ICTP-SAIFR/MITP WORKSHOP ON MULTINEUTRON CLUSTERS IN NUCLEI AND IN STARS

June 2 – 6, 2025
at Principia Institute, São Paulo, Brazil

Reactions induced by the ^{6}He exotic nucleus: recent results from RIBRAS

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

- Motivation to study nuclear reactions
- Exotic nuclei: some of their properties
- Methods for production of exotic nuclei: radioactive ion beams
- The RIBRAS system
- The research program
- Conclusions

Why to study nuclear reactions?

1. Investigating Atomic Structure;
2. Understanding different reaction mechanisms;
3. Insights into nuclear processes in star and cosmic events: Origin and Evolution of the Universe;
4. Understanding the production of new isotopes and elements;
5. Applications: medicine, arts, arqueology, industry (technological advancements).

1980: Starts new era of experiments

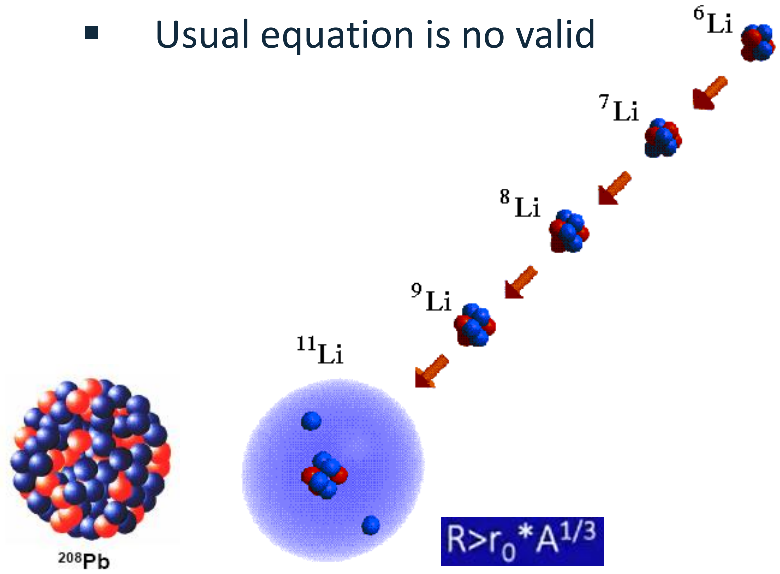
1985: Significant milestone in Nuclear Physics

Opened up new perspectives for studying nuclear structure and properties

- Tanihata discovers the ^{11}Li
  - Large radius
  - Usual equation is no valid

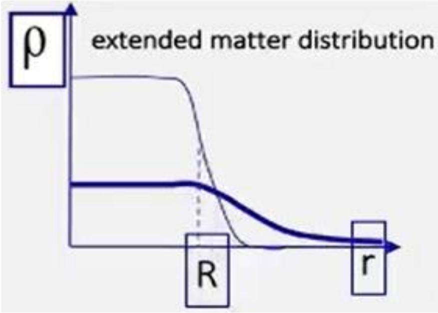
Saturation of the nuclear force implies a constant density.

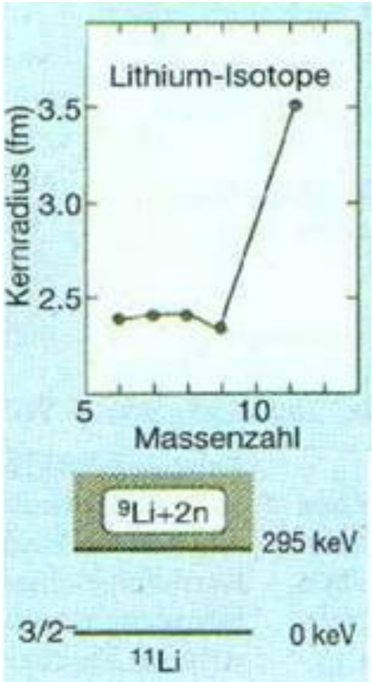
$R = r_0 * A^{1/3}, r_0 \sim 1.3$ fm



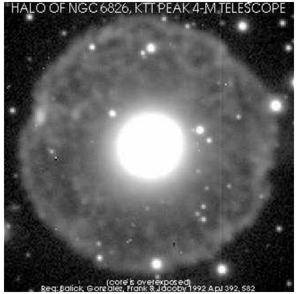
$R > r_0 * A^{1/3}$

Unusual distributions of nuclear matter.



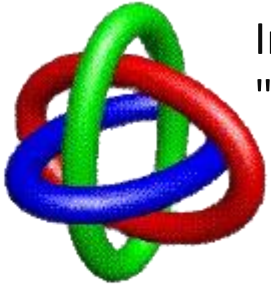


Halo effect and Borromean Nucleus

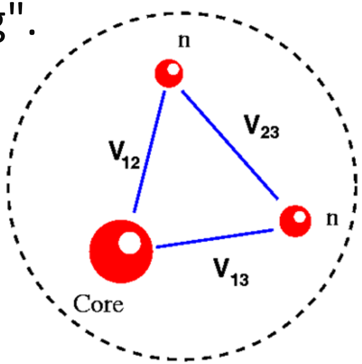


Distribution of nuclear particles beyond the typical range of nuclear forces

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

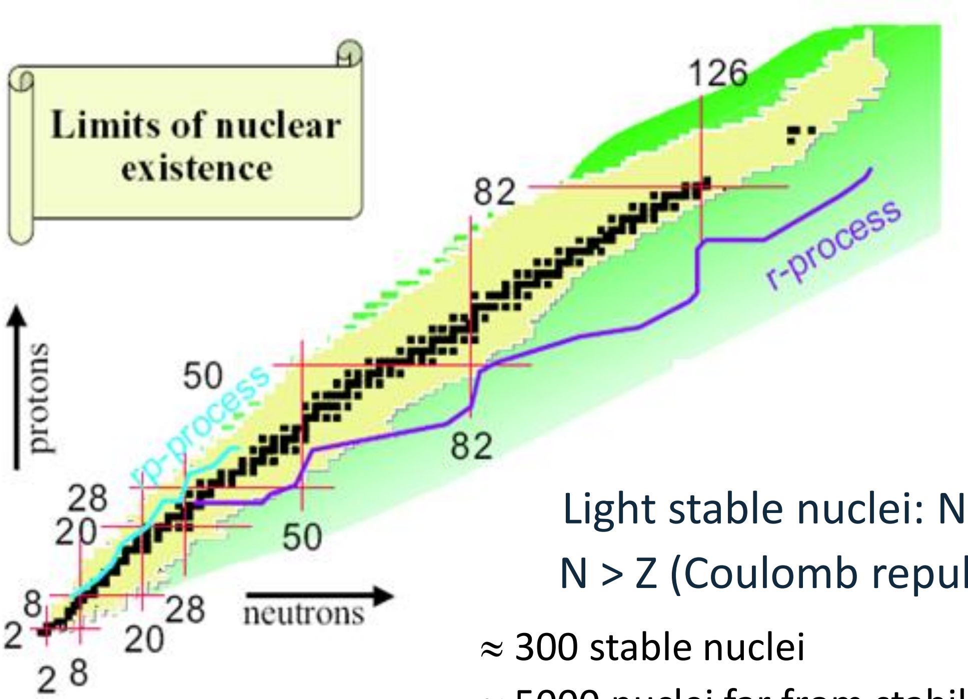
2n

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

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

not bound

The nuclide chart: Nuclear Physics' field of study



Light stable nuclei: N ≈ Z

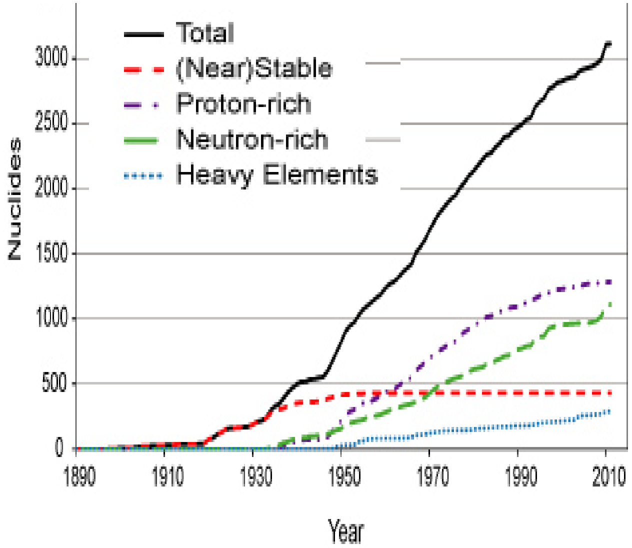
N > Z (Coulomb repulsion)

≈ 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



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)	
^{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.

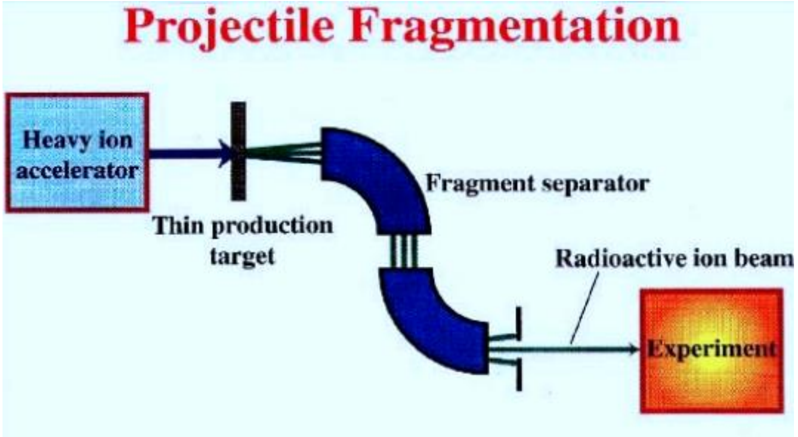
Why study nuclei outside the stability line?

- 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.

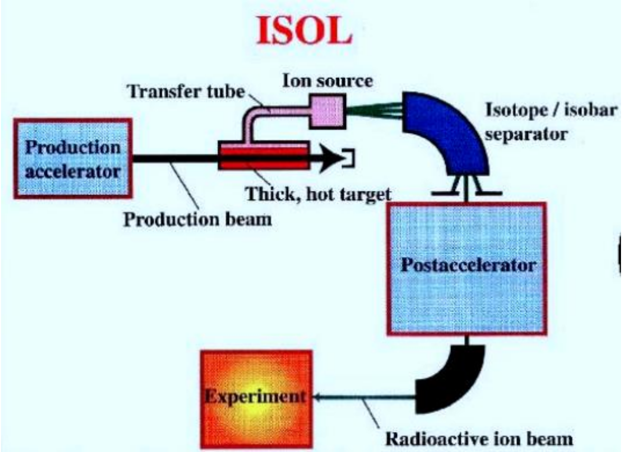
How to study nuclei outside the stability line?

- ❑ How to produce nuclei outside the stability line?
  - ❑ High-intensity accelerators: $10^{12\text{-}14}$ pps

Methods for the production of radioactive beams

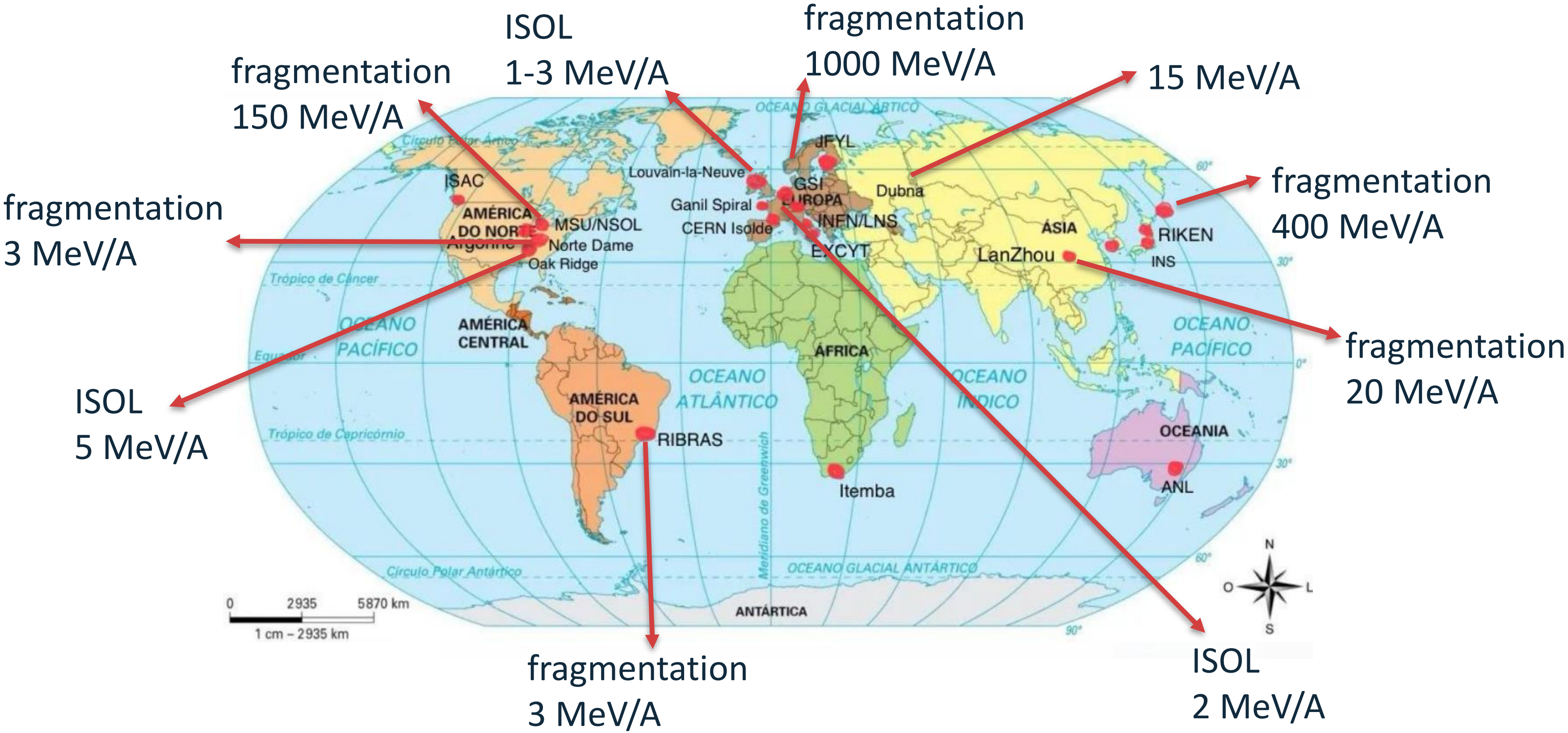


In-flight production: thin target + separator

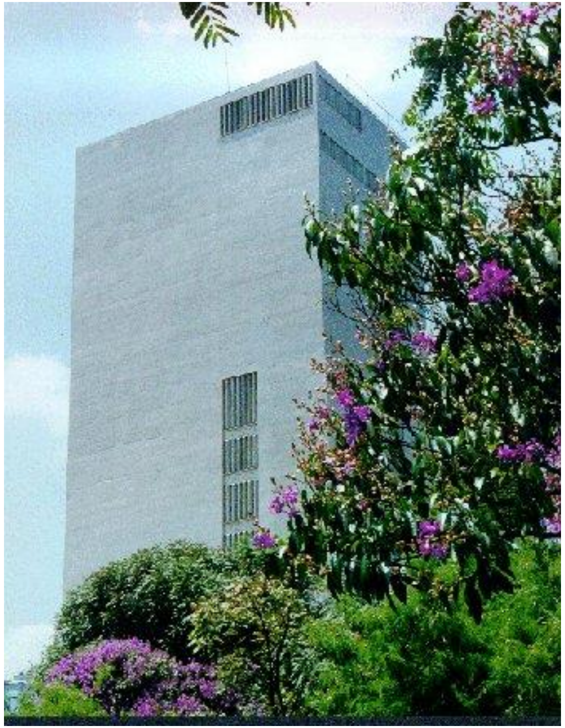


Online separation: thick target + ion source + separator + post-accelerator

Rare Isotopes Beam facilities in the world

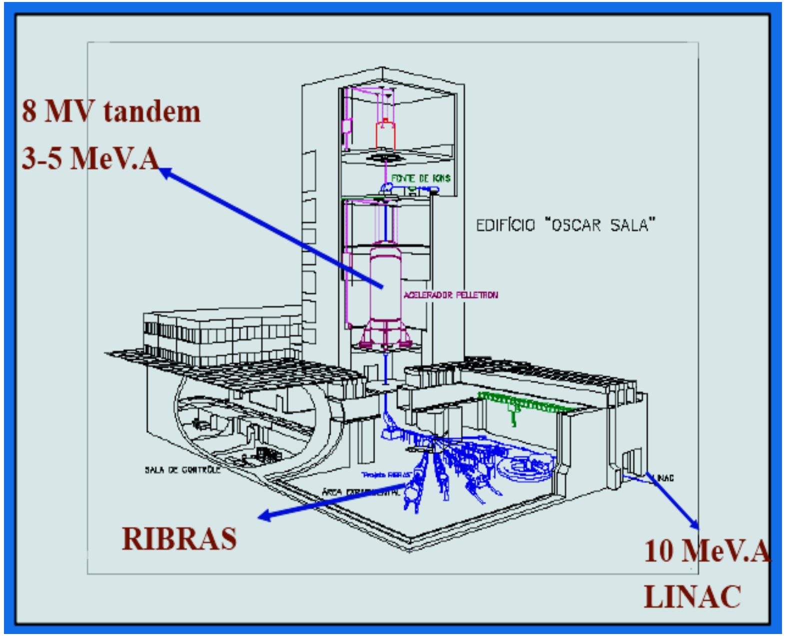


Major Facility for Nuclear Physics research in Brazil



Tandem Accelerator
Pelletron 8UD

University of São Paulo
Brazil

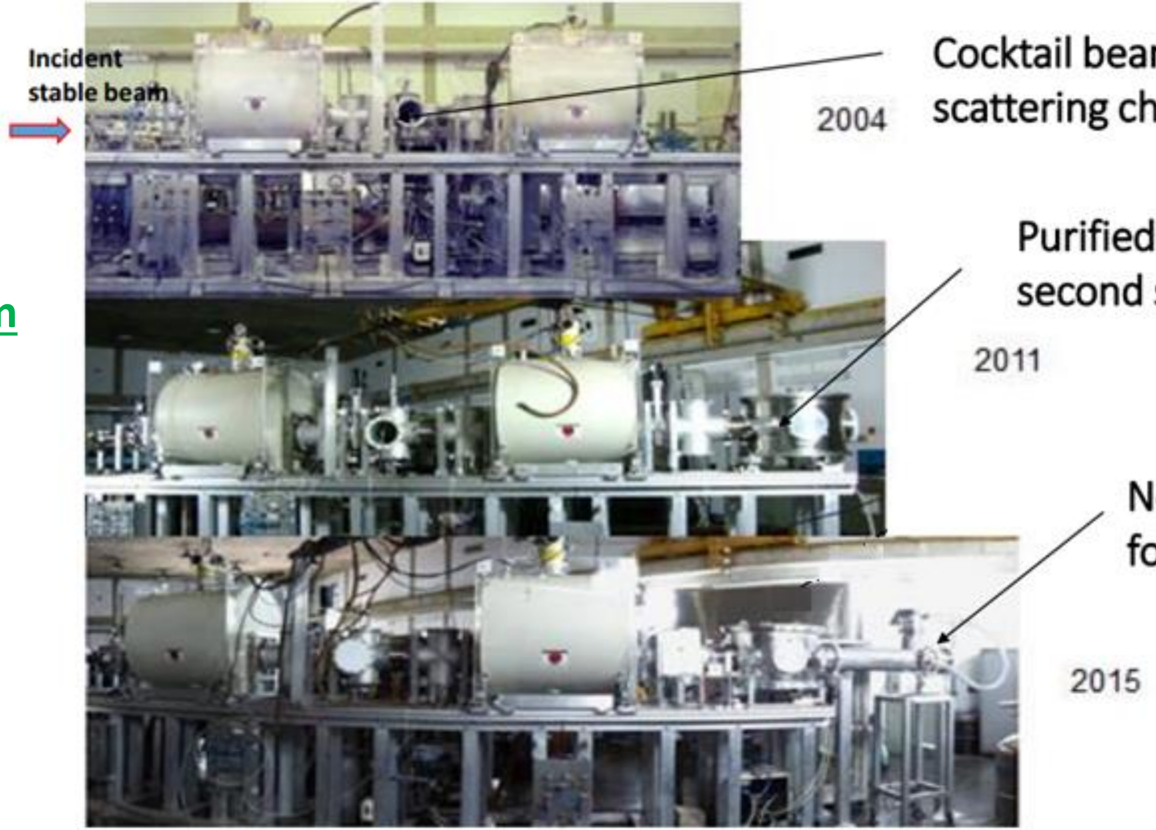


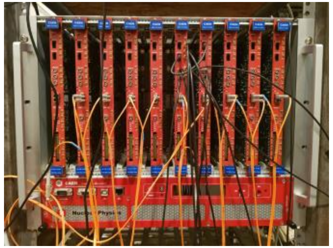
primary beams:

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

RIBRAS - Radioactive Ion Beams in Brasil

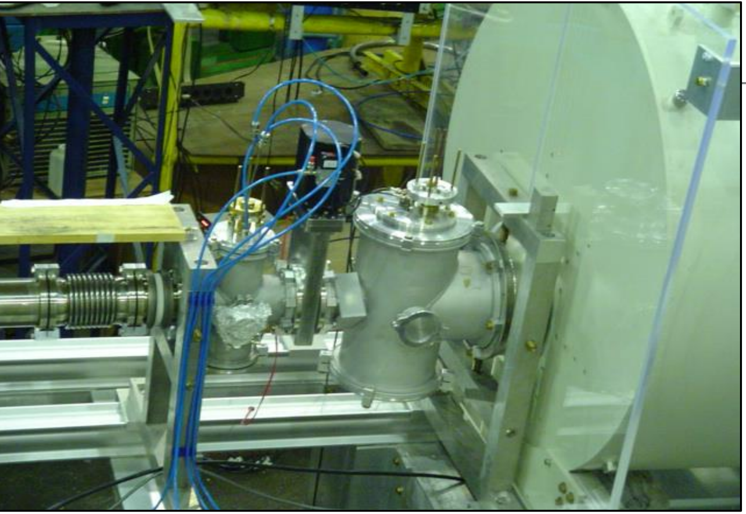
First RIB facility in the Southern Hemisphere, installed in 2004





2022

Evolution over the years

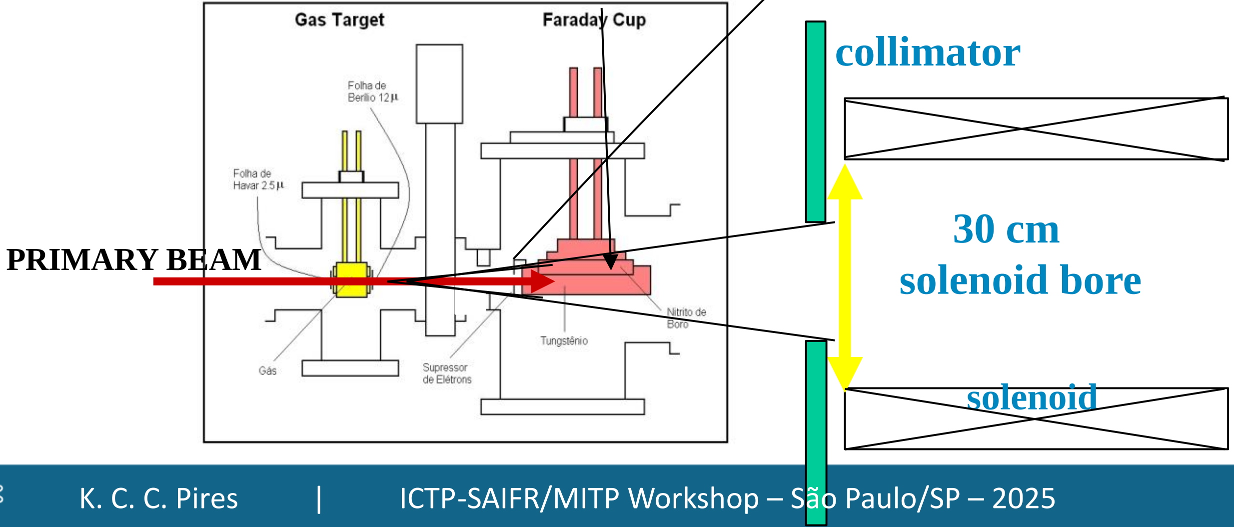


Production target

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

Angular acceptance

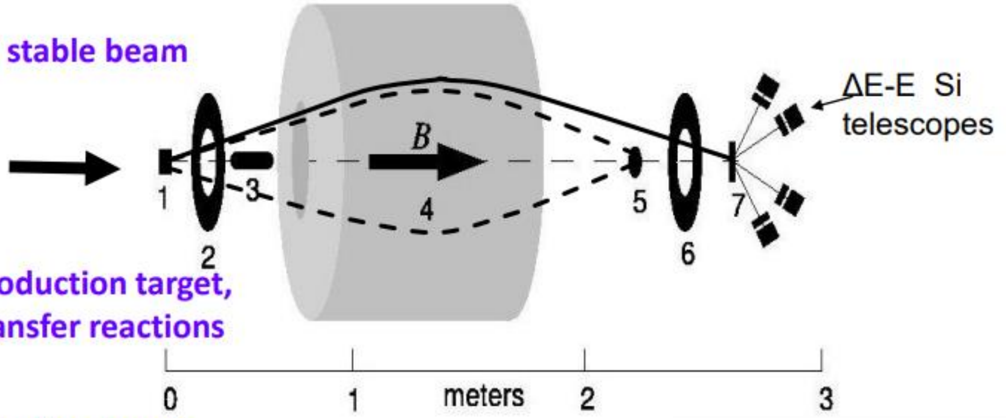
$$2\,\deg \le \Delta\theta \le 6\,\deg \longrightarrow 30\text{msr}$$



Selection with the first solenoid

IFUSP
Instituto de Física da USP

primary stable beam

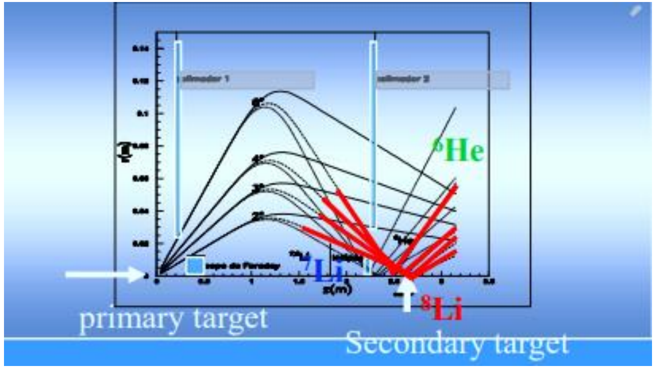


Production target,
transfer reactions

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



Production reactions beams at RIBRAS

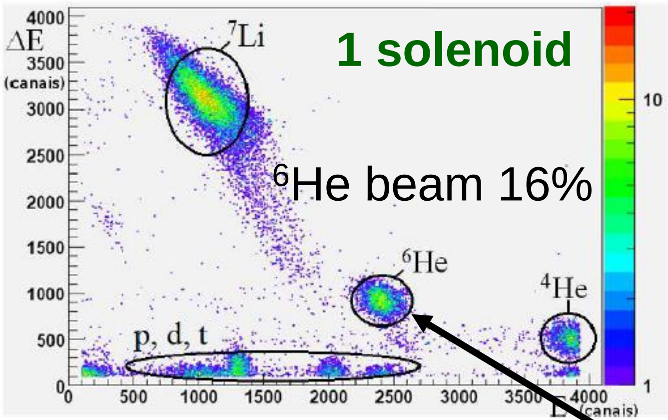
target(projectile,ejectile)recoil

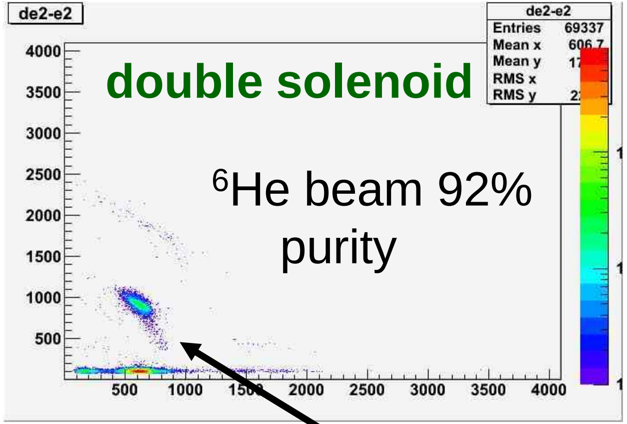
- target → primary target
- projectile → primary beam
- ejectile → secondary beam

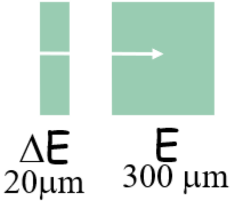
Secondary Beam	Production Reaction	Intensity (pps)
^{6}He	^{9}Be(^{7}Li,^{6}He)	10^{+5}
^{8}Li	^{9}Be(^{7}Li,^{8}Li)	10^{+5}
^{7}Be	^{3}He(^{6}Li,^{7}Be)	10^{+5}
^{7}Be	^{3}He(^{7}Li,^{7}Be)	10^{+5}
^{8}B	^{3}He(^{6}Li,^{8}B)	10^{+4}
^{10}Be	^{9}Be(^{11}B,^{10}Be)	10^{+4}
^{7}Be	^{7}Li(^{6}Li,^{7}Be)	10^{+5}

($I_{primary}$ ~ 300 nAe)

Beam purification using double solenoids





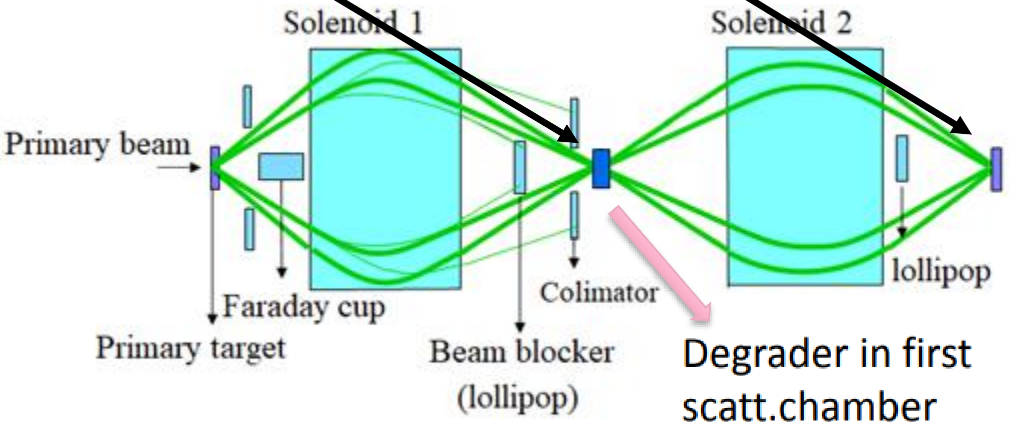


S=300 mm²

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

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

$$^7\text{Li} + {}^9\text{Be} \left\{ \begin{array}{l} ^7\text{Li} \\ ^8\text{Li} \\ ^6\text{He} \\ ^4\text{He} \\ \text{t} \\ \text{d} \end{array} \right.$$



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

Degrader in first scatt.chamber

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

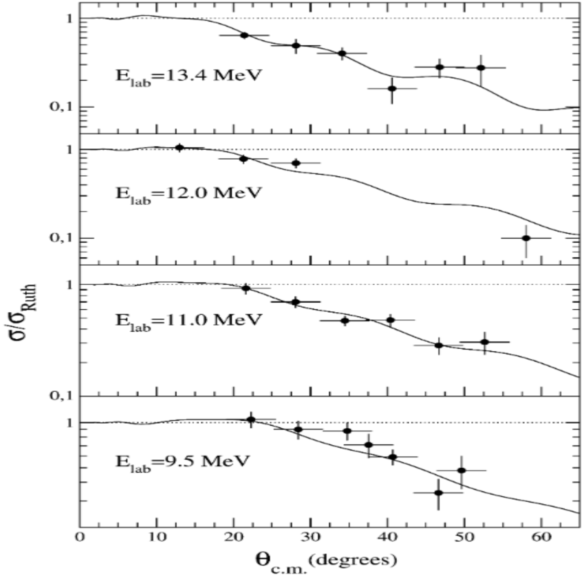
Physics Letters B 647 (2007) 30–35

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

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

First results of RIBRAS

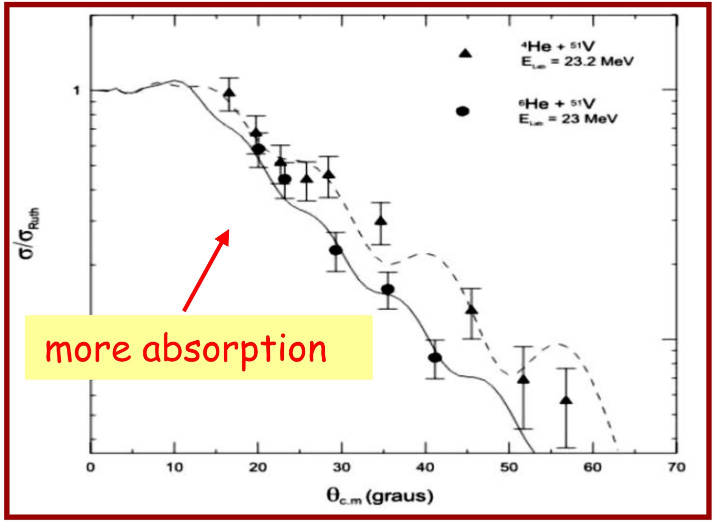
Optical Model calculation São Paulo potential (N_I~0.7 ; a=0.56(2)=normal nuclear diffuseness)



No effect of breakup coupling.

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

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

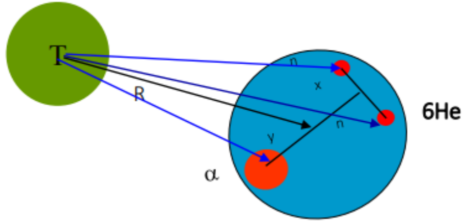


Simulates long range absorption due to breakup coupling

$^6He+^9Be$ elastic scattering

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

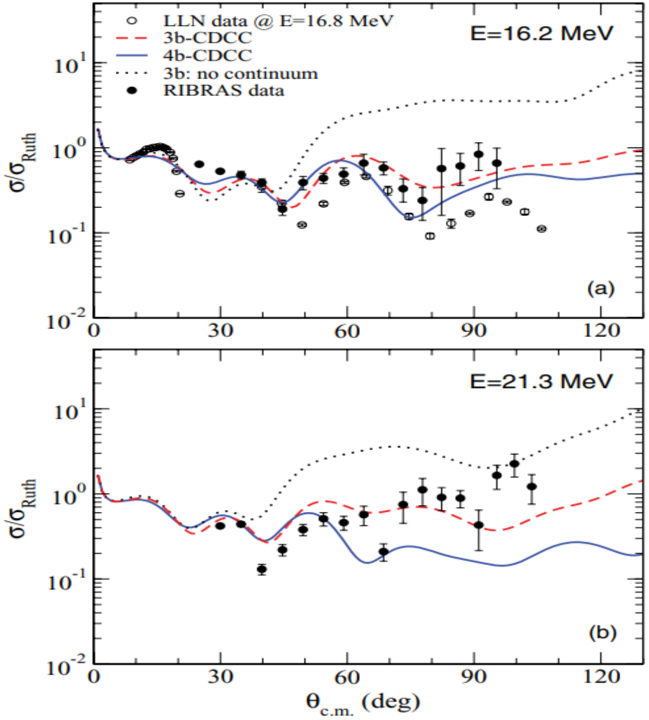
The cluster-target potentials are obtained from scattering data from previous experiments.



^6He is 3 body Borromean system
$^6He \rightarrow$ alpha+2n 3b-CDCC -----
$^6He \rightarrow$ alpha +n+n 4b-CDCC

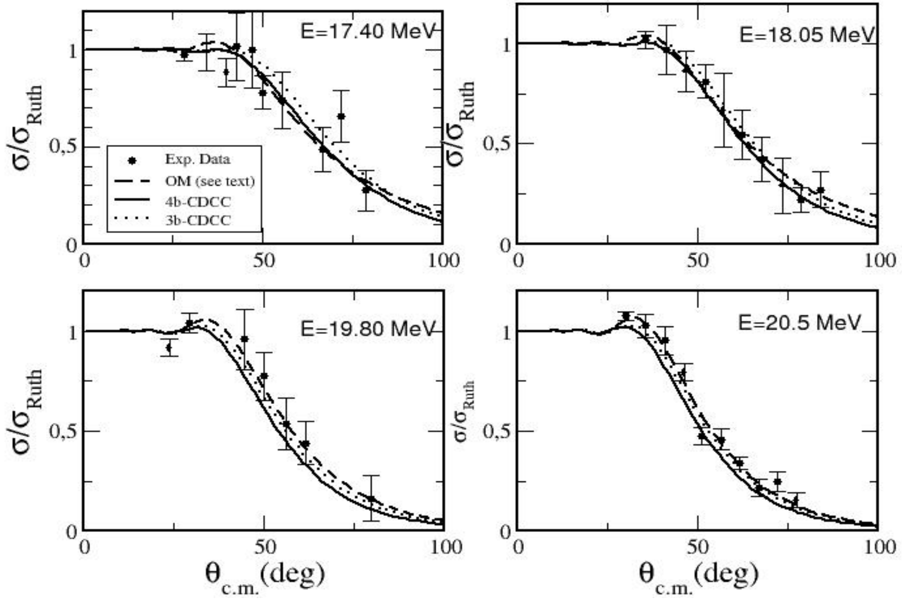
4b-CDCC calculations:
- cluster model for the ^6He-target potential
- coupling to continuum (breakup states)

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



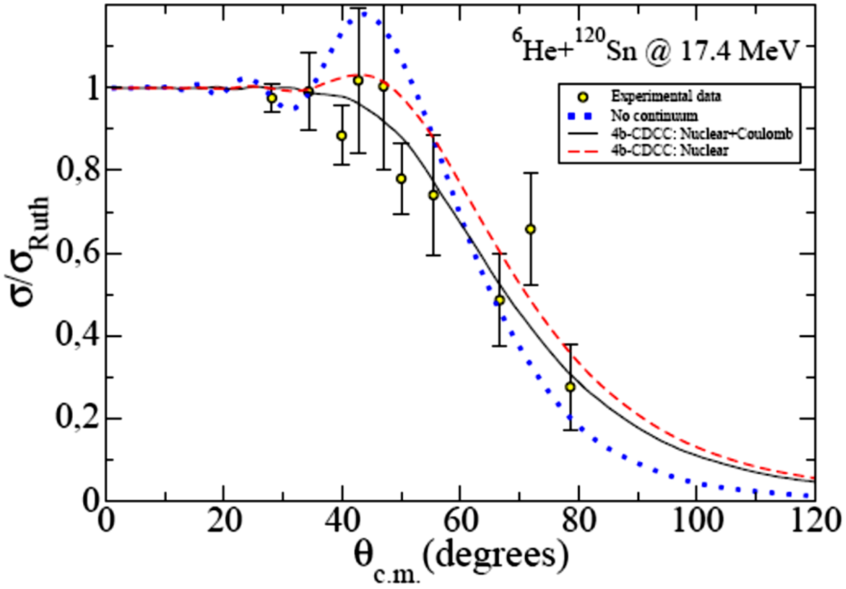
*couplings to nuclear breakup channels are important in ^6He reactions by **light** targets*

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



PHYSICAL REVIEW C 81, 044605 (2010)

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



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!!

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

Physics Letters B 732 (2014) 228–232

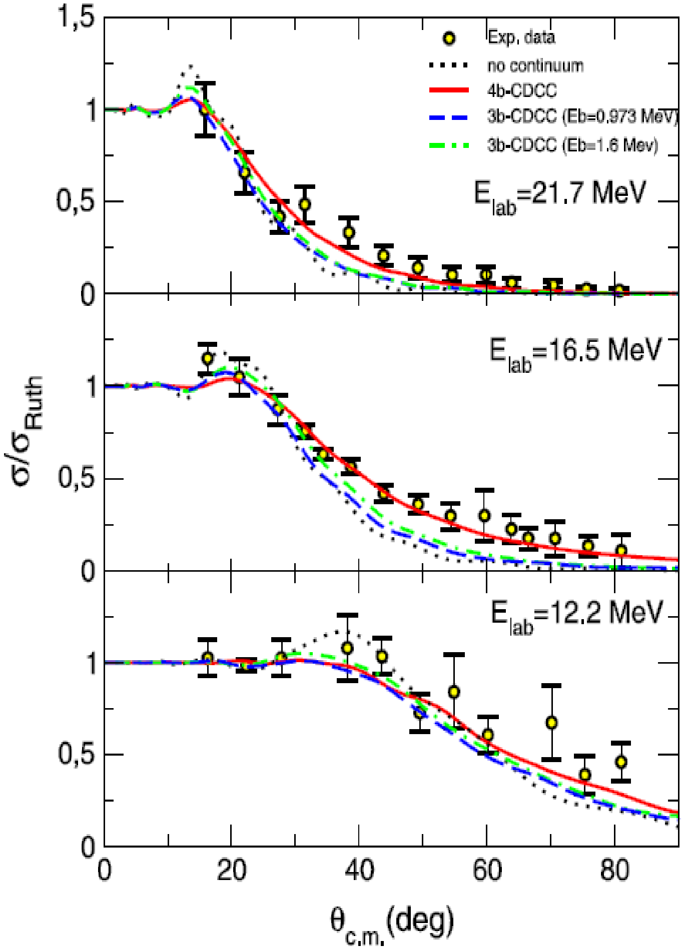
Four-body effects in the $^{6}He + ^{58}Ni$ scattering

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.

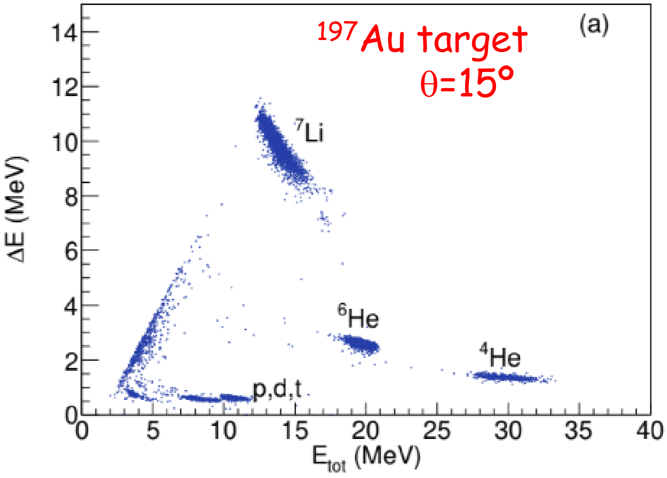
3-body and 4-body CDCC calculations give different cross Sections at $\theta_{cm} > 40^{o}$.

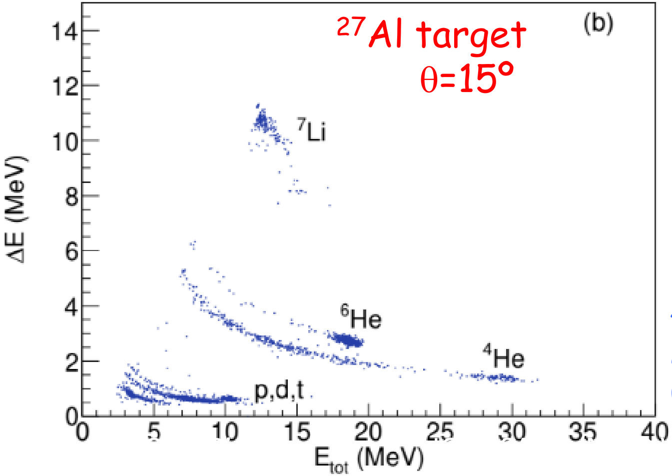
Excellent agreement with 4-body CDCC calculation



^{6}He+^{27}Al elastic scattering @ E_{lab}=18 MeV (work in progress)

IFUSP
Instituto de Física da USP

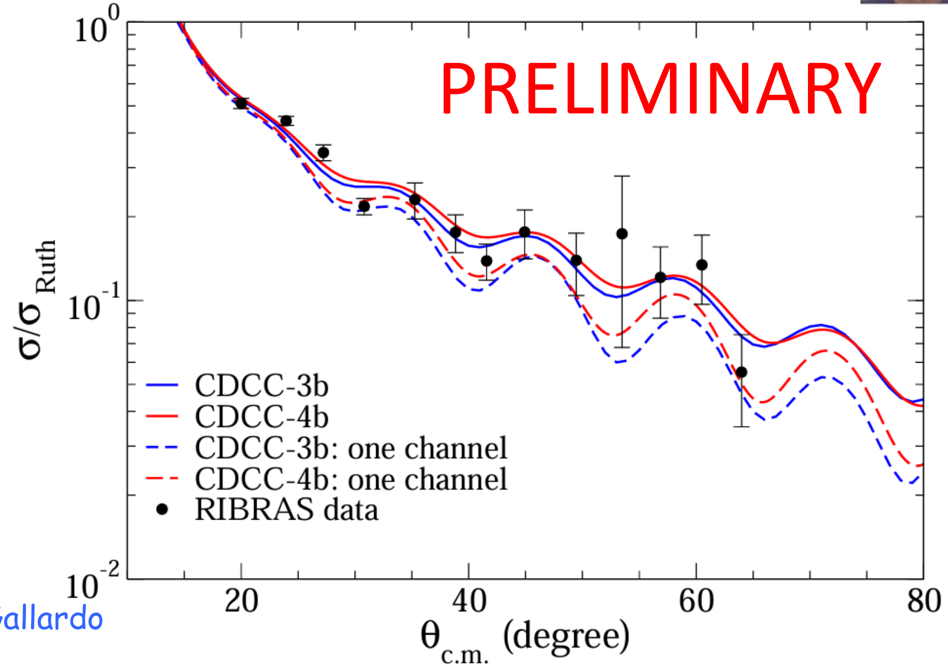




IDEA:

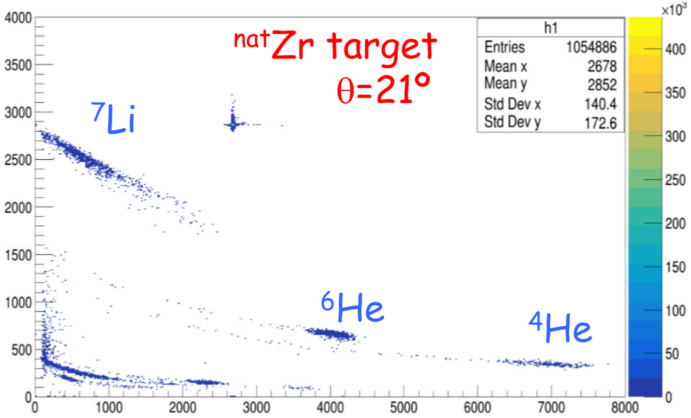
To verify the no effect on the breakup coupling

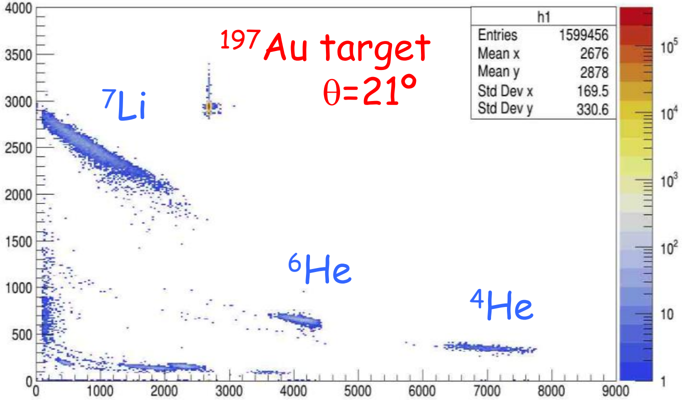
Master project of H. F. G. de Arruda (in progress)



4b-CDCC
M. Rodríguez-Gallardo
(Univ. Seville)

$^{6}He+^{nat}Zr$ elastic scattering @ E_{lab}=18.1MeV (work in progress)



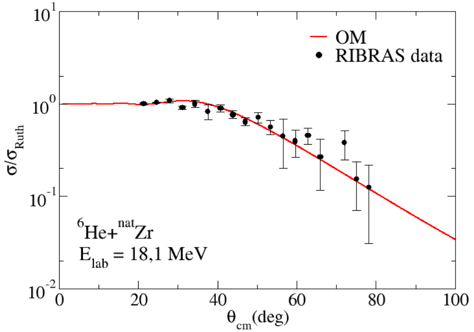


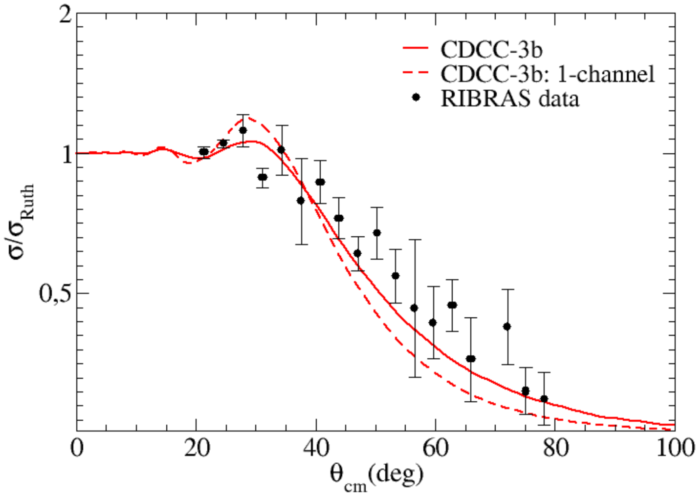
IDEA:

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

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

V_0 (MeV)	r_0 (fm)	a_0 (fm)	W_0 (MeV)	r_i (fm)	a_i (fm)	σ_{Reac} (mb)
111,92	1,18	0,97	17,56	1,63	0,87	1329



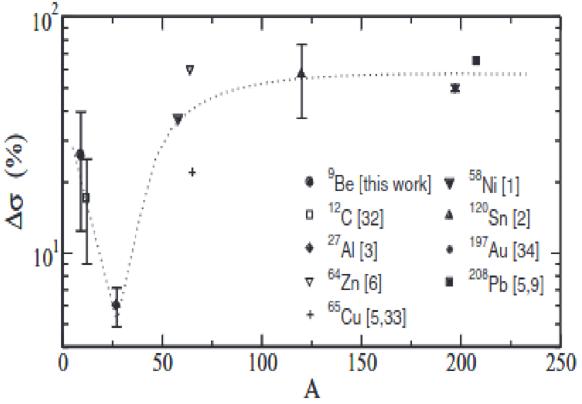


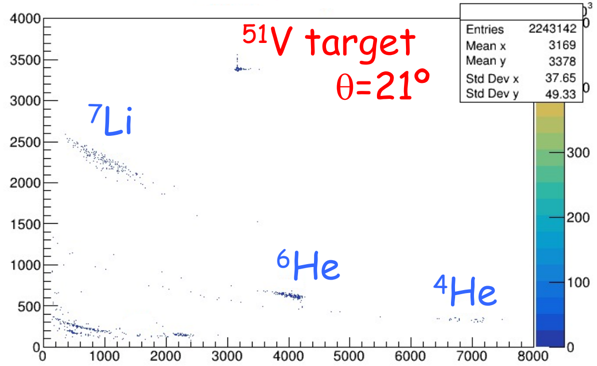
$^{6}He+^{51}V$ elastic scattering @ E_{lab}=18 MeV (work in progress)

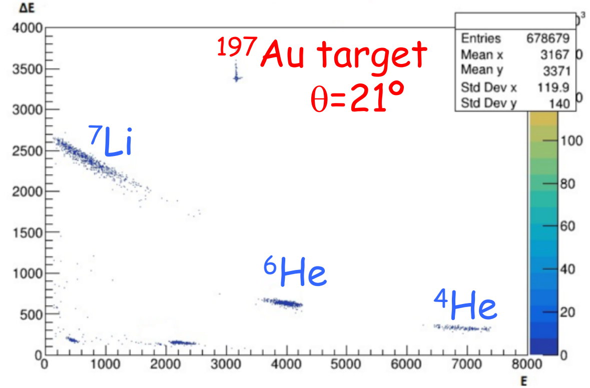
IFUSP Instituto de Física da USP

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



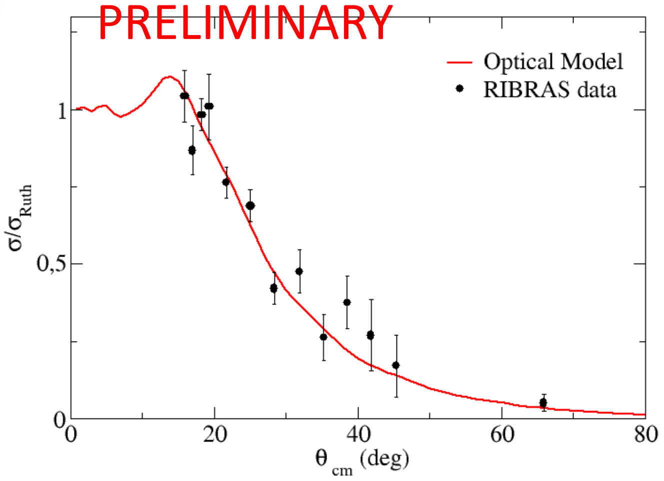




IDEA:

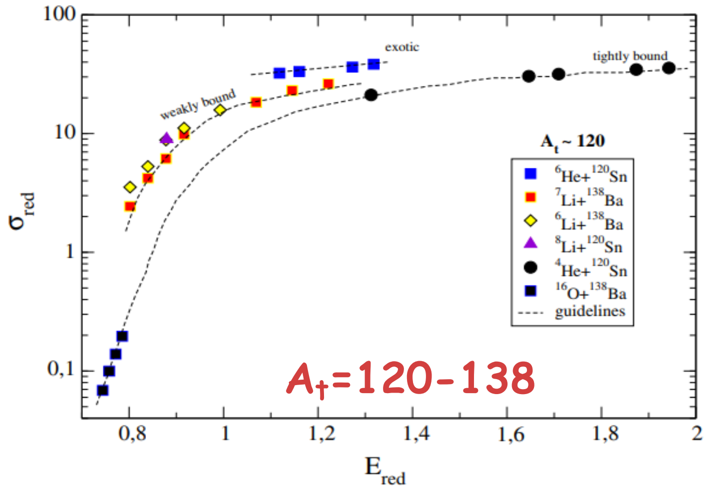
Verify the decrease in the σ^{reac} for the ^{6}He in relation to ^{6}Li. The A=27-58 massa range requires additional information

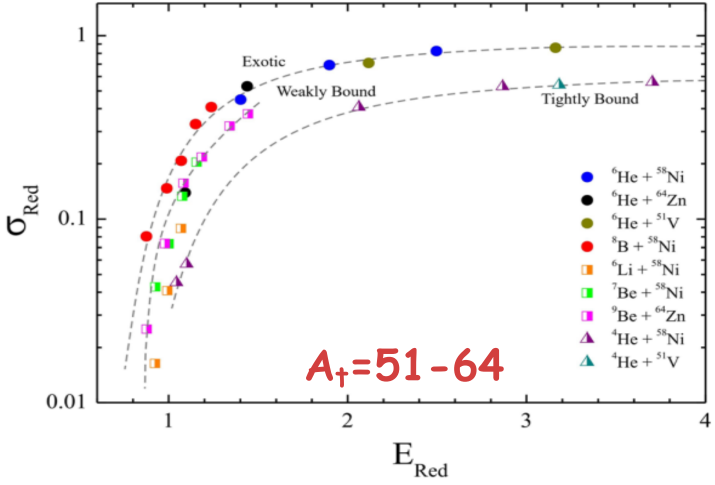
Master project of J. A. E. Narváez (in progress)

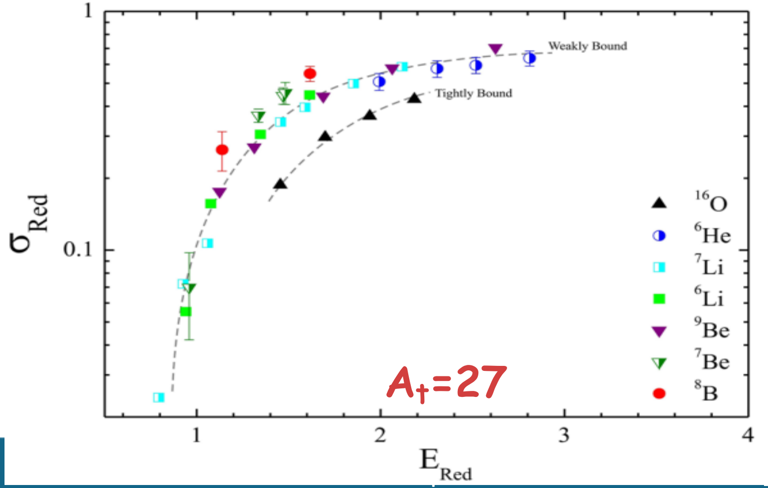


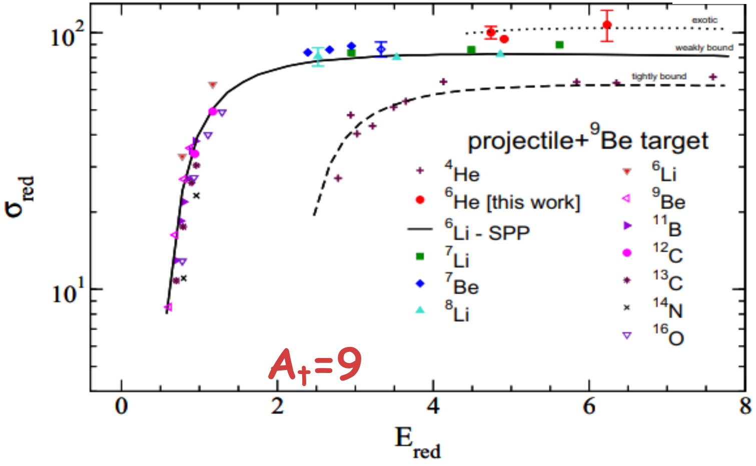
Sistema	V (MeV)	r (fm)	a (fm)	W (MeV)	rw (fm)	aw (fm)	σ_{reac} (mb)	χ^2
$^{6}He+^{51}V$	5	1,3	0,65	5,0	1,5	0,7	1829,6	1.116

Total Reaction Cross Section









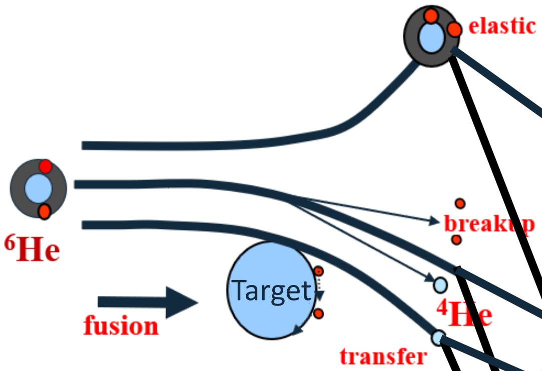
Systematics obtained from elastic scattering

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

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

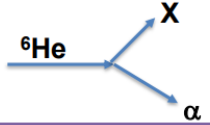
Which are the reaction channels responsible for this enhancement?

α-production with ^{6}He beam measured at RIBRAS



Large amount of alpha particles produced in ^{6}He+^{120}Sn and ^{6}He+^{9}Be reactions

^{6}He is a Borromean-halo nucleus formed by alpha+n+n with 0.975 MeV breakup energy

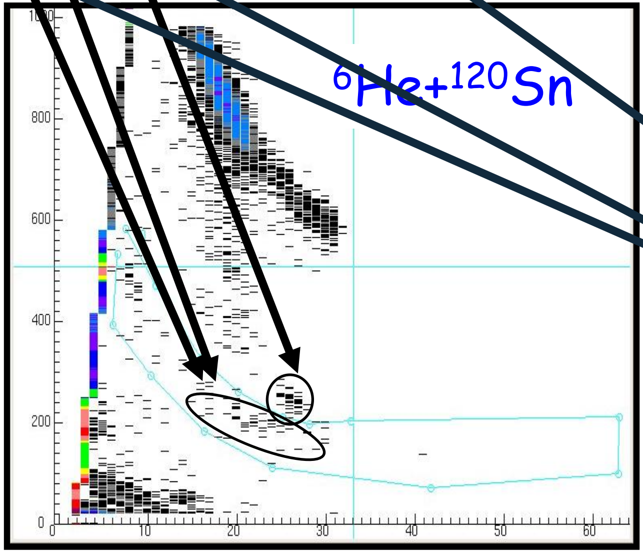


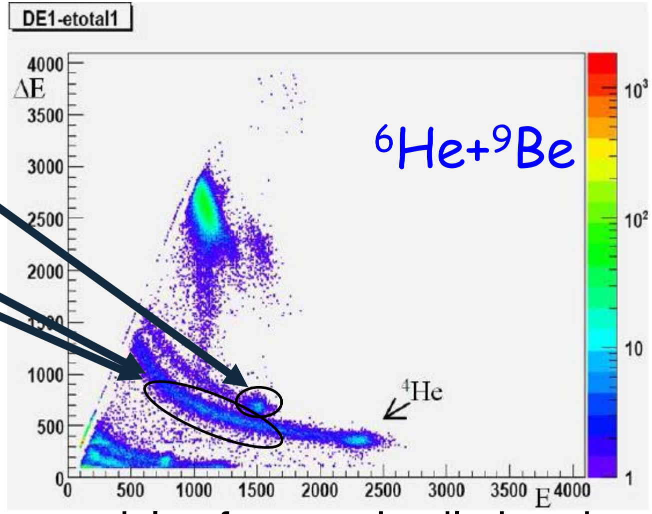
X=n+n+^{120}Sn; elastic breakup

X=n+^{121}Sn*; 1nêutron transfer

X=^{122}Sn*→n+^{121}Sn*; 2 nêutron transfer

X=^{126}Te* → a + n+ n complete fusion





α -particles from projectile break-up + target break-up + contaminants

Energy spectra and angular distributions of α-particles from $^{6}He+^{120}Sn$ collision

PHYSICAL REVIEW C **82**, 034602 (2010)

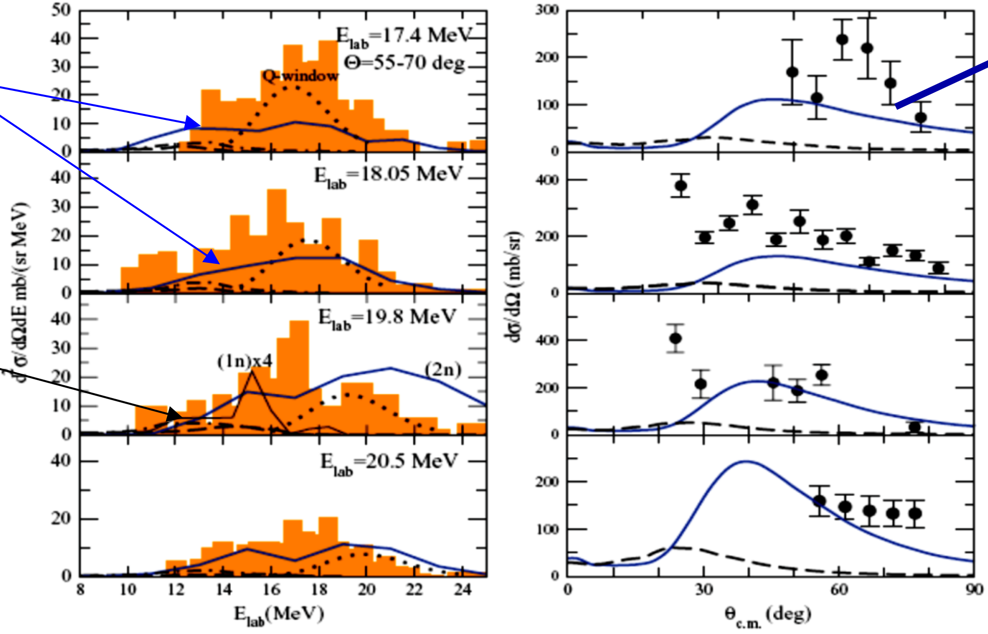
α-particle production in $^{6}He + ^{120}Sn$ collisions

P. N. de Faria,[1] R. Lichtenthäler,[1] K. C. C. Pires,[1] A. M. Moro,[2] A. Lépine-Szily,[1] V. Guimarães,[1]
D. R. Mendes Jr.,[1] A. Arazi,[3] A. Barioni,[1] V. Morcelle,[1] and M. C. Morais[1]
[1] *Instituto de Fisica, Universidade de São Paulo, Caixa Postal 66318, 05314-970 São Paulo, Brazil*

α-particles resulting from 2n-transfer reaction mostly

$^{120}Sn(^{6}He,^{4}He)^{122}Sn$

$^{6}He+^{120}Sn \rightarrow ^{4}He+^{120}Sn+2n$



total cross section

650 mb

DWBA 2n-transfer to continuum and bound states (A. Moro)

Fusion-evapor

3b-CDCC breakup calculation (A. Moro)

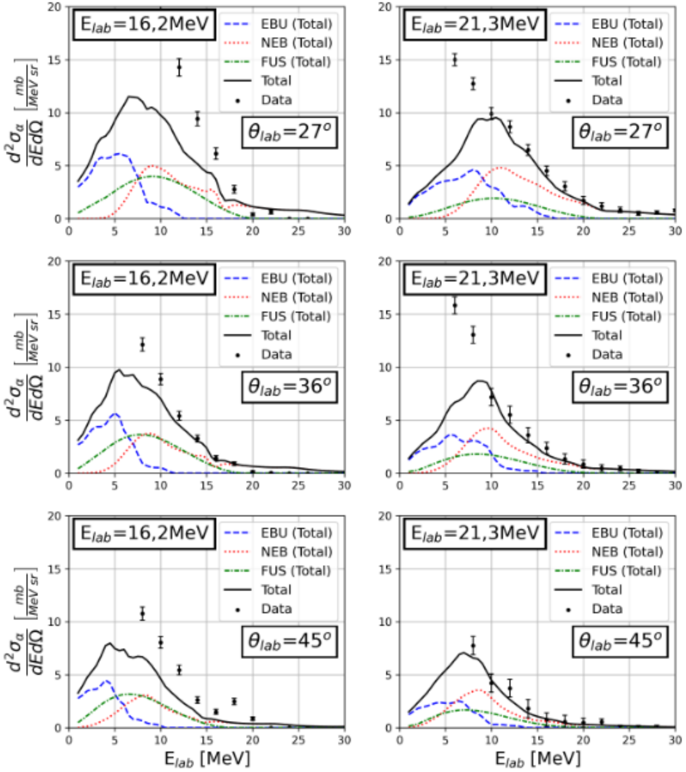
Q-optimum window for 2n transfer (R. Broglia)

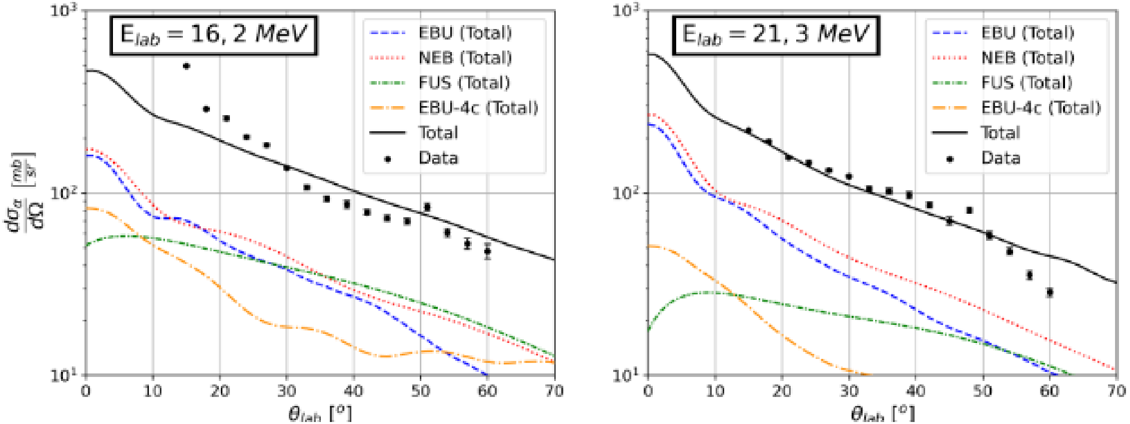
R. A. Broglia and A. Winther, Phys. Rep. ***4****, 153 (1972)*

DWBA 1n-transfer

Energy spectra and angular distributions of α-particles from ^{6}He+^{9}Be collision

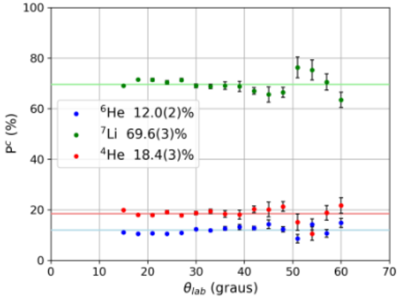
Master project of B. P. Monteiro (finished 2023)

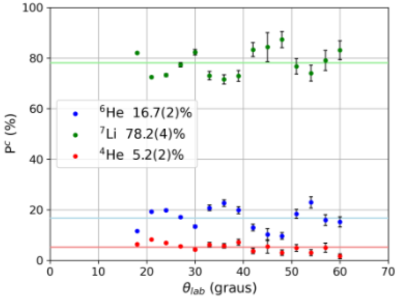




- The sum of the theoretical calculations was made considering the contribution of each particle in the secondary beam (weighted sum)

B. P. Monteiro et al. In preparation





Sistema	Energia	CDCC-3c	CDCC-4c	IAV	PACE	**TOTAL**
^{4}He+^{9}Be	24,7	-	-	-	119,30	119,30
^{6}He+^{9}Be	**16,2**	29,25	-	29,44	3,46	62,15
^{7}Li+^{9}Be	13,1	91,87	-	134,36	45,45	271,67
^{9}Be+^{4}He	55,6	-	33,83	-	-	33,83
^{9}Be+^{6}He	24,3	-	3,18	-	-	3,18
^{9}Be+^{7}Li	16,8	-	11,99	-	-	11,99
TOTAL		121,12	48,99	163,79	168,20	**502,11**

Sistema	Energia	CDCC-3c	CDCC-4c	IAV	PACE	**TOTAL**
^{4}He+^{9}Be	32,3	-	-	-	27,64	27,64
^{6}He+^{9}Be	**21,3**	28,85	-	26,18	9,45	64,48
^{7}Li+^{9}Be	17,6	102,56	-	140,11	51,82	294,49
^{9}Be+^{4}He	72,6	-	9,83	-	-	9,83
^{9}Be+^{6}He	31,9	-	17,32	-	-	17,32
^{9}Be+^{7}Li	22,6	-	20,07	-	-	20,07
TOTAL		131,41	47,22	166,29	88,91	**433,83**

E_{lab}=16,2 MeV

σ_{reac}=1488 mb

elastic
+
inelastic breakup
+
total fusion:
1450,5 mb

2,52%

E_{lab}= 21,3 MeV

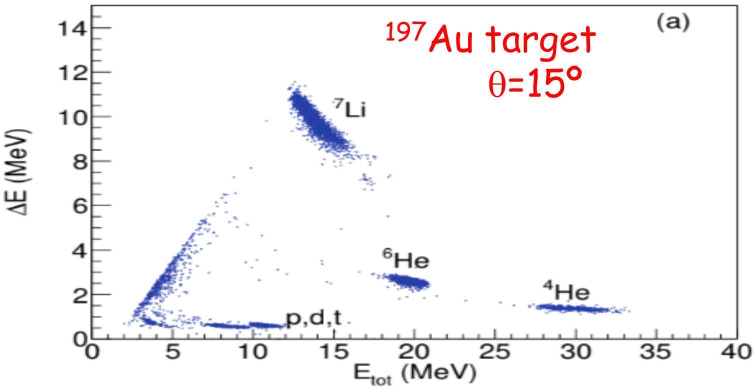
σ_{reac}= 1483 mb

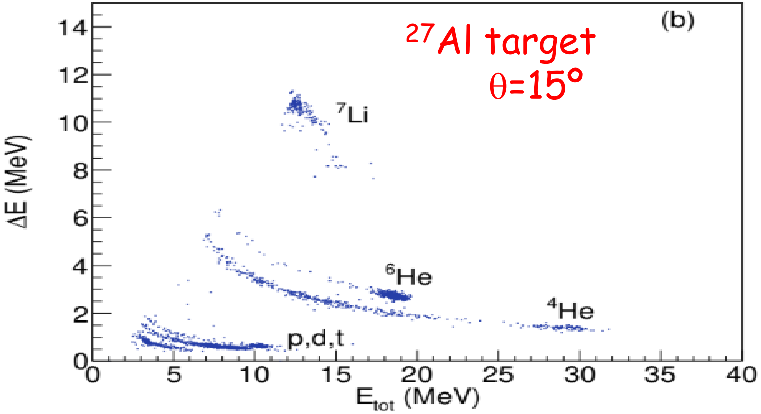
elastic
+
inelastic breakup
+
Total fusion:
1037,1 mb

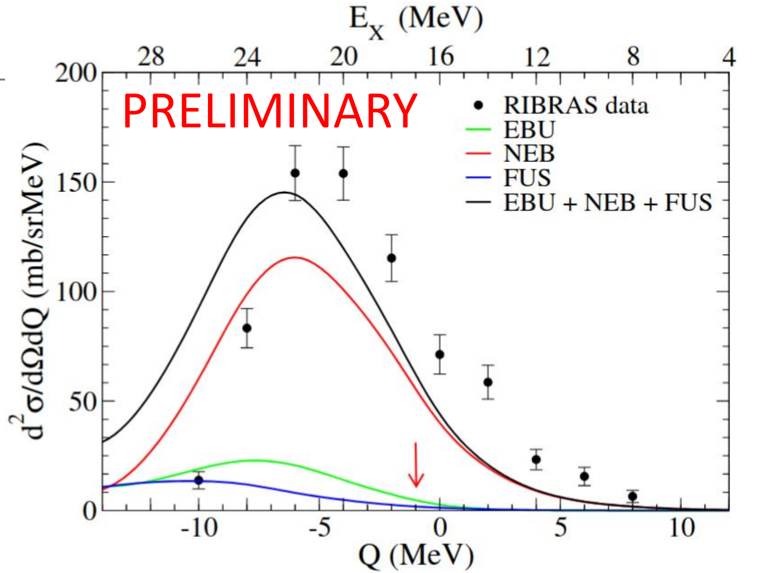
30,07%

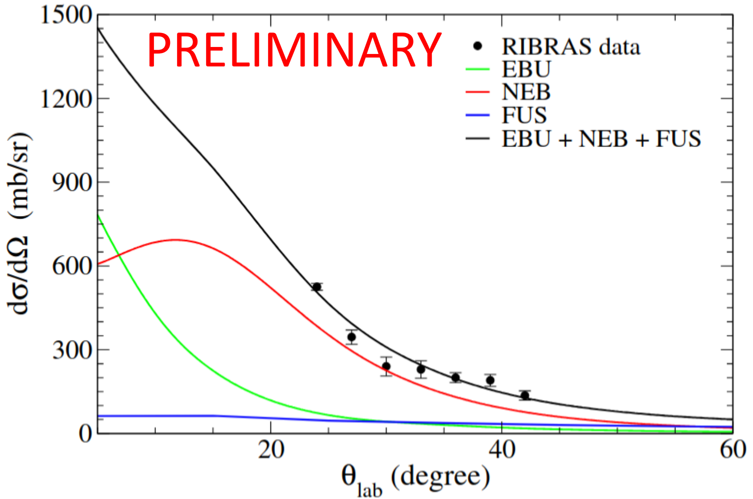
difference in relation to the total reaction cross section

Energy spectra and angular distributions of α-particles from $^{6}He+^{27}Al$ collision

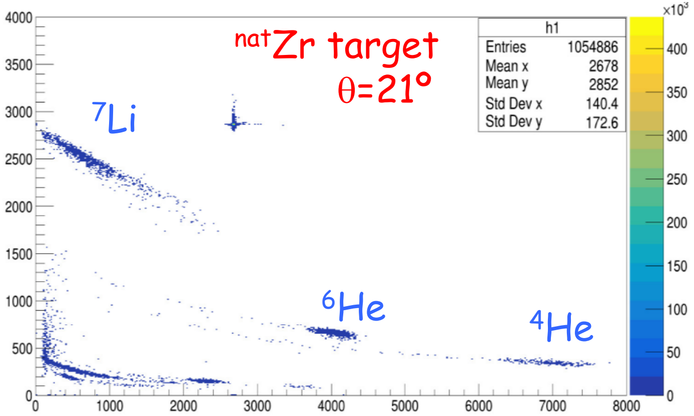


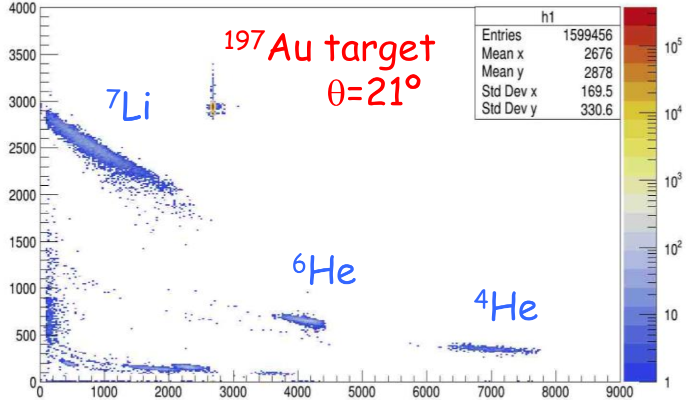


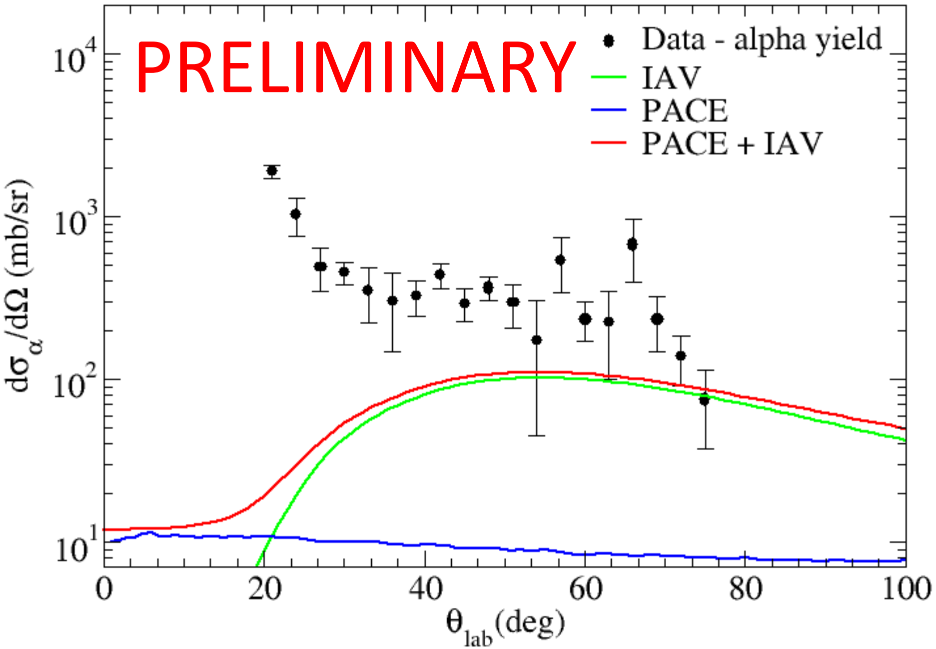




Angular distributions of α-particles from ^{6}He+^{nat}Zr collision







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.

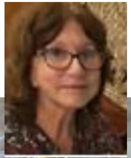
- Increase the detection capability for charged particles and γ-rays at RIBRAS.

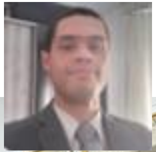
- Exclusive measurements of nuclear reactions with weakly bound radioactive at energies around the Coulomb barrier;
- The plan consists in the use of existing and the installation of new digital equipment (strip detectors for charged particles, Lyso gamma detectors and electronic devices mainly digitizers)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

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

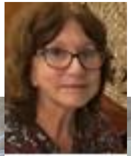
RIBRAS COLLABORATION

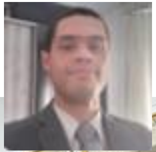
UFF
UFRRJ
UNIFESP
TANDAR
CEADEN
Univ. Sevilha
Univ. Notre Dame
Univ. Berkley ....



RIBRAS COLLABORATION





UFF
UFRRJ
UNIFESP
TANDAR
CEADEN
Uni

Thank you for your attention