Nuclear Physics Open Laboratory of the São Paulo University

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BRASIL-JINR FORUM

FRONTIERS IN NUCLEAR, ELEMENTARY PARTICLE AND CONDENSED MATTER PHYSICS

Dubna, June 15-19, 2015

Outline

- The Pelletron accelerator
- Experimental setups
- Research and Results
- The new LINAC accelerator
- Concluding remarks

Nuclear Physics Open Laboratory

Laboratório Aberto de Física Nuclear (LAFN)

South America

São Paulo State

About 90000 students

São Paulo University

Nuclear Physics Open Laboratory

Laboratório Aberto de Física Nuclear (LAFN)

Physics Institute

8UD Pelletron Accelerator

Control Room

1100 undergraduated students
290 graduated students

Electrostatic 8UD Tandem Accelerator

Project of 1970 (Prof. Oscar Sala)

Initiated the activities in 1972

About 100 Master thesis, 80 PhD thesis and 220 articles in scientific magazines.

12 technicians (accelerator maintenance, ion beam source, vacuum, target maker, electronics, mechanical workshop)

Main research areas

- Nuclear Reaction Mechanisms
- Nuclear Structure
- In-flight radioactive beams
- Applied Nuclear Physics

Program Advisory Committee (PAC)

- About 100 users
- 30 proposals approved (190 days)
- From 100 to 150 used days per year

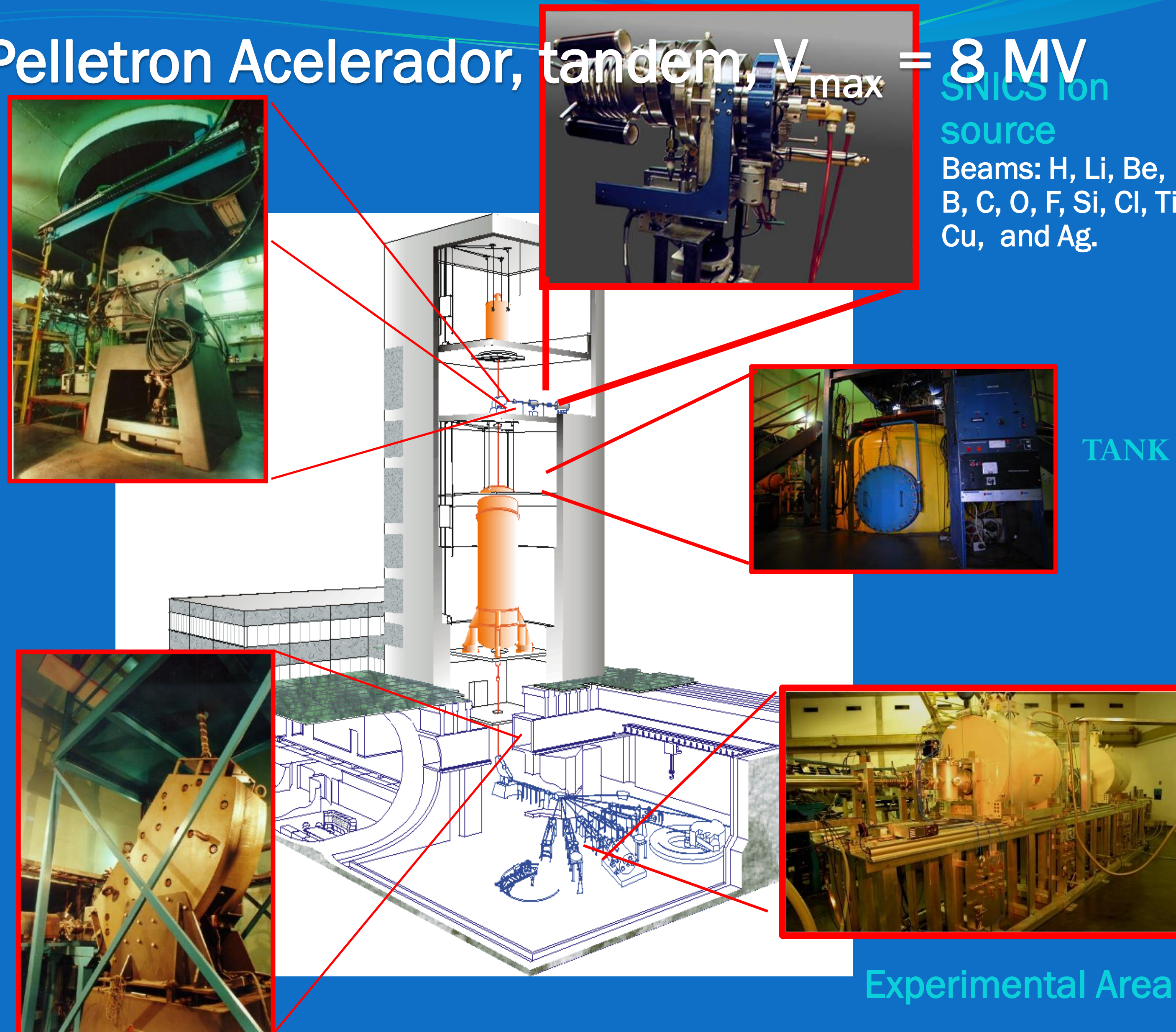
Airton Deppman
Luiz Carlos Chamon
Manfredo Tabacniks
Paulo Roberto Gomes
Roberto V. Ribas

http://portal.if.usp.br/fnc/node/368

O. Sala and G. Spalek, Nucl. Inst. Meth. 112 (1974) 213

Pelletron Acelerador, tandem, V_{max} = 8 MV

LAFN



SNICS Ion source

Beams: H, Li, Be, B, C, O, F, Si, Cl, Ti, Cu, and Ag.

Mass selection ME20

TANK

Energy Selection ME200

Experimental Area

Beam lines

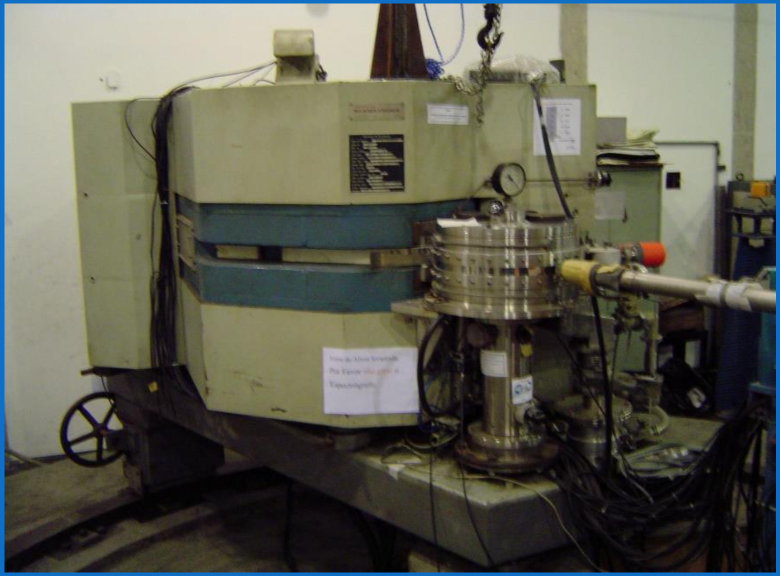
Large scattering chambers to study reaction mechanisms and applied nuclear physics

Beam lines

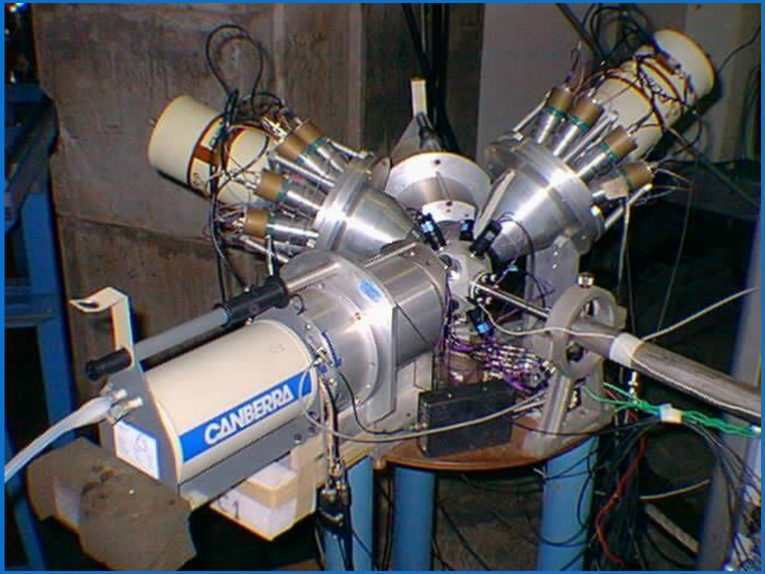
The RIBRAS (Radioactive Ion Beams in Brasil) Facility

Enge split-pole Facility

Transfer reactions



Beam lines



γ-ray spectrometer

Nuclear structure and reaction mecanism studies

New beam line with three scattering chambers

Applied Nuclear Physics studies

The Radioactive Ion Beam Facility in Brazil

- *RIB in the world*
- **The RIBRAS (Radioactive Ion Beams in Brasil) system**
- **Experiments with the single solenoid:**

  elastic scattering measurements, α-particle production, total reaction cross section
- **Experiments with the double solenoid system:**

  resonant scattering measurements

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Rubens Lichtenthaler Rubens@if.usp.br
Valdir Guimarães valdirg@if.usp.br

The study of nuclei out of the line of stability is one of the most active fields in low energy nuclear physics

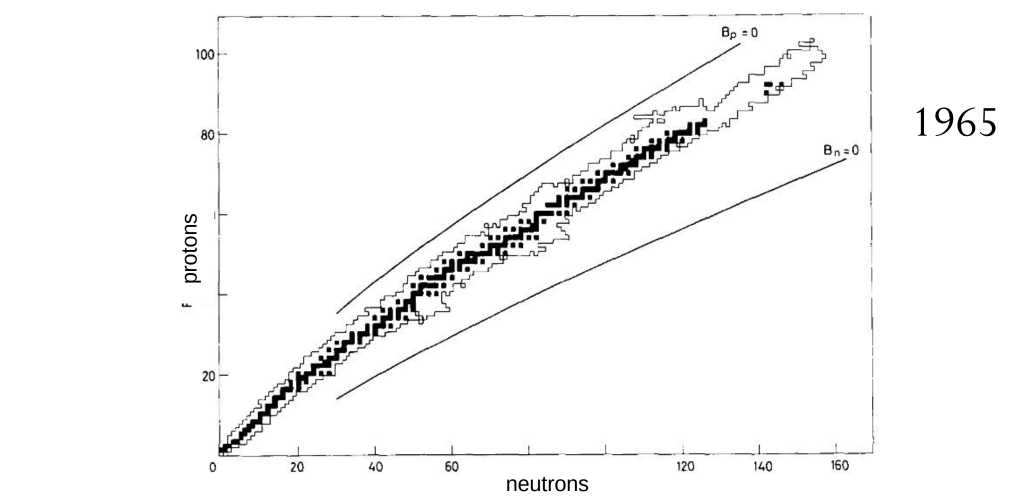
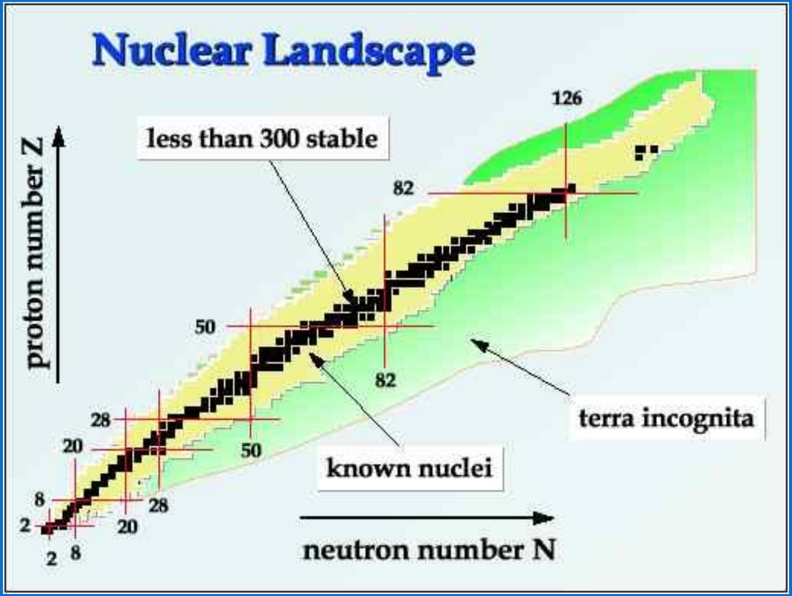


Fig. 1. Isotopic chart showing stable or very long-lived (half-life > 10^9 year) nuclides as filled squares and known radioactive nuclides as open squares. The curves $B_p = 0$ and $B_n = 0$ correspond to zero proton and neutron binding energy, respectively.

1965

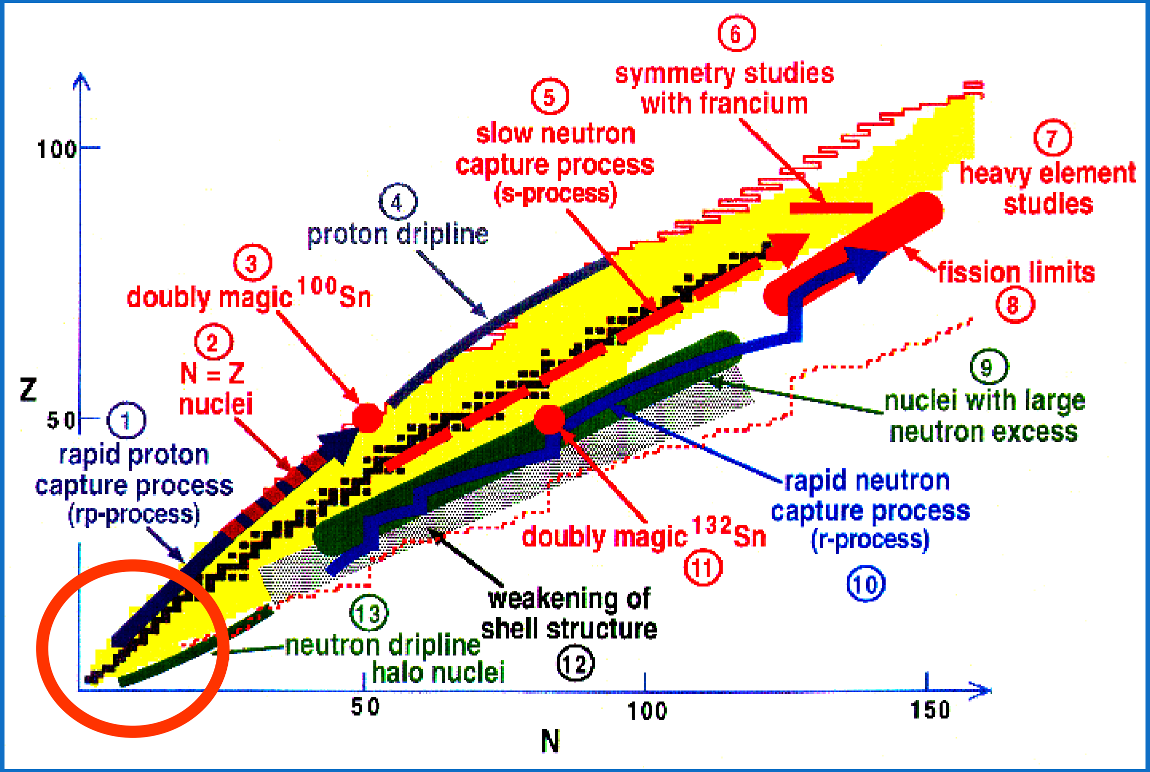
~1200 known nuclides



Presently, more than 3000 known nuclei and increasing …

http://www.physics.fsu.edu/users/roberts/roberts_weak.html

The physics out of the stability line



Halos and skins

Borromean nuclei (3-body systems)

New magic numbers and quenching of the shell gaps.

Importance in astrophysics –

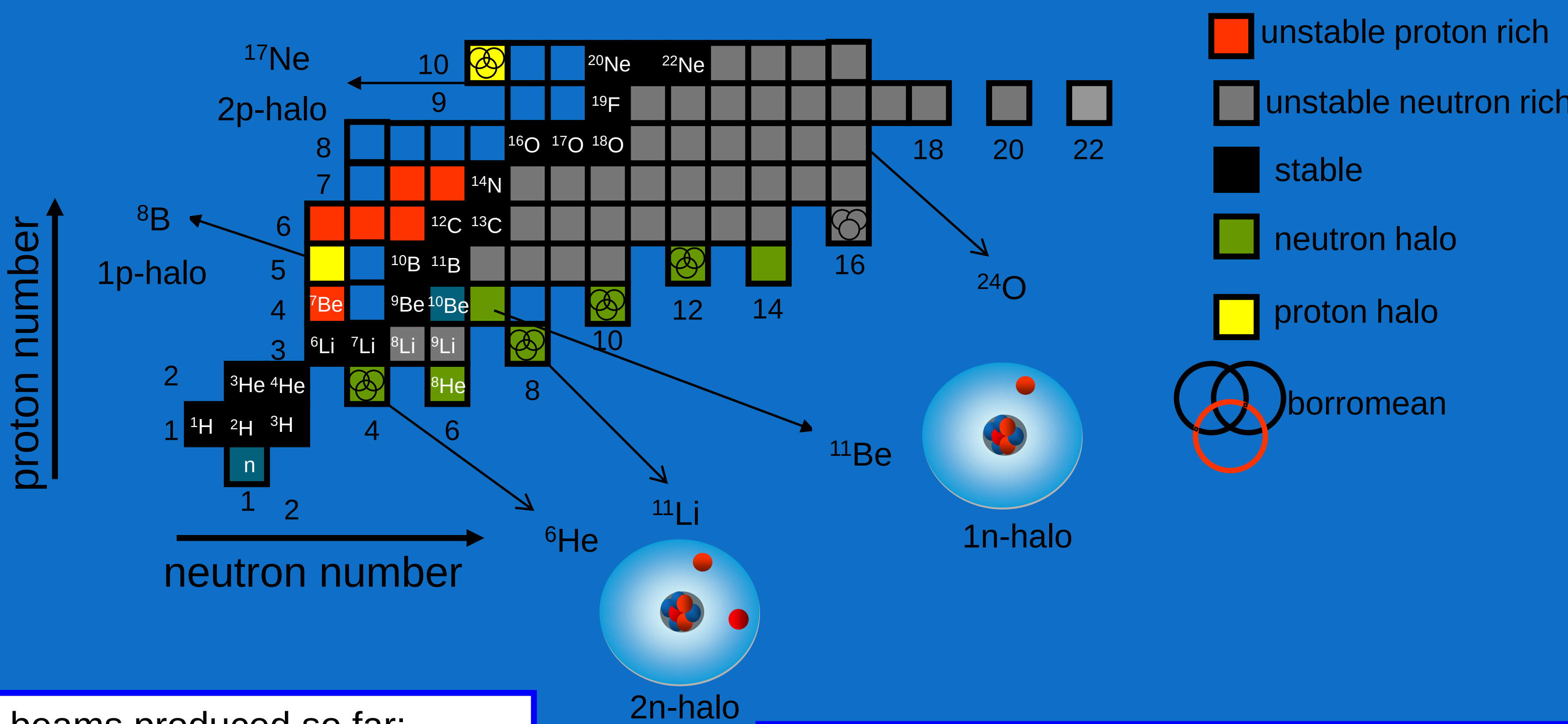
- overcoming the A=5,8 gap
- synthesis of elements heavier than Fe

New shapes and deformations – fundamental symmetries

Superheavy elements

Light exotic nuclei

Halos, skins, 3-body systems



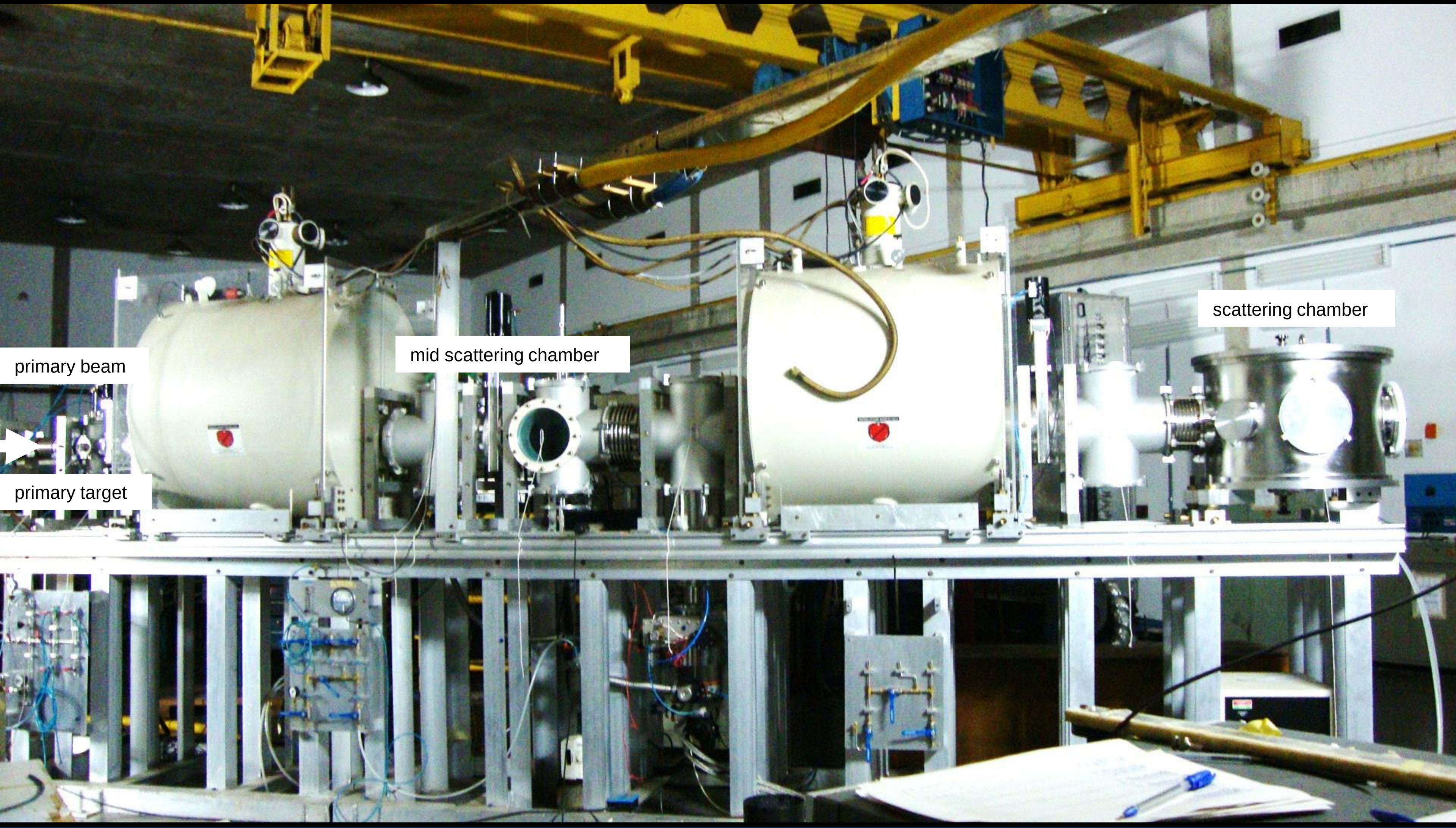
Ion beams produced so far:

^{6}He, ^{8}Li, ^{7}Be, ^{10}Be, ^{8}B, ^{12}B

Elastic and inelastic scattering to study the interaction potencial and the reaction mechanisms between weakly bound and halo projectiles on light, medium and heavy mass targets.

nuclei	B.E(MeV) (structure)
^{11}Li ($T_{1/2}$=8.75ms)	0.300 (n+n+^{9}Li)
^{6}He ($T_{1/2}$=807ms)	0.973 (2n+alfa)
^{11}Be ($T_{1/2}$=13.81s)	0.501 (n+^{10}Be)
^{8}B ($T_{1/2}$=770 ms)	0.137 (p+7Be)

The RIBRAS system

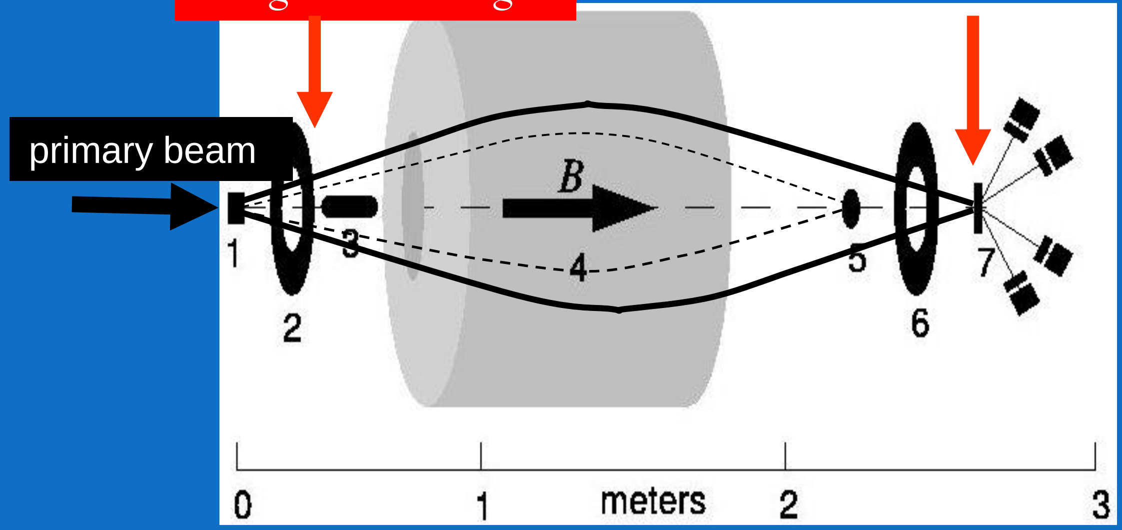


Two superconducting solenoids with 6.5 T
Three scattering chambers.

The focusing system for 1 solenoid

The secondary beam is produced in 1
and focused in 7 by the first solenoid

angular acceptance
2 deg<Δθ <6 deg



High acceptance

ΔΩ=30 msr

Important at low energies
where the production cross sections are low

Bρ selection

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

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

Secondary beams and production reactions at RIBRAS

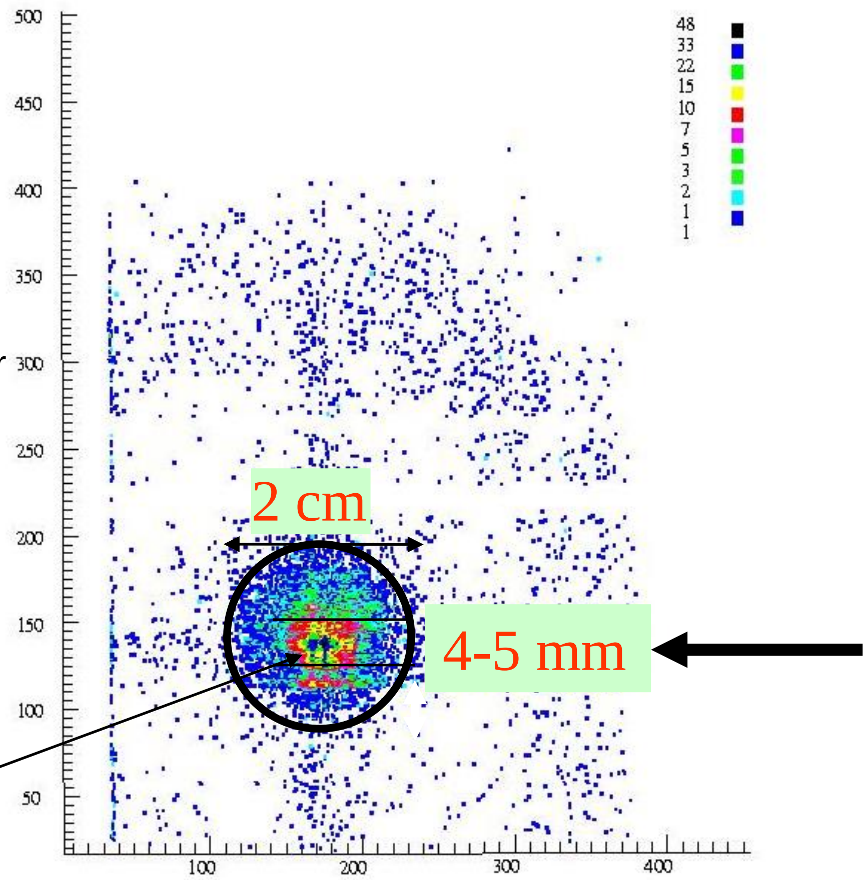
Secondary Beam	Production reaction		Intensity (pps) $I_{primary}$ ~ 300 nAe
^{6}He	$^{9}Be(^{7}Li,\underline{^{6}He})$	→ Neutron halo	10^{5}
^{8}Li	$^{9}Be(^{7}Li,\underline{^{8}Li})$	Borromean	10^{5}
^{7}Be	$^{3}He(^{6}Li,\underline{^{7}Be})$		10^{5}
^{7}Be	$^{3}He(^{7}Li,\underline{^{7}Be})$		10^{5}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

Energy of the secondary beams 9-32 MeV depending on the beam.

Secondary beam spot:

reaction $^{9}Be(^{7}Li,^{8}Li)$

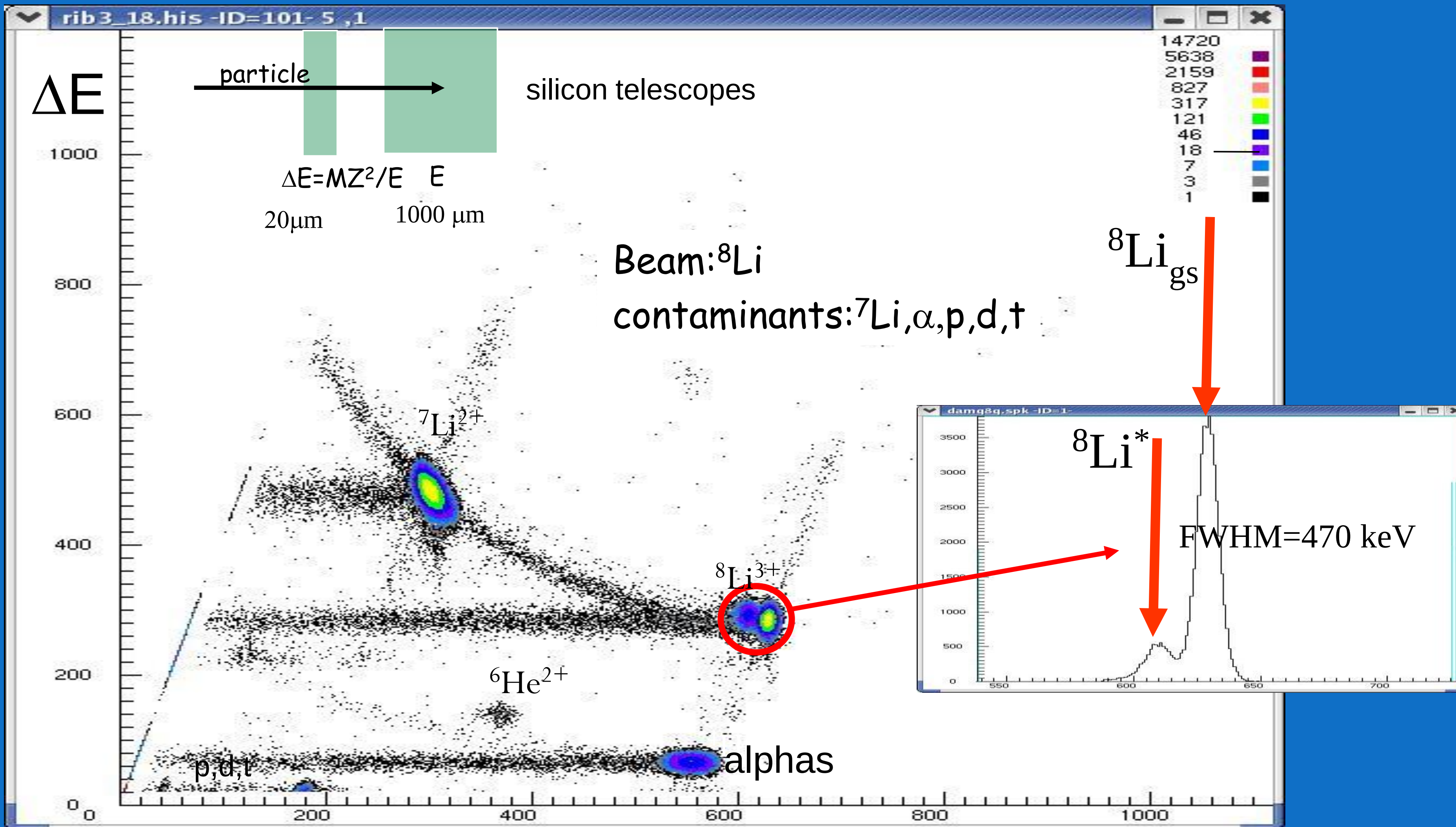
Measured with a Parallel Plate Avalanche Counter (PPAC)
X-Y position sensitive gas detector
C. Mazur Saclay



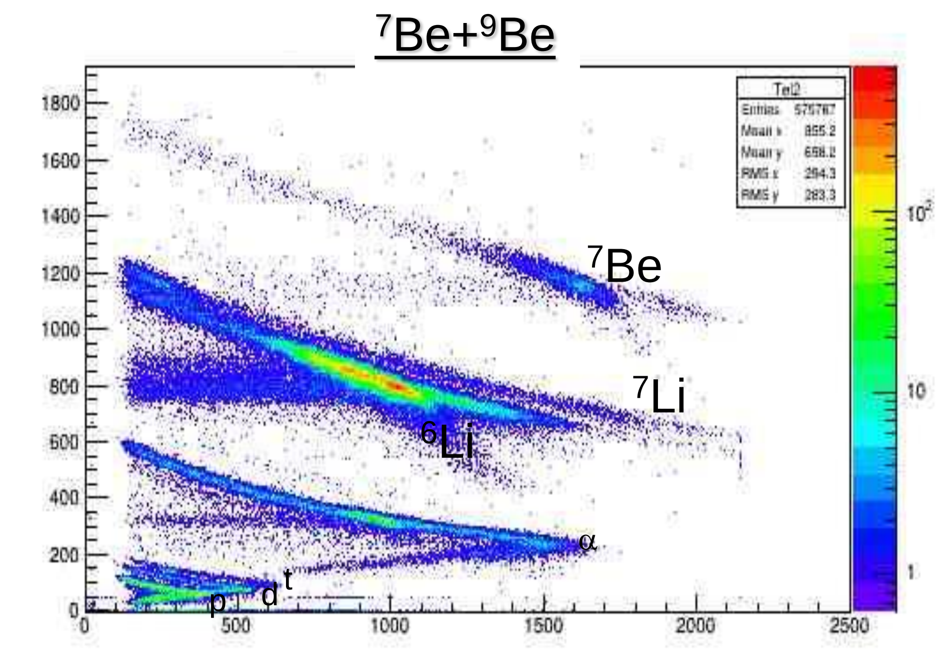
3-4mm Primary beam spot
+
magnifying factor 1.5
of the 1st solenoid

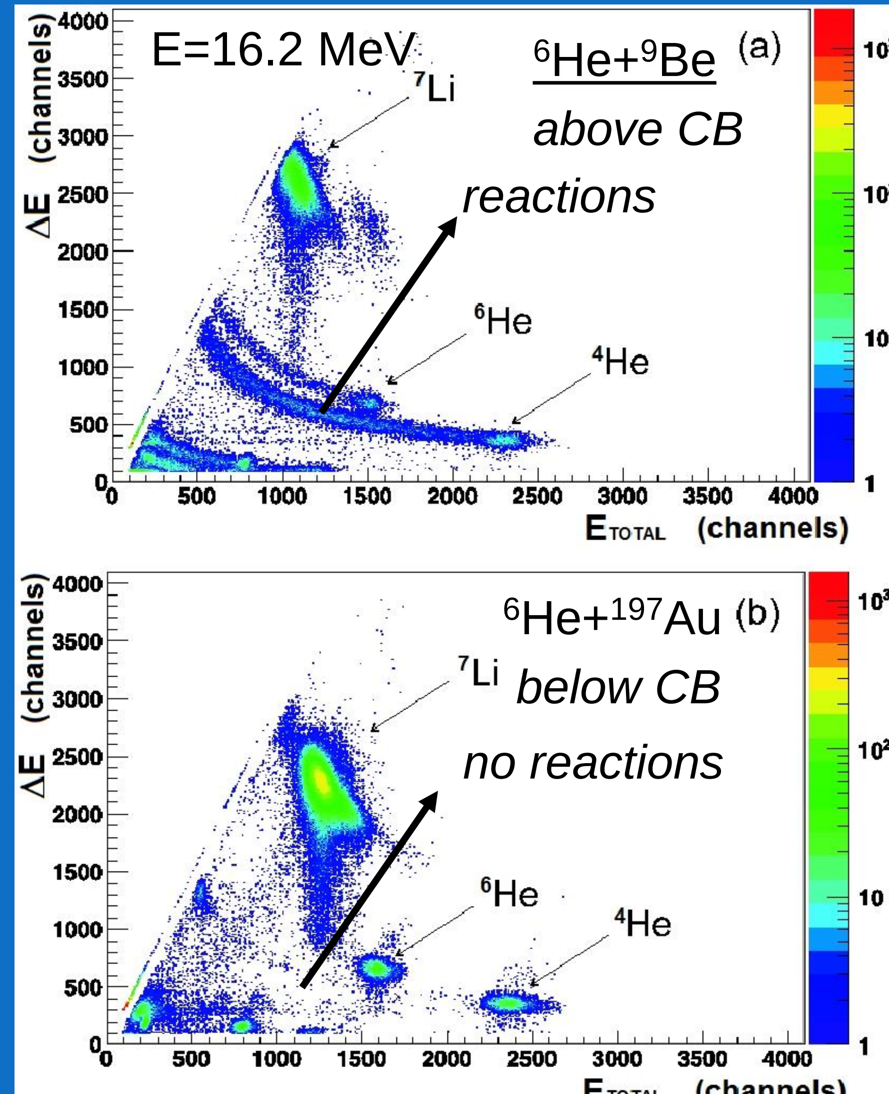
Identification spectrum

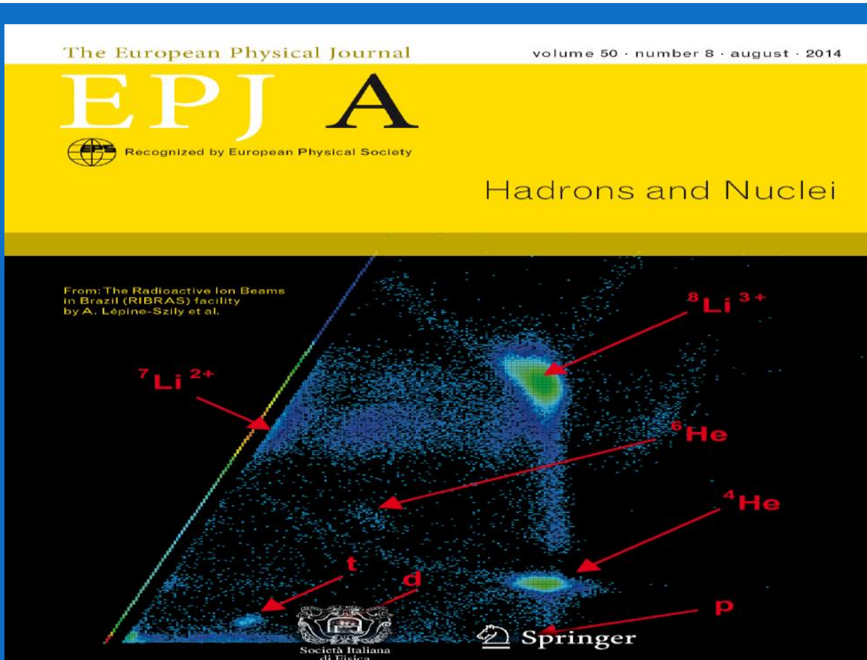
cocktail beam



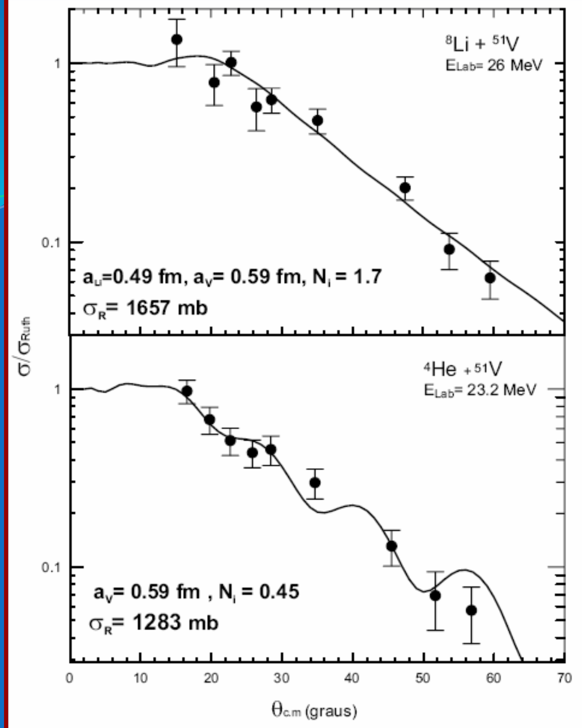
more identification spectra ΔE-E

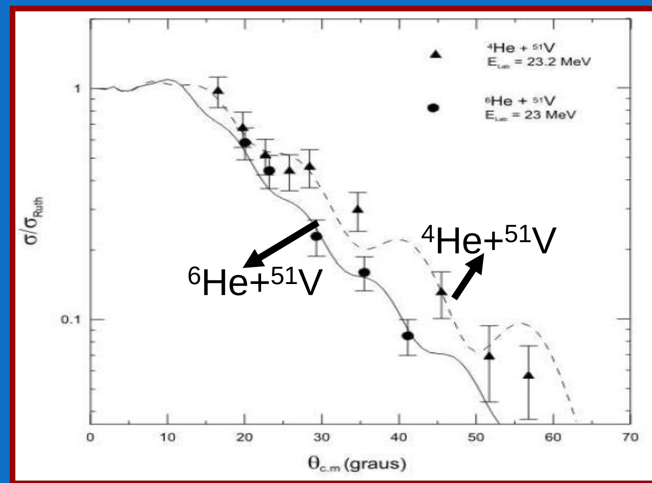






Elastic scattering measurements: angular distributions



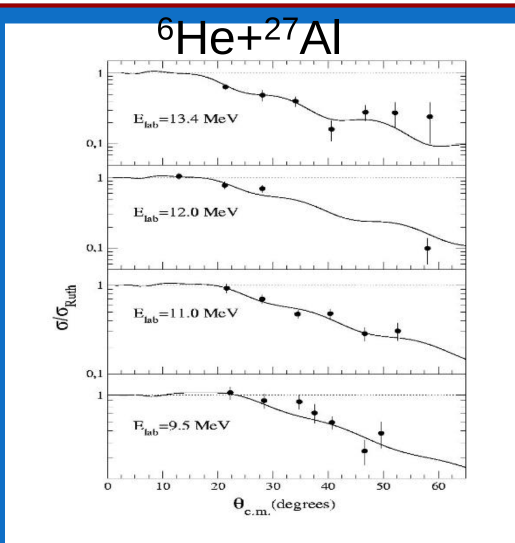


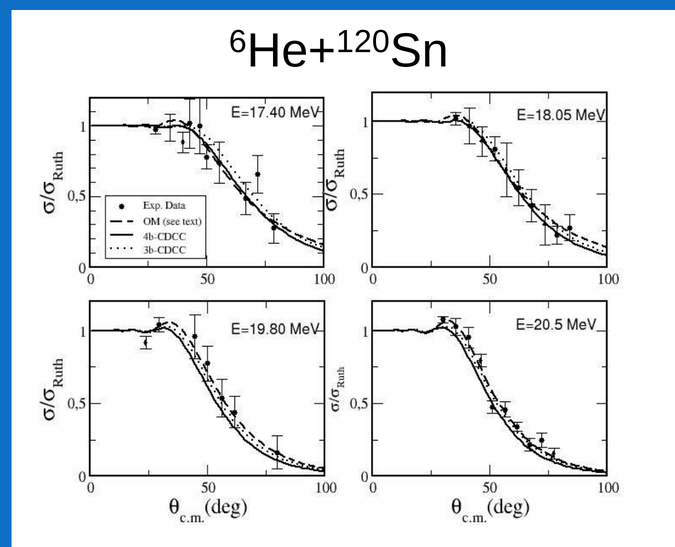
Calculations

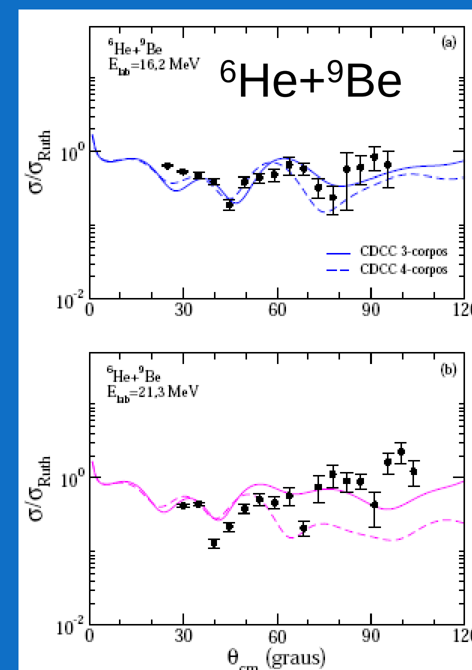
Optical Model

CDCC 3 and 4 body

(Continuum and discretized coupled-channel method)







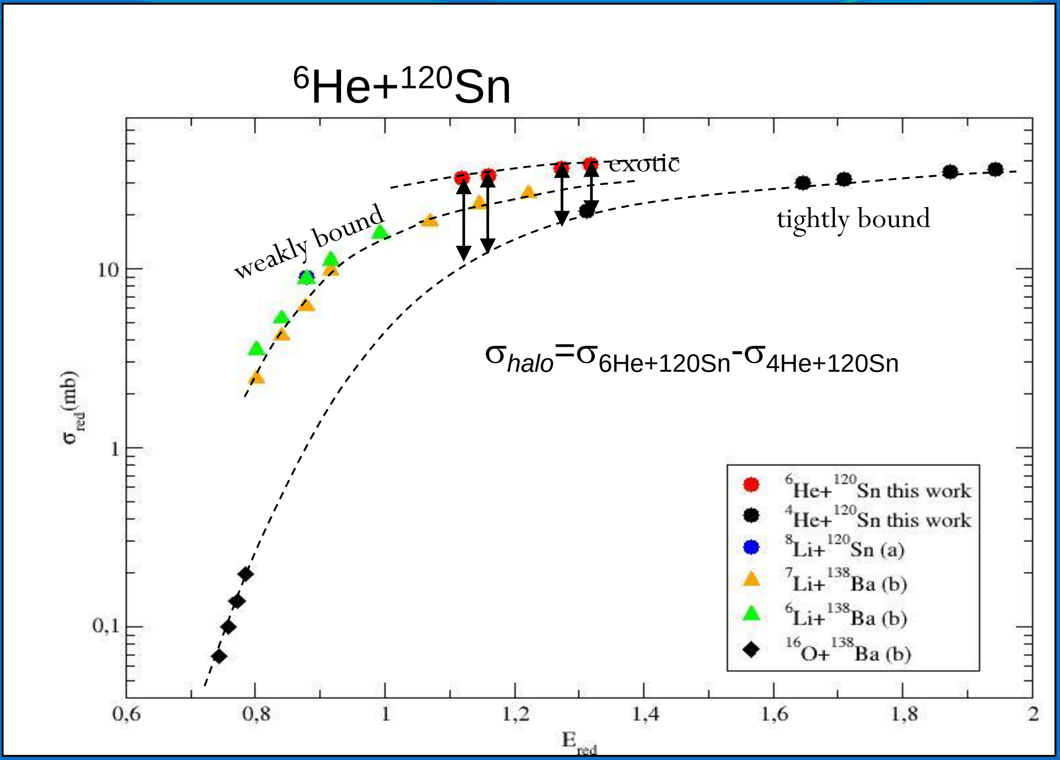
A. Lépine-Szily , R. Lichtenthaler, and V. Guimarães Eur. Phys. J. A. 50 (2014)

Total reaction cross section obtained from the elastic scattering

Reaction cross-section obtained from the elastic scattering (CDCC,OM,CC)

$$\sigma_{red} = \frac{\sigma_{reac}}{(A_p^{1/3} + A_t^{1/3})^2}$$

$$E_{red} = \frac{E_{cm}(A_p^{1/3} + A_t^{1/3})}{Z_p Z_t}$$



P. N. DE FARIA *et al.* PHYSICAL REVIEW C **81**, 044605 (2010)

TABLE II. Total reaction cross sections for the ^{6}He + ^{120}Sn system obtained from the OM and CDCC calculations. The fourth column is the average between the second and third columns (see text for more details).

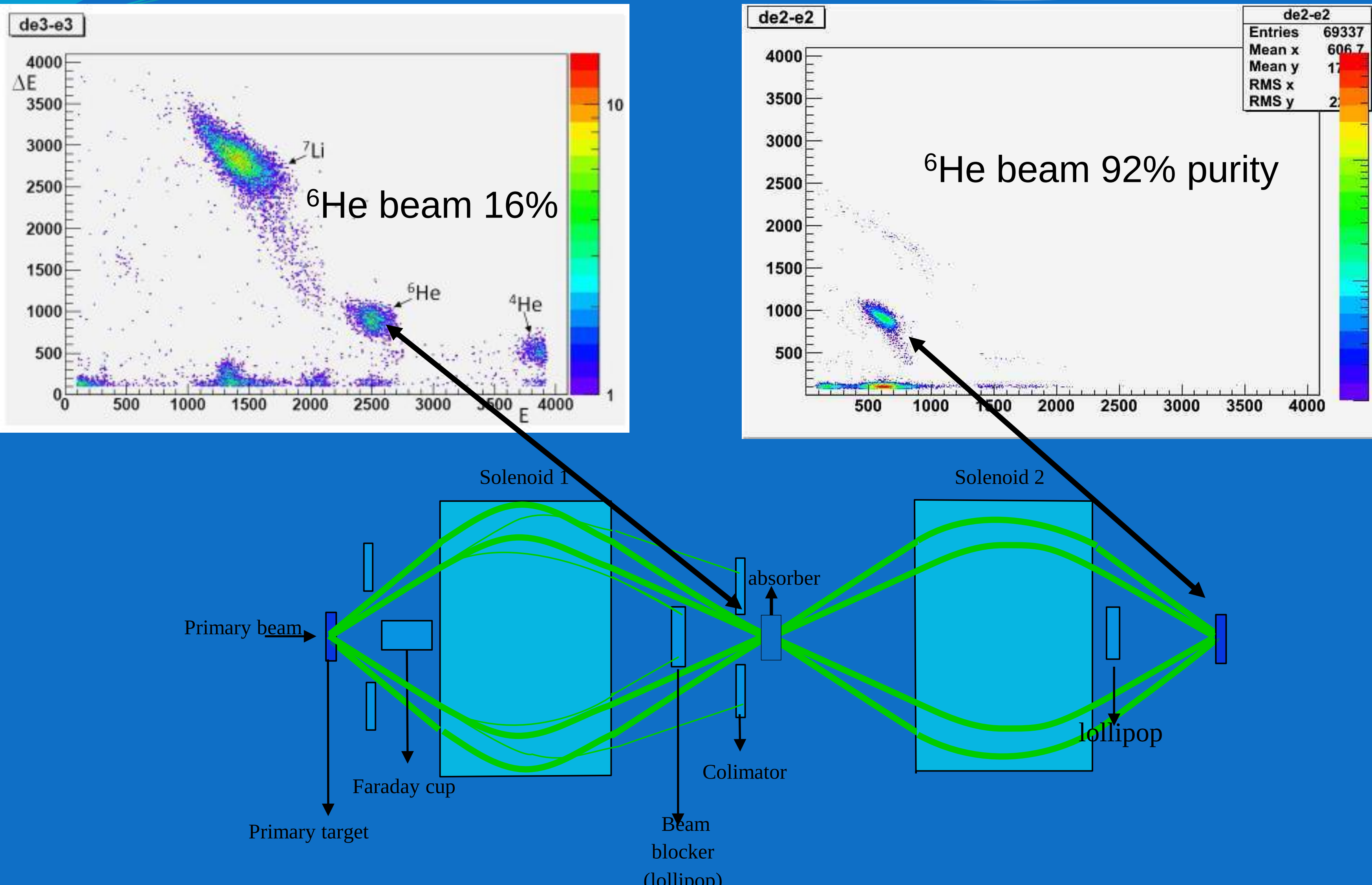
E (MeV)	σ_{reac}^{OM} (mb)	σ_{reac}^{CDCC} (mb)	σ_{reac}^{av} (mb)	σ^{halo} (mb)	$\sigma_{fus} = \sigma_{reac}^{av} - \sigma^{halo}$ (mb)	σ_{fus}^{Bass} (mb)
17.40	1451	1491	1471	768	703	618
18.05	1445	1592	1519	763	756	703
19.80	1475	1834	1655	739	916	900
20.50	1579	1916	1748	762	986	1065

The double solenoid system – since 2011

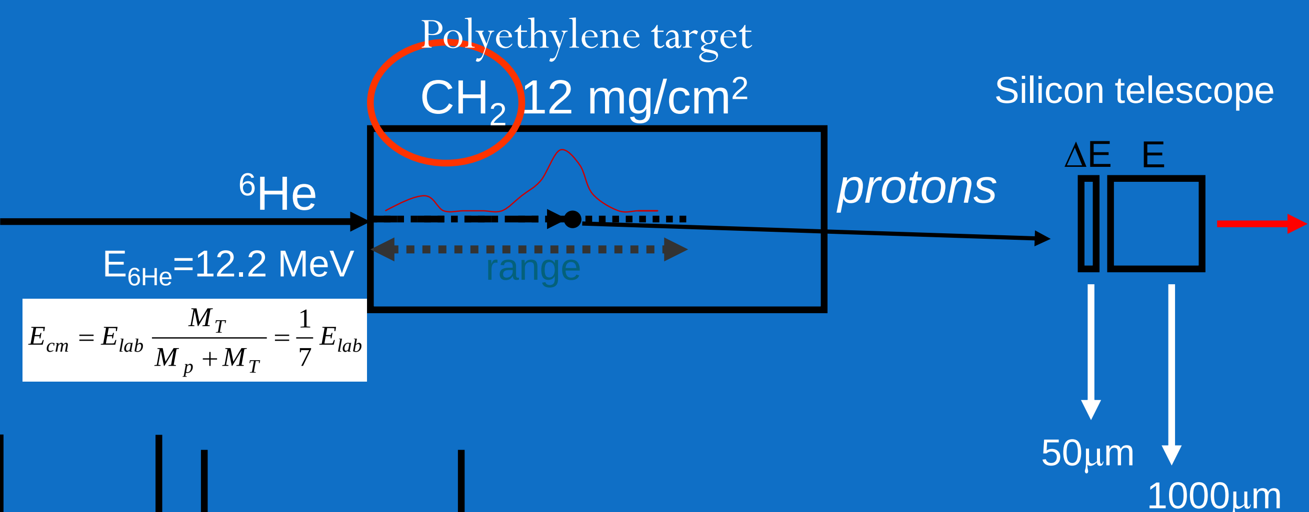
^{6}He Beam purity

1 solenoid

2 solenoids



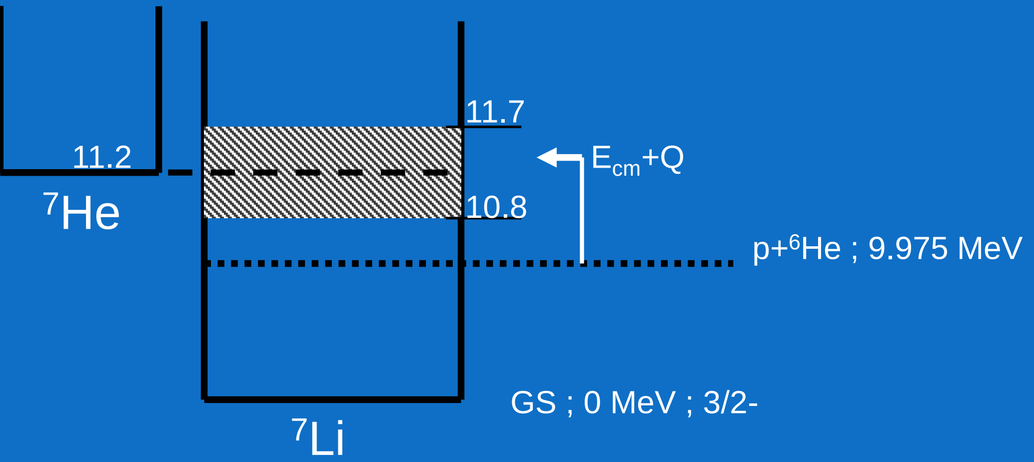
Excitation function measurements. Experiments with the thick target method -resonances in $^6He+p={}^7Li$ and $^8Li+p={}^9Be$.

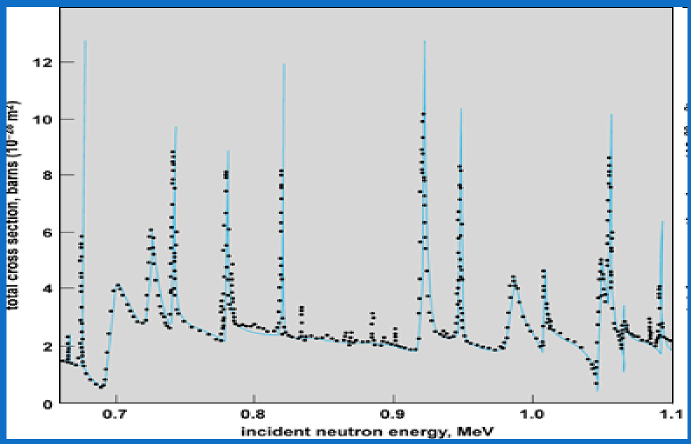


$$E_{cm} = E_{lab}\frac{M_T}{M_p + M_T} = \frac{1}{7}E_{lab}$$

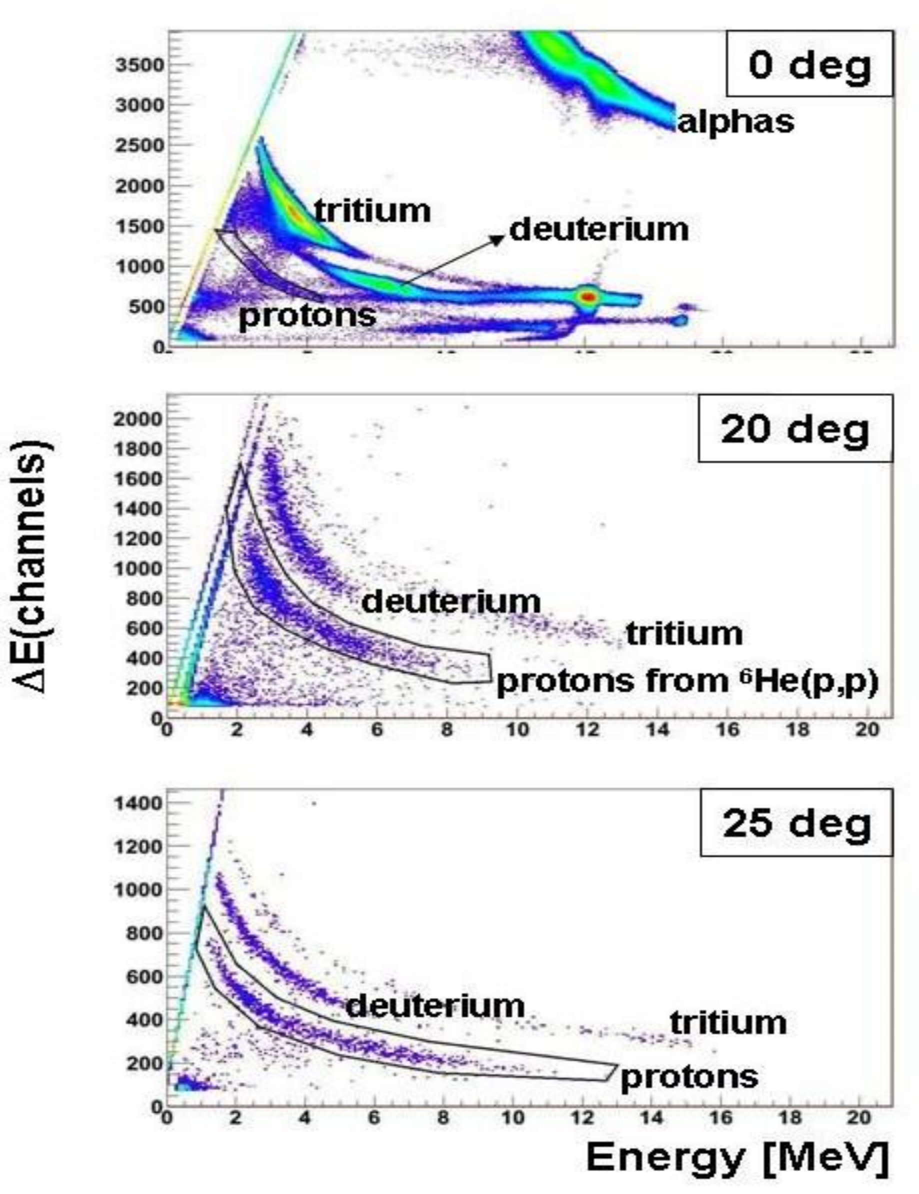
spectrum of light particles

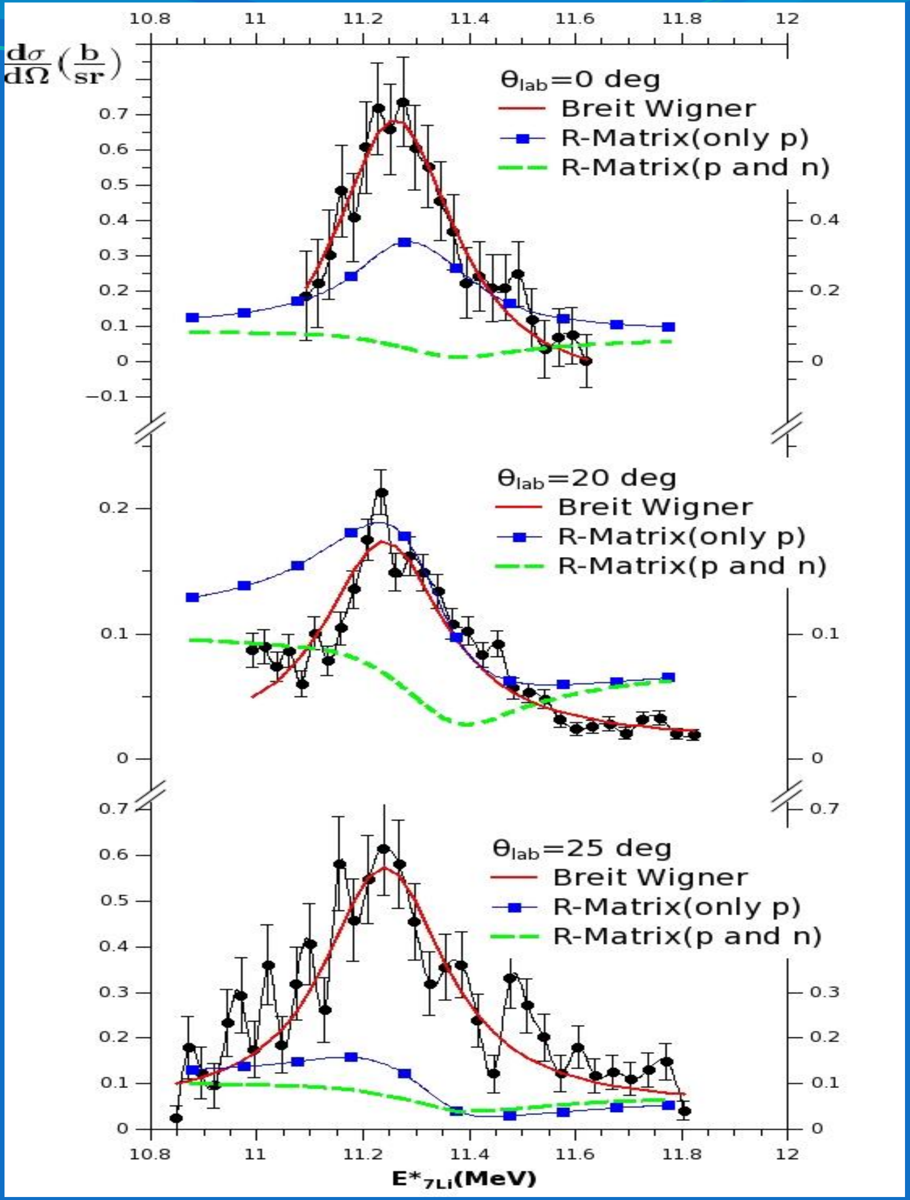
resonances in the CN

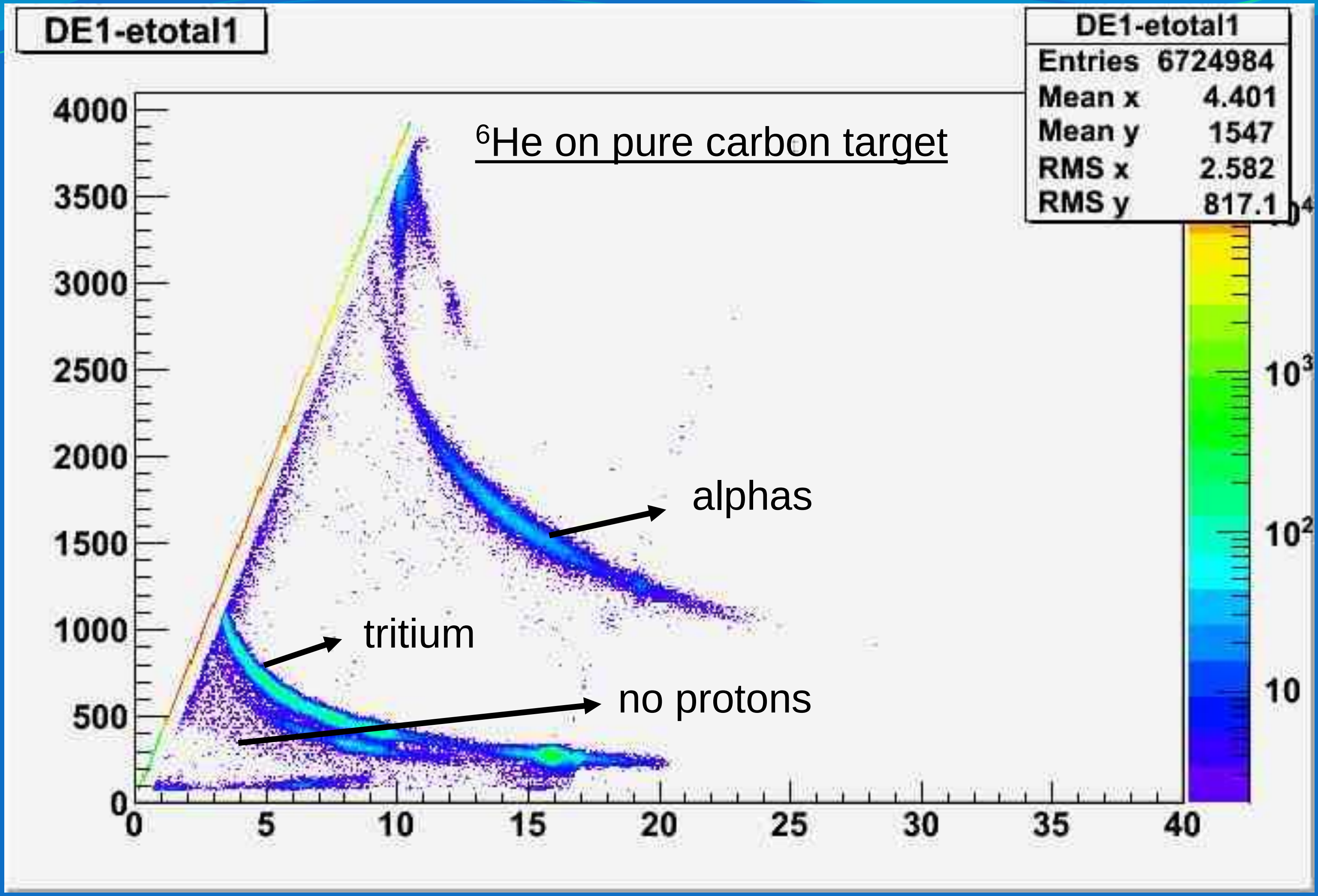




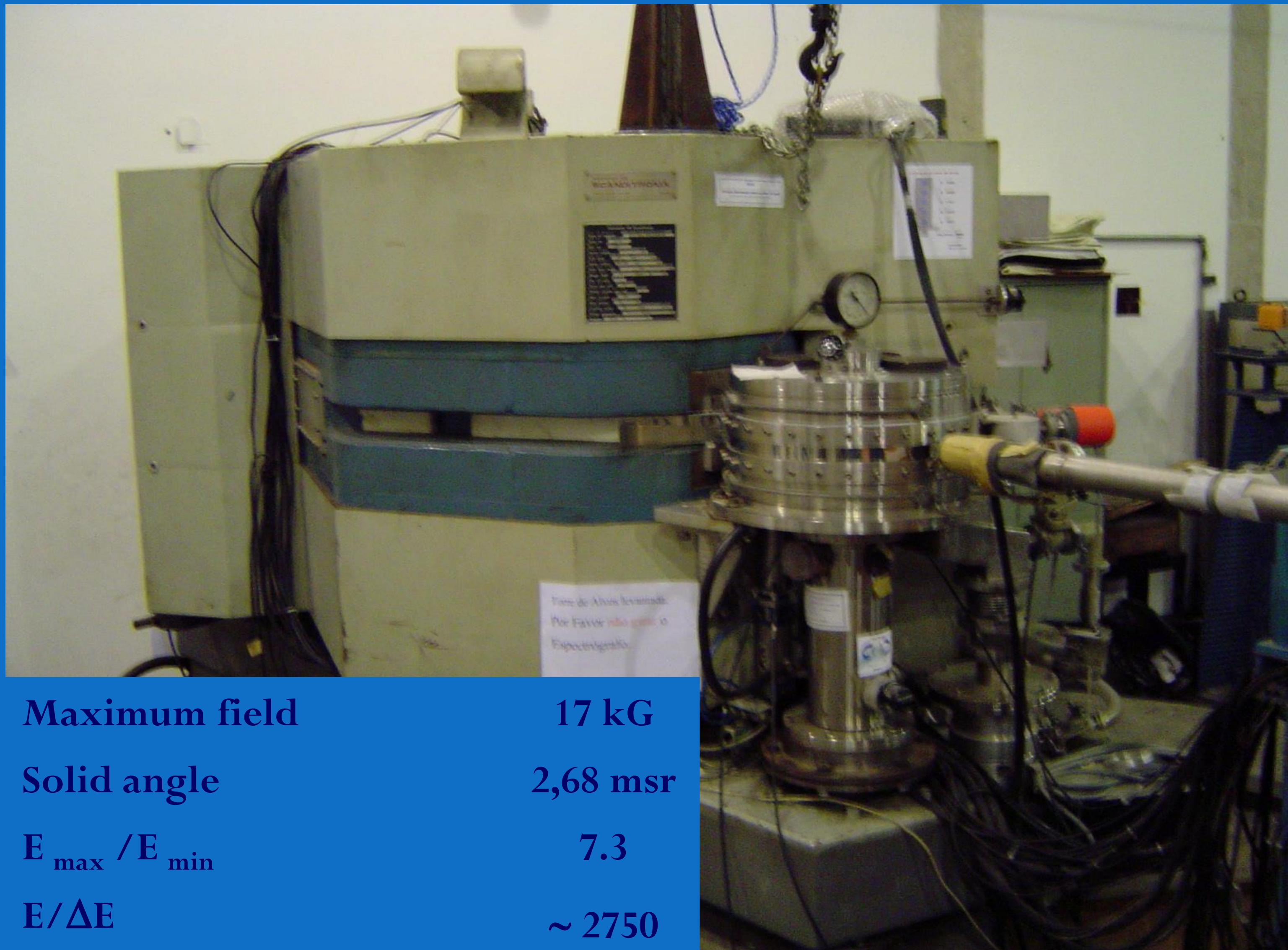
$p(^6He,p)^6He$ | $p(^6He,p)^6He$ excitation functions






DE1-etotal1
DE1-etotal1
Entries 6724984
Mean x 4.401
Mean y 1547
RMS x 2.582
RMS y 817.1
6He on pure carbon target
alphas
tritium
no protons
4000
3500
3000
2500
2000
1500
1000
500
0
0
5
10
15
20
25
30
35
40
10
10²
10³

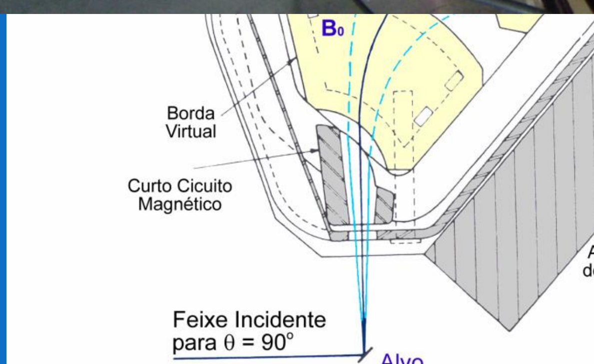
Enge-Split-Pole-Spectograph Facility



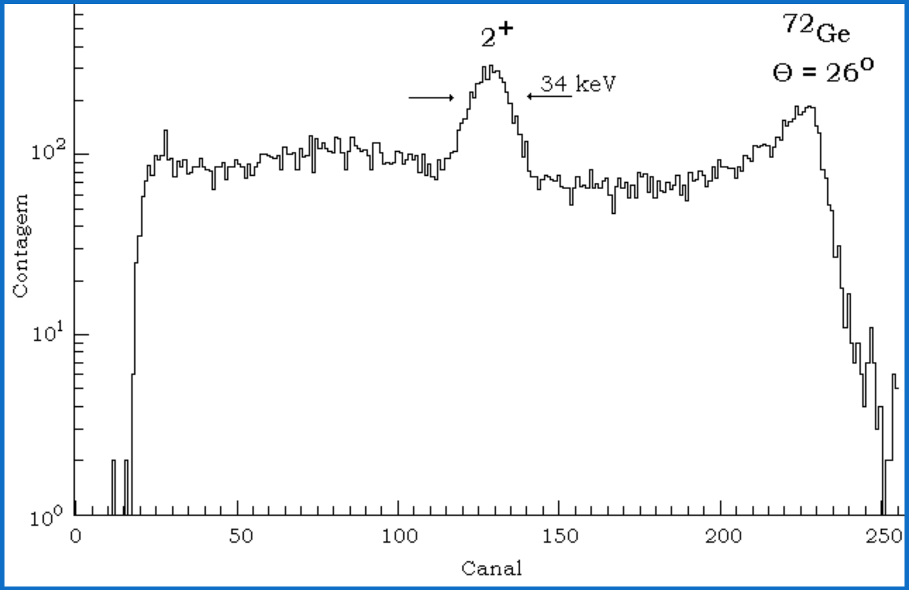
Maximum field	**17 kG**
Solid angle	**2,68 msr**
E_{max} / E_{min}	**7.3**
$E/\Delta E$	**~ 2750**

Marcia Rodrigues: marciadr@if.usp.br

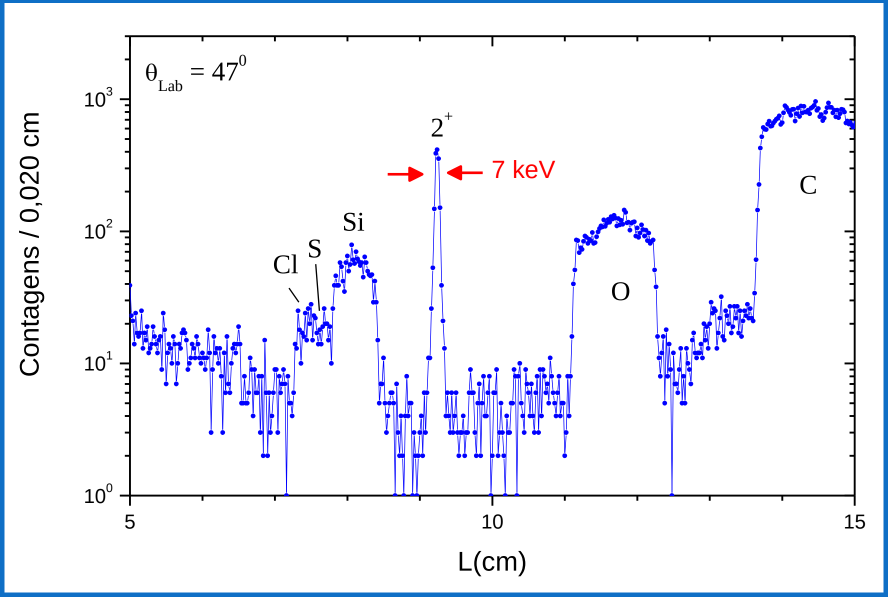
Pelletron-Enge-Split-Pole-Spectograph facility



Pelletron-Enge-Split-Pole-Spectograph facility
High resolution measurements



$^{72}Ge(^{6}Li, ^{6}Li') ^{72}Ge$ $E_{6Li} = 28$ MeV
Surface barrier position-sensitive Detector (PSD), 500 μ*m thick with an area of* 47 × 8 mm^2, beam defining slits of 1.0 × 2.0 mm^2
^{72}Ge self-suported target 30 $\mu g/cm^2$
E/ΔE ~ 800



$^{104}Pd(d, d') ^{104}Pd$ $E_d = 13$ MeV
Fuji G7D nuclear emulsion plates, 50 μ*m thick, 25* cm along focal plane, beam defining slits of 1.2 × 3.0 mm^2
^{104}Pd target 20 $\mu g/cm^2$ *with a C backing* 10 $\mu g/cm^2$
E/ΔE ~ 1850

Research lines:

Transitional mass regions

Evolution of the nuclear structure scenario along isotopic chains

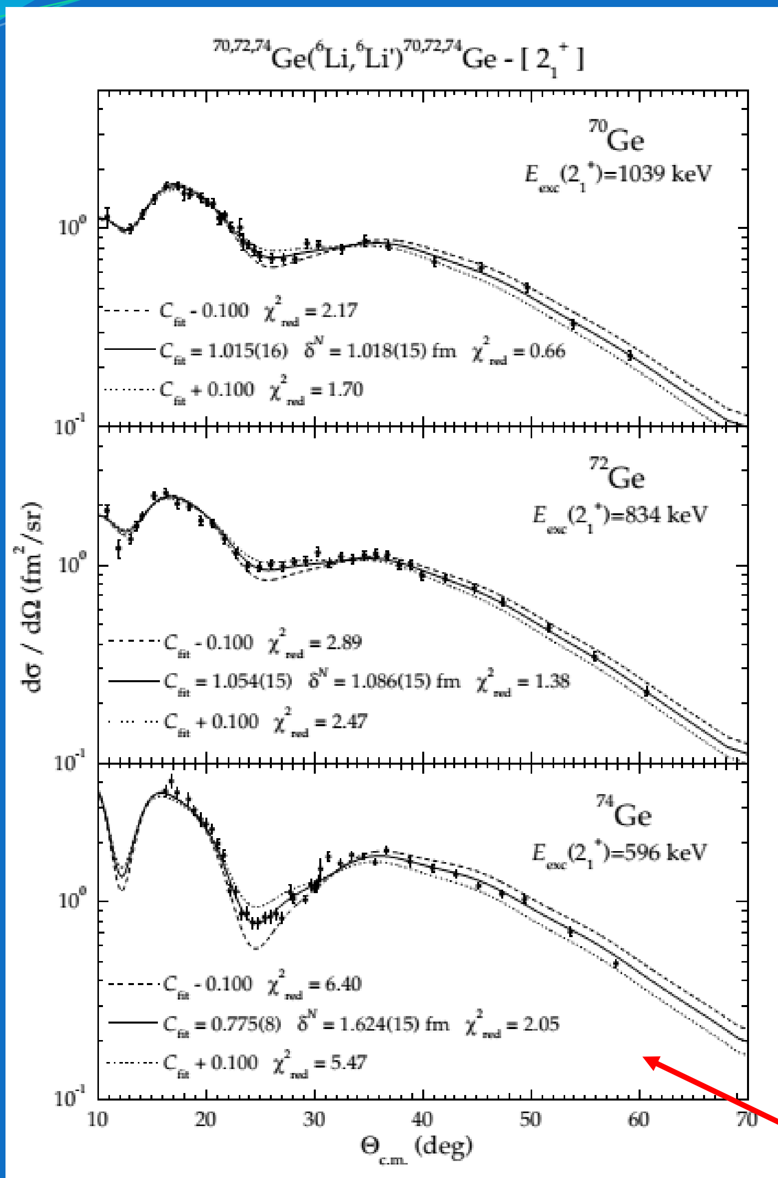
- transfer reactions and Coulomb-Nuclear Interference in the inelastic scattering using isoscalar (T=0) projectiles

α-cluster phenomenon on light mass nuclei

α-clustering on ($x\alpha$) and ($x\alpha$ + n) nuclei through (^{6}Li,d) reaction

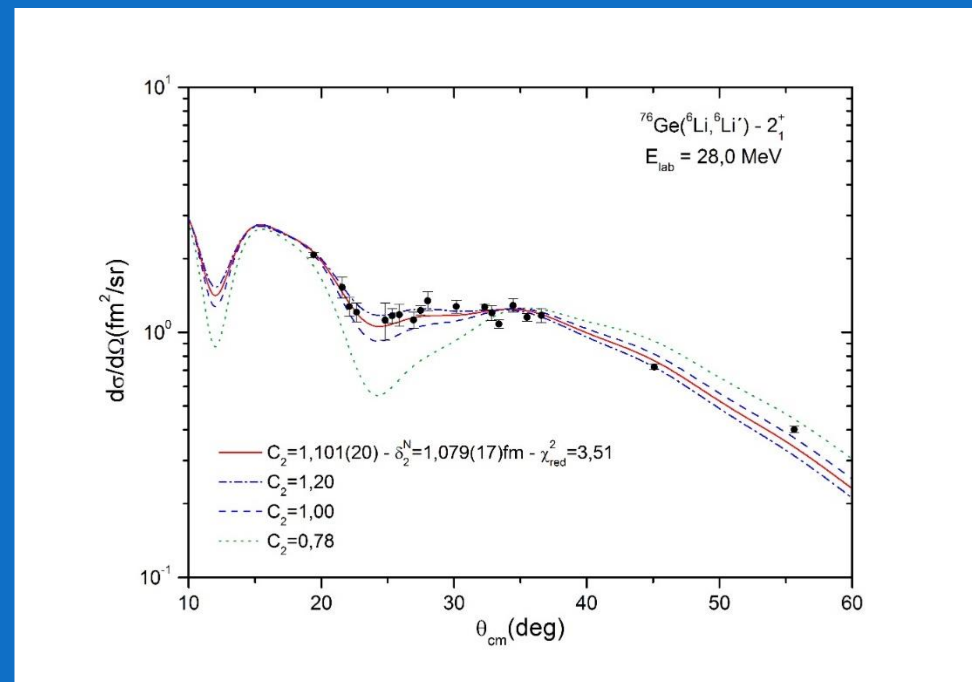
- resonant states near the thresholds.

Coulomb-Nuclear Interference - A ~ 70



Barbosa et al., Phys. Rev. C **71**, 024303 (2005)

Inelastic scattering angular distributions
^6Li of 28 MeV on $^{70,72,74,76}Ge$
DWBA-DOMP prediction



Zhang et al., IOP Conference Series (accepted) (2015).

C is the charge to isoscalar deformation lengths

neutron role is strongly enhanced in ^{74}Ge (C<1)

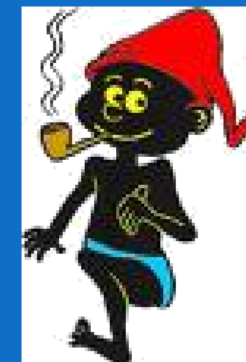
Saci-Perere γ-ray Spectrometer

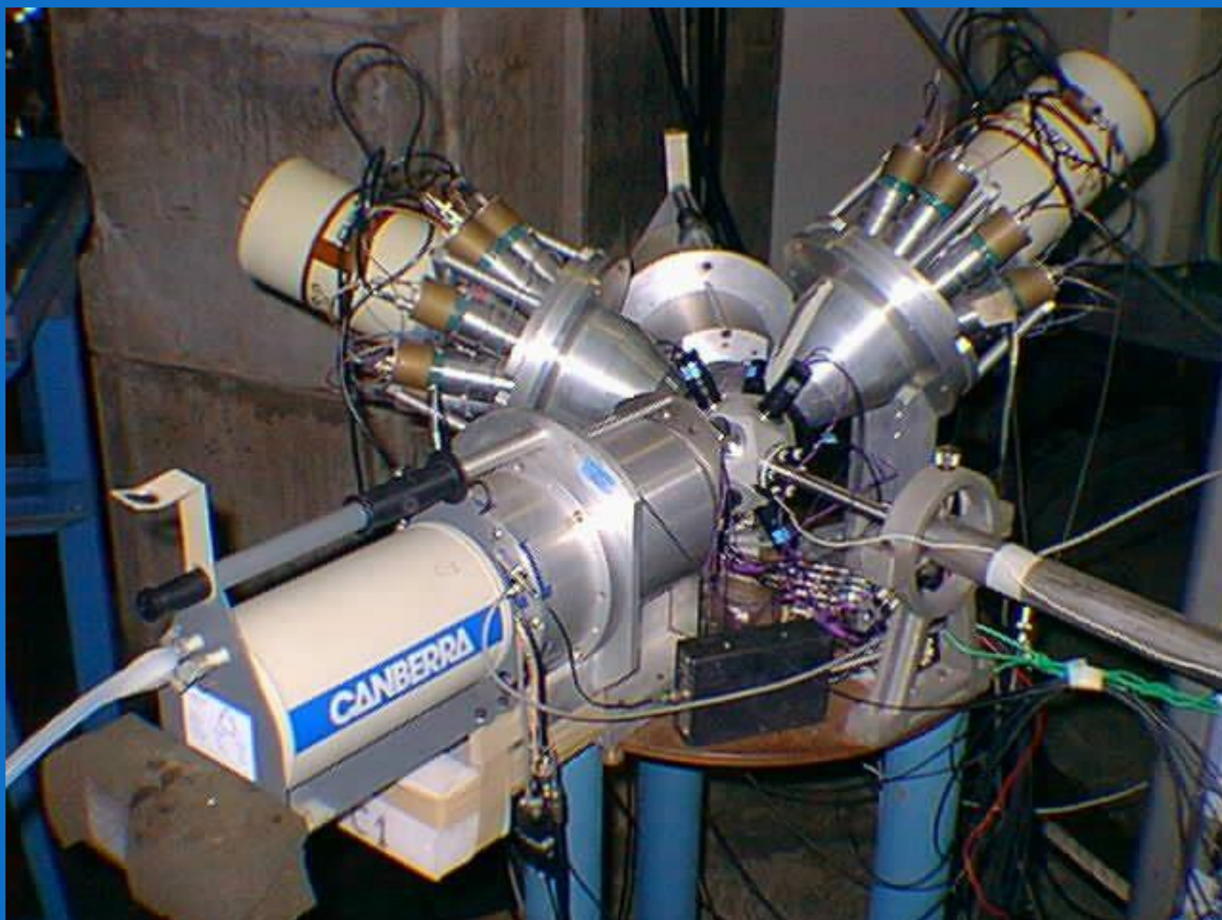
Perere: 4 Compton supressed germanium detectors

Pequeno Espectrômetro de Radiação Eletromagnética com Rejeição de Espalhamento

Saci: 11 ΔE-E plastic scintillator detectors.

Sistema Ancilar de Cintiladores





J.A. Alcántara-Nuñez et al., Nucl. Inst. Meth. Phys. Res. A 497, 429 (2003)

Odd-odd nuclei

A=130

$\pi h_{11/2} \times \nu h_{11/2}$ γ-driving force competition

J.R.B. Oliveira et al., Phys. Rev. C 39 (1989) 2250

Cranking Shell Model

A=50

^{58}Co nuclear structure

M.A.G. Silveira Phys. Rev. C 74 (2006) 064312

Large Scale Shell Model

A=70

The role of the $g_{9/2}$ orbital in the odd-odd ^{64,66,68,70}Ga isotopes

P.R.P. Allegro, PhD thesis 2013

Large Scale Shell Model

Odd-nuclei

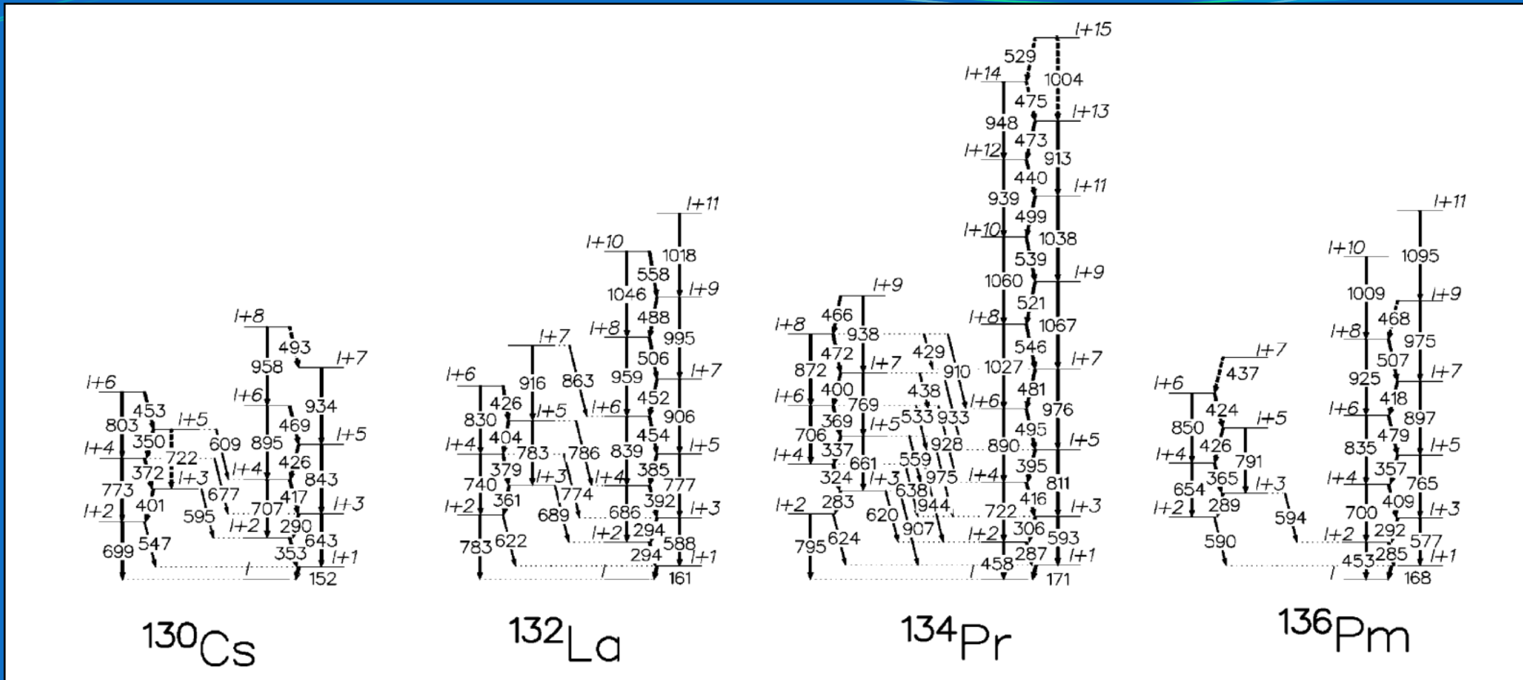
A=100

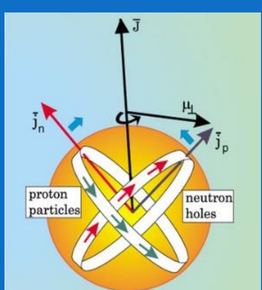
Chiral bands in ^{105}Rh

J.A. Alcántara-Núñez et al., Phys. Rev. C 69 (2004) 02431.

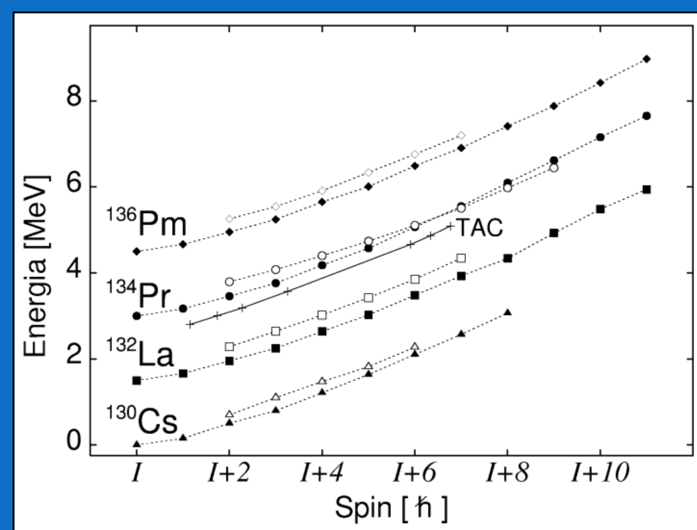
Tilted Axis Cranking Shell Model

Chiral Bands



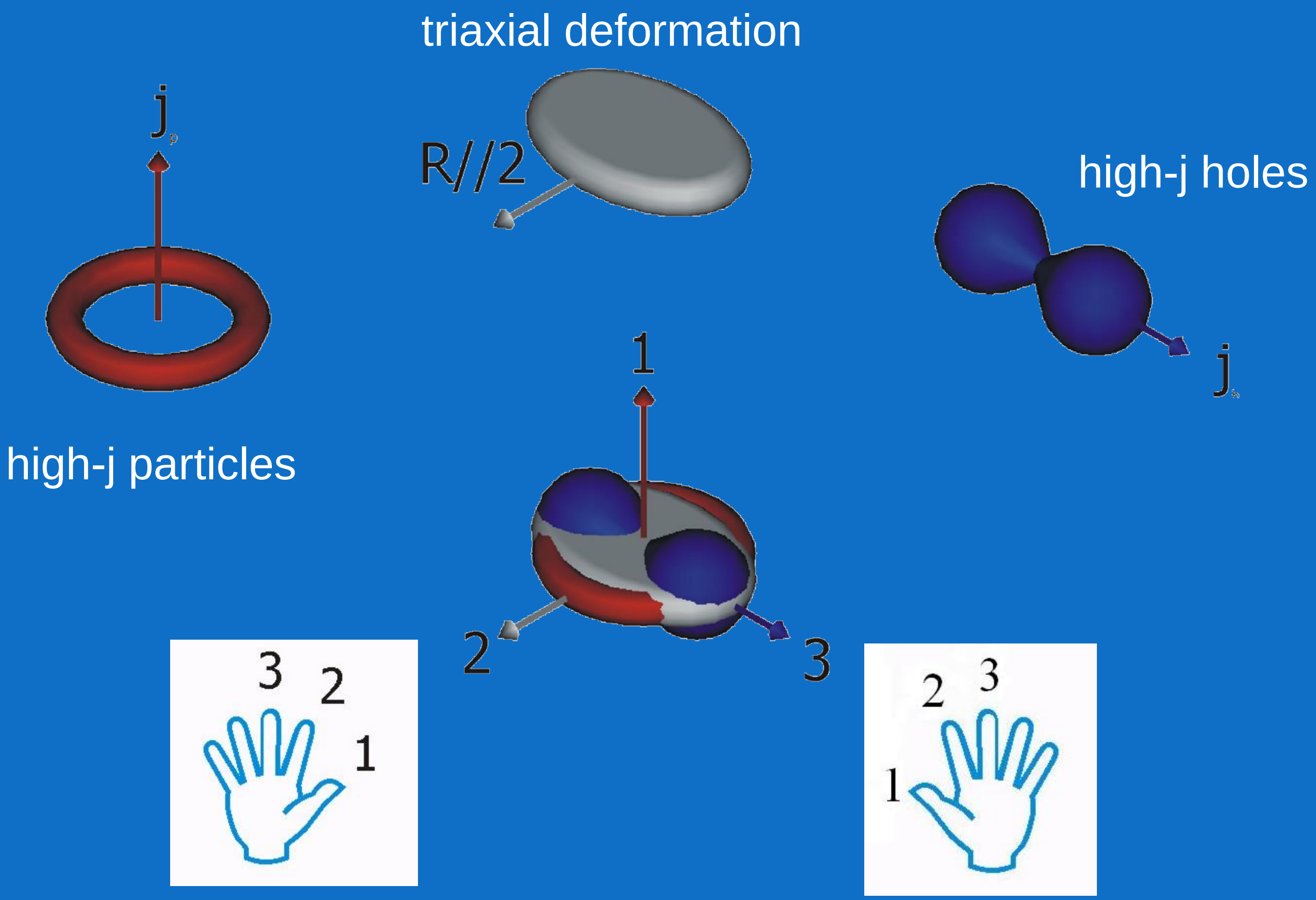


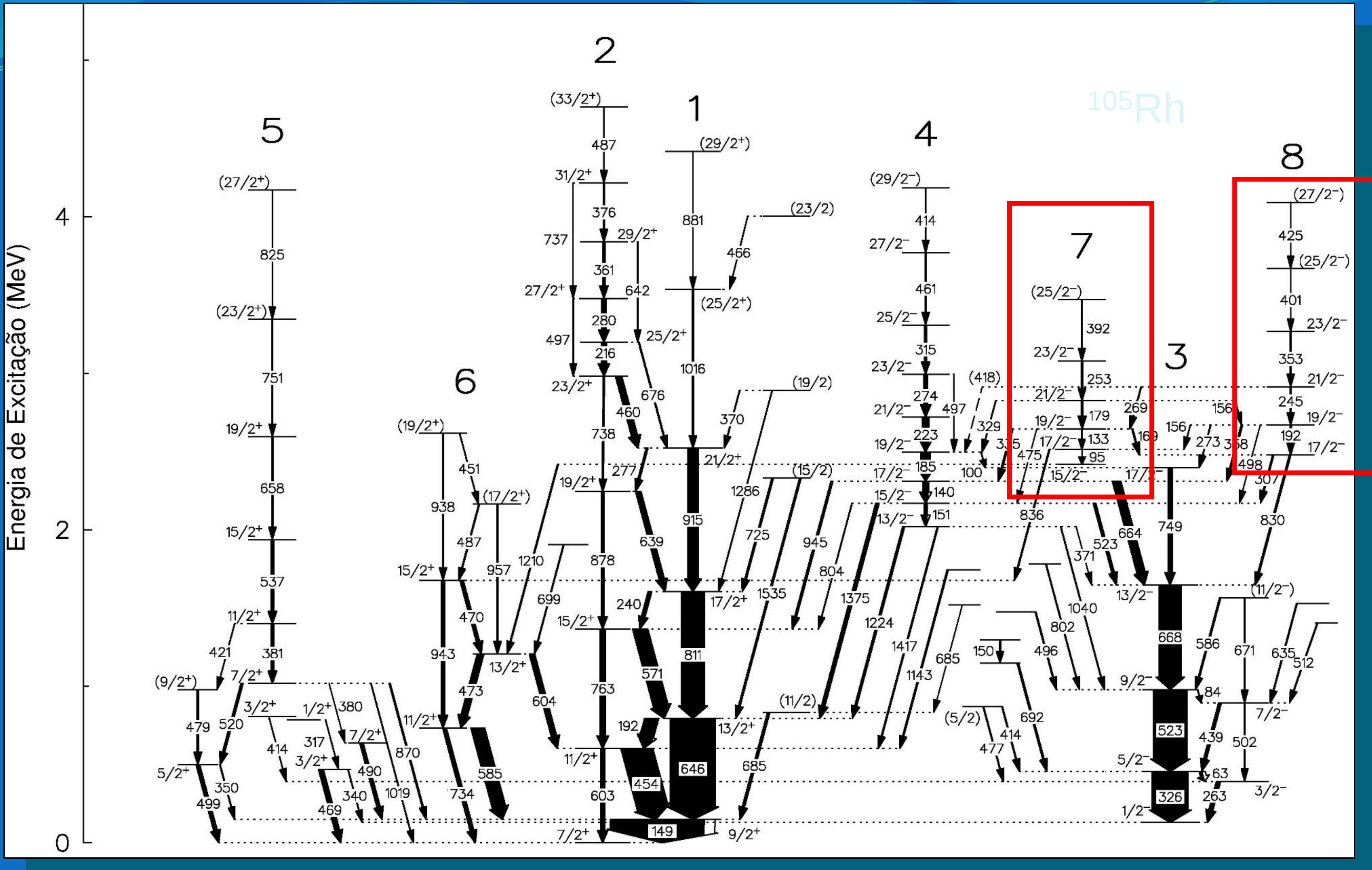
Degenerate bands
Strong M1 transitions
- **Triaxial nuclei**
- **high-j particles**
- **high-j holes**



S.Frauendorf and J. Meng Nucl Phys. **A617** 131(1997)

Chiral Symmetry in the Nuclear Intrinsic System



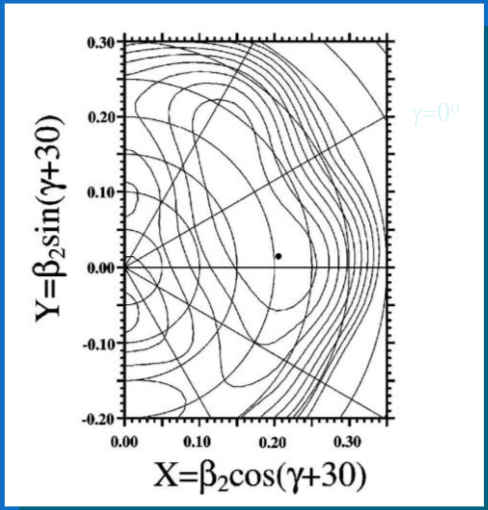


J.A. Alcántara-Núñez et al., Phys. Rev. C 69, 024317 (2004)

Nearly degenerate bands

Chiral configuration $\pi g_{9/2}^{-1} \otimes \nu h_{11/2} \otimes \nu g_{7/2}$

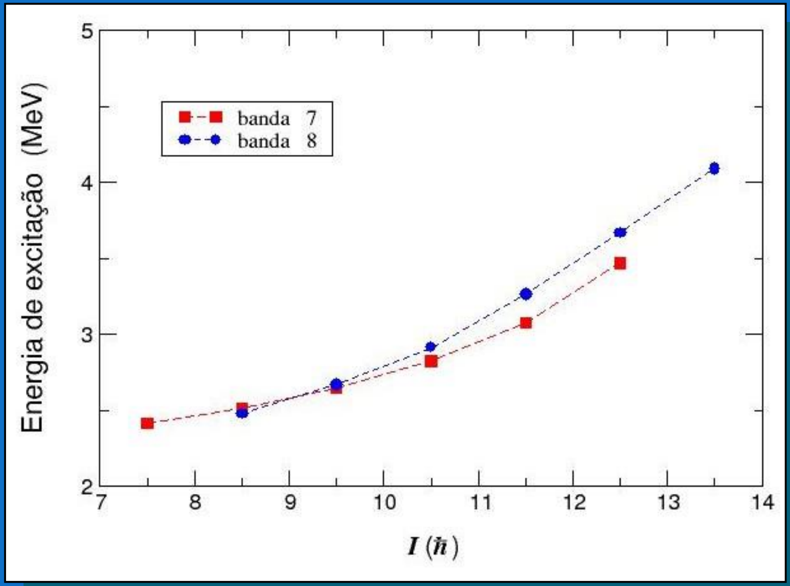
axis (1) (3) (2)

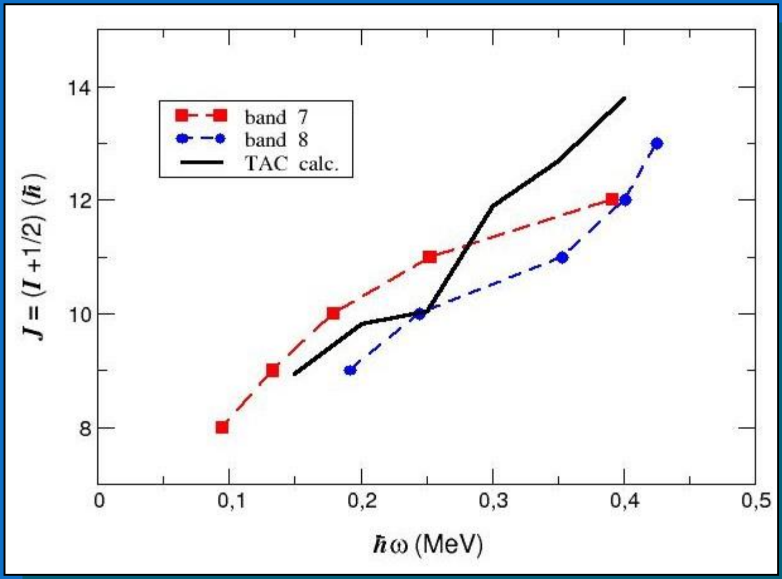


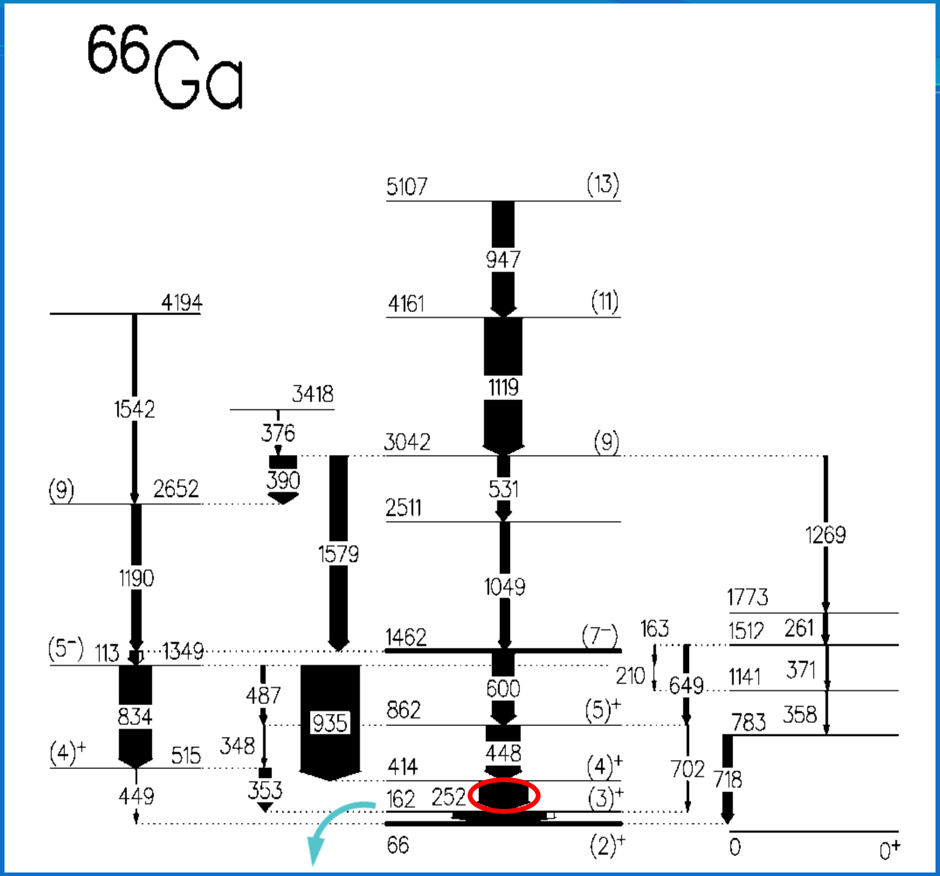
Total Routhian surface calculations

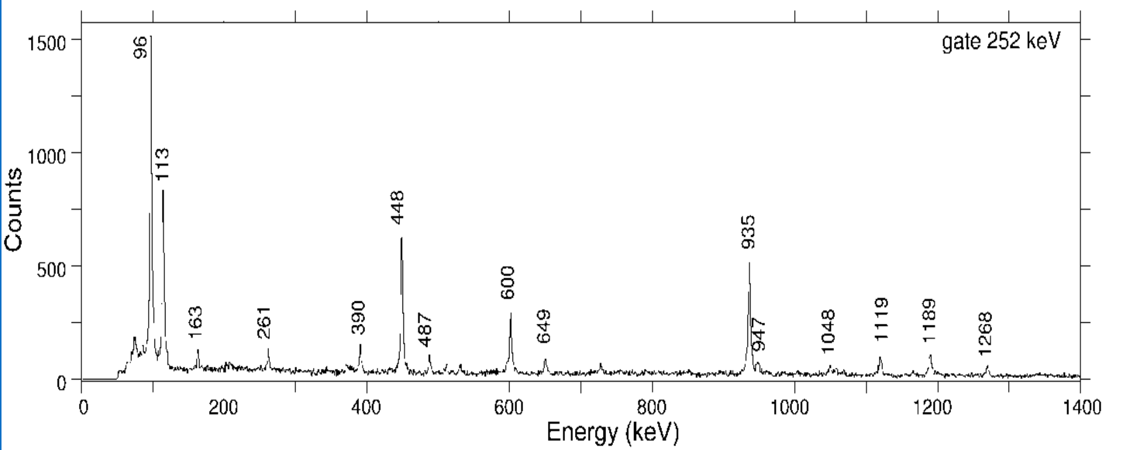
at $\hbar\omega$ = 0,19 MeV in ^{105}Rh.

β=0.21 and -30°≤γ≤30°







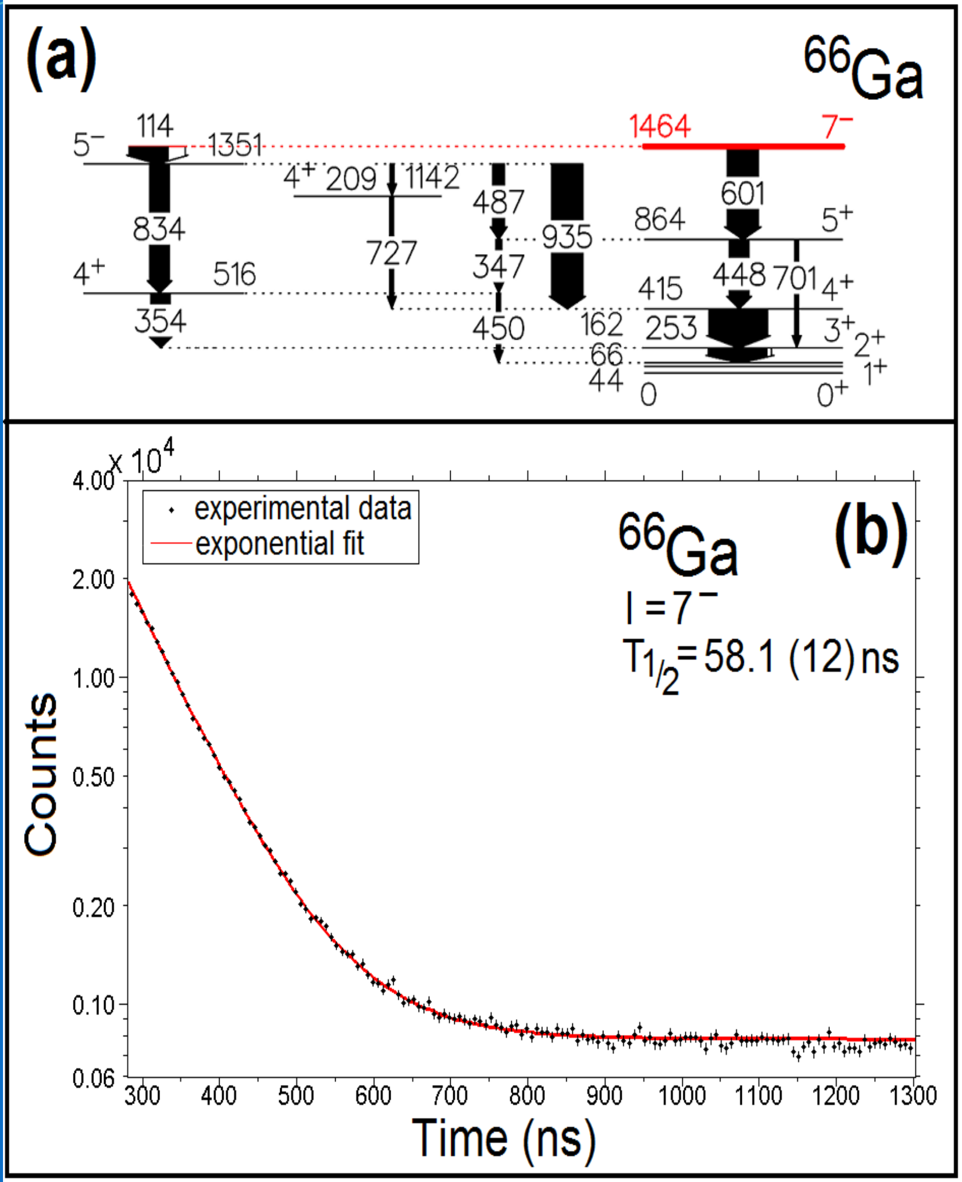


$^{58}Ni(^{11}B,2pn)^{66}Ga$

45 MeV beam energy

γ–γ–proton matrix

Lifetime measurement



$T_{1/2} = 57.3\ (14)$ ns

A. Filevich et al., Nucl. Phys. A 295, 513, 1978.

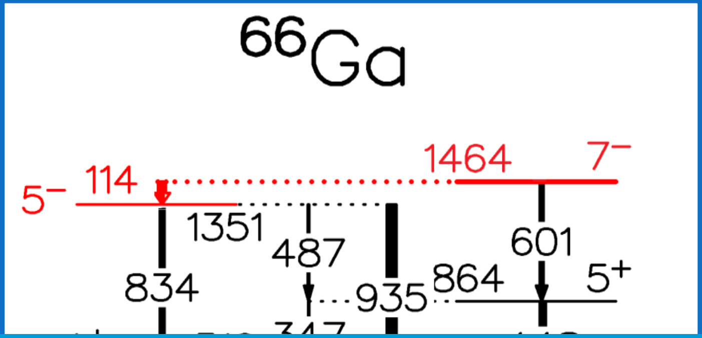
or

~~$T_{1/2} = 39\ (2)$ ns~~

~~T. Kouda et al., Ann. Rep. 1996, Radio-isotope Center, Tohoku University, Japan, p. 19, 1997.~~

D.L. Toufen et al., Rev. Sci. Inst. 85 (2014) 073501

B(E2) for the ^{66}Ga 7^{-} Isomeric State
Large Scale Shell Model



$$B_{EXP}(E2) = \frac{\ln(2) \text{ x } I\gamma}{1.23\text{x}10^{9} \text{ x } T_{1/2}\ I_{total}\ E\gamma^{5}}$$

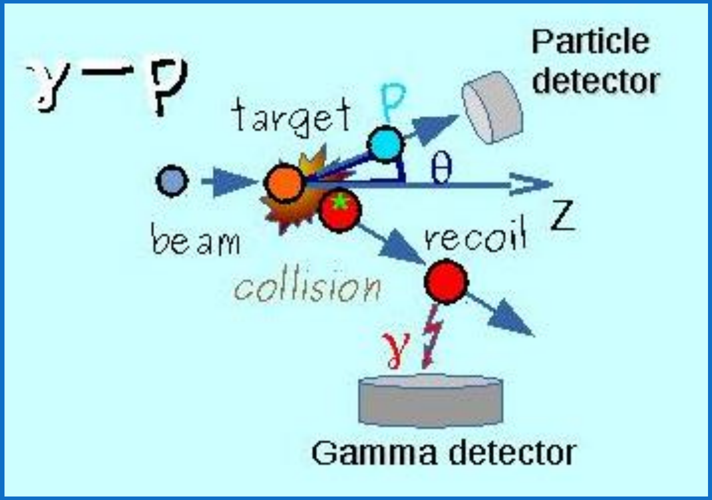
Good description for ^{64,66,68,70}Ga level schemes, and reduced transition probabilities by the Large Scale Shell Model FPG and JUN45 effective interactions.

$$B(E2, J_i M_i \zeta \rightarrow J_f M_f \xi) = \frac{1}{2J_i+1} |\langle J_f \xi || \mathbf{O}_{E2} || J_i \zeta \rangle|$$

$B_{JUN45}(E2) = 301\ e^2fm^4$ $\quad$ $B_{FPG}(E2) = 259\ e^2fm^4$

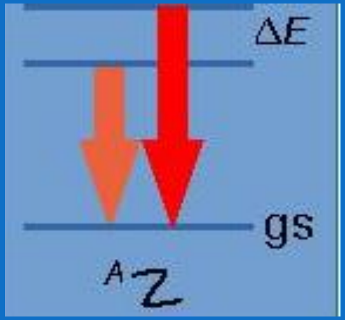
Antoine Code: CAURIER, E; NOWACKI, F. , Acta Physica Polonica B, v. 30, n. 3, p. 705, 1999.
FPG residual interaction: SORLIN, O. et al., Physical Review Letters **88**, 092501 (2002).
JUN45 residual interaction HONMA, H. et al., Physical Review C **80**, 064323 (2009).

γ–ray spectroscopy and reaction mechanisms



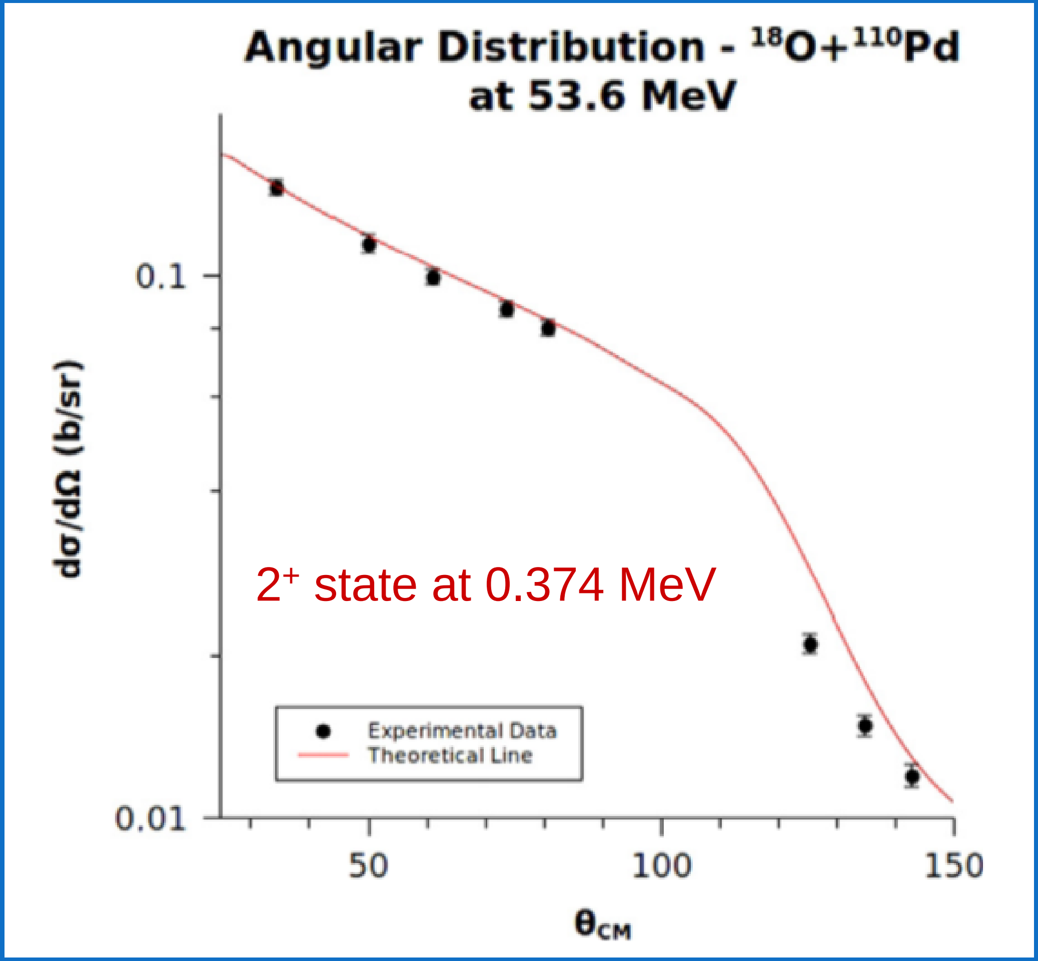
- **Inelastic scattering**
- **Inelastic transfer**
- **Complete or incomplete fusion**
- **Multiple transfer DIC**
- **Inelastic *Break-up***

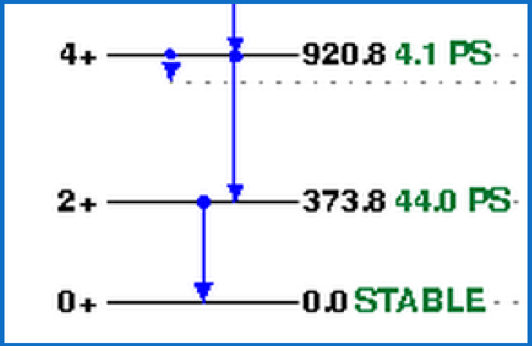
Characteristic γ-rays



José Roberto B. de Oliveira zero@if.usp.br

Particle-gamma coincidence measurements





^{110}Pd

V.B. Zagatto et al., Nuclear Instruments and Methods in Physics Research A 749 (2014) 19–26

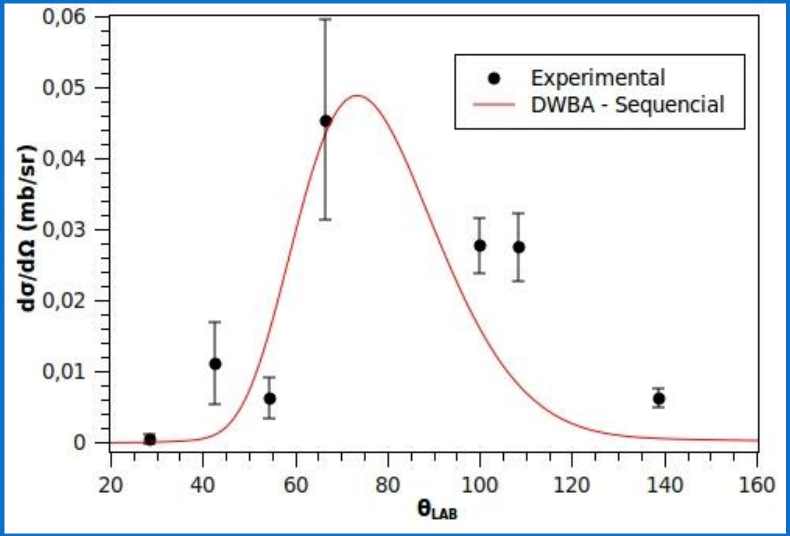
α–particle coincidence measurement

$^{7}Li + ^{120}Sn$ @ 24 MeV

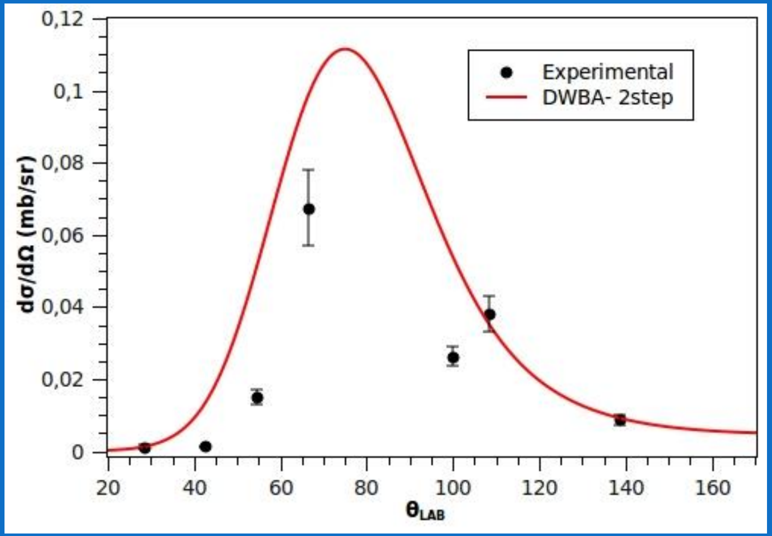
(1p-pickup) → $^{8}Be\ (\rightarrow \alpha + \alpha) + ^{119}In + \gamma$

(2n-stripping) → $^{5}Li\ (\rightarrow p + \alpha) + ^{122}Sn + \gamma$

$3/2^{-}$ state at 0.604 MeV of ^{119}In



5^{-} state at 2.245 MeV of ^{122}Sn



V.B. Zagatto, PhD Thesis (2015)

Study of the $^{9}Be + ^{120}Sn$ reaction

Identified reaction processes:

Inelastic excitation with and without breakup of ^{9}Be (γ-rays of ^{120}Sn in coincidence with Z=4 and α-particles);

Complete fusion (γ-rays of ^{126}Xe);

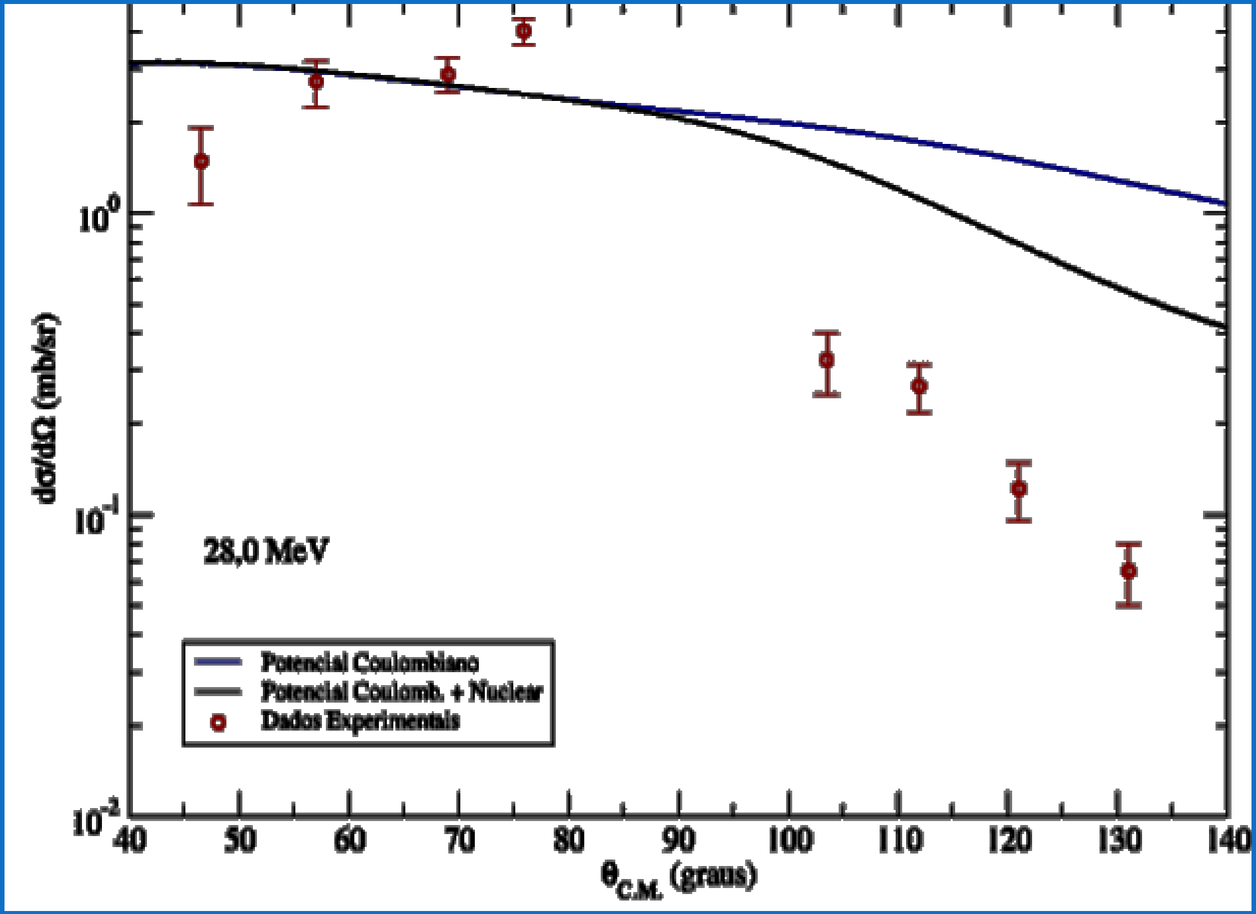
Incomplete fusion (γ-rays of ^{123}Te and ^{124}Te in coincidence with α–particles);

n-stripping (γ-rays of ^{121}Sn in coincidence with α-particles).

Leandro Gasques: lgasques@if.usp.br
André Freitas: ihsou@ig.com.br

Inelastic cross section supression due to breakup of ^{9}Be.

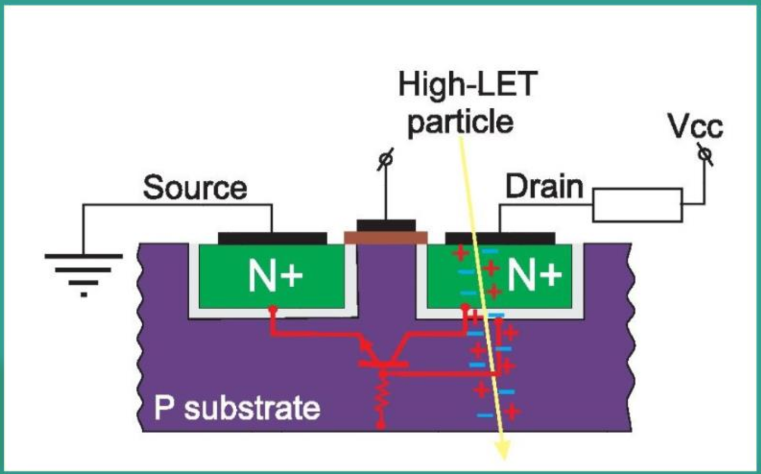
$^9Be + ^{120}Sn$ @ 28 MeV

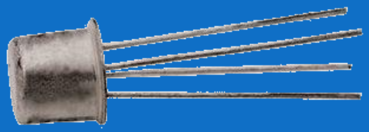


A.S. Freitas, Master thesis (2014)

Applied Nuclear Physics

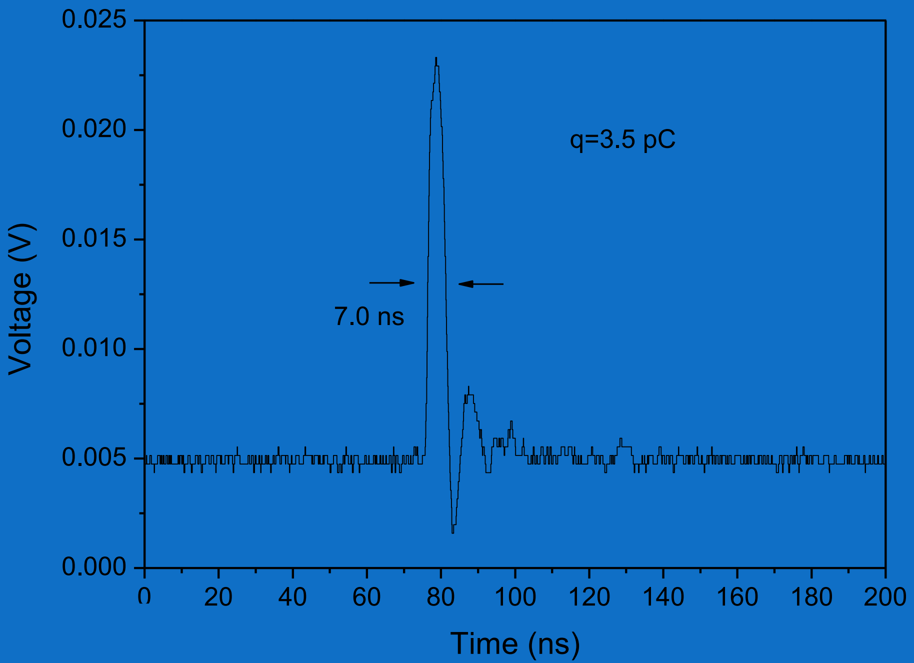
SEU measurements in a p-channel MOSFET transistor (3N163)





$V_G = -0.13\ V$
$V_{DS} = -4.5\ V$

Single Event Upsets using ^{35}Cl heavy ion beam at 75 MeV.

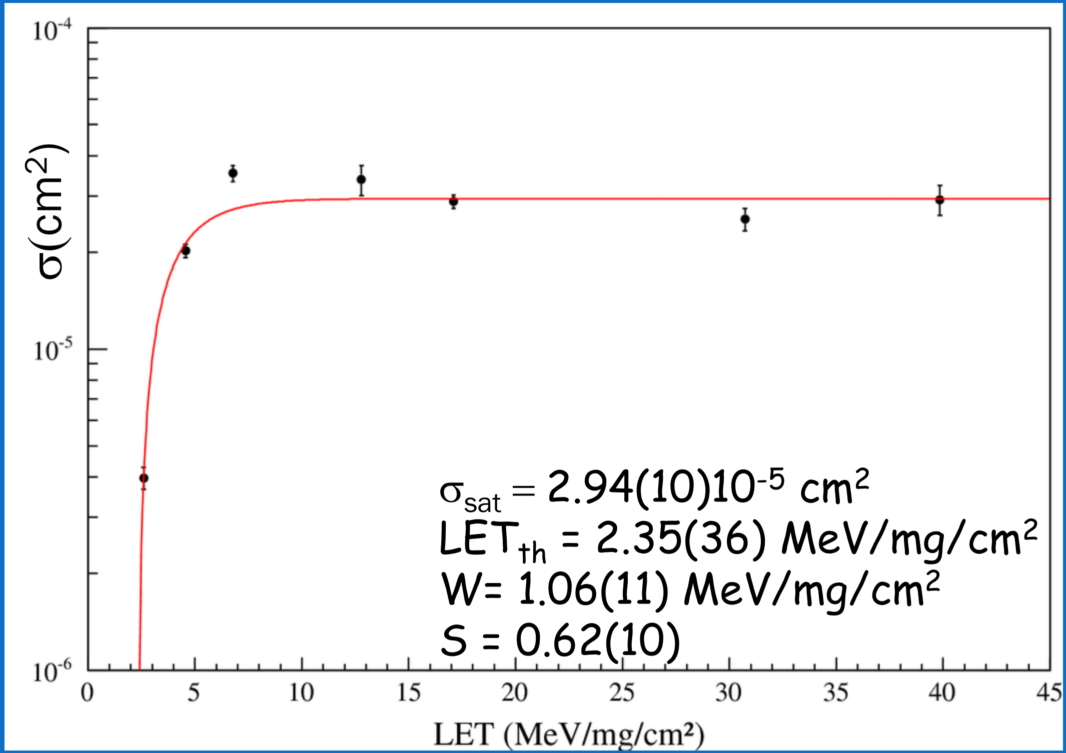


Sampling rate 10 G samples/s
1-GHz Rohde & Schwarz RTO1012 scope

First SEU measurement with heavy ions in Brazil

^{12}C, ^{16}O, ^{19}F, ^{28}Si, ^{35}Cl, ^{63}Cu, and ^{107}Ag beams

$$\sigma_{SEE} = \frac{events}{\Phi}$$



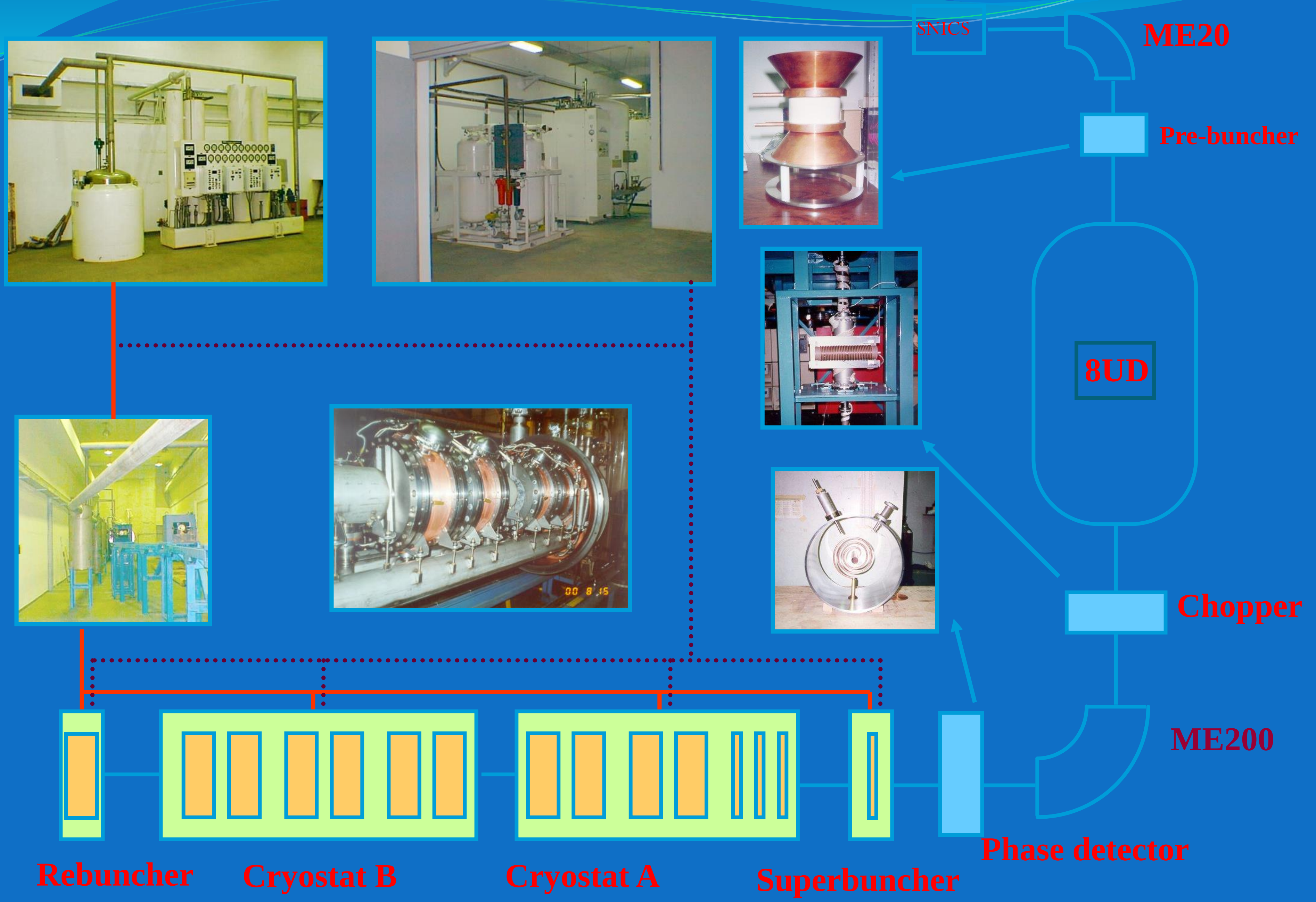
Weibull Function

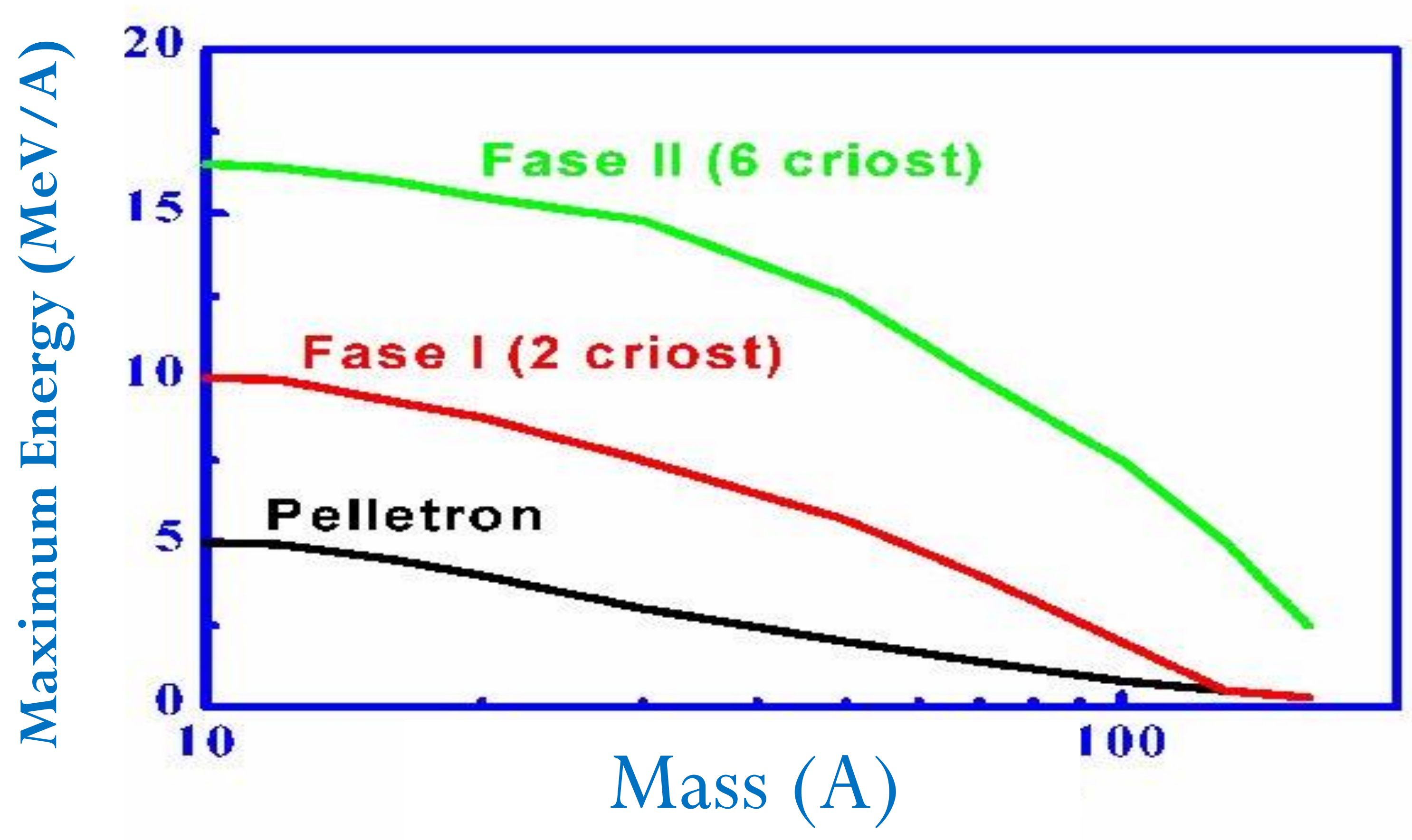
$$\sigma = \sigma_{sat}\left[1 - e^{\left(\frac{LET - LET_{th}}{W}\right)^{s}}\right]$$

N.H. Medina et al., proc. 2014 IEEE Radiation Effects Data Workshop, Paris, France, 2015

Nemitala Added: nemitala@if.usp.br

Linear Superconductiong Accelerator - LINAC





Maximum Energy (MeV/A)
20
15
10
5
0
10
100
Mass (A)
Fase II (6 criost)
Fase I (2 criost)
Pelletron

Concluding remarks

8MV Tandem accelerator

- Large scattering chambers
- Radioactive Ion beam Facility (RIBRAS)
- Enge split-pole spectrograph
- γ-ray spectrometer

Linac accelerator

Basic nuclear physics

Applied nuclear physics

Experiment design, electronics, target, vacuum, beam transport, data acquisition system, programming, data analysis, result interpretation, theoretical models, etc.

Большое спасибо

Nilberto H. Medina
Universidade de São Paulo, Brazil