An overview of exotic nuclei studies using the “Radioactive Ion Beams in Brasil” (RIBRAS) facility

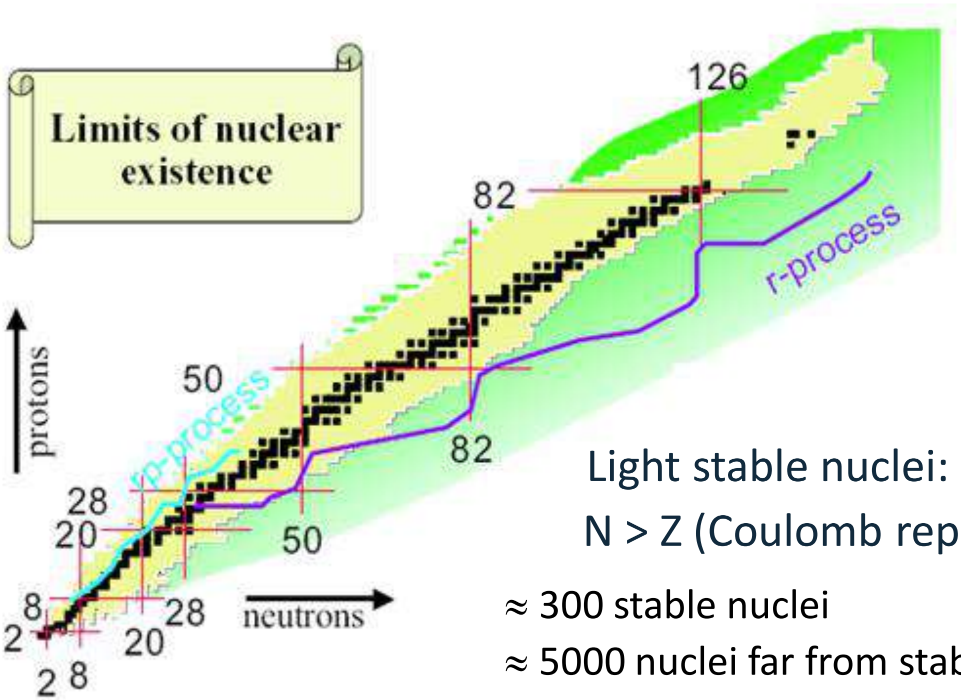
K. C. C. Pires, R. Lichtenthäler, A. Lépine-Szily, O. C. B. dos Santos, U. Umbelino, A. S. Serra, B. P. Monteiro, H. F. G. Arruda, D. A. Santana, F. R. Loureiro, J. A. E. Narváez and RIBRAS Collaboration

IF-USP

Outline

- Exotic nuclei: some of their properties
- Motivation to study nuclei outside the stability line
- The RIBRAS system
- The research program
- Conclusions

The nuclide chart: Nuclear Physics' field of study



Light stable nuclei: N ≈ Z

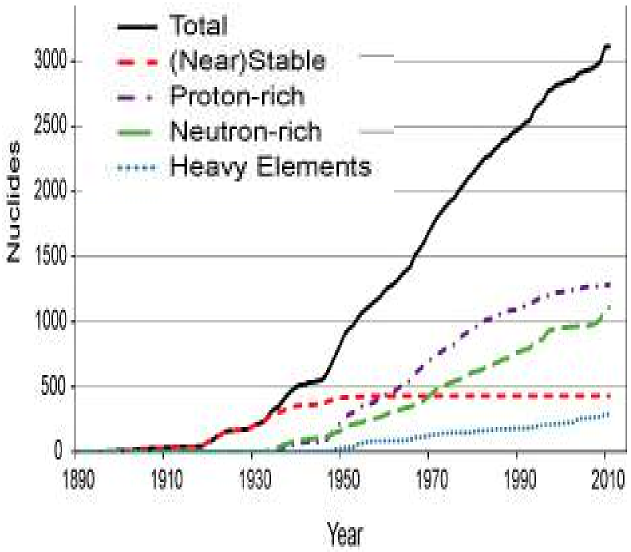
N > Z (Coulomb repulsion)

≈ 300 stable nuclei

≈ 5000 nuclei far from stability line

A lot of nuclei not observed but foreseen nuclear BE

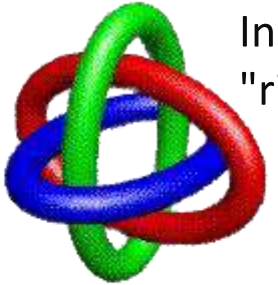
M Thoennessen
Rep. Prog. Phys. **76 (2013)** 056301



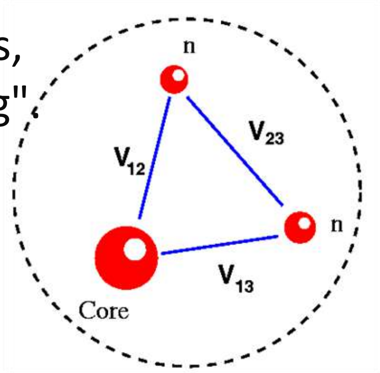
Halo effect and Borromean Nucleus

Distribution of nuclear particles beyond the typical range of nuclear forces

Particles around the nucleus, which significantly increases its radius



In nuclear physics, "rings" = "binding",



Borromean Nucleus:

$^{6}He = {}^{4}He + 2n$

$^{11}Li = {}^{9}Li + 2n$

System of N nucleons, where removal of any one nucleon renders the system unbound

2n

$^{5}He = {}^{4}He + n$

$^{10}Li = {}^{9}Li + n$

not bound

Other properties of exotic nuclei

- Exotic nuclei in general are far from the line of stability
- Show different properties from those of stable nuclei.
    - an excess of protons (proton-rich) or neutrons (neutron-rich),
    - low binding energy;
    - half-lives that can vary from days to minutes to microseconds.

weakly bound nuclei	B.E(MeV) (structure)
^{6}Li	1.47 (α+d)
^{7}Li	2.46 (α+t)
9Be	1.67 (α+α+n)

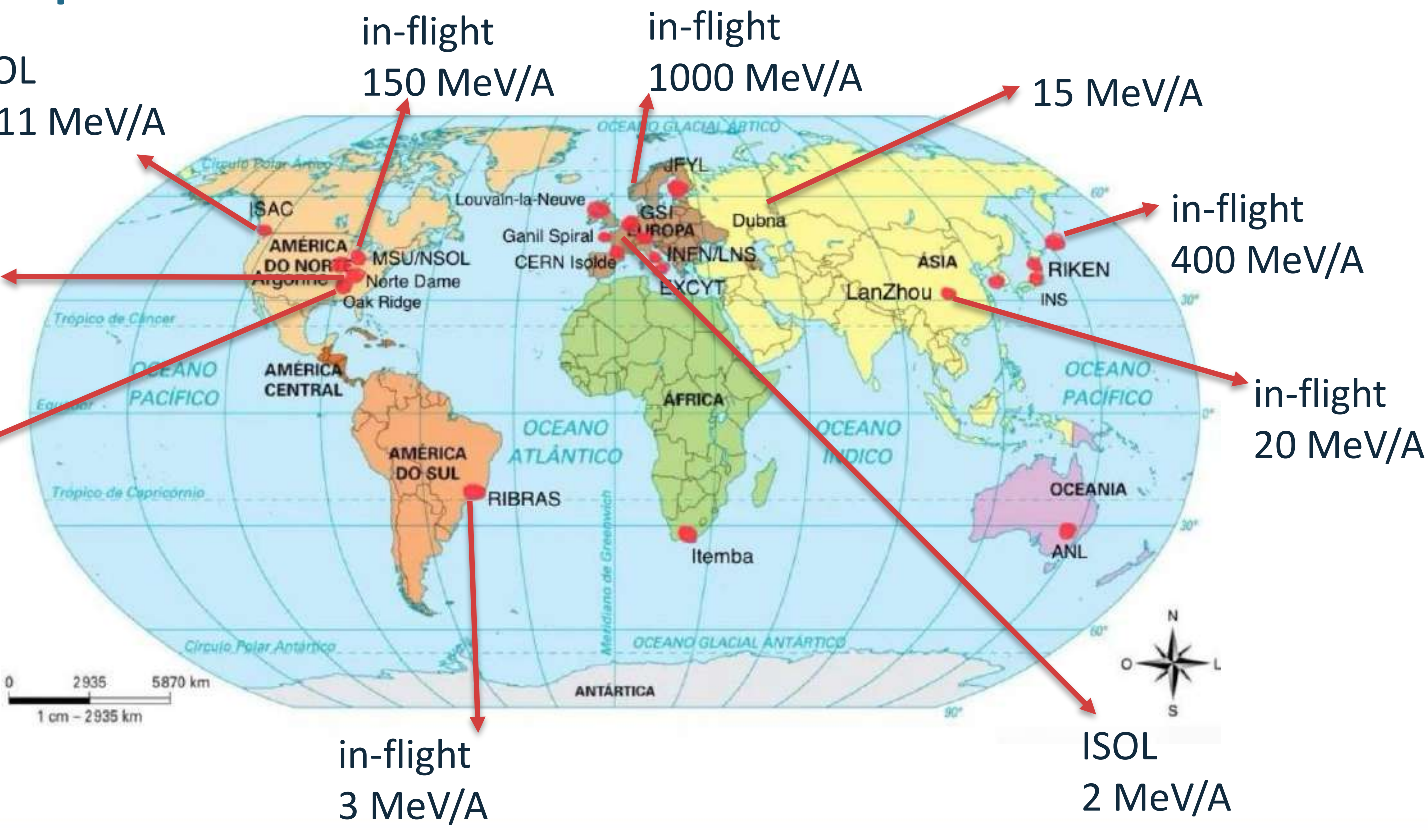
exotic nuclei	B.E(MeV) (structure)	
^{11}Li ($T_{1/2}$=8.75ms)	0.300 (n+n+^{9}Li)	→ three-body
^{6}He ($T_{1/2}$=807ms)	0.973 (n+n+alfa)	↗ three-body
^{11}Be ($T_{1/2}$=13.81s)	0.501 (n+^{10}Be)	
^{8}B ($T_{1/2}$=770 ms)	0.137 (p+^{7}Be)	
^{17}F (64.5 s)	0.6 MeV (p+^{16}O)	
	0.1 MeV for 1st ^{17}F excited state	

Stable nuclei have separation energies for protons and neutrons around 7-10 MeV.

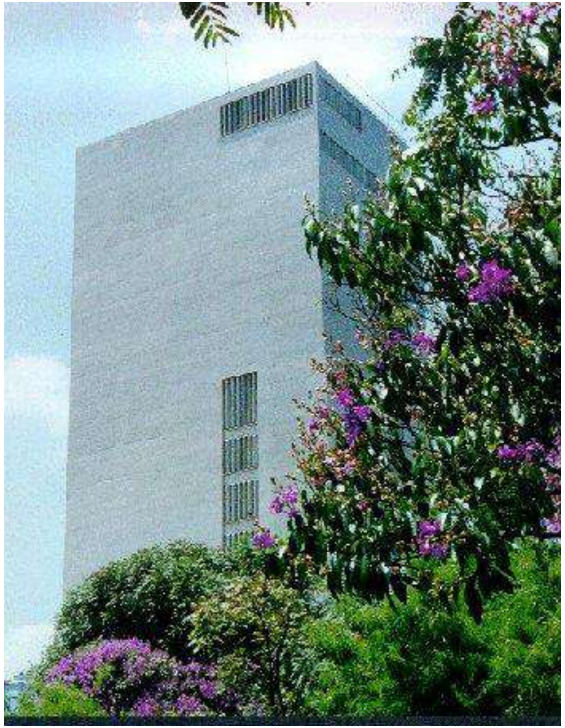
Why to study nuclei outside the stability line?

- What are the limits of the atomic nucleus?
- Testing nuclear models under extreme conditions of isospin and very low binding energies. Nuclear models were developed based on data from nuclei near the stability line.
- How does nuclear structure depend on isospin?
- Measurements of masses and radii of nuclei near the drip line. New phenomena such as neutron and proton halos / neutron skin.
- Nuclear Astrophysics: The nucleosynthesis of elements in stars involves paths that include exotic nuclei.
- Applications: Production of radioisotopes for medicine.

Rare Isotopes Beam facilities in the world

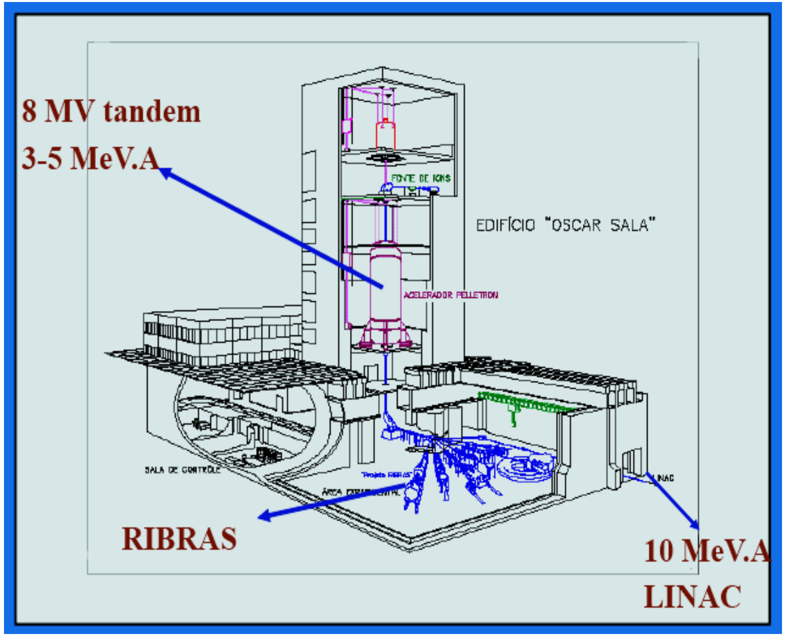


Major Facility for Nuclear Physics research in Brazil



Tandem Accelerator
Pelletron 8UD

University of São Paulo
Brazil



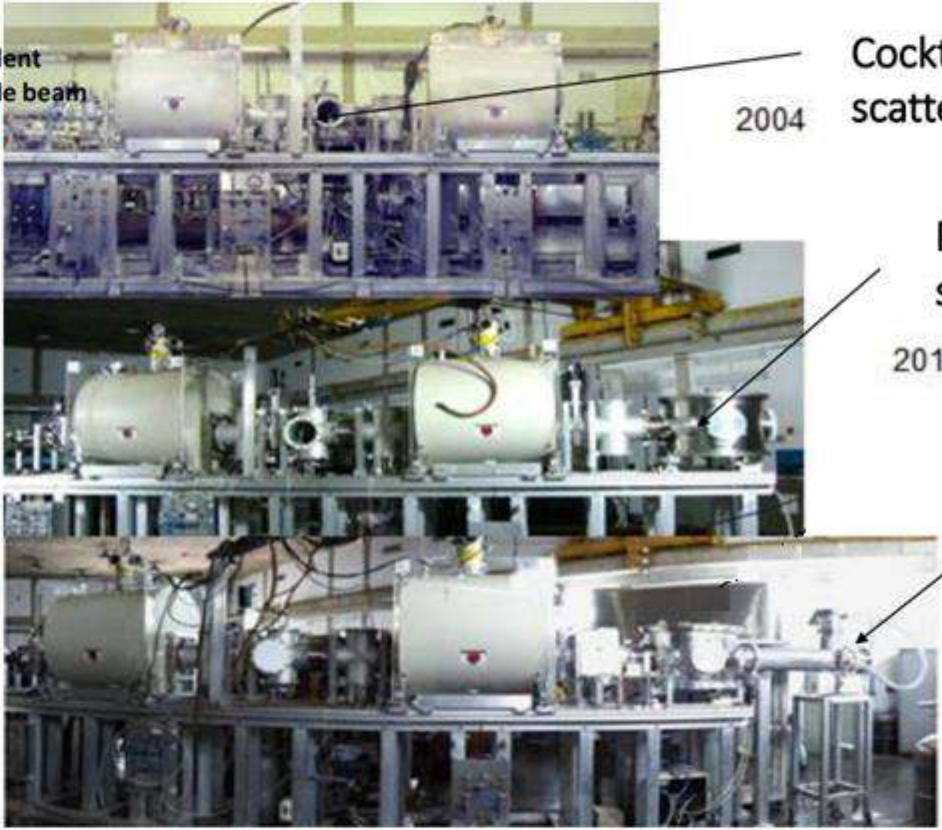
primary beams:

^{6}Li, ^{7}Li, ^{10,11}B, ^{9}Be, ^{12}C, ^{16,17,18}O, ...

RIBRAS - Radioactive Ion Beams in Brasil

First RIB facility in the Southern Hemisphere, installed in 2004

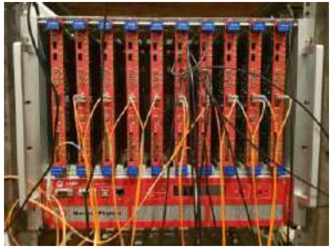
Incident stable beam



2004 Cocktail beams in central scattering chamber

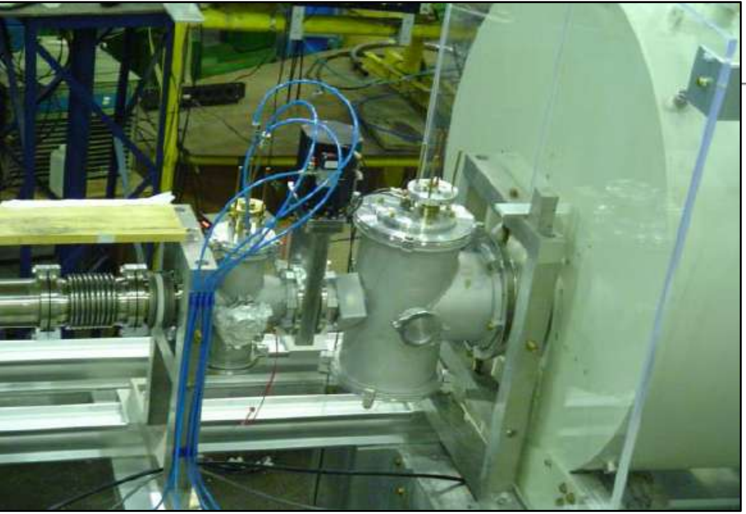
2011 Purified beams after second solenoid

2015 New chamber for γ-detectors



2022

Evolution over the years

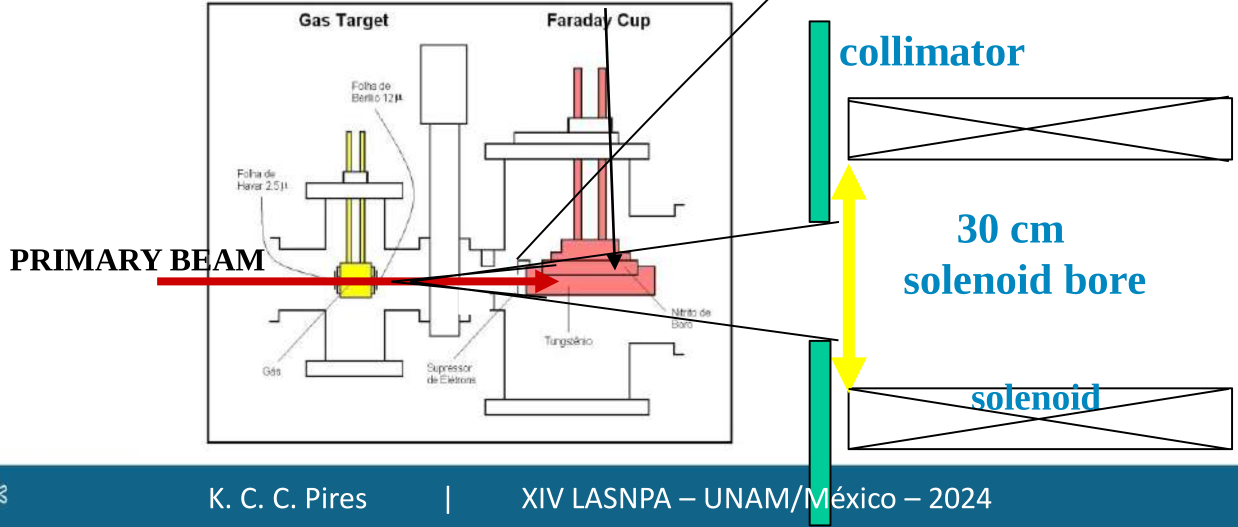


Production target

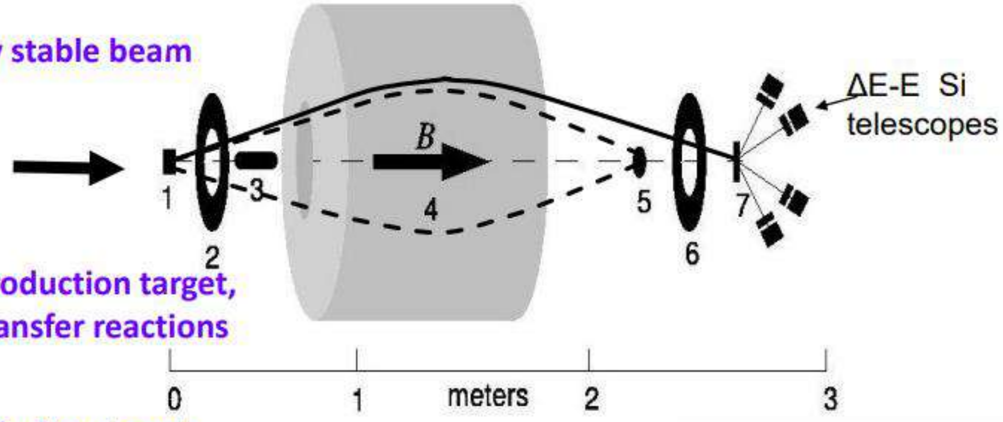
Solid targets: ^{9}Be, LiF, ^{12}C, etc
or gas targets

Angular acceptance

$$2\,\text{deg} \leq \Delta\theta \leq 6\,\text{deg} \longrightarrow 30\text{msr}$$



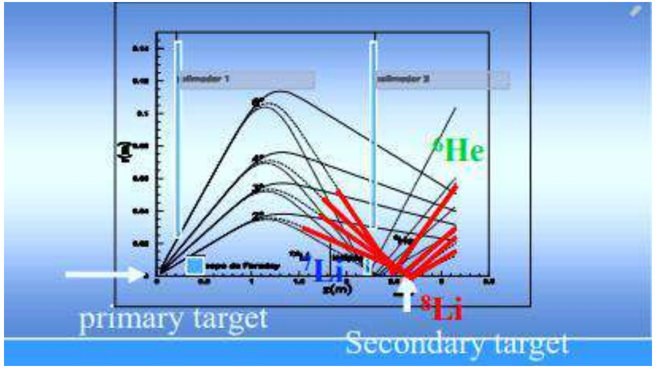
Selection with the first solenoid



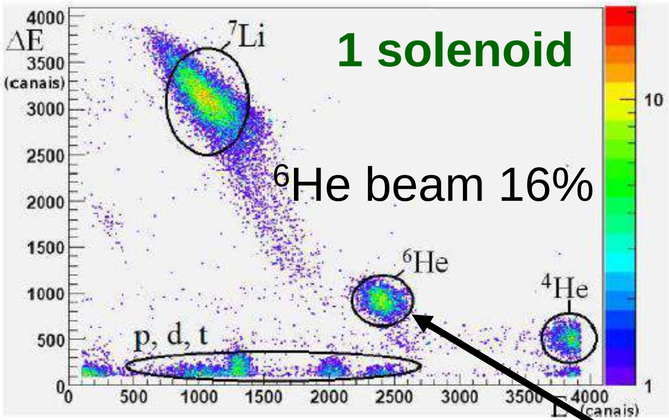
1- production target
2- collimator
3- Faraday cup
4- solenoid
5- lollipop blocker
6- collimator
7- scattering chamber,
secondary target and
detectors

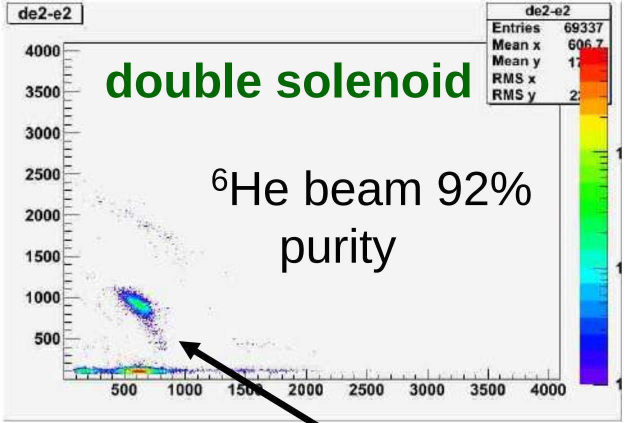
$$B\rho = \frac{mv}{q} = \frac{\sqrt{2mE}}{q}$$

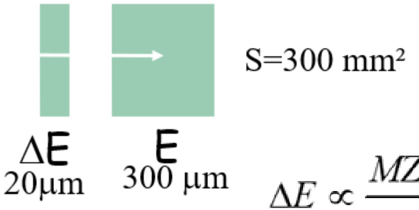
Maximum Bρ=1.8Tm



Beam purification using double solenoids



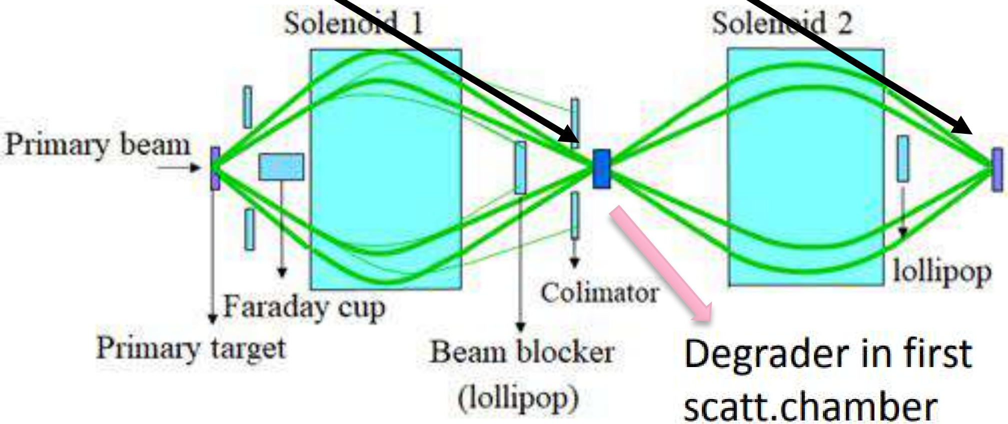




$$\Delta E \propto \frac{MZ^2}{E}$$

$$B\rho = \frac{mv}{q} = \frac{\sqrt{2mE}}{q}$$

$^{7}Li + {}^{9}Be \rightarrow$ ^{7}Li, ^{8}Li, ^{6}He, ^{4}He, t, d



Degrader in first scatt.chamber

Second solenoid helps cleaning the secondary beam: degrader changes the Bρ of the particles with different Z (q)

Production reactions beams at RIBRAS

target(projectile,ejectile)recoil

↓ primary target — ↓ primary beam — ↓ secondary beam

Secondary Beam	Production Reaction	Intensity (pps)	
^{6}He	$^{9}Be(^{7}Li,\underline{^{6}He})$	10^{+5}	($I_{primary}$ ~ 300 nAe)
^{8}Li	$^{9}Be(^{7}Li,\underline{^{8}Li})$	10^{+5}	
^{7}Be	$^{3}He(^{6}Li,\underline{^{7}Be})$	10^{+5}	
^{7}Be	$^{3}He(^{7}Li,\underline{^{7}Be})$	10^{+5}	
^{8}B	$^{3}He(^{6}Li,\underline{^{8}B})$	10^{+4}	
^{10}Be	$^{9}Be(^{11}B,\underline{^{10}Be})$	10^{+4}	
^{7}Be	$^{7}Li(^{6}Li,\underline{^{7}Be})$	10^{+5}	

Scientific interest at RIBRAS

IFUSP Instituto de Física da USP

Inclusive measurements of nuclear reactions with weakly-bound, cluster-structured, low-energy, light, radioactive ion beams

Elastic scattering:

- $^{6}He + ^{9}Be, ^{27}Al, ^{51}V, ^{58}Ni, ^{120}Sn$
- $^{7}Be + ^{9}Be, ^{27}Al, ^{51}V$
- $^{8}B + ^{9}Be, ^{27}Al$
- $^{8}Li + ^{9}Be, ^{58}Ni, ^{120}Sn, ^{12}C$
- $^{7}Be, ^{9}Be, ^{10}Be$ on ^{12}C
- $^{12}B + ^{58}Ni$

(only first solenoid,cocktail beams)

Breakup measurements: $^{6}He + ^{120}Sn \rightarrow ^{4}He + X$ (2 neutron transfer)

$^{8}Li + ^{58}Ni \rightarrow ^{7}Li + ^{59}Ni$ (1 nêutron transfer)

Resonance scattering with radioactive beams on H target

$^{8}Li + p, ^{6}He + p, ^{10}B + p$

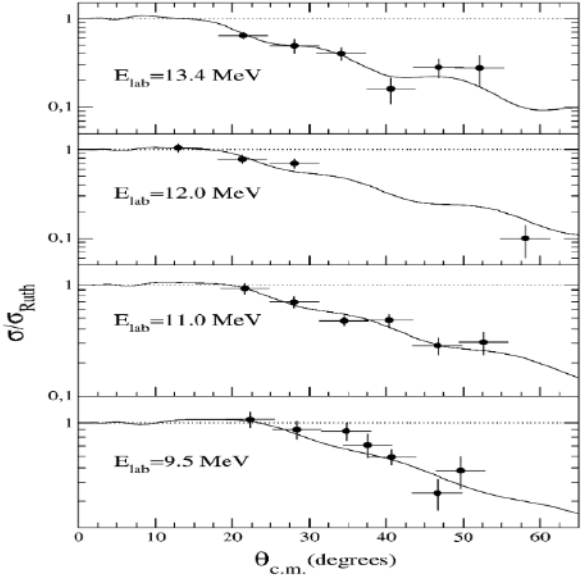
Some results at RIBRAS

Physics Letters B 647 (2007) 30–35

$^{6}He+^{27}Al$ elastic scattering

First results of RIBRAS

Optical Model calculation São Paulo potential (N_I~0.7 ; a=0.56(2)=normal nuclear diffuseness)

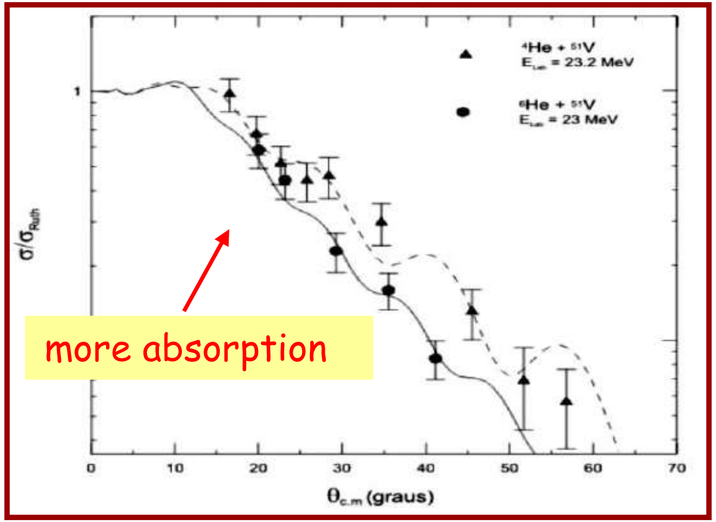


No effect of breakup coupling.

Nuclear Physics A 834 (2010) 491c–494c

$^{6}He+^{51}V$ elastic scattering

Optical Model calculation São Paulo potential (N_I~1.4(4) ; a=0.67(3) larger than normal nuclear absorption and diffuseness)

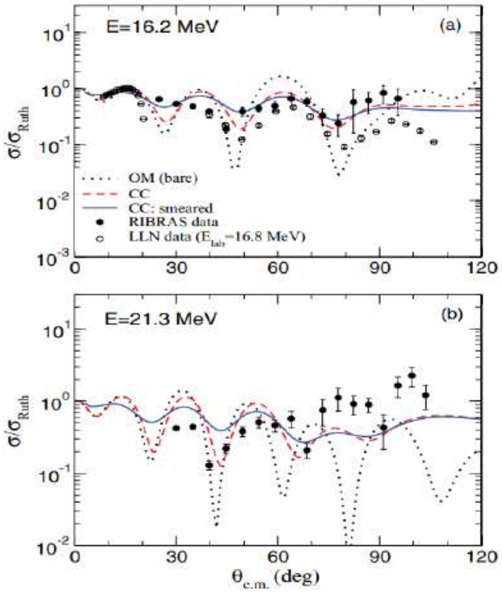


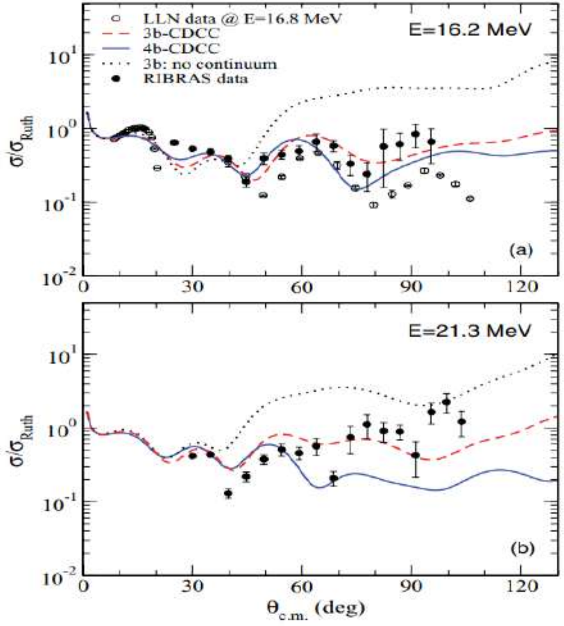
Simulates long range absorption due to breakup coupling

$^{6}He+^{9}Be$ elastic scattering

PHYSICAL REVIEW C 83, 064603 (2011)

Experimental study of $^{6}He + ^{9}Be$ elastic scattering at low energies





couplings to nuclear breakup channels are important in ^{6}He reactions by light targets

Coupled Channels calculation: includes low lying excited states of ^{9}Be and 2^{+} state of ^{6}He (is more important)
Optical Potential: real part: Sao Paulo potential.
Imaginary part: Wood-Saxon potential used for $^{6}Li+^{9}Be$

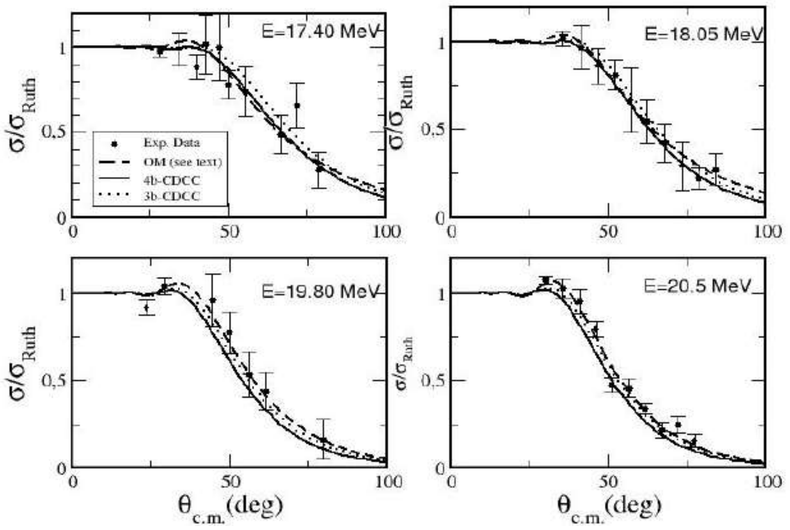
^{6}He is 3 body Borromean system
^{6}He→alpha+2n 3b-CDCC -----
^{6}He→alpha +n+n 4b-CDCC ——

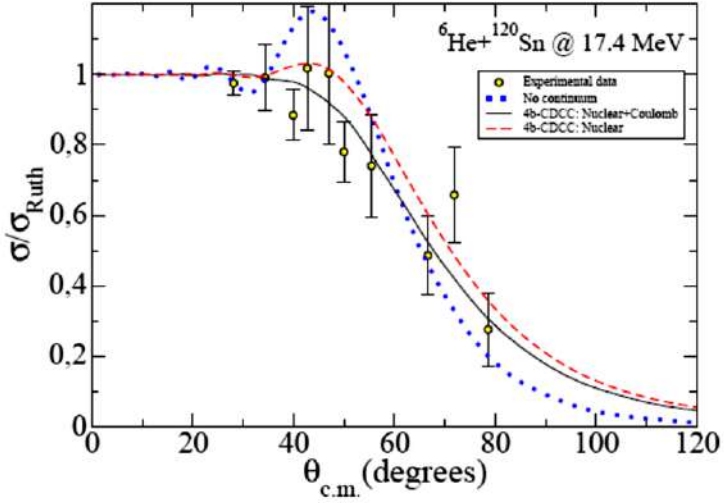
3 and 4 body CDCC calculations for ^{6}He (continuum discretized coupled-channel)

$^{6}He+^{120}Sn$ elastic scattering

PHYSICAL REVIEW C 81, 044605 (2010)

Elastic scattering and total reaction cross section of $^{6}He + ^{120}Sn$





Details of the coupling to the break-up channel

No-coupling to exited states, equiv to optical model calculation

4b-CDCC only nuclear coupling

4b-CDCC Coulomb + nuclear coupling

Not a fit!!

$^6He+^{58}Ni$ elastic scattering

Physics Letters B 732 (2014) 228–232

Four-body effects in the $^6He + ^{58}Ni$ scattering

V. Morcelle[a,b], K.C.C. Pires[c,d], M. Rodríguez-Gallardo[e], R. Lichtenthäler[d,*], A. Lépine-Szily[d], V. Guimarães[d], P.N. de Faria[b], D.R. Mendes Junior[b], A.M. Moro[e], L.R. Gasques[d], E. Leistenschneider[d], R. Pampa Condori[d], V. Scarduelli[d], M.C. Morais[f], A. Barioni[g], J.C. Zamora[i], J.M.B. Shorto[h]

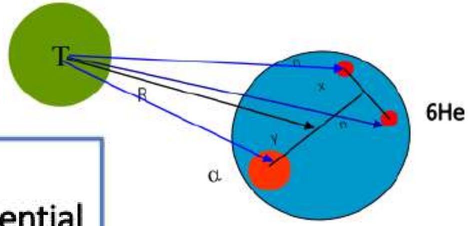
Comparison with CDCC calc.

3-body and 4-body CDCC calculations give different cross Sections at $\theta_{cm} > 40^{o}$.

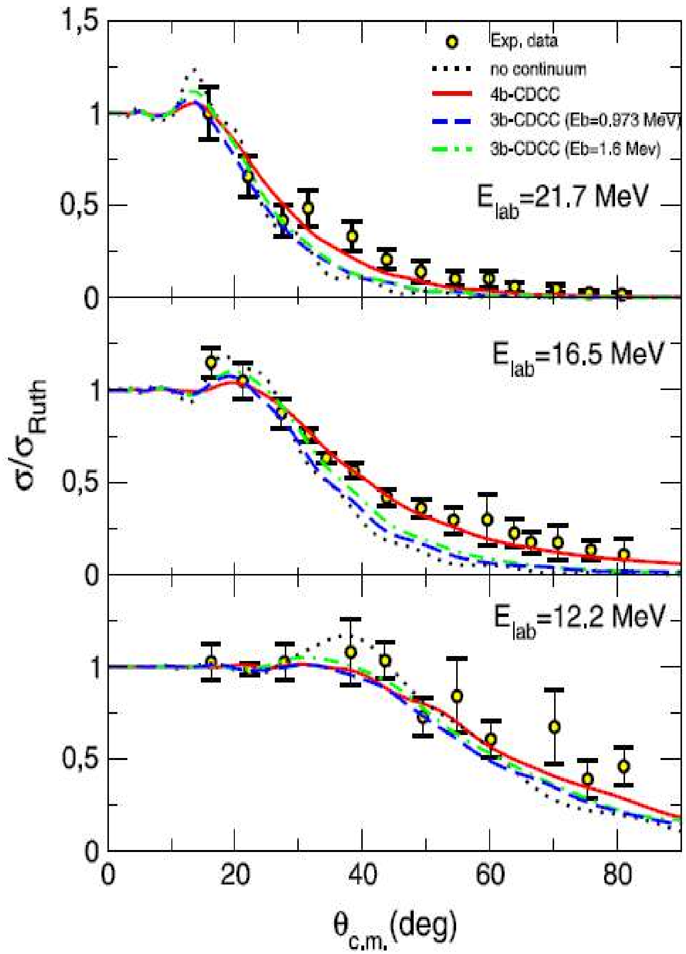
Excellent agreement with 4-body CDCC calculation

No free parameters!
^6He - target potential
$U_{6He-T} = \langle \phi_{6He} | U_{\alpha-T} + U_{n-T} + U_{n-T} | \phi_{6He} \rangle$

The cluster-target potentials are obtained from scattering data from previous experiments.



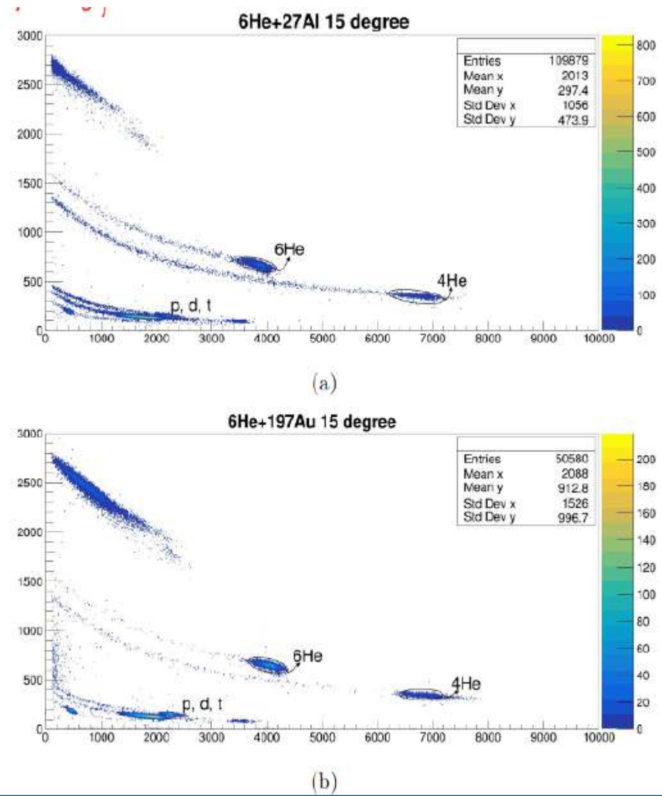
4b-CDCC calculations:
- cluster model for the ^6He-target potential
- coupling to continuum (breakup states)

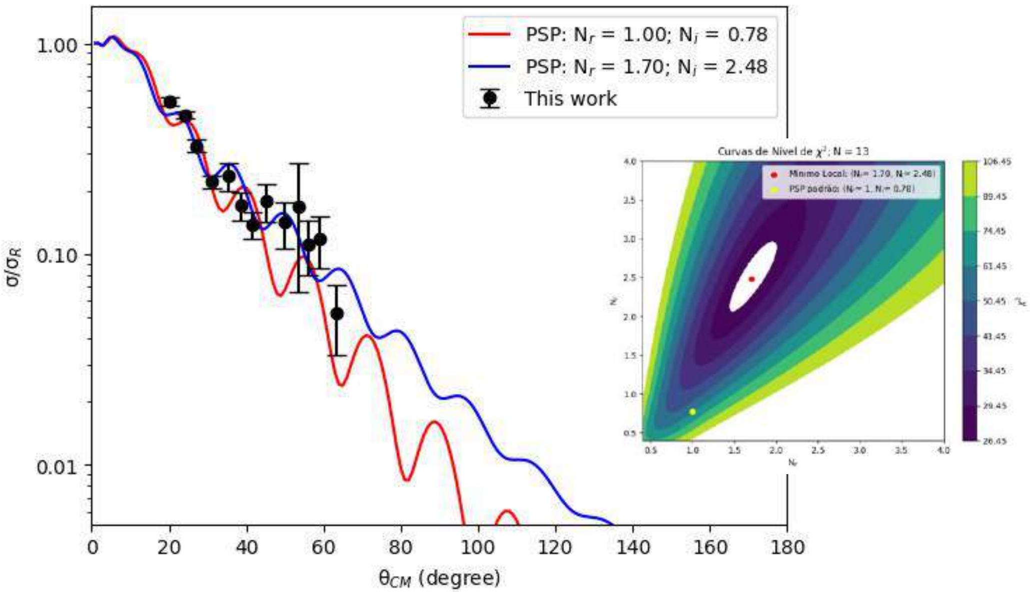


Works in progress:

$^{6}He+^{27}Al$ system @ E_{lab}=17.5MeV

Master project of H. F. G. de Arruda (in progress)





IDEA:

To verify the no effect on the nuclear coupling

Works in progress:

$^{6}He+^{27}Al$ system @ E_{lab}=17.5MeV

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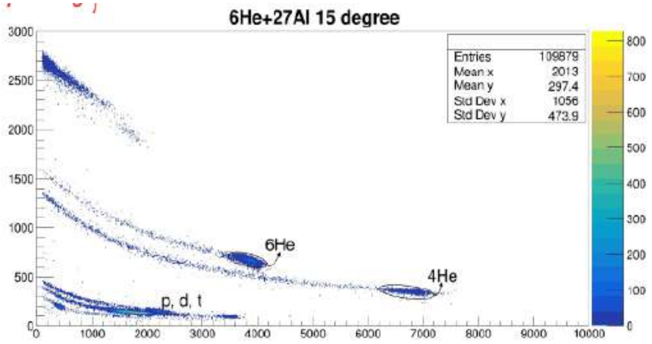
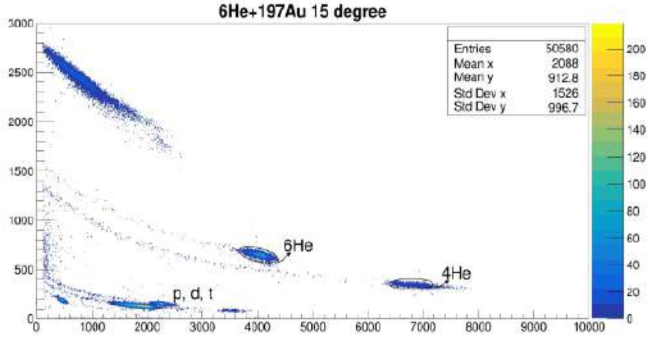
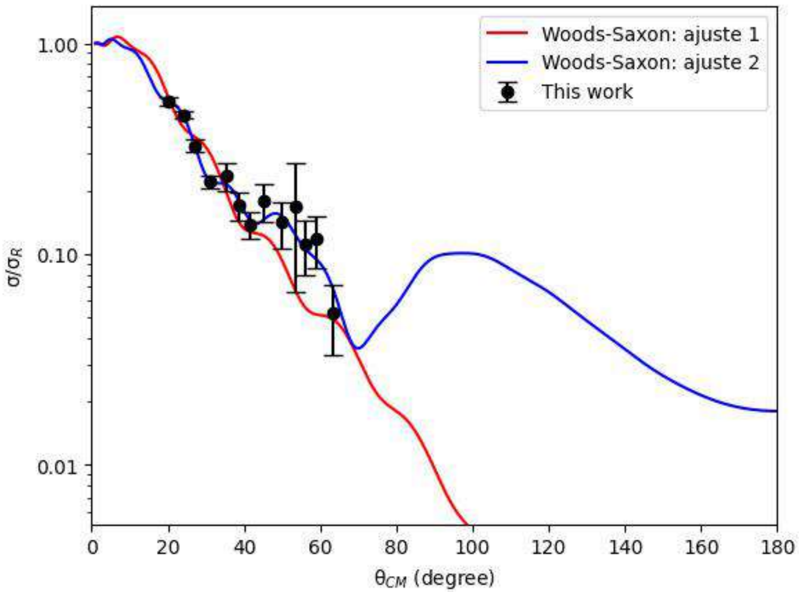


(a)



(b)

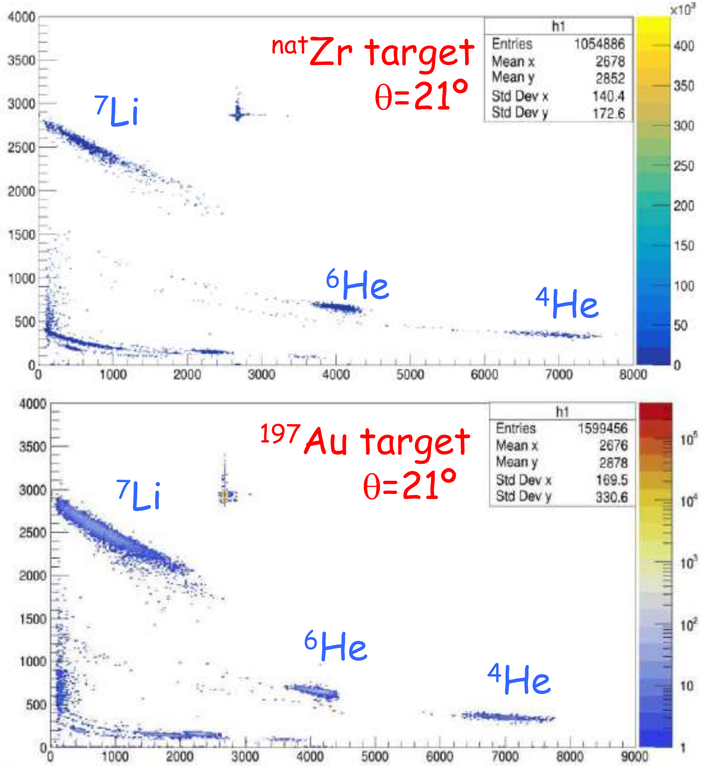


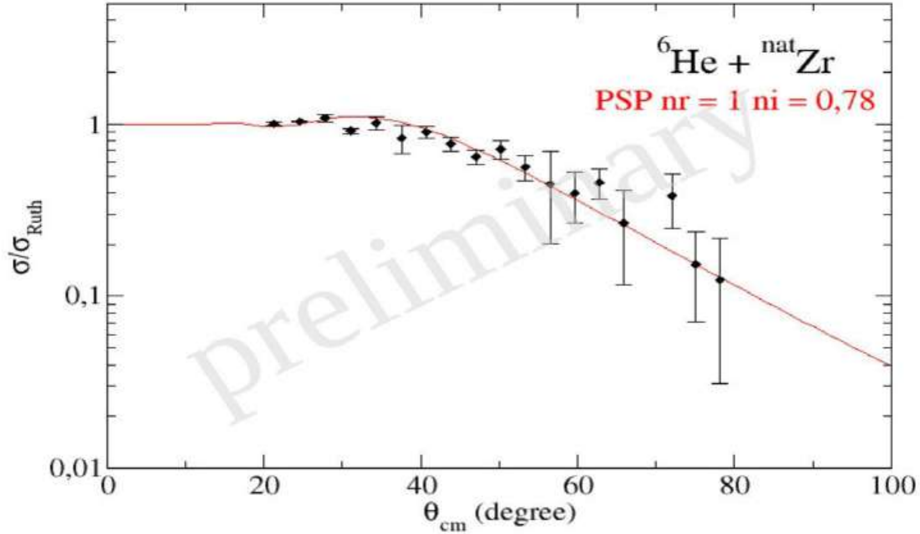
IDEA:

To verify the no effect on the nuclear coupling

$^{6}He + ^{nat}Zr$ system @ E_{lab}=18MeV

Master project of F. R. Loureiro (in progress)





IDEA:

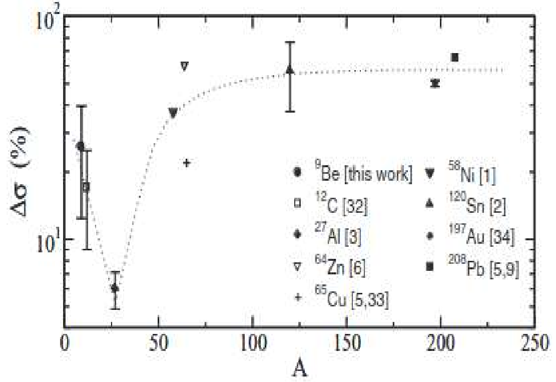
Target mass region not yet explored located between ^{64}Zn and ^{120}Sn.

^{6}He+^{51}V system @ E_{lab}=18MeV

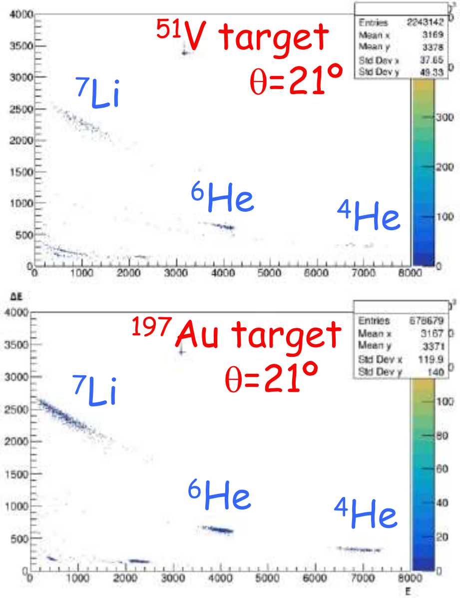
Master project of J. A. E. Narváez (in progress)

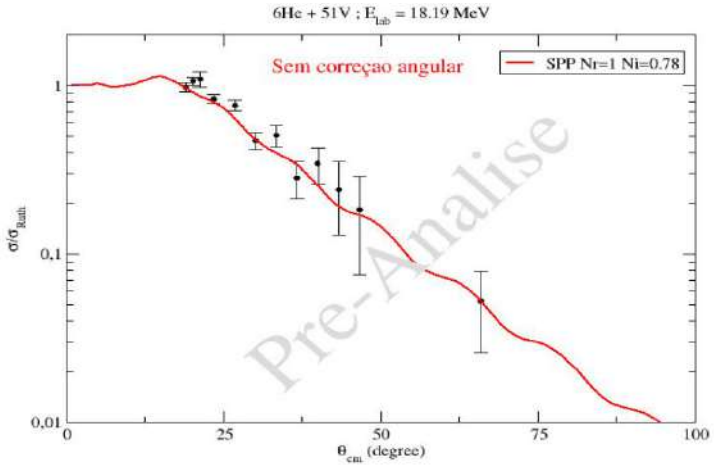
New method to calculate the nuclear radius from low energy fusion and total reaction cross sections

K. C. C. Pires, S. Appannababu, R. Lichtenthäler, and O. C. B. Santos
Phys. Rev. C **98**, 014614 – Published 23 July 2018



$$\Delta\sigma(\%) = 100\frac{\sigma_{reac}(^{6}\mathrm{He}) - \sigma_{reac}(^{6}\mathrm{Li})}{\sigma_{reac}(^{6}\mathrm{Li})},$$



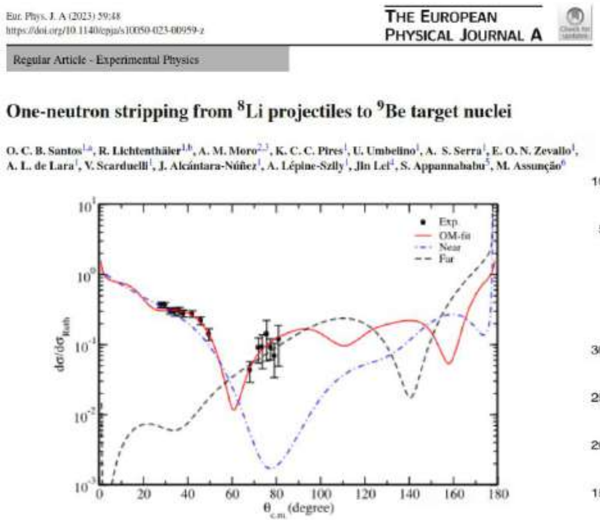


IDEA:

Verify the decrease in the σ^{reac} for the ^{6}He in relation to ^{6}Li.

The A=27-58 massa range requires additional information

$^{8}Li+^{9}Be$ system @ Elab = 21 and 26 MeV

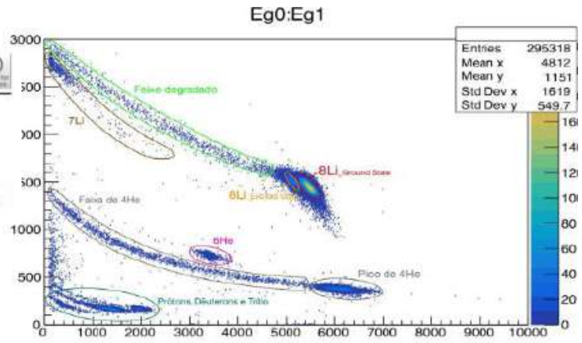

Eur. Phys. J. A (2023) 59:48
https://doi.org/10.1140/epja/s10050-023-00959-z

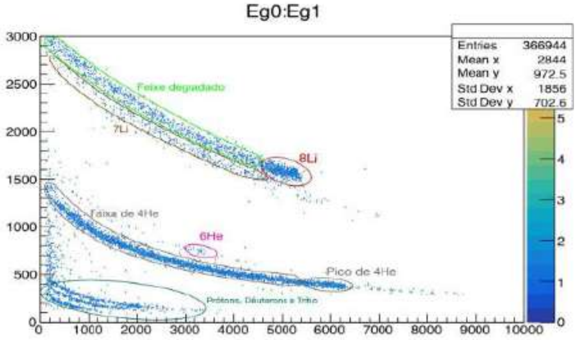
THE EUROPEAN PHYSICAL JOURNAL A

Regular Article - Experimental Physics

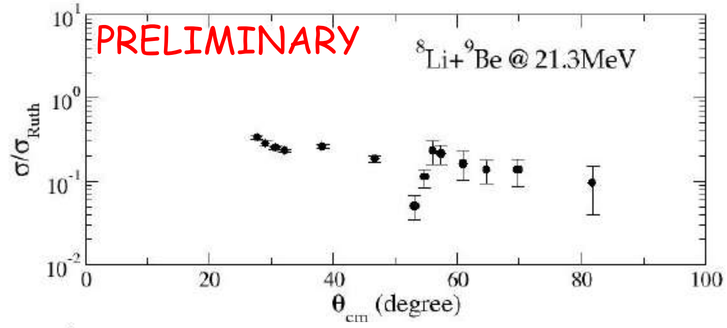
One-neutron stripping from ^{8}Li projectiles to ^{9}Be target nuclei

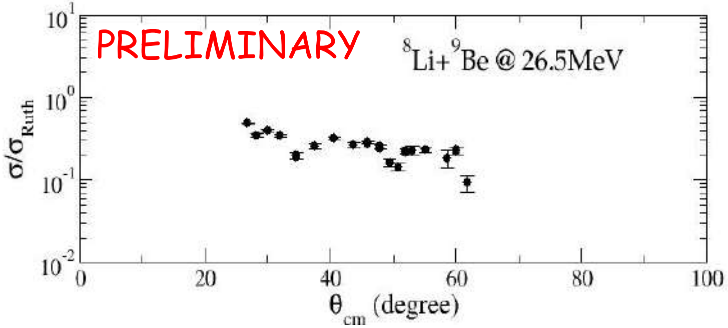
O. C. B. Santos, R. Lichtenthäler, A. M. Moro, K. C. C. Pires, U. Umbelino, A. S. Serra, E. O. N. Zevallo, A. L. de Lara, V. Scarduelli, J. Alcántara-Núñez, A. Lépine-Szily, Jin Lei, S. Appannababu, M. Assunção





Master project of D. A. Santana (in progress)

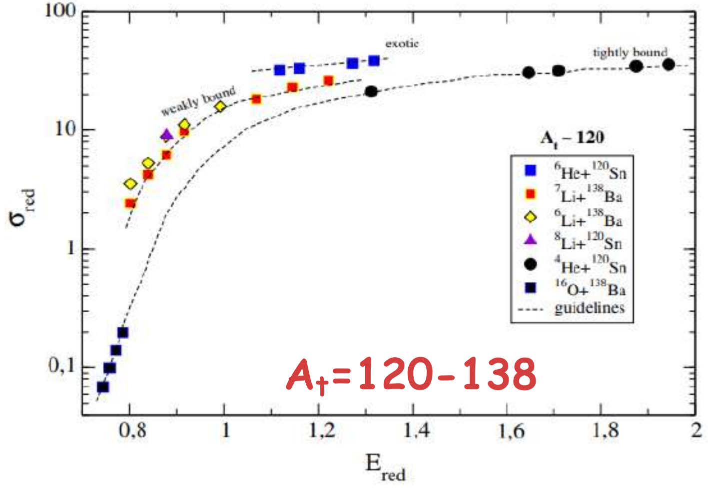


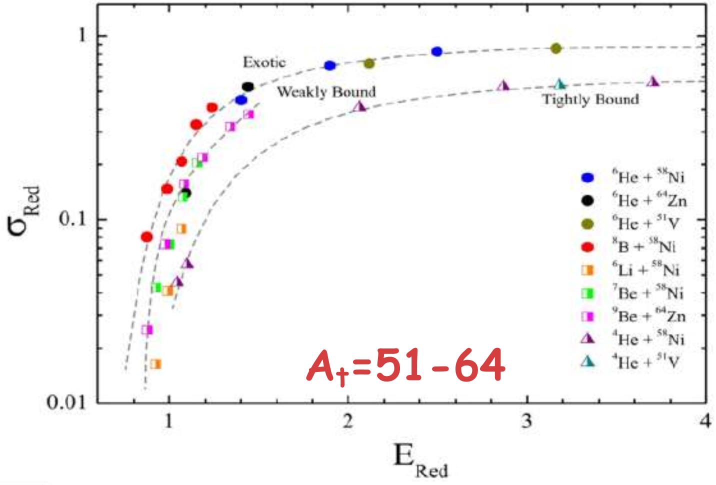


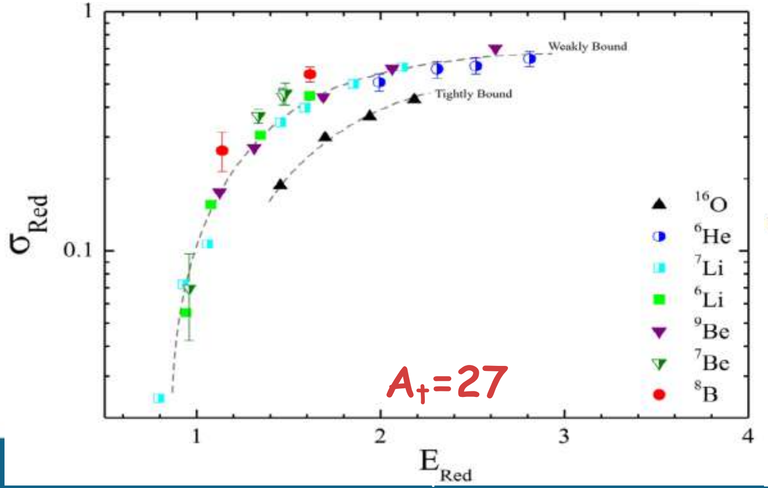
IDEA:

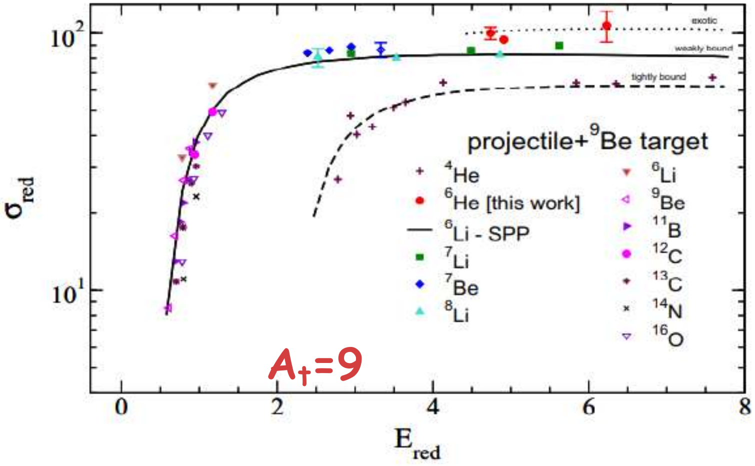
Verify a significant contribution from the *farside* component, resulting in an increase in the elastic scattering cross section for backward angles, observed in a recent work.

Total Reaction Cross Section









Systematics obtained from elastic scattering

$$\sigma_{red} = \frac{\sigma_{exp}}{(A_1^{1/3} + A_2^{1/3})^2}$$

$$E_{red} = \frac{E_{cm}(A_1^{1/3} + A_2^{1/3})}{Z_1 Z_2}$$

Which are the reaction channels responsible for this enhancement?

Future research plans at RIBRAS

- Main research objectives: Study in detail the reaction mechanism of weakly bound, cluster structured radioactive nuclei with light, medium and heavy mass targets at energies around the Coulomb barrier.

- Increase the detection capability for charged particles and γ-rays at RIBRAS.

- Exclusive measurements of nuclear reactions with weakly bound radioactive at energies around the Coulomb barrier;
- The plan consists in the use of existing and the installation of new digital equipment (strip detectors for charged particles, Lyso gamma detectors and electronic devices mainly digitizers) at LAFN $\Rightarrow$ Breakup, transfer $\Rightarrow$ coincidence measurements

- Fusion measurements with weakly bound radioactive beams at energies below and around the Coulomb barrier

- A low-energy, light, radioactive beam facility, as RIBRAS, can make competitive contribution in nuclear reaction studies.

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Thank you for your attention