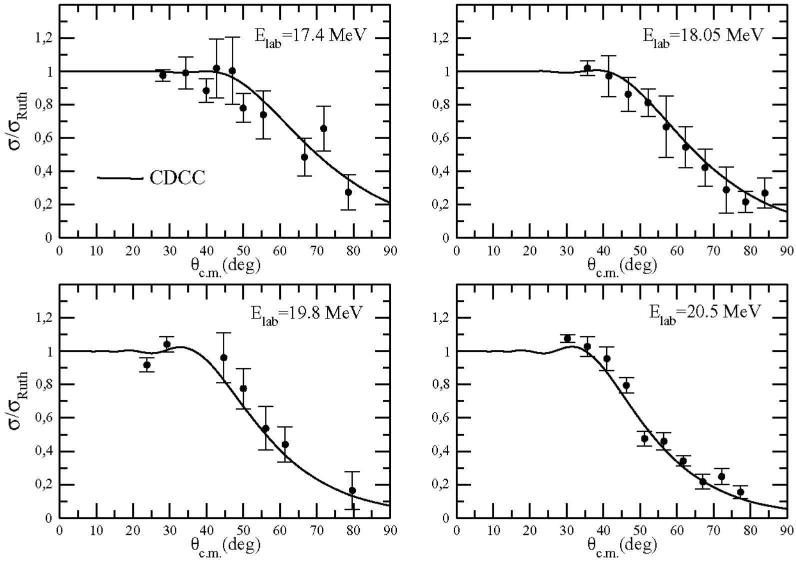


**FIGURE 3.** $^{6}$He+$^{120}$Sn elastic angular distributions compared to CDCC calculations

In figure 5 we show the elastic scattering angular distributions compared with CDCC calculations considering the breakup of the projectile $^{6}He \rightarrow \alpha + 2n$.

In this calculation an improved two body model is used to describe the wave function of the $^{6}$He [10] which simulates the realistic three body wave function. The elastic angular distributions are well reproduced by the CDCC calculations at the four energies measured. The total reaction cross obtained indicate that there is an enhancement with respect to systematics of the weakly bound projectiles on medium mass targets [7]. However the breakup cross sections which comes out from the CDCC calculations are much lower than the total alpha yield measured indicating that processes other than the projectile breakup are contributing to the alpha yield. The $1n$ transfer followed by the $^{5}$He breakup and the $2n$ transfer between the $^{6}$He projectile and the target are processes that produce alpha particles in the exit channel and could contribute to the observed alpha yield. As the transfer processes are known to be selective in Q-value, it is interesting to analyse not only the angular distributions but also the energy distribution of the alpha particles emitted.

The Q-value of a transfer reaction is determined by the difference in binding energies ($E_B > 0$ for bound states) of the transfered particle between the final and initial states $Q = E_{bf} - E_{bi}$ where $E_{bi}$ is refering to the binding energy of the transfered particle in the projectile (ground state) and $E_{bf} = E_{bf}^{gs} - E^{exct}$ refers to the transfered particle to a state of the final nucleus either the ground state $E_{bf}^{gs}$ or any excited state $E^{exct}$.

It is well known that there is an optimum value for the reaction $Q_{opt}$ around which the transfer process is more probable to occur. A simple estimate of the $Q_{opt}$ value is given by the formula:$Q_{opt} = E_{cm}[\frac{Z_3 Z_4}{Z_1 Z_2} - 1]$ [11]. This formula means that for neutrons

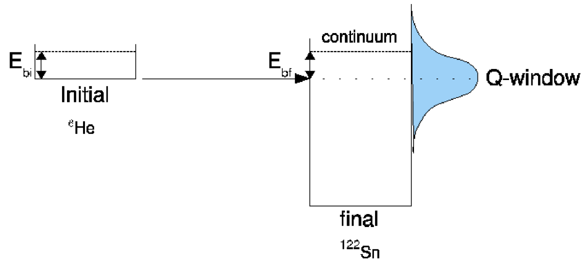


**FIGURE 4.** The picture represents the di-neutron transfer process. The transfer to weakly bound states in the final nucleus is favoured by the Q-window.

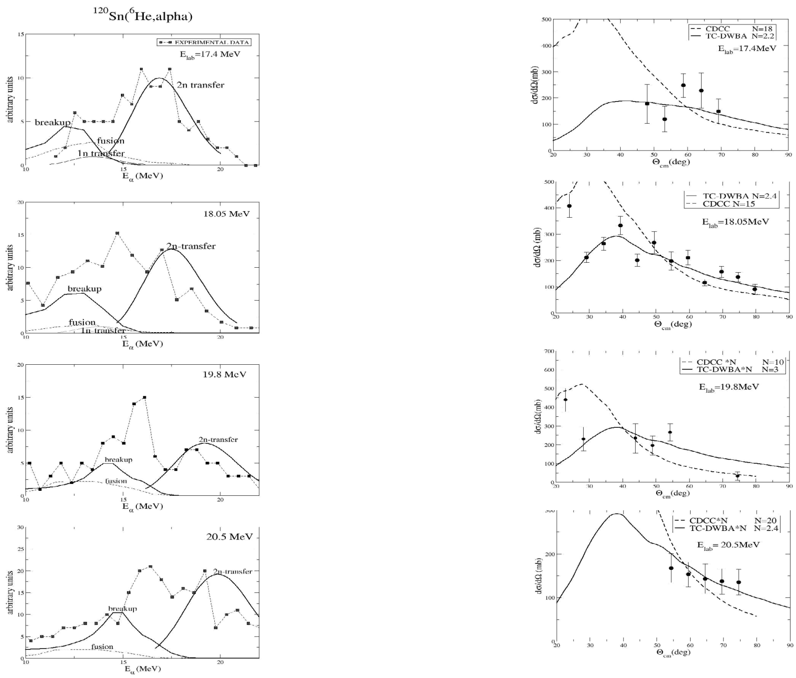


**FIGURE 5.** $^{120}$Sn($^6He,\alpha$) reaction. Energy spectra of the alphas(left) and angular distributions(right).

$Q_{opt} = 0$ and consequently the transfer to excited states of the final target nucleus for which $E_{bf} \approx E_{bi}$ would be enhanced. As for the weakly bound exotic projectile $^6$He, the initial binding energy of the transfered particle $E_{bi} = 0.973$ MeV is small, final states of low binding energies (but still bound states) will be favoured in the transfer process. Possibly final states in the continuum would also be populated due to the Q-window width (see Fig.4 above).

In the Fig. 5 we present energy spectra of the alpha particles corrected for the energy losses in the target, and compare to the Q-window calculations using the formula of [12] and suposing that the alpha particles are produced by the $2n$-transfer reaction $^{120}Sn(^{6}He,\alpha)^{122}Sn$. We see that at 17.4 MeV most of the alpha spectrum is reproduced by the Q-window indicating that the $2n$-transfer can be an important process. The breakup (CDCC) calculation on the other side predicts an energy distribution centered at lower energies. The $1n$-transfer reaction $^{120}Sn(^{6}He,^{5}He)^{121}Sn$ followed by the $^{5}He$ breakup predicts alpha particles of energies lower than the $2n$-transfer but higher than the $^{6}$He breakup in agreement with a part of the observed spectra at 18.05, 19.8 and 20.5 MeV.

We are presently performing DWBA calculations for $1n$ and $2n$ transfers considering the transfer to both, bound states and continuum states. The transfer to continuum (TC) resulted a much higher cross section compared to the breakup. Also the shape of the angular distributions in the TC calculations is in better agreement with the data compared to the breakup results (see Fig. 5 (right)) indicating that the neutron transfer is an important reaction channel.

## SUMMARY

The research program at RIBRAS so far consisted basically of elastic scattering measurements of $^{6}$He, $^{8}$Li and $^{7}$Be on light, intermediate and heavy mass targets at energies around and above the Coulomb barrier. These measurements can provide a systematic study of the interacting potential of exotic systems and the determination of total reaction cross sections which can be compared to other stable systems. We plan to extend this research program to identify other reaction channels such as fusion and transfer which could be responsible by the enhancement in the reaction cross section observed with halo projectiles.

## ACKNOWLEDGMENTS

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