Fusion of ^{6}He + ^{121}Sb : effect of the 2 neutron halo of ^{6}He on the fusion cross section.

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Abstract

The RIBRAS system, placed at the Institute of Physics, University of Sao Paulo, Brazil, is the first experimental facility to produce exotic projectiles in the Southern Hemisphere. So far many experiments have been performed to study the effect of the break-up of the exotic projectiles mainly on the elastic scattering. The present project proposes to measure fusion cross sections at low incident energies, using projectiles with neutron halo (^{6}He). The break-up of the projectile affects the fusion cross sections as it has been already seen with weakly bound stable projectiles, as i.e. ^{6,7}Li, ^{9}Be. At above barrier energies the fusion cross section is suppressed mainly due to the attenuation of flux due to the break-up. At below barrier energies there seem to be an enhancement due to the lowering of the Coulomb barrier, due to the larger barrier radius of weakly bound projectiles. However, there are not many measurements using radioactive halo nuclei as projectiles. There are some previous measurements using very heavy targets (^{209}Bi, ^{197}Au, ^{238}U) or targets around A~60. We propose to measure the ^{6}He +^{121}Sb fusion cross sections. Comparing the fusion cross section of ^{6}He +^{121}Sb and ^{4}He +^{121}Sb, where ^{6}He is a 2 neutron halo, weakly bound nucleus and ^{4}He is the tightest bound nucleus, we will learn about the static effects of the large neutron halo and the dynamic effects of the break-up of ^{6}He affecting the fusion cross section.

A widely used method for the measurement of fusion cross sections is the gamma-ray spectroscopy method, where the fusion events are identified by the detection of a characteristic gamma-ray emitted by an evaporation residue. We propose to measure the ^{6}He +^{121}Sb fusion cross sections using the gamma-ray spectroscopy method. If the evaporation residues are not stable, and their half-lives are sufficiently long, their decay can be measured off-line. If the evaporation residues are stable then the measurement has to be on-line, with particle-gamma coincidences. It will become possible in the near future with the recent upgrades that are being performed at the RIBRAS system: prolongation of the beam line of the RIBRAS system and installation of a new small chamber for gamma detection. The high purity gamma detectors have to be very well shielded from the neutrons produced in the production target; they will be installed behind a neutron shielding after the second superconducting solenoid, also called “gamma cave”. The gamma cave will allow the measurements of particle-gamma coincidences in nuclear reactions which will enhance the possibility to identify different channels populated in the decay of the compound nucleus, formed in the fusion process. For the above measurements, we plan to have two time scales: For the first year we begin with the activation-off-line measurements, which do not demand any modification in the RIBRAS and can be realized at any moment. When the up-grade is finished (probably in middle 2017) we can perform the on-line measurements using the gamma-cave. With this system it is possible to measure the yield of medically important radionuclide ^{124}I (3n)..

Introduction. Physics of Halo nuclei

Since the beginning of nuclear physics, the atomic nucleus remains a fascinating quantum-laboratory, which is still full of surprises and challenges. Earlier, the knowledge of nuclear physics was somewhat restricted to stable nuclei, which, for mass number A<60 contains almost equal number of protons and neutrons. Now-a-day, the availability of Radioactive Ion Beams (RIBs) has started a new era not only in the field of nuclear physics but also in nuclear astrophysics, nuclear biology and nuclear medicine. Some very weakly bound radioactive nuclei, close to the drip-line, present a normal core and halo of neutrons (1 or 2), as ^{11}Li, ^{11}Be, ^{6}He, ^{8}He etc. This strange effect is due to the absence of Coulomb and centrifugal barrier for the valence neutrons, which can be found at quite large distances from the core (several fermis). Owing to the unique characteristics of halo nuclei, the reactions induced by them differ in a fundamental way from those involving tightly bound nuclei. For instance, small binding energy, large values of isospin, Borromean structure, large break up probabilities, etc. of halo nuclei are expected to strongly affect all the possible reaction channels over a wide energy range. Among all reaction channels, the fusion has attracted a great deal of attention from the beginning of nuclear reaction studies.

Over the last decade, new experimental techniques have been developed world wide, for the production of RIBs. In this respect a low energy facility pushing to produce light exotic projectile was installed in 2004 at the Sao Paulo Pelletron laboratory of the University of Sao Paulo, Brazil. This facility extends the capabilities of the original 8MV Pelletron accelerator and is named as RIBRAS (Radioactive Ion Beams in Brazil) [1]. With this facility many elastic experiments have been performed so far, starting from lighter targets (A=9,12, 27)[1] to medium and heavy mass targets (A=51,58,120) [1]. The reason of choosing the elastic scattering experiments is the possibility to clearly distinguish the elastic events from other events produced by the contamination of secondary beams. This was an experimental circumstance, which during the first years of RIBRAS did not allow the production of purified radioactive beams. On the other hand, the elastic scattering experiments may provide information on the structure of light nuclei near the drip line. After the recent up-grade of RIBRAS finished with the installation of a large scattering chamber after the second solenoid, we are in excellent conditions to perform other reactions also, as fusion, inelastic and transfer reactions.

Starting with the first experimental measurement of fusion with halo projectiles, the ^{6}He+^{209}Bi system at energies above the barrier [2,3] was studied. The fusion cross-section was extracted using an activation technique by detecting α-particles emitted in the on-line and off-line decay of the evaporation residues. An enhancement of the sub-barrier fusion cross-section was observed, when compared with a statistical model calculation, single barrier penetration calculations [3] and, fusion induced by ^{4}He onto the same ^{209}Bi target. Further, the effect of break up processes associated with light exotic projectiles impinged on heavy targets (^{206}Pb, ^{238}U) were studied [4-6], where very large total reaction cross sections have been observed. The enhancement in the total fusion cross-section with heavy targets may be due to the intense long range coulomb field. As such, Coulomb break up predominates for heavy systems. To explore the break up dynamics with medium mass targets, Navin *et al.* [7] measured neutron-transfer and fusion cross-sections for the ^{6,8}He +^{63,65}Cu system, at energies around the Coulomb barrier. They compared the data of ^{6,8}He with ^{4}He+^{63,65}Cu systems and observed large cross-section for neutron transfer channels. Recently, Scuderi et al [8] reported the enhancement for the ^{6}He+^{64}Zn system at below barrier energies.

On the side of theoretical calculations, a qualitative model is proposed by K. Hagino [9], where coupling to channels leading to break up enhances fusion cross-section below the fusion barrier, but suppresses it above. However, a realistic modeling to understand the effect of break up on fusion is extremely complex, requiring incorporation of excitation mechanism, break up lifetimes, subsequent motion of the fragments, and probabilities of absorption of one or both fragments. Such a model will be needed to interpret future measurements of fusion with weakly bound radioactive nuclei. Moreover, Diaz-Torres *et al.* [10] proposed a three-dimensional classical model for low-energy breakup fusion reactions. This model allows a consistent calculation of break up, incomplete, and complete fusion cross-sections but is limited only for certain weakly bound projectiles. To solve the controversy about the presence of suppression or enhancement effects in the fusion cross section and to disentangle static (halo) and dynamic (break-up) effects more good quality data are needed.

In view of the above, we propose to study the elastic scattering, fusion, (and transfer + breakup) channels for the ^{6}He + ^{121}Sb system at energies starting from below the Coulomb barrier to above it. The available fusion measurements with ^{6}He projectile were made in the target mass regions A~60 [7,8] and A~200 [2-6], there are no experimental data around A~120. The proposed system, will help to enlighten the influence of the ^{6}He halo structure on the reaction mechanism, because available experimental data for the systems as ^{4}He + ^{121}Sb and ^{4}He+^{123}Sb are present over a wide energy range starting from Coulomb barrier in literature [11,12]. Comparing the results of the proposed experiment ^{6}He + ^{121}Sb with ones with ^{4}He projectile and the same target ^{121}Sb may enlighten the influence of the ^{6}He halo structure on the reaction mechanism. During the analysis of the proposed system, there may be a chance to measure the yield of medically important radio nuclide ^{124}I(3n) [12]. It should be mentioned that the measurements will be done using the ^{6}He beam delivered by the RIBRAS system at the Institute of Physics of the University of Sao Paulo, Brazil. At present most experiments performed at RIBRAS were on elastic scattering angular distributions and excitation functions. In order to have better understanding on the issues related to break up effects, we are going to extend by the study of fusion reactions. The capabilities are in upgrade by the installation of a Gamma cave beyond secondary scattering chamber after second superconducting solenoid [13]. Although, a complete description of the RIBRAS system is available elsewhere [1], however, a short account of the RIBRAS system and its extension is detailed in next section. In section 3, the investigated reaction channels, their Q-values and the reaction products together with their decay characteristics is presented.

II.The RIBRAS system

The Radioactive Ion Beams in Brazil (RIBRAS) [1] is a system based on two superconducting solenoids to produce secondary beams of unstable nuclei. The use of the two magnets in RIBRAS is important to purify the secondary beams. To produce these secondary radioactive beams, the RIBRAS system uses the "in-flight method", where the radioactive beams are produced on-line by a nuclear reaction (one or two-nucleon transfer reactions), triggered by a stable primary beam on a stable production target. The continuous stable beams are accelerated by the long standing 8UD Pelletron Tandem accelerator [14]. At present the maximum energies are between 2–5MeV/nucleon. The RIBRAS system consists of two large air-cores (30 cm clear warm bore), superconducting solenoids with 6.5T maximum central field. The system has three chambers, one before the first solenoid (small ISO chamber) called as chamber-1, which contains the production target. A central scattering chamber (25 cm diameter ISO chamber) located between the two solenoids and called chamber-2. Recently, a large (70 cm diameter) scattering chamber was installed after the second solenoid, named as chamber-3. A typical photograph of the RIBRAS system is shown in Fig.1 along with their lateral, upper, and schematic views of the three chambers.

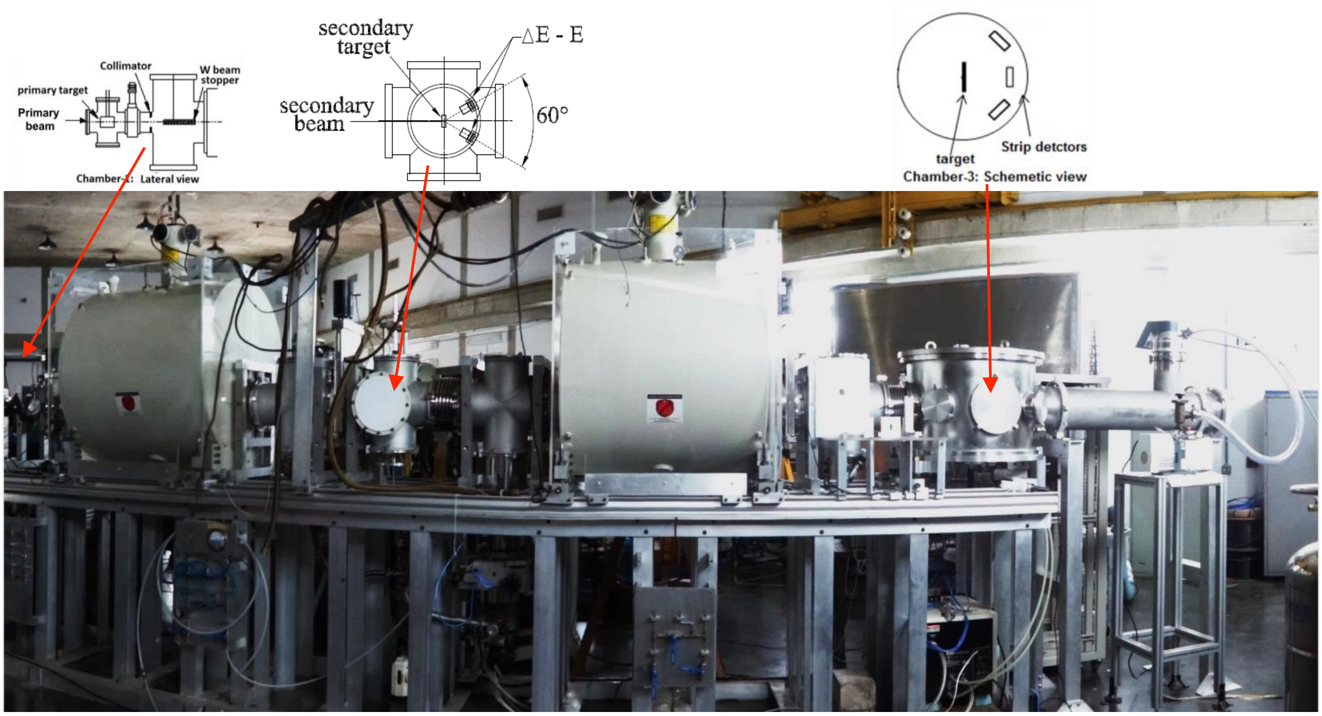


Fig. 1. A typical snapshot of RIBRAS set-up: the stable beam comes from the left, the production target, located in chamber-1 is followed by the W beam stopper and the first solenoid, which is followed by the central scattering chamber-2, with the secondary target and detectors installed in it, followed by the second solenoid and the large scattering chamber-3. A Turbo pump is installed on the beam line mounted in continuation after the chamber-3. The "gamma-cave" will be installed on this beam-line.

The first solenoid makes an in-flight selection by the magnetic rigidity of the reaction products emerging from the primary target in the forward angle region (i.e. 2^0 to 6^0). The secondary beams produced after first solenoid may have contaminations, since all particles with the same magnetic rigidity but different masses, charges and energies are focused at the same point. A system of blockers and collimators are positioned strategically along the RIBRAS beam line. The blockers are circular obstacles (*lollipop*) and can be conveniently positioned at any point along the beam axis. On the other hand, the collimators limit the angular range and cut contaminants that have angular ranges larger than the beam of interest.

Even with the use of these blockers and collimators the beam in the chamber-2 is a cocktail beam, with different beam particles of same magnetic rigidity. To obtain complete beam purification, one has to use both solenoids, and the experiment should be performed in chamber 3. When degraders of different materials, such as Al, Au, kapton or $[CH_2]_n$ polyethylene foils are mounted in the chamber 2, the energy loss of particles with different A,Z will be different and after the degrader they will not have any more the same magnetic rigidity. As a typical example for the ^{6}He secondary beam, a purification from 16% in chamber-2 to 92% in chamber-3 was obtained by using a $[CH2]_n$ foil of 12 μm as a degrader placed in chamber-2 [1,15], as shown on Figure 2.

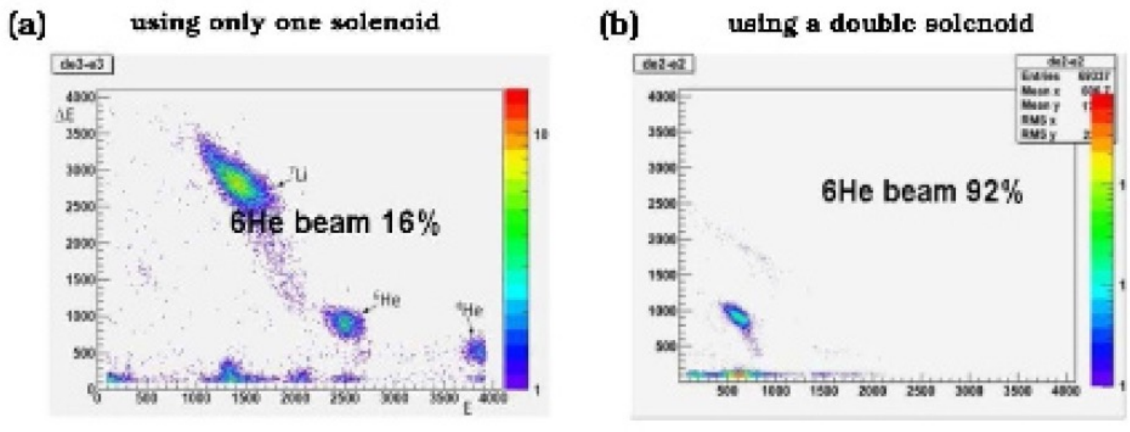


Figure 2. Spectra ΔE-E in the chamber-2 (a) and in the chamber-3 (b). A degrador was used in chamber-2 to improve the purity of the secondary ^{6}He beam from 16% to 92%.

III.Probing break up effects for A=121

Much interest has been shown in recent years in the study of break up fusion reaction dynamics in light exotic interactions at low incident energies, i.e, from below the Coulomb barrier (E~0.8 Vcb) to above Coulomb barrier (E~1.5Vcb) [1-9]. An important step in this study is to identify the reaction channels responsible for the increase of the total reaction cross section. As discussed earlier, the neutron transfer reactions and projectile break up processes have been identified as important channels induced by the neutron rich ^{6}He projectile when impinged on heavy or medium mass targets. Information of considerable value may be obtained from elastic scattering angular distributions which help in developing the optical model analysis and allow determining the total reaction cross section, which is a quantity of great interest. Also, higher quality data are needed to observe the effect of Borromean nature of ^{6}He on the reaction cross section at low energies.

In view of the above, it is proposed to measure the elastic scattering and fusion cross-sections for the system ^{6}He+^{121}Sb below and above the Coulomb barrier. This projectile-target combination forms the composite excited nucleus ^{127}I*. In literature, fusion cross sections for the systems ^{4}He+^{121}Sb and ^{4}He+^{123}Sb [11,12] are available over a wide energy range (i.e. starting from Coulomb barrier to well above it). Comparison of the experimental data obtained from the proposed experiment with the one already existing on $^{4}He+^{121}Sb$ may give valuable information about the effect of the halo of the Borromean nucleus. The comparison will be useful to determine the two neutron halo cross section [1] ($\sigma^{halo} = [\square^{6He+121Sb} - \square^{4He+121Sb}] \times (A_P^{1/3} + A_T^{1/3})^2$).

IIIa Measurement of the fusion cross sections.

We will divide the project in two parts: the first one will use the RIBRAS as it is operational today: with purified beam but without the “gamma-cave” facility. The second one can be realized when the gamma-cave becomes operational, probably from the second semester of 2017.

In the fusion process of two nuclei the compound nucleus is formed at high excitation energy, which de-excites by the emission, “evaporation” of light fragments, mainly neutrons, protons and α-particles, leaving behind the evaporation residues (ER), which can be excited stable or unstable nuclei. The cross section of fusion can be measured by the detection and identification of the γ rays and x-rays emitted by the evaporation residues (ER) and their daughters. If ER are unstable and decay by β^{+}, β^{-} or electron conversion (EC) and their half-lives are long enough, than the measurement can be realized off-line, and one will use the RIBRAS as it is operational today: with purified beam but without the “gamma-cave” facility. If the evaporation residues (ER) are stable, their γ-de-excitation is instantaneous and the measurement has to be realized on-line. These measurements can only be realized when the gamma-cave is operational and will constitute de 2nd part of the work.
The off-line measurements which will be realized in the first part can be divided in two operations:
1.Activation part: during the time Ti (irradiation time) the target is irradiated by the beam, the reaction produces the compound nucleus (CN), which evaporates, neutrons, protons and alphas, and the evaporation residues (ER) are produced, but they also decay to their daughters.
2.Detection part: After Ti, the activation stops, the irradiated target is dismounted and is taken to the detection system, where 3 HPGe detectors and a Si-pin detector will begin to measure the γ and/or x-ray de-excitation of the daughters of the evaporation residues. The detection time is called Td. The time lost between the end of irradiation and the beginning of detection is called Tm.
In the following we will give some details of the spectroscopic properties of the evaporation residues, their daughters and the simulations performed to predict the counting rates and show the feasibility of the measurements.

III.b.Proposed system:

P-T*	Projectile	Target	CN	Status
A	$^{6}_{2}He$	$^{121}_{51}Sb$	$\mathbf{^{127}_{53}I}$	Not present
C	$^{4}_{2}He$	$^{121}_{51}Sb$	$\mathbf{^{125}_{53}I}$	Available [11,12]

*P-T : Projectile target

III.c.Organization of work elements:

Proposed system: $^{6}He+^{121}Sb \Rightarrow ^{127}I^{*}$
Coulomb barrier (V_{cb}) in MeV $\Rightarrow$ 15.3 MeV
Irradiation energies (E_{Lab}) $\Rightarrow$ from 0.8 Vcb= 12 MeV to 1.5Vcb= 23 MeV.

Radius ⇒ 9.60 fm

Separation energies for ^6He projectile ⇒

$^6He \to {}^5He + n$	Neutron	S_n	→ 1.866 MeV	
$^6He \to {}^4He + 2n$	Two neutrons	S_{2n}	→ 0.972 MeV	
$^6He \to {}^5H + p$	Proton*	S_p	→ 22.594 MeV	Large separation energies
$^6He \to {}^4H + d$	Deuteron*	S_d	→ 21.441 MeV	
$^6He \to {}^3H + t$	Triton*	S_t	→ 12.305 MeV	

*As the separation energy for proton, deuteron and triton are quite high for ^{6}He radioactive isotope, therefore, in the present work we may not have break up particle (Z=1) in the forward cone. However, we may have particle emission (z=1,2) via de-excitation of compound nucleus.

Spectroscopic properties of the reaction residues populated in $^6He + ^{121}Sb$ system ⇒ See Table-A below

Table A: List of populated reaction channels with spectroscopic properties of ER and daughters of ER•.

•Data has been taken from NNDC website: (http://www.nndc.bnl.gov/)

Nuclear Reaction	**Q-value (MeV)**	**Half-life of ER**	**J^π**	**E_γ (MeV) of daughter of ER**	**Decay prob. f_d^i (%)**
^{121}Sb(^{6}He,n)^{126}I	+7.833	12.93d	2^-	388.6(^{126}Xe)	34.1
				666.3(^{126}Te)	33.1
				753.8(^{126}Te)	4.16
				491.2	2.85
^{121}Sb(^{6}He,2n)^{125}I	+0.688	59.4d	$5/2^+$	35.5(^{125}Te)	6.68
^{121}Sb(^{6}He,3n)^{124}I	-8.854	4.18d	2^-	602.3(^{124}Te)	61.00
				723.4(^{124}Te)	10.06
^{121}Sb(^{6}He,4n)^{123}I	-16.384	13.2h	$5/2^+$	158.9(^{123}Te)	83.3
				528.95(^{123}Te)	1.39
^{121}Sb(^{6}He,5n)^{122}I	-26.282	3.62 m	1^+	564.37(^{122}Te)	18
				692.9(^{122}Te)	1.28
^{121}Sb(^{6}He,α)^{123}Sb	+14.79	STABLE•	7/2+	-	-
^{121}Sb(^{6}He,αn)^{122}Sb	+5.830	2.7 d	2^-	564.7	70
				692.9	3.82

Table B: List of stable ER with their spectroscopic properties in the present work (^{6}He+^{121}Sb).

Nuclear Reaction	**Q-value (MeV)**	**Half-life of product**	**J^π**	**Threshold energy (E_{th})**
^{121}Sb(^{6}He,p)^{126}Te	+10.769	STABLE•	2^-	No Threshold
^{121}Sb(^{6}He,d)^{125}Te	+3.800	STABLE•	$5/2^+$	No Threshold
^{121}Sb(^{6}He,t)^{124}Te	+3.596	STABLE•	2^-	5.15 MeV
^{121}Sb(^{6}He,tn)^{123}Te	-5.855	STABLE•	$5/2^+$	15.05 MeV

$^{121}Sb(^{6}He,t2n)^{122}Te$	-12.788	STABLE▪	1^{+}	22.32 MeV
$^{121}Sb(^{6}He,\alpha)^{123}Sb$	+14.79	STABLE▪	7/2+	No Threshold
$^{121}Sb(^{6}He,\alpha 2n)^{121}Sb$	-0.970	STABLE▪	2^{-}	1.02 MeV

From the above tables (A & B), one can find that the neutron emission channels (^{6}He,xn) lead to unstable ER with half-lives which vary between 13.2 hours (4n) and 59.4 days (2n). The 3n channel has 4.18 days of half-life. These measurements are feasible with the actually existing RIBRAS system. The use of purified beam is absolutely necessary since one of the main contaminant beams is the ^{4}He, which could also produce the same ER and contaminate our results. $^{121}Sb(^{4}He,n)^{124}I$ has the same ER as $^{121}Sb(^{6}He,3n)^{124}I$ and $^{121}Sb(^{4}He,2n)^{123}I$ as $^{121}Sb(^{6}He,2n)^{123}I$.

On the other side the charged particle reaction channels are leading to stable ER and cannot be studied by the activation, off-line detection techniques and will not be the subject of our studies at the beginning. However, these reaction channels can be studied with the help of on-line measurements using particle-gamma coincidence techniques and will be the subject of our proposal in the second part, when the gamma-cave becomes operational.

In the following we present the results of theoretical calculations of the cross sections for all decay channels of the fusion reaction. We have used 2 codes, PACE4 which assumes the formation of equilibrated compound nucleus and its decay and ALICE91, which calculates the decay of the pre-equilibrium stage of the CN also. The equilibrium cross sections are similar by both calculations, however the pre-equilibrium decay by n-emission is very important at higher energies for the (^{6}He,n) and (^{6}He,2n) channels, as it can be seen on Fig.3.

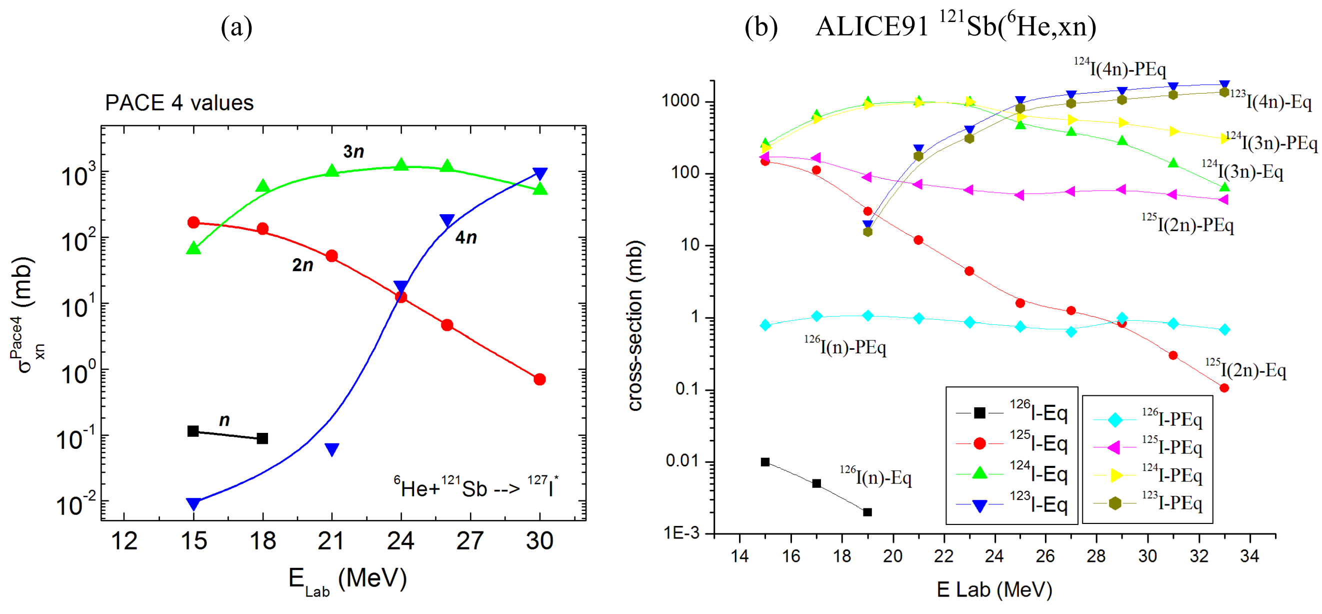
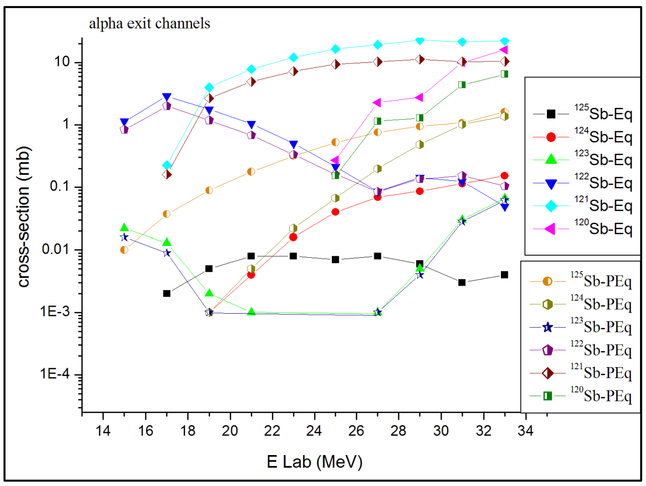


Figure 3. (a) PACE4 calculations of the neutron evaporation channels of the $^{121}Sb + ^{6}He \rightarrow ^{127}I^{*}$ compound nucleus. (b) ALICE91 calculations of the same quantities. The equilibrium cross sections are similar by both calculations, however the pre-equilibrium decay by n-emission is very important at higher energies for the (^{6}He,n) and (^{6}He,2n) channels.

At energies below the Coulomb barrier (E<15 MeV) the (^{6}He,2n) channel is the most important, while above the barrier the 3n and 4n channels become predominant, with high corss section, between 100 and 1000mb. The 1n channel has very low cross section at all energies, even including the pre-equilibrium contribution.

The charged particle decay channels are shown below on Figure 4. They present lower cross-sections at the energies of interest, alpha-xn evaporation channels are less than 10mb and the p-xn less than 100mb, while the xn channels were less than 1000mb.

(a) $^{121}Sb(^{6}He,\alpha xn)Sb$ (b) $^{121}Sb(^{6}He,pxn)Te$



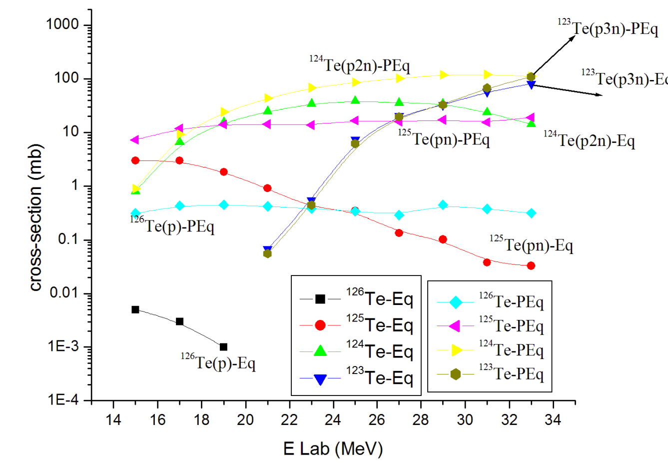


Figure 4. (a) ALICE91 calculations of the alpha-xn evaporation channels of the $^{121}Sb + ^{6}He \rightarrow ^{127}I^*$ compound nucleus. (b) ALICE91 calculations of the p-xn evaporation channels of the $^{121}Sb + ^{6}He \rightarrow ^{127}I^*$ compound nucleus.

IIId Calculations for the feasibility of the experiment:

Prevision of the number of γ-rays detected for the $^{121}Sb+^{6}He$ fusion reaction

Phase I: off line measurements

Beam: ^{6}He produced by the $^{9}Be(^{7}Li,^{6}He)^{10}B$ reaction. CH_2 degrader in chamber-2.

Beam intensity in the chamber-3 ~10^4-10^5 pps

Target: 99.4% enriched ^{121}Sb isotope, metallic foil of 2mg/cm^2. The natural Sb has 2 stable isotopes 121Sb (57%) and 123Sb (43%). The use of natural Sb, with 123Sb also present, would superimpose 121Sb(6He,4n) and 123Sb(6He,2n) channels and make impossible to disentangle the 2 contributions.

Energy losses: The 6He beam loses from its incident energy 0.5 MeV (for E=12.5 MeV) and 0.36 MeV (for E=22.5MeV). Thus the excitation function of the fusion reaction will have a certain uncertainty in energy due to this energy loss. The evaporation residues stop in the target.

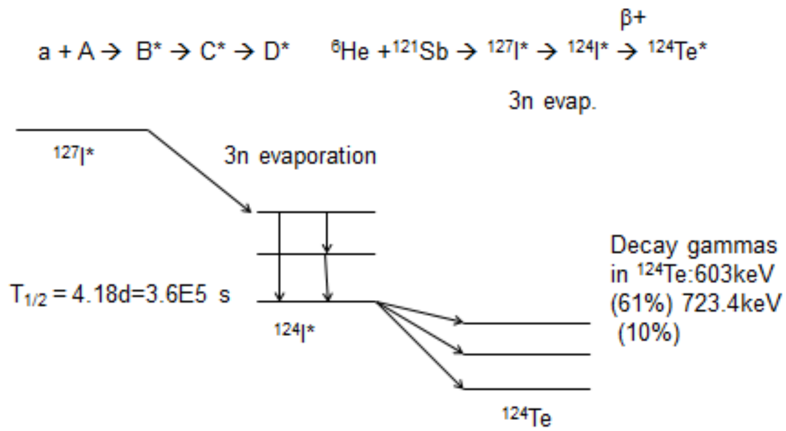
Chamber: We will use the chamber-3, since the use of purified beam is absolutely necessary because one of the main contaminant beams is the ^{4}He, which could also produce the same ER and contaminate our results. $^{121}Sb(^{4}He,n)^{124}I$ has the same ER as $^{121}Sb(^{6}He,3n)^{124}I$ and $^{121}Sb(^{4}He,2n)^{123}I$ as $^{121}Sb(^{6}He,2n)^{123}I$.

Beam intensity measurement: During the experiment we can measure the beam intensity indirectly, measuring the elastic scattering of 6He on a gold target, which is Rutherford at forward angles.. The gold target should be mounted before the 121Sb target, the gold target well fixed on the target holder ladder and the Sb target easily removable.

Elastic scattering measurement : Several Si telescopes mounted in the chamber, on a rotating plate centered with the target will measure the elastic scattering on Gold and on 121Sb, during the 4 days irradiation time.

Calculations of the counting rate we can expect for the 3n channel, and for the 2n and 4n channels

For example:



Nc(t) = (Qc/λc) (1- exp(- λc t))   this gives the number of nuclides C in the target after time t of irradiation.

If we irradiate during Ti, have a dead time Tm(between stopping the irradiation removing target, installing in front of HPGe detectors and begin the counting) and count during Td, the number of decays of the nuclide C during the counting time Td will be ΔNc:

ΔNc = (Qc/λc)* (1- exp(- λc Ti))*(1- exp(- λc Td))* exp(-λc Tm)

where is the yield of the production of nuclide C

$Qc= N_{target} /cm^2 * N_{inc}/s * \sigma_c$ ~4.5/s for σ_c~1000mb

where σ_c =cross-section of production of nuclide C and $\lambda c=\ln 2/ T_{1/2}$

We can plot ΔNc as a function of T1/2 for different sets of Ti and Td in order to optimize the measurements

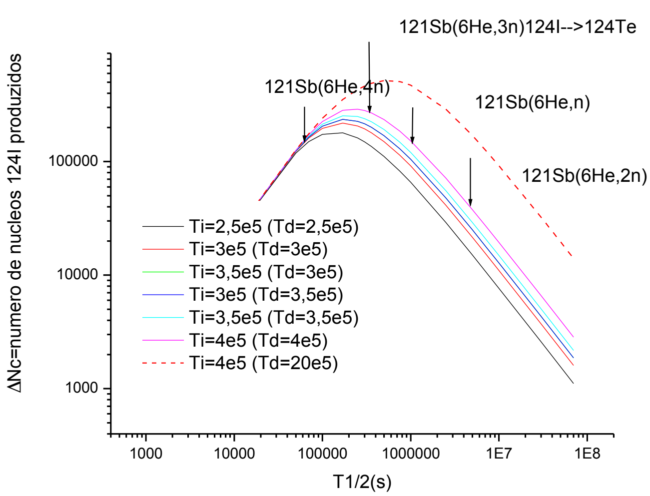


Figure 5 ΔNc as a function of T1/2 for different sets of Ti and Td, supposing 2mg/cm2 121Sb target.

The number of gamma-rays detected is obtained multiplying ΔNc by the total detector efficiency and the decay procentage f_d^i :

We assume the total efficiency (intrinsic*geometric) of the 2 HPGe array as 0.5%,
Ti=Td= 4,6 days , the (6He,3n) channels will count respectively 1000 counts of the 603keV γ-ray, and the (6He,4n) channel will count 700 counts of the 153 keV γ-ray.
For the (6He,2n) channel which has T1/2=59.4 days and x-ray of 35.5 keV, we will leave the target in front of a Si(Li) detector for 23 days, and expect to have also about 1000 counts (the intrinsic efficiency of the Si(li) is close to 100%).

III.e Experimental Plan:

The experiment will be carried out at the RIBRAS facility of the Pelletron Accelerator Laboratory of the Institute of Physics, University of Sao Paulo, Brazil.
The measurements will be performed in 2 steps;
First phase:
Elastic scattering measurements and Fusion Excitation function measurements using activation-off line detection
Second phase:
Particle-gamma coincidence measurements

i) Elastic Scattering measurements: The elastic scattering angular distribution measurements for the ^{6}He+^{121}Sb system will be studied in Chamber 3 of RIBRAS facility, simultaneously with the activation measurements. The detection system consists of several surface barrier $\Delta E - E$ Si telescopes, with thin (20–25 μm) ΔE detectors, followed by E detectors of 300, 500 or 1000 μm. During the irradiation time Ti (typically ~4 days for each beam energy) the telescopes will move and a total angular distribution can be measured for the beam energy in question. The target ^{121}Sb and a gold target should be mounted together and the scattering of 6He on the gold target will monitor the secondary beam intensity and to provide an absolute normalization of the cross sections. As such, the scattering of these radioactive projectiles on gold, at the energies and angles is pure Rutherford.
The elastic scattering cross section in the center-of mass frame, for the system of interest, will be deduced using an expression below:

$$\sigma_{cm}(\theta) = \frac{N_c}{N_c^{Au}}\frac{N_b^{Au}}{N_b}\frac{N_t^{Au}}{N_t}\frac{J}{J^{Au}}\sigma_{cm}^{Au}(\theta)$$

where N_c is the area of the peak of interest, J is the Jacobian, a factor of transformation from the laboratory to the center of mass system, N_b is the total number of beam particles during the run, N_t is the surface density of the target of interest in number of atoms/cm^2, N_c^{Au}, J^{Au}, N_b^{Au} , N_t^{Au} are the corresponding numbers with the gold target. This expression has the advantage of being independent of the detector solid angle. The ratio N_b^{Au}/ N_b is taken as the ratio of the accumulated charge of the primary beam, measured with the integrator during the runs with gold and the target of interest, and in our case will be 1.

ii) Fusion Excitation function measurements using the activation method: In these measurements, the 121Sb target will be irradiated during Ti ~4 days, dismounted, put in front of the HPGe and/or Si(li) detection systems in a well shielded area (probably mounted in the LINAC experimental area), to measure the γ and x-rays of deexcitation of the ER daughter nuclei. The characteristic γ-lines and half-lives of the residue will be used to identify the reaction channels and their intensity will be used to determine the absolute cross-sections for the reactions of interest. As said above, for the 3n and 4n channel the detection time will be 4 days, if necessary we can use larger times for the 2n channel. A new target is mounted in chamber-3, the accelerator energy is changed, the solenoid currents are changed and a new irradiation begins at a new beam energy. Again the irradiation time is about 4 days. We will need several 121Sb targets (at least 2) and the total activation time for the excitation function for the fusion reaction $^{6}He+^{121}Sb$ will be N*4 days, where N is the number of beam energies in the excitation function.

<u>iii) Particle-gamma coincidence measurements:</u> It is planned to use the SACI-PERERE Gamma Detector Array and Charged Particle Array [18] installed in a new small chamber (Chamber-4 in project) well shielded from the neutrons (gamma-cave) produced at the production target in chamber-1, to measure the charged particle reaction channels, which are leading to stable ER in $^{6}He+^{121}Sb$ system, as well as 2n-transfer reaction and incomplete fusion. The Gamma cave will have the array of 3 high purity Germanium (HPGe) detectors which will detect the prompt gammas in coincidence with particles emitted from reactions; this is an important step to enhance our capability to separate different reaction channels of interest. As has already been discussed, the solenoids of RIBRAS have no magnetic shielding, thus, the residual field in the region of the scattering chambers-2 or -3, where the detectors could be mounted, can be as high as tens or even hundreds of Gauss. Magnetic fields of such intensities prevent the use of detectors that depend on electron collection such as ionization chambers, proportional counters, micro-channel plates, and photomultiplier tubes. Only silicon detectors and fast avalanche detectors like parallel plate avalanche counters (PPAC) work in such magnetic fields. In order to operate with the usual gamma detectors, a new scattering chamber is being produced, distant from the solenoids, in a region where the magnetic field is sufficiently small to not affect photo-multiplier operation. Therefore as an extension of the RIBRAS system a Gamma Cave is already in preparation. In addition, a shield for the neutrons will be necessary since the secondary neutron beam of RIBRAS is intense and could damage the Ge detectors.

In the present work, the energy of the break up α particle from the ^{6}He light exotic projectile in forward cone is calculated at the highest studied energy ($E_{Proj} \approx 25$ MeV) and is found to be $E_{BU}^{\alpha} \approx 16.6\,MeV$ (using equation $E_{BU}^{\alpha} = E_{proj} \times \frac{A_{eject}}{A_{proj}}$, where E_{proj} is energy of the projectile in lab frame, A_{eject} is mass of the spectator and A_{proj} is the mass of the projectile). On the other hand, the alpha-particle after the de-excitation of the CN has energy$E_{CN}^{\alpha} = 13.53\,MeV$, at the 25MeV projectile energy calculated from the PACE4 model. One can see that both alpha-particles can be disentangled and appropriate gates can be generated to study 2n-transfer reaction process (i.e. $^{123}Sb^{*}$). It may be mentioned that, nuclei formed in the present work are well known rotational nuclei and the data on prompt gammas transitions are available in literature [15-16]. The energy of the particle (z=1) has also calculated from the PACE4 code and has been found to be 7.0-8.5 MeV at the proposed studied energies. Therefore, the charged particle reaction channels can be studied with the proper gating conditions. The Gamma cave is the well neutron shielded chamber-4 on the RIBRAS beam-line after the Chamber-3 which will contain the SACI-PERERE system consisting of a 4π charged particle detector-ball and 3 Compton suppressed n-type HPGe detectors.

Chronogram:
First-phase: 1 year.
activation off-line measurements + elastic scattering: first 6 months of the pos-doc stage.
Data-analysis of the above data: next 6 months
Second-phase: 1year
Particle-gamma coincidences to measure other reaction channels: incomplete fusion, 2n-transfer, break-up etc.

Summary:
The fusion reaction of the system 6He+121Sb will be measured in the first year, using the activation + off-line gamma spectroscopy to measure and identify the de-excitation channels of the compound nucleus. The elastic scattering can be measured simultaneously with the activation. The RIBRAS system is ready to perform this measurement. Other reaction channels could be measured in a second phase, using a neutron shielded new chamber with the HPGe+charged particle detector array (SACI PERERE) [18], and the particle-gamma coincidence method. The interest is due to the 2n-halo structure of the projectile 6He which can strongly affect all reaction channels observed.

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Proposta de Experimento | **Nº:**

Período: 1 ano

Título: Medidas de fusão do sistema $^{6}He+^{121}Sb$
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e-mail: alinka@if.usp.br
Número de dias solicitados: 20 dias
Datas preferidas:
Datas realmente impossíveis:
Canalização: 45º B

Feixe	Est. Carga	$I_{mínima}$ (feixe primário)	V_{min}	V_{max}
^{7}Li	3	500 nA	4 MV	8.0 MV

Alvos: 121Sb, ^{197}Au
Pastilhas: oxido de 7Li
Características de Feixe Pulsado:
Continuação da Experiência já Aprovada N°:
Outras informações:

Vamos usar o metodo de ativação e espectrosopia gamma off-line para medir a secao de choque de fusao. Devido a vidas medias longas envolvidas (entre 4,18 e 59,4 dias) devemos ter longos periodos de irradiacao (Ti=4 dias) durante os quais tambem estaremos medindo distribuicao angular elastica. Para termos 5 energias na funcao de excitacao da fusao, em torno da barreira, necessitamos de 20 dias de feixe. Sera aprimeira medida de fusao com nucleo halo 6He no Pelletron-RIBRAS.