Study of structure and reactions of radioactive nuclei using the RIBRAS facility

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IF-USP

ICTP-SAIFR/FAIR Workshop on Mass Generation in QCD

Outline:

- Some properties of nuclei far from the stability valley: change from well established behavior.
- Production methods of radioactive beams, at different energies.
- Large effort and investments in new accelerator facilities: FAIR (Germany), FRIB (USA), SPIRAL (France), RIKEN-RIBF (Japan), RAON (South Korea), HIAF (China) etc.
- RIBRAS (Radioactive Ion Beams in Brazil) and its results

Study of properties of nuclei far from the stability valley

Matter rms radius measurement of Li isotopes at LBL Bevalac

I.Tanihata et al. Phys. Rev. Lett. 55, 2676 (1985)

R_{rms} (^{11}Li) = 3.27(24) fm

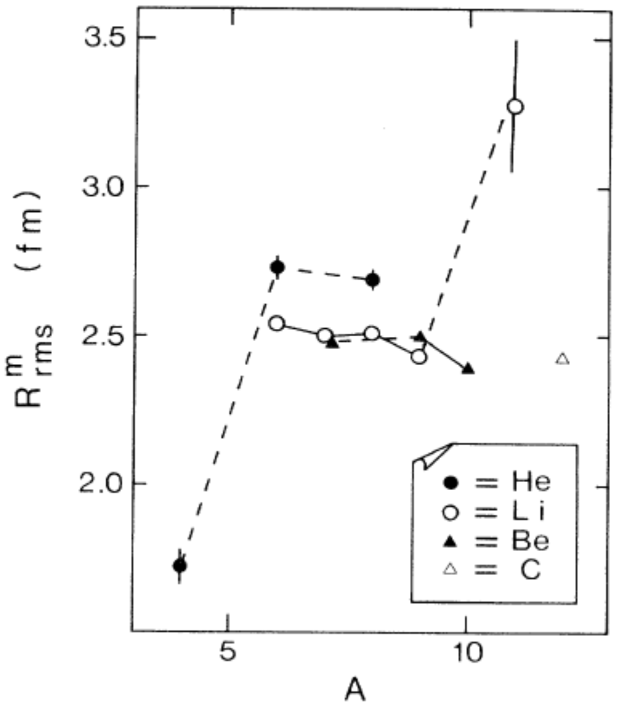
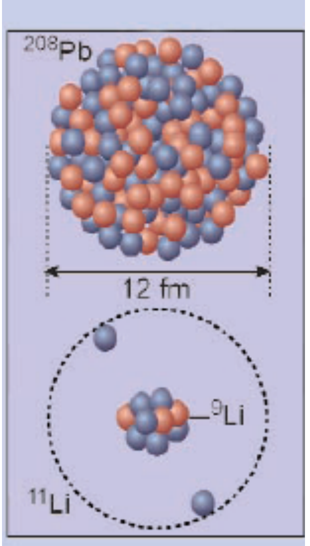


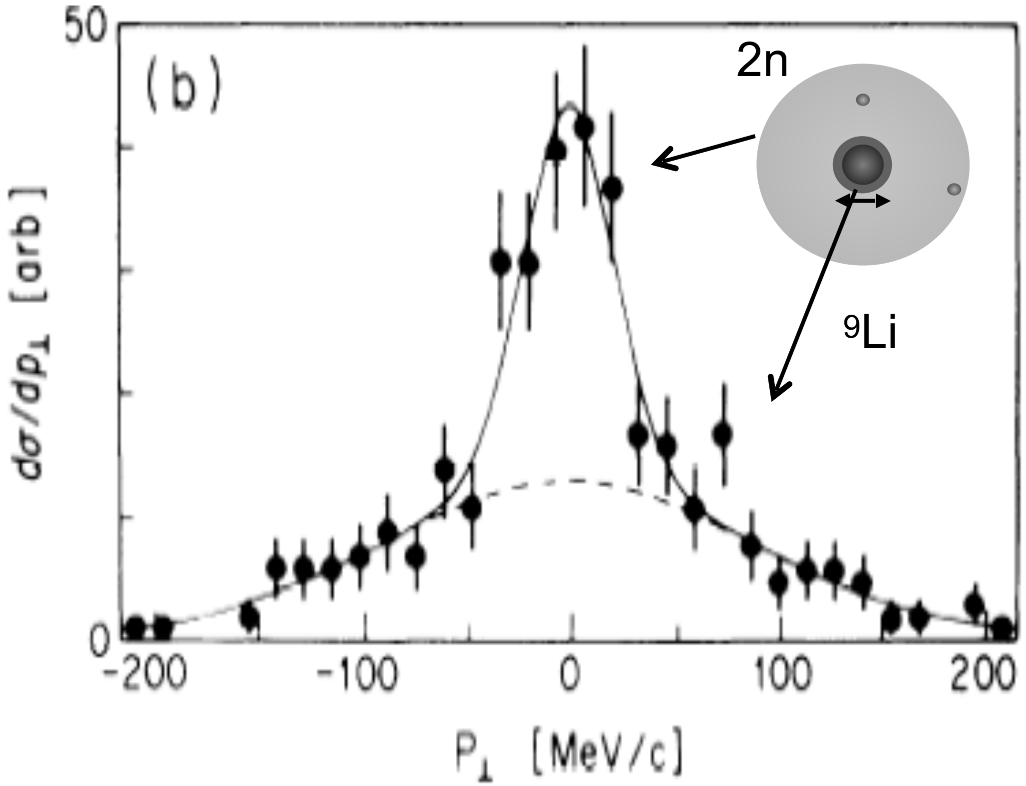
FIG. 3. Matter rms radius R^m_{rms}. Lines connecting isotopes are only guides for the eye. Differences in radii are seen for isobars with $A = 6, 8$, and 9. The ^{11}Li isotope has a much larger radius than other nuclei.

Breakup of ^{11}Li on ^{12}C target $^{11}Li \rightarrow$ $^{9}Li + n + n$



Kobayashi et al. measured the momentum distribution of ^{9}Li: 2 widths:
--- a large width Δp distribution → well localized ^{9}Li core, small Δr
--- a small width Δp ditribution → 2 neutrons, large Δr distribution →
$\Delta r \sim 8.26$ fm ~ $R(^{208}Pb)$

Uncertainty principle of Heisenberg: $\Delta p \, \Delta r \sim \hbar$



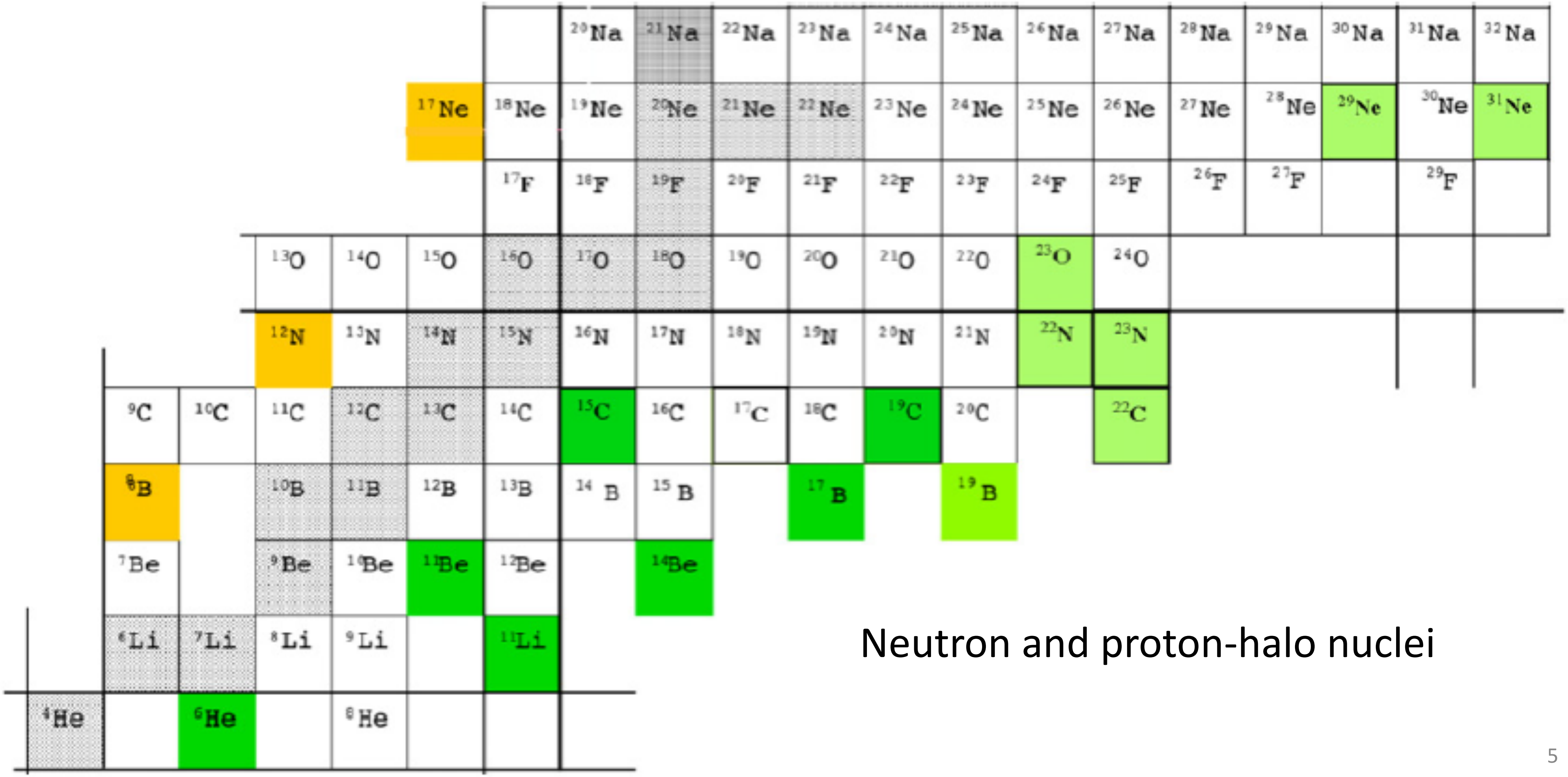
T.Kobayashi et al, PRL 60(1988)2599

$$\Delta p_{wide} = 95 \pm 12 MeV/c \rightarrow normal \rightarrow R = 2.07\, fm$$

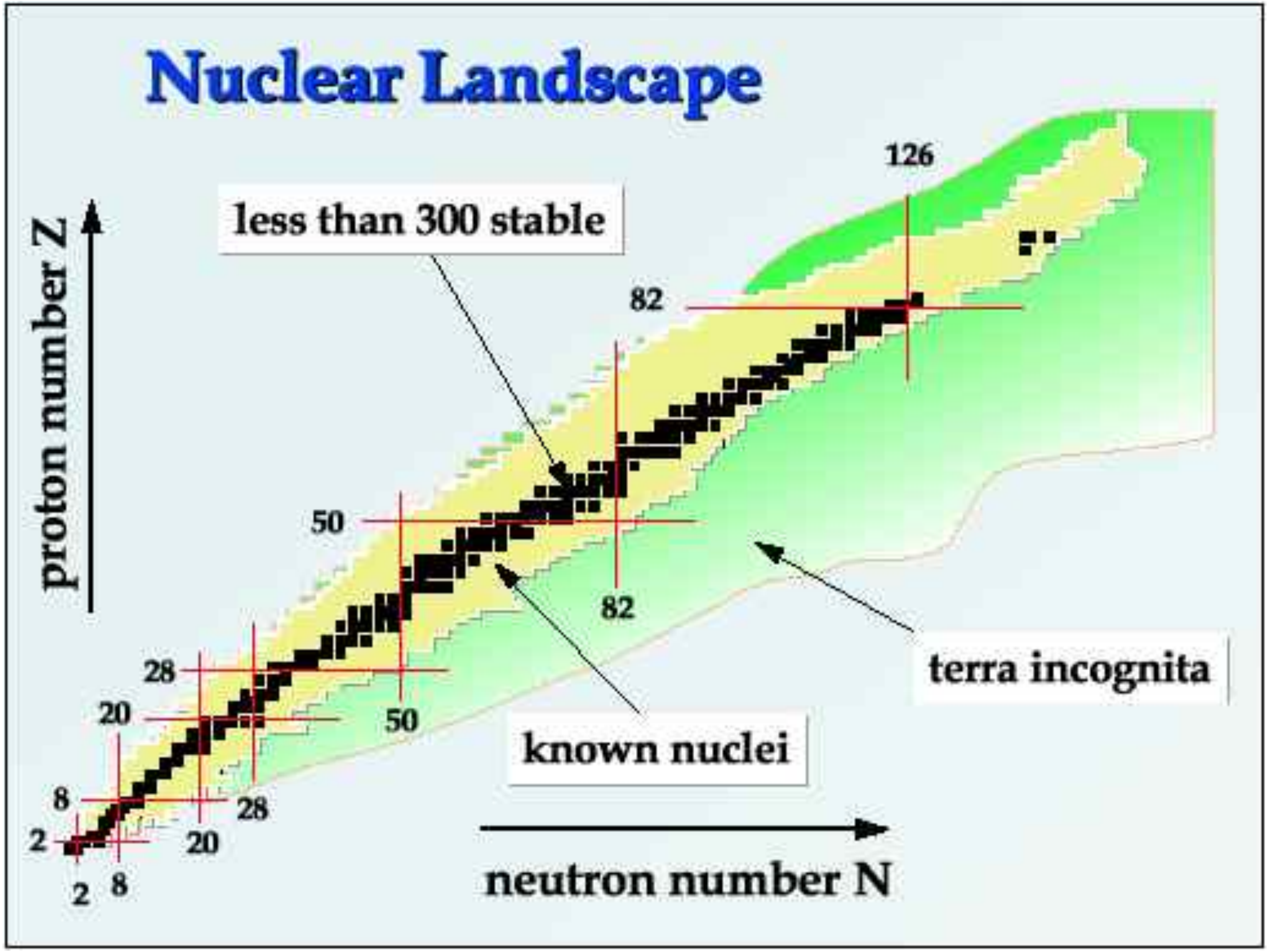
$$\Delta p_{narrow} = 23 \pm 5 MeV/c \rightarrow exotic \rightarrow R = 8.26\, fm$$

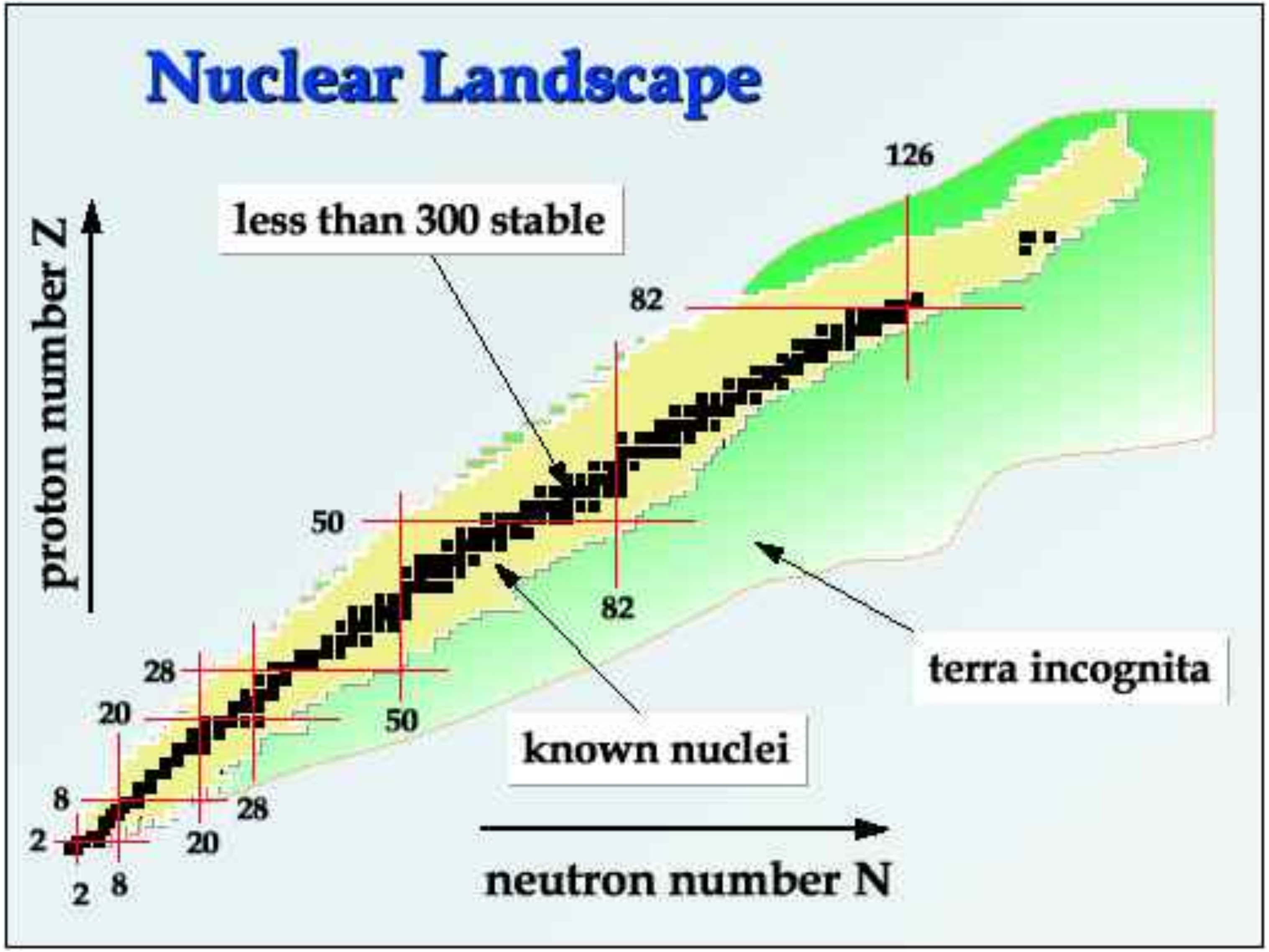
$$R_{11Li} = \frac{9}{11} 2.07 + \frac{2}{11} 8.26 = 3.19\, fm$$

I. Tanihata et al. / Progress in Particle and Nuclear Physics 68 (2013) 215–313

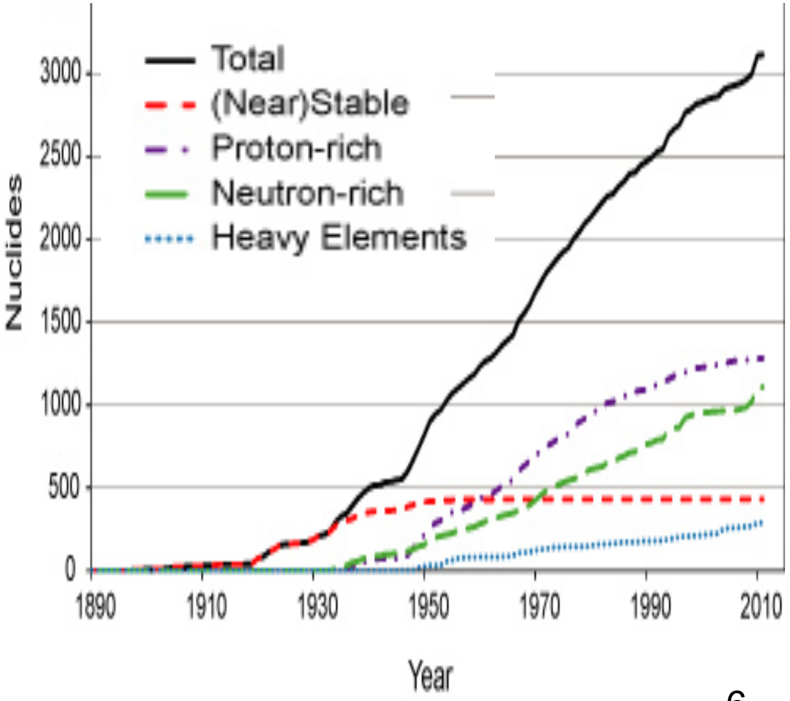


Neutron and proton-halo nuclei

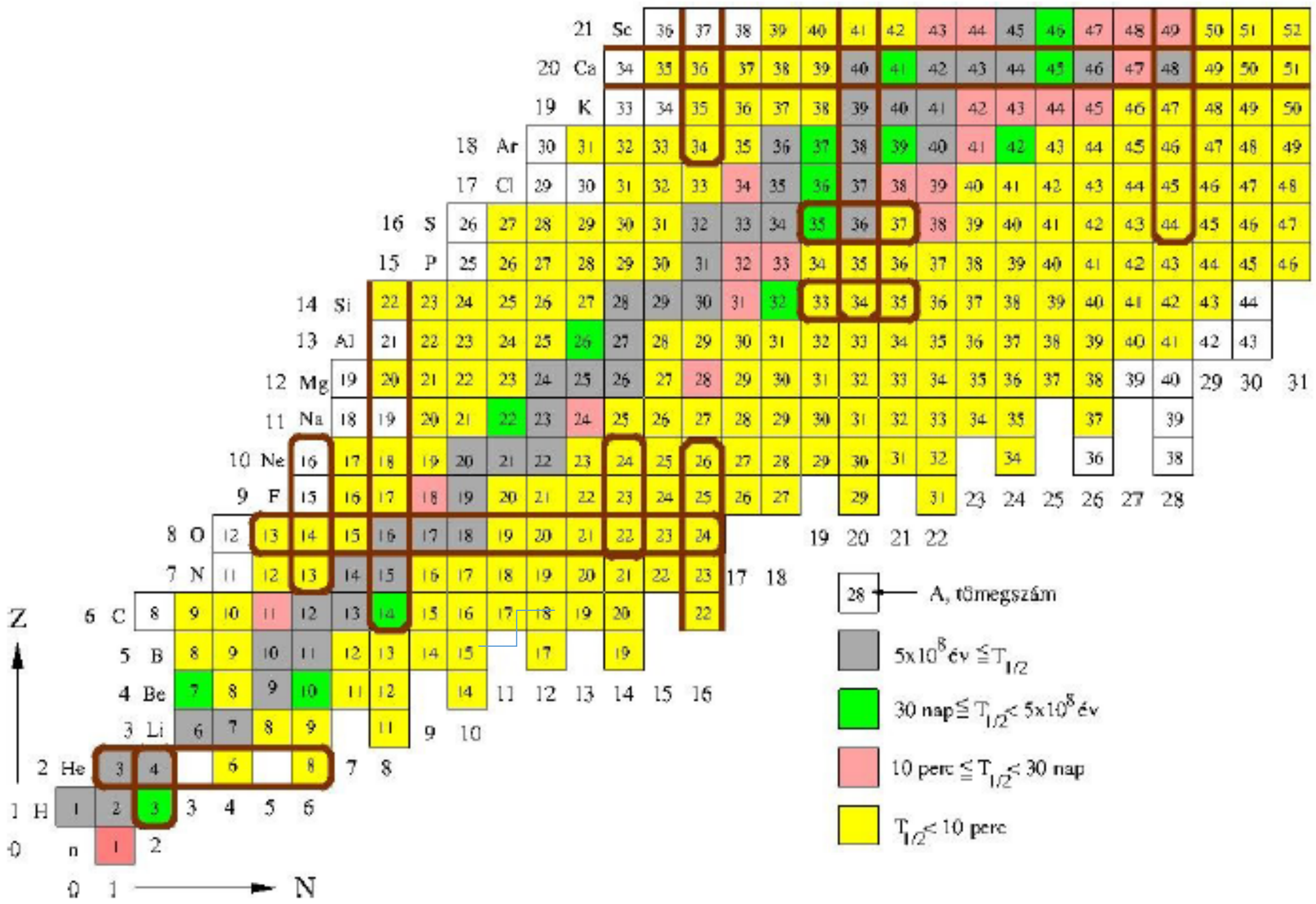

Nuclear Landscape
proton number Z
less than 300 stable
126
82
50
28
20
8
2
2
8
20
28
50
82
known nuclei
terra incognita
neutron number N



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



One of the foreront of nuclear structure and dynamics research is the study of « exotic nuclei »

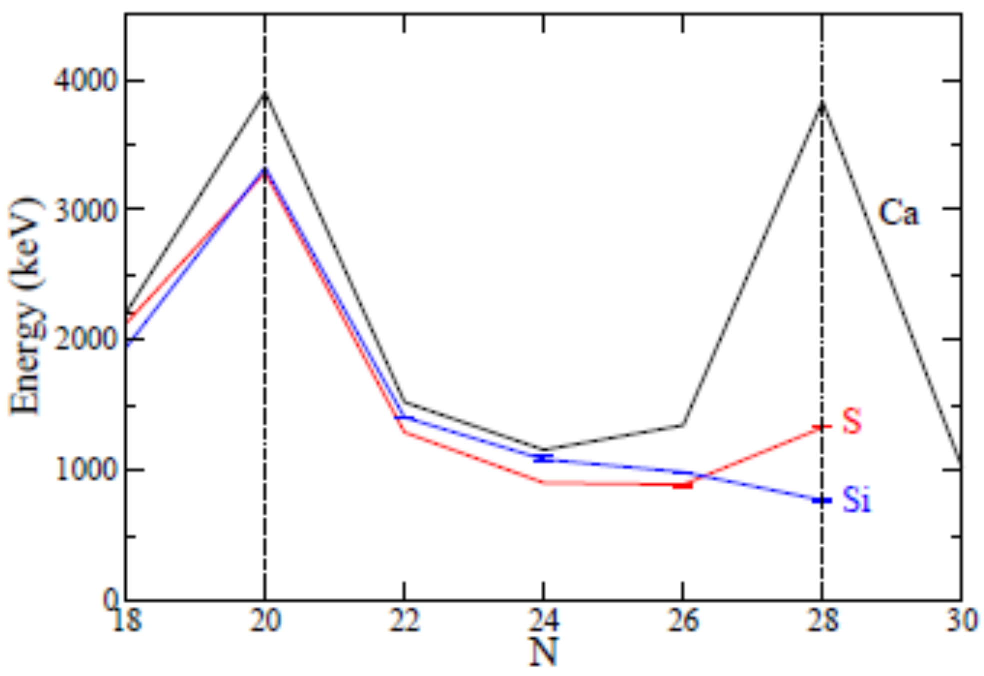


3- body borromean system

→ The 2 n interaction bounds the ^{11}Li nucleus

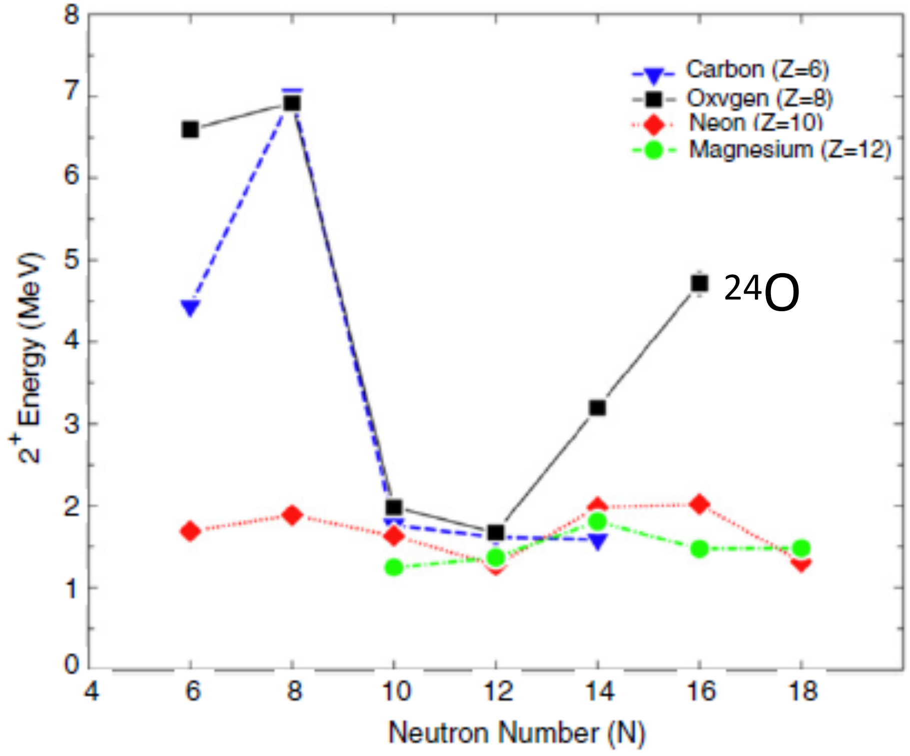
Exotic nuclei: close to the dripline, very low binding energy, very short half life, strange properties (halo, skin, change in shell structure etc)

Change in magic numbers close to the drip lines : : 8 → 6, 20 → 16 , 28→ 30,32 blue is stable, red close to the dripline.



Sorlin, O.; Porquet, M. -G. PROGRESS IN PARTICLE AND NUCLEAR PHYSICS, 61, 602-673 (2008)

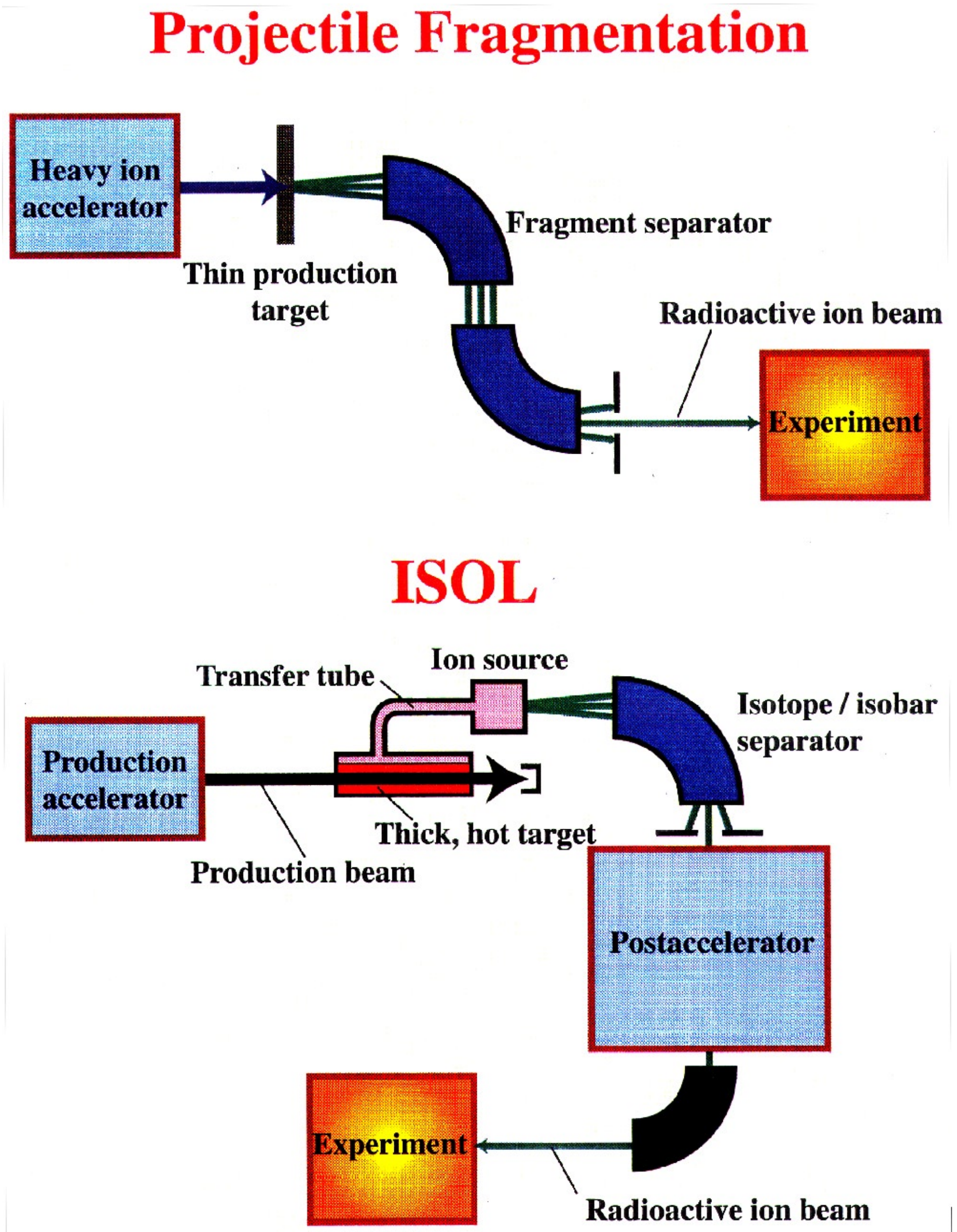
N=28 is not magic number for Z=14 and 16.



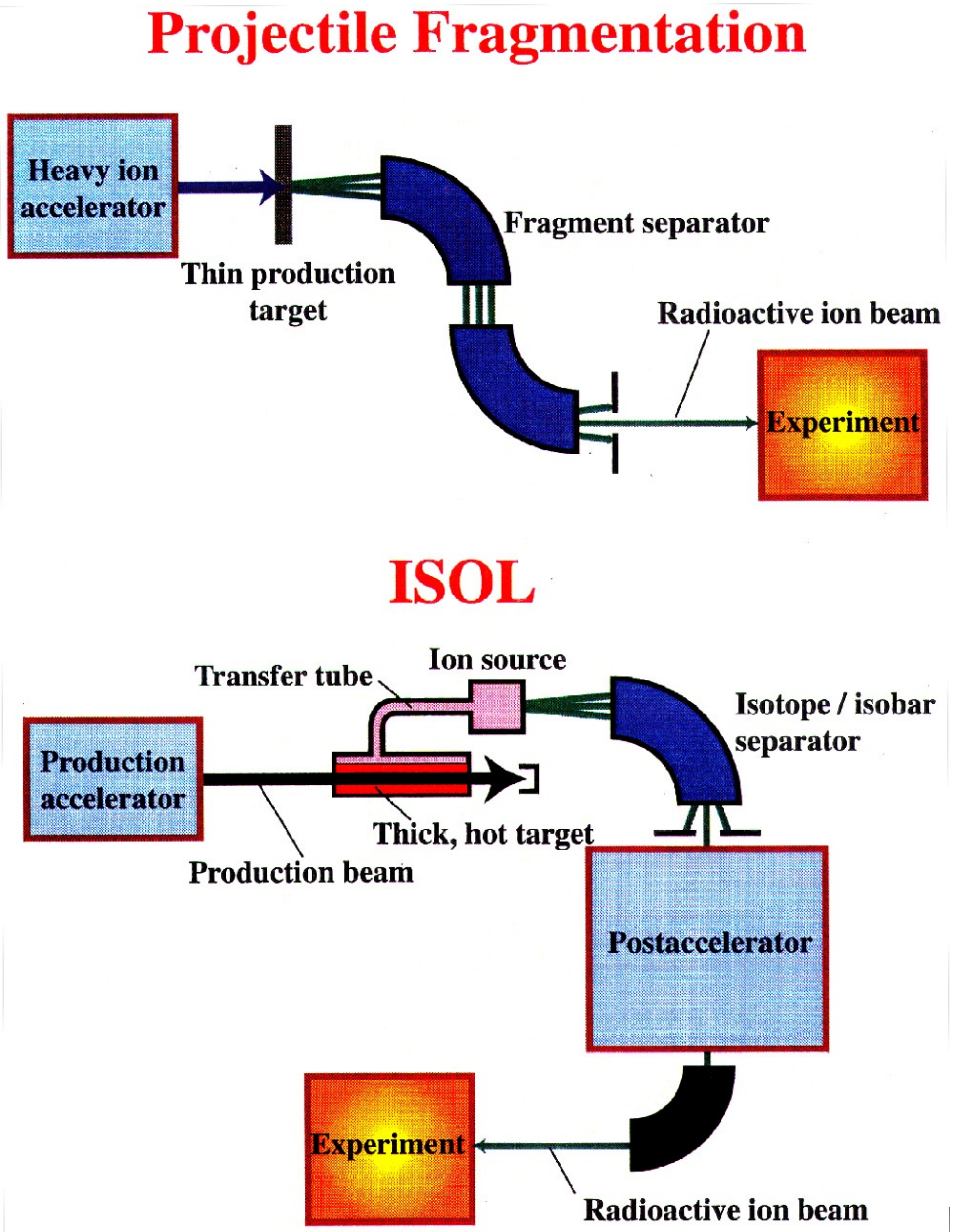
C.R.Hoffman et al. Phys. Lett.B672,17 (2009)

^{24}O is doubly magic (Z=8, N=16) spherical nucleus on the neutron drip-line (the last 2 neutrons are in a $2s_{1/2}$ shell)

Production methods of radioactive beams



Production methods of radioactive beams



–Fragmentation on thin target

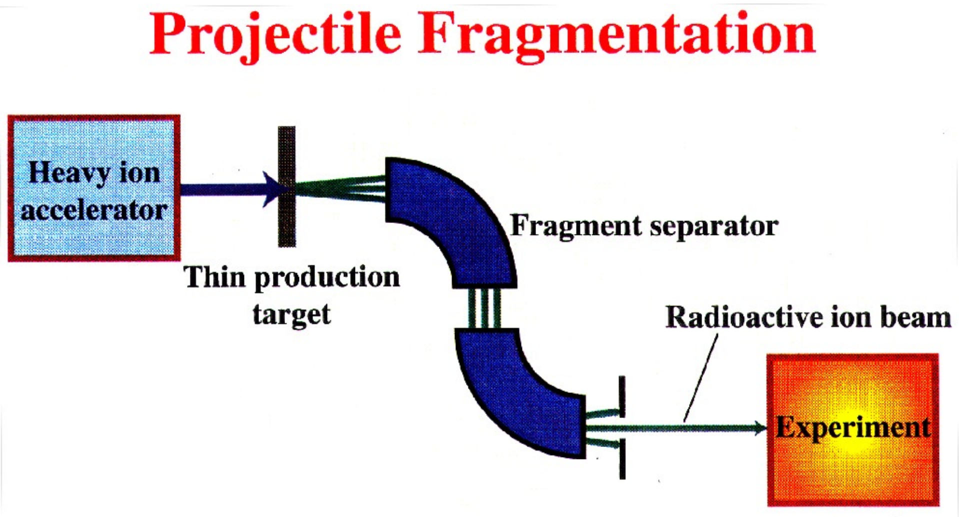
Intermediate to high energy:100 MeV/u to GeV/u, **in-flight separation**.

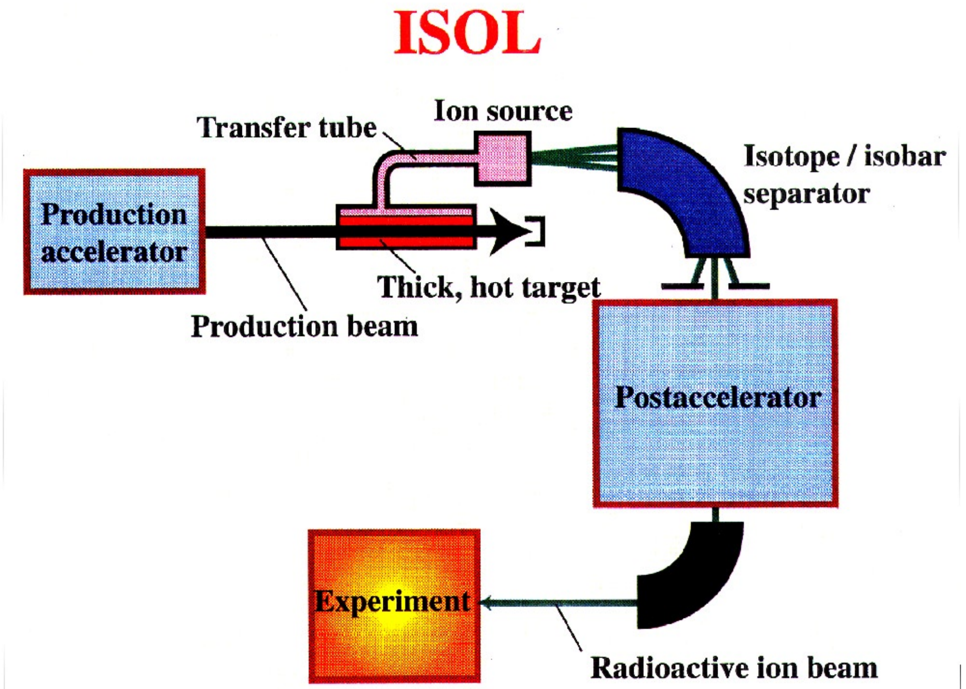
--Quick process, the secondary beam has similar velocity to the primary stable beam.

very short lived radioactive nuclei

GANIL, RIKEN-RIBF, GSI, MSU-NSCL, FRIB, FAIR

Production methods of radioactive beams





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ISOL(isotope separation on line)

High energy (GeV/n) stable projectile on thick target: spallation.

Re-acceleration produces low energy beams of longer halflives

CERN-ISOLDE, TRIUMF, FRIB

Large investments for new accelerator facilities : FAIR (Germany), FRIB (USA), SPIRAL (France)**, RIKEN (Japan), RAON (South Korea), HIAF (China) etc.**

All new accelerator facilities will have Radioactive Ion Beams (RIB):

Method: projectile fragmentation on thin target
Characteristics: RIB of relatively high energy, 200 – 2700 MeV/u (for U)
Large variety of RIBs, becoming truly exotic (very n-rich)
Large increase in beam intensities

Some will have also low energy beams, stopping and reaccelerating, ISOL method.

However low energy RIB also has interest : spectroscopy, mass and radius measurements, fusion below the Coulomb barrier, nuclear astrophysics etc

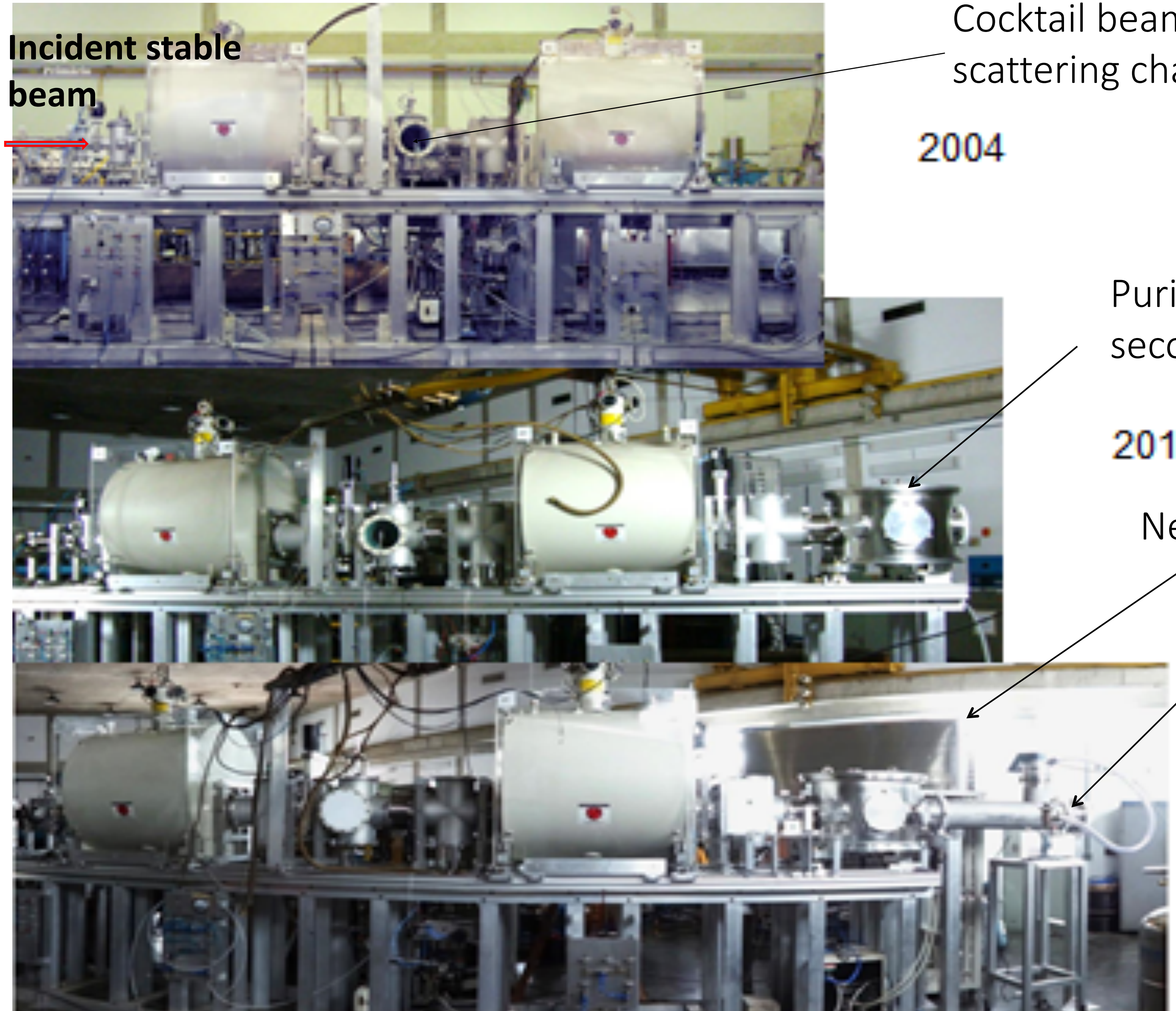
Low-energy accelerators can also produce radioactive beams, using transfer reactions, fusion, fission, fragmentation.

Ex: University of São Paulo, RIBRAS (Radioactive Ion Beam in Brasil)

Others : Notre Dame University, TwinSol Double solenoid
Florida State University
Argonne National Laboratory

2004 First RIB facility in Southern Hemisphere RIBRAS – 2 superconducting solenoids

Evolution of the RIBRAS system



Cocktail beams in central scattering chamber

2004

Purified beams after second solenoid

2011

Neutron Wall

New chamber for γ-detectors,

2015

Eur. Phys. J. A (2014) **50**: 128
DOI 10.1140/epja/i2014-14128-4

THE EUROPEAN PHYSICAL JOURNAL A

Review

The Radioactive Ion Beams in Brazil (RIBRAS) facility

Description, program, main results, future plans

A. Lépine-Szily[a], R. Lichtenthäler, and V. Guimarães

Instituto de Física da Universidade de São Paulo, Caixa Postal 66318, 05314-0970, São Paulo, SP, Brazil

Eur. Phys. J. A (2014) **50**: 128
DOI 10.1140/epja/i2014-14128-4

THE EUROPEAN PHYSICAL JOURNAL A

Review

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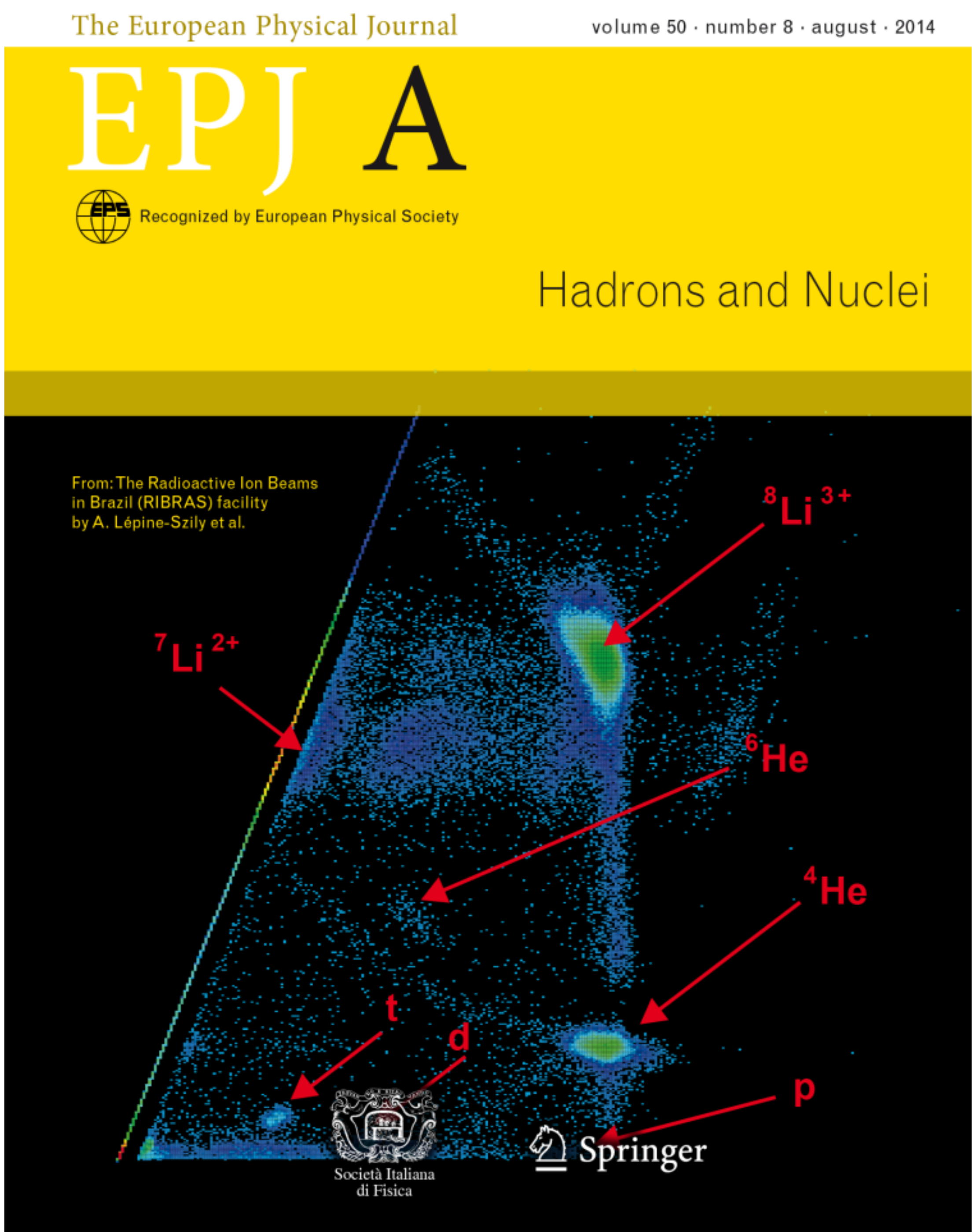
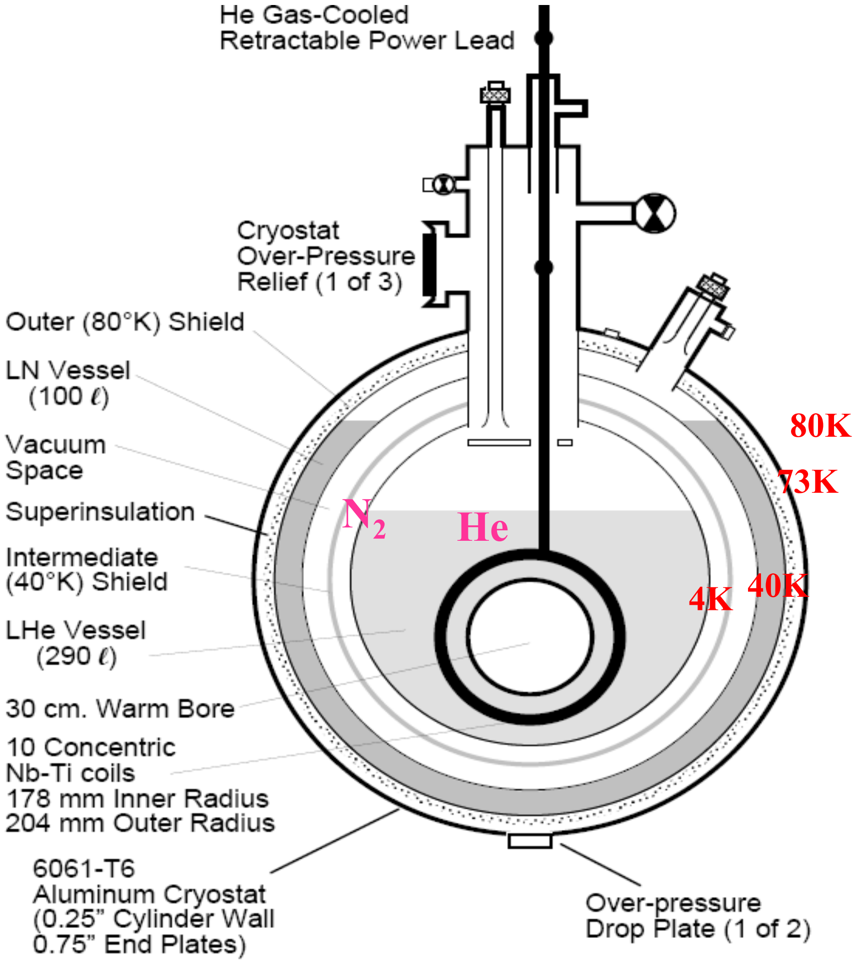
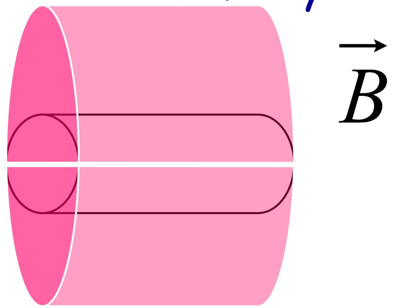


Superconducting Solenoid



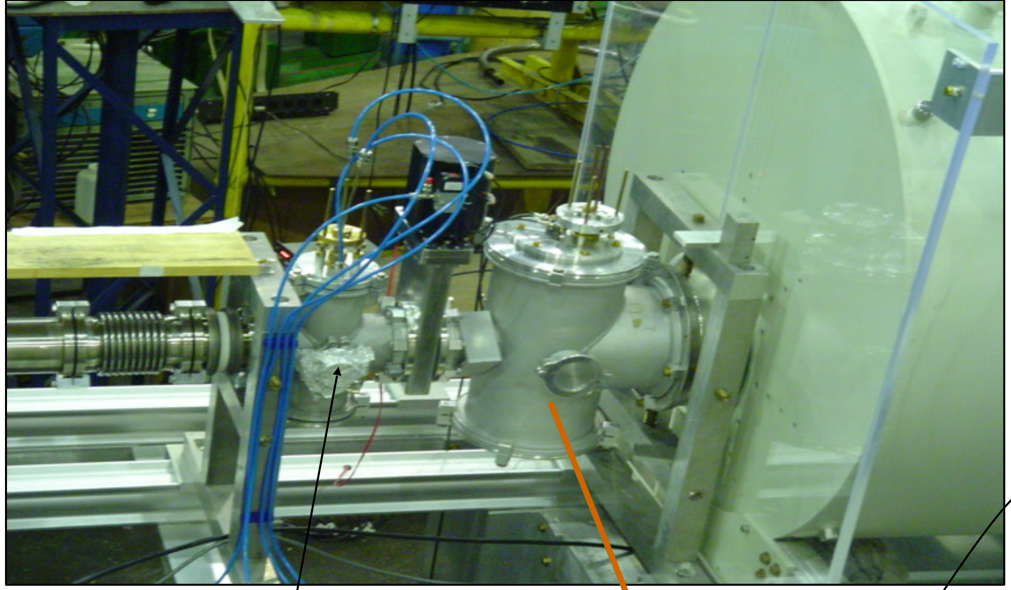
Fabricant: Cryomagnetics Inc, Oak Ridge USA

- Magnet – NbTi
- Field integral – 5 T.m.
- Max. central field – 6.52 T
- Max. current – 91.86 A
- Inductance – 309 H
- Stored Energy – 1.3 MJ
- LHe vessel 250 litros
- LHe boil-off rate 3.4 liters/day
- LN2 Vessel 130 Litros
- LN2 – 15 liters/day



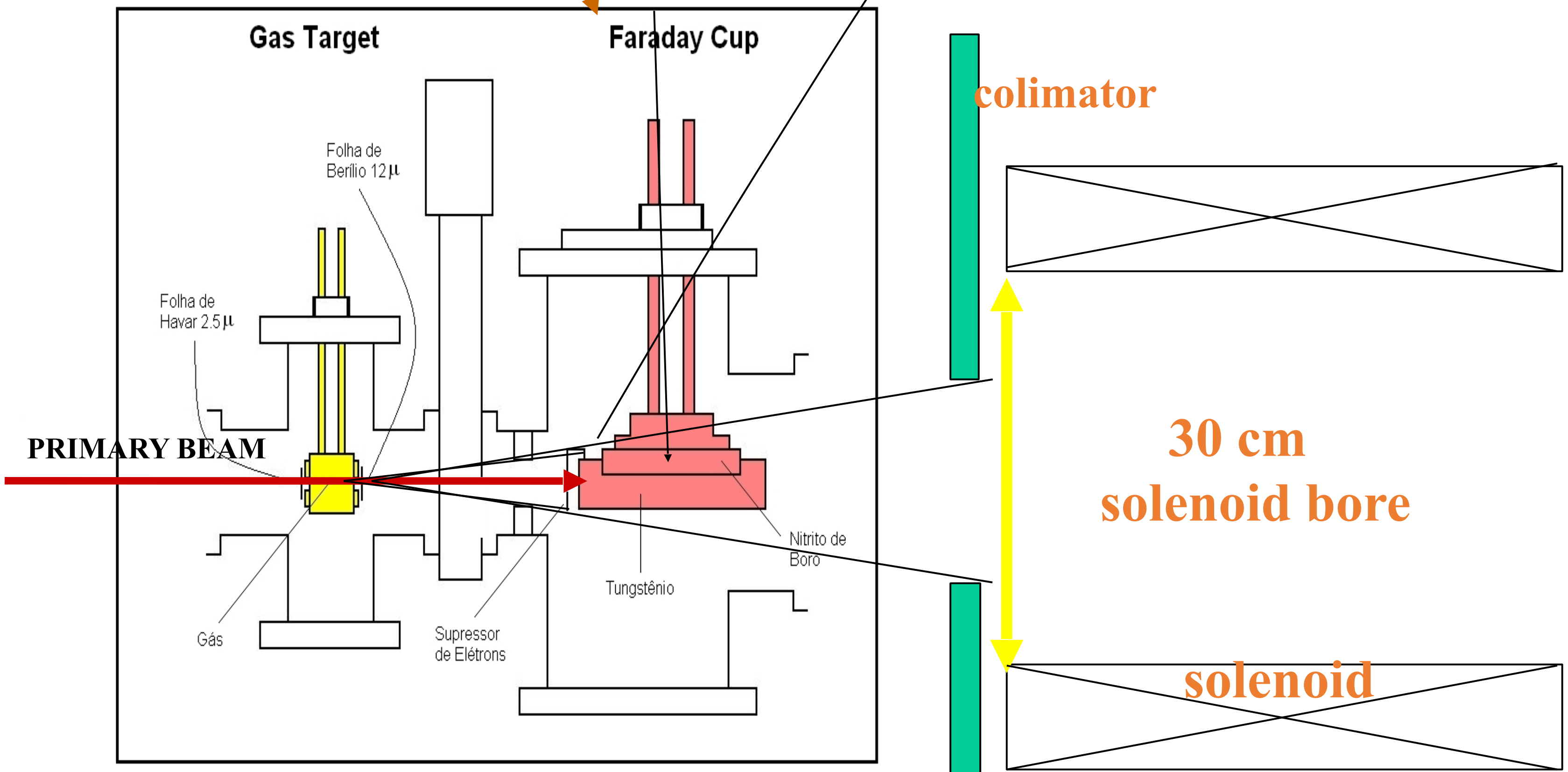
Production target

Solid ^{9}Be foil, LiF or gas targets



Angular acceptance

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



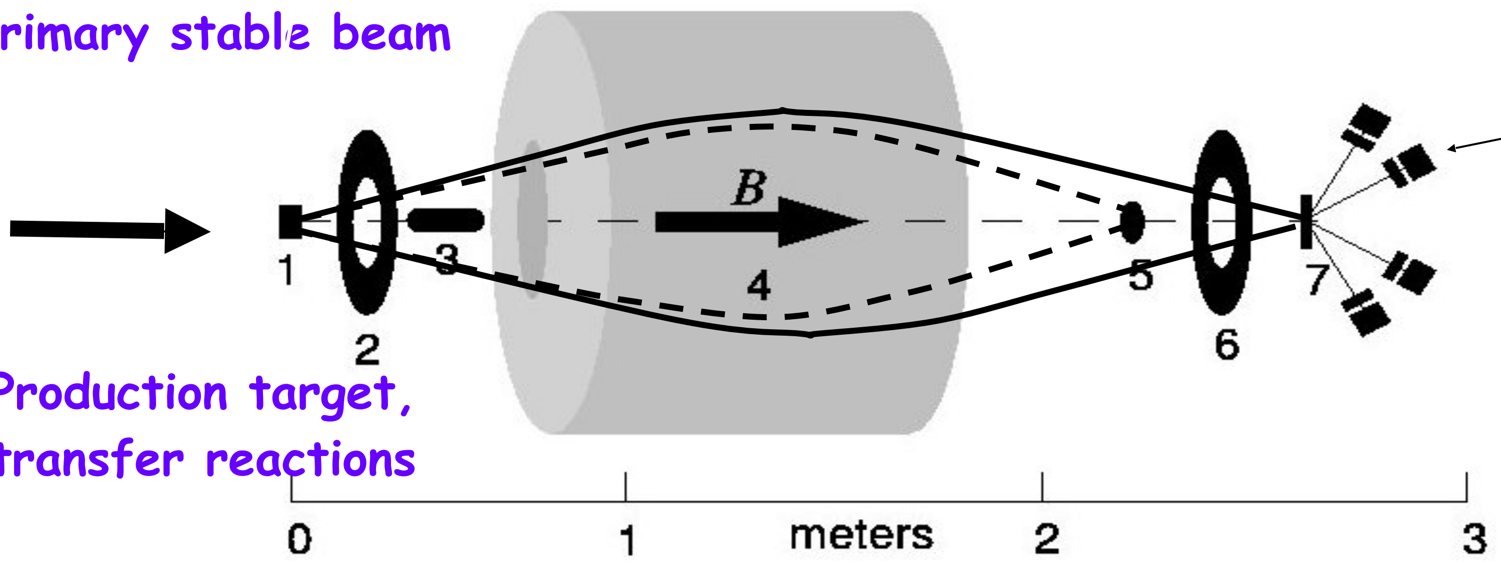
Selection with the first solenoid

angular acceptance → 30msr
2 deg - 6 deg

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

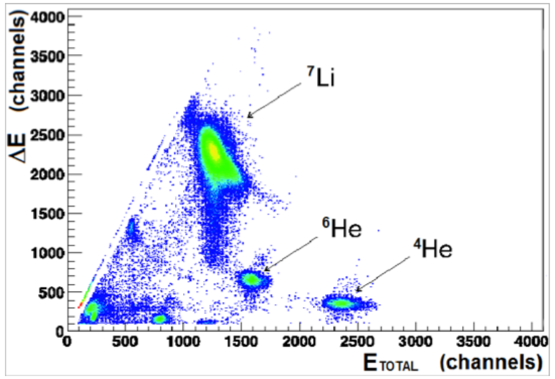
Maximum Bρ=1.8Tm

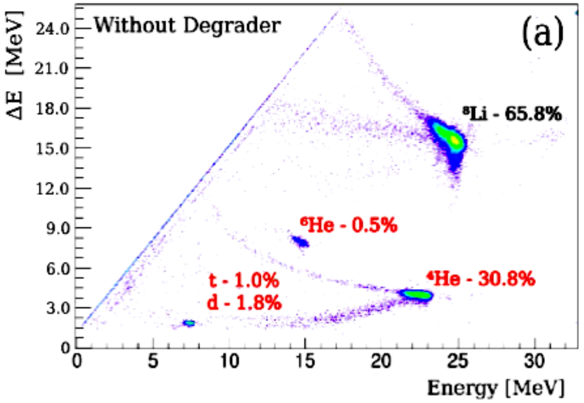
primary stable beam



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

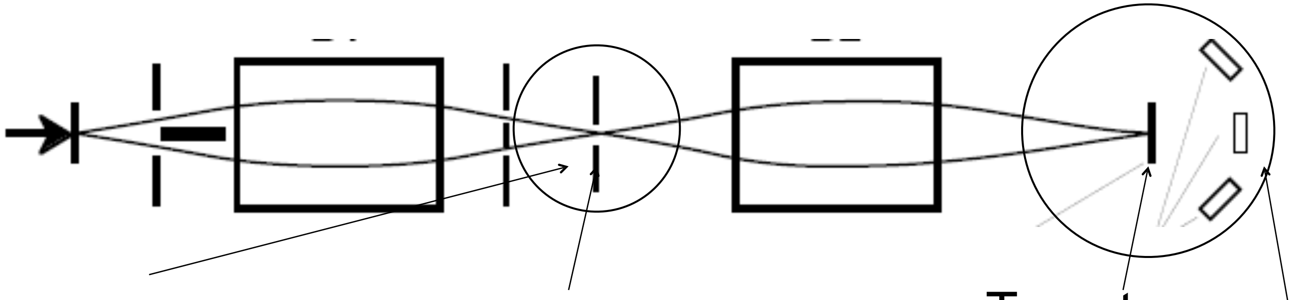


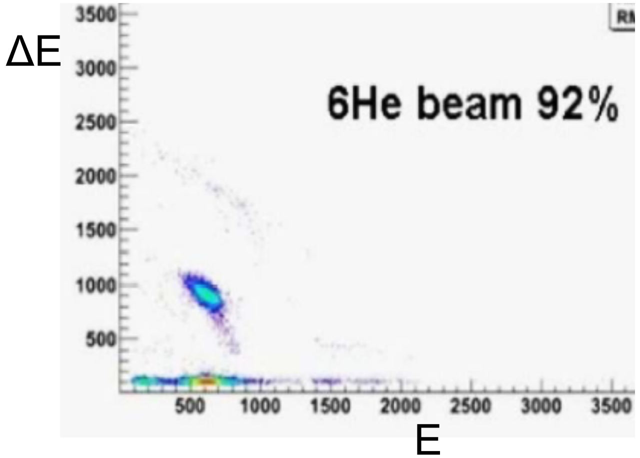


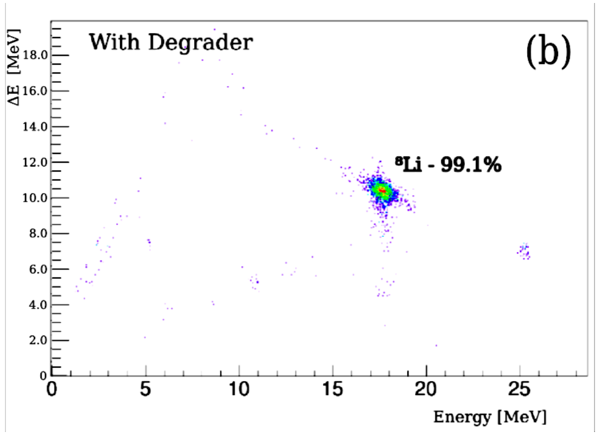
Beams of interest: ^{6}He, only 16%, ^{8}Li 65%

Double solenoids (cross-over mode)

Second solenoid helps cleaning the secondary beam:
Degrader changes the $B\rho$ of the particles with different Z (q)







$$(B\rho)^2 = k\frac{AE}{q^2}$$

Present radioactive beams at RIBRAS

secondary ion	reaction	intensity / 1μA of primary beam
^{6}He	$^{9}Be(^{7}Li,^{6}He)$	2×10^{5} p/s
^{8}Li	$^{9}Be(^{7}Li,^{8}Li)$	10^{6} p/s
^{7}Be	$^{3}He(^{6}Li,^{7}Be)$	$6x10^{5}$ p/s
^{7}Be	$^{6}Li(^{7}Li,^{7}Be)$	10^{5} p/s
^{10}Be	$^{9}Be(^{11}B,^{10}Be)$	2×10^{3} p/s
^{8}B	$^{3}He(^{6}Li,^{8}B)$	10^{4} p/s
^{12}B	$^{9}Be(^{11}B,^{12}B)$	10^{4} p/s
^{18}F	$^{12}C(^{17}O,^{18}F)$	10^{4} p/s
^{17}F	$^{3}He(^{16}O,^{17}F)d$	*

Scientific interest at RIBRAS: study of nuclear reactions with weakly-bound, cluster-structured, low-energy, light, radioactive ion beams

Elastic scattering:

(only first solenoid)

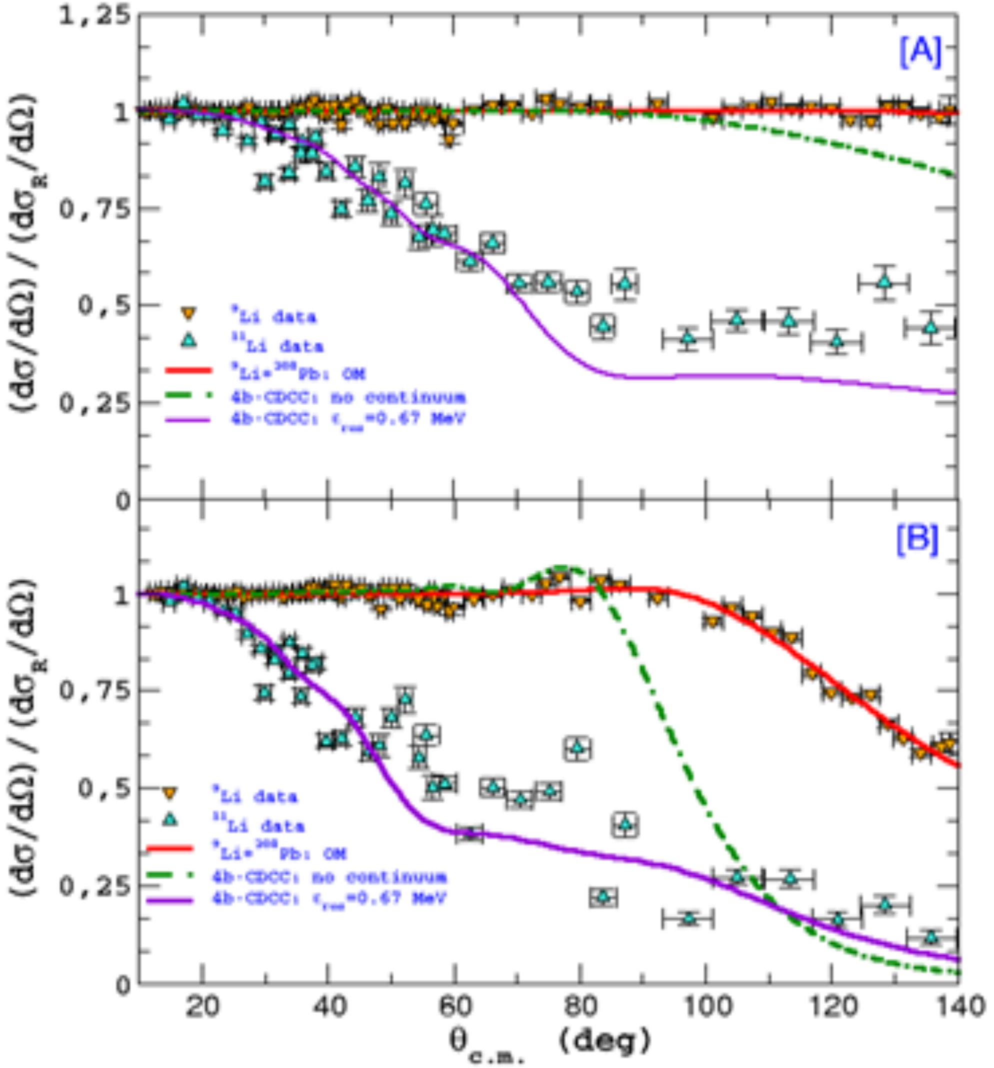
- ^{6}He + ^{9}Be, ^{27}Al, ^{51}V, ^{58}Ni, ^{120}Sn
- ^{7}Be + ^{27}Al, ^{51}V
- ^{8}Li + ^{9}Be, ^{51}V
- ^{8}B + ^{27}Al
- ^{8}Li, ^{7}Be, ^{9}Be, ^{10}Be on ^{12}C

^{8}Li + p, ^{6}He + p

Transfer reactions: ^{8}Li(p,α)^{5}He, ^{12}C(^{8}Li,^{9}Li)^{11}C

State of the art: Elastic scattering of ^{11}Li and ^{9}Li on ^{208}Pb at the Coulomb barrier

Cubero, M.et al, Phys. Rev. Lett. 109, 262701 (2012)

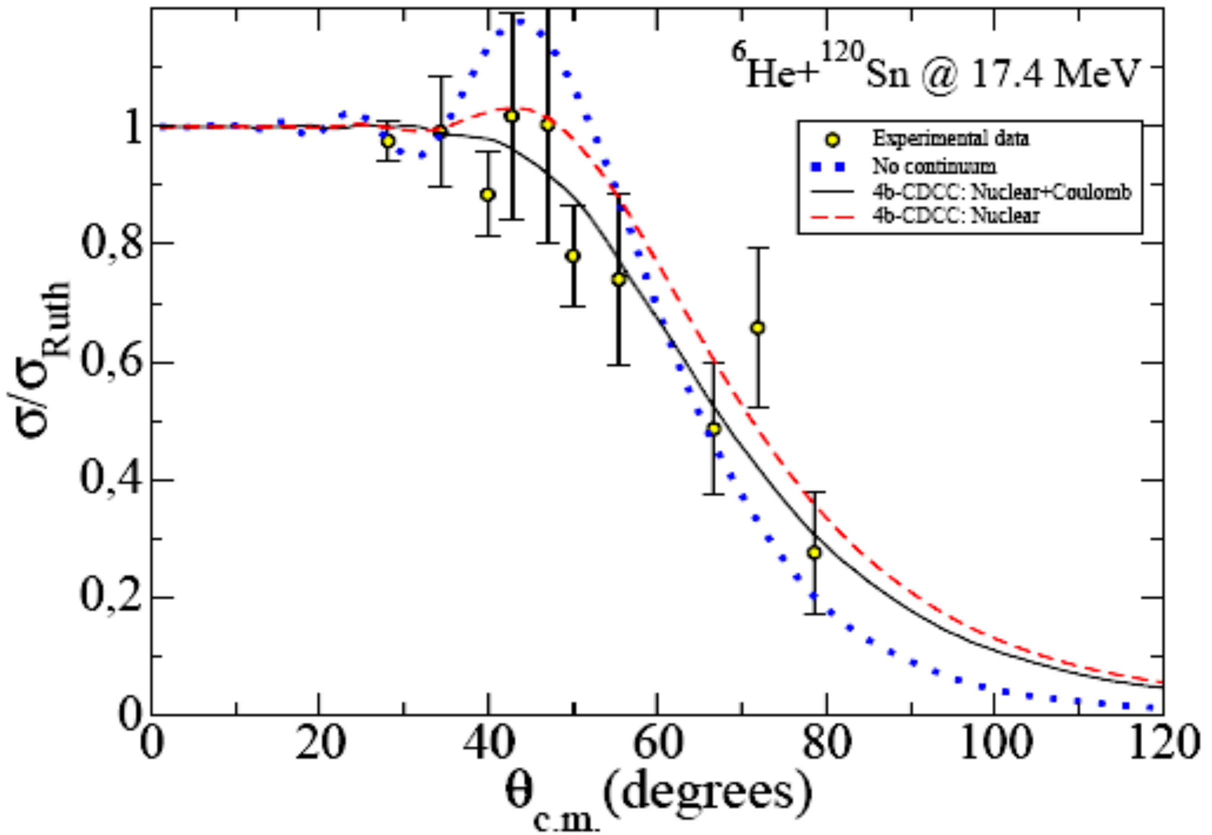


Elastic differential cross section of **^{9}Li and ^{11}Li on ^{208}Pb** , plotted as a ratio to the Rutherford cross section. In the upper part it is shown for energies below the barrier, $E_{c.m.}$ = 23.1 MeV, and in the bottom part for $E_{c.m}$ = 28.3 MeV. The optical model (OM) calculation for the **^{9}Li+^{208}Pb** system is also shown in each panel.

Coupling to the breakup of ^{11}Li (states in the continuum) explains the strong reduction in cross section. CDCC (Continuum Discretized Coupled Channels) calculation reproduces the data.

^{6}He + ^{120}Sn elastic scattering, measured at RIBRAS

^{6}He is a 2 neutron halo nucleus



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

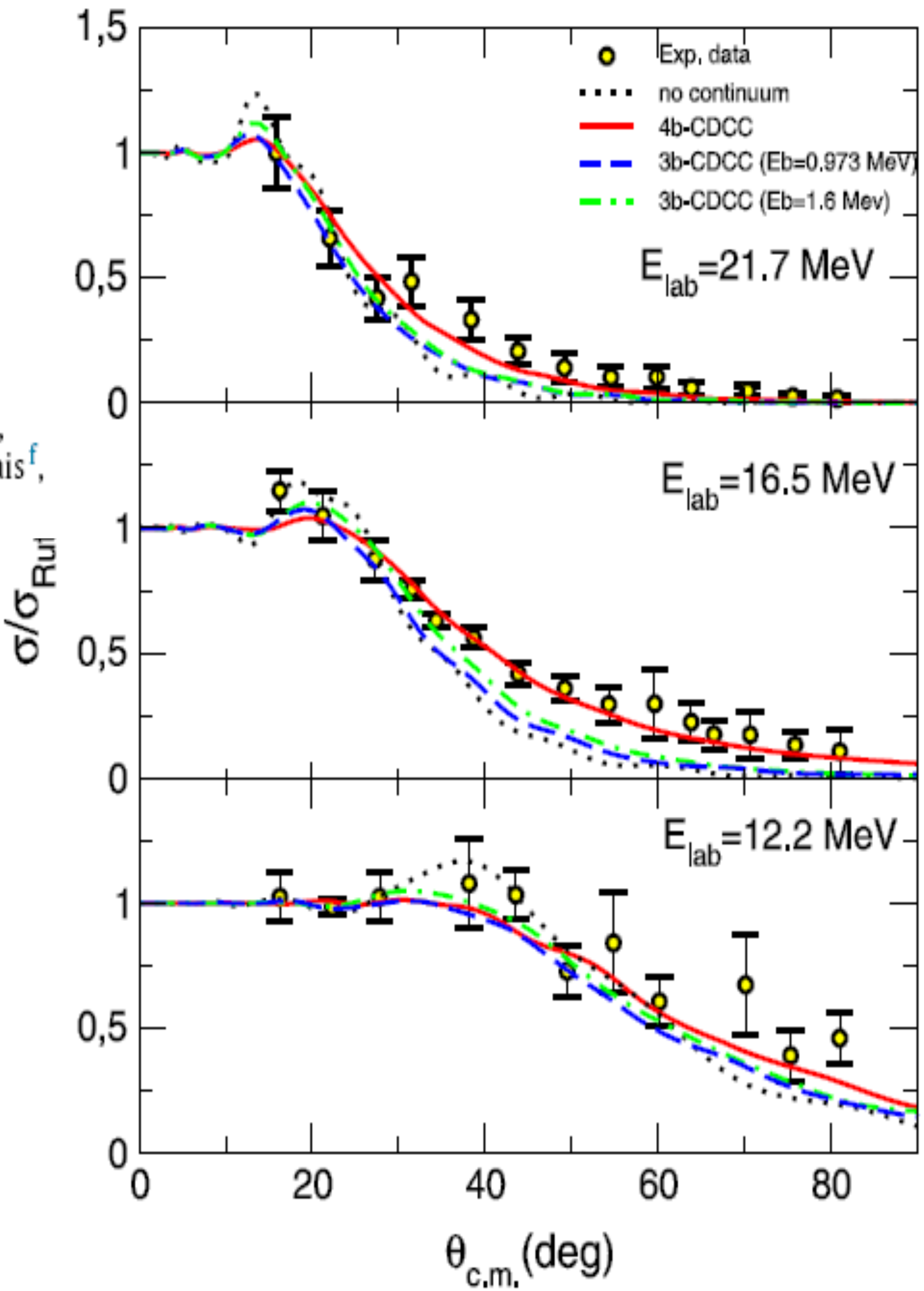
Four-body effects in the $^{6}He + ^{58}Ni$ scattering

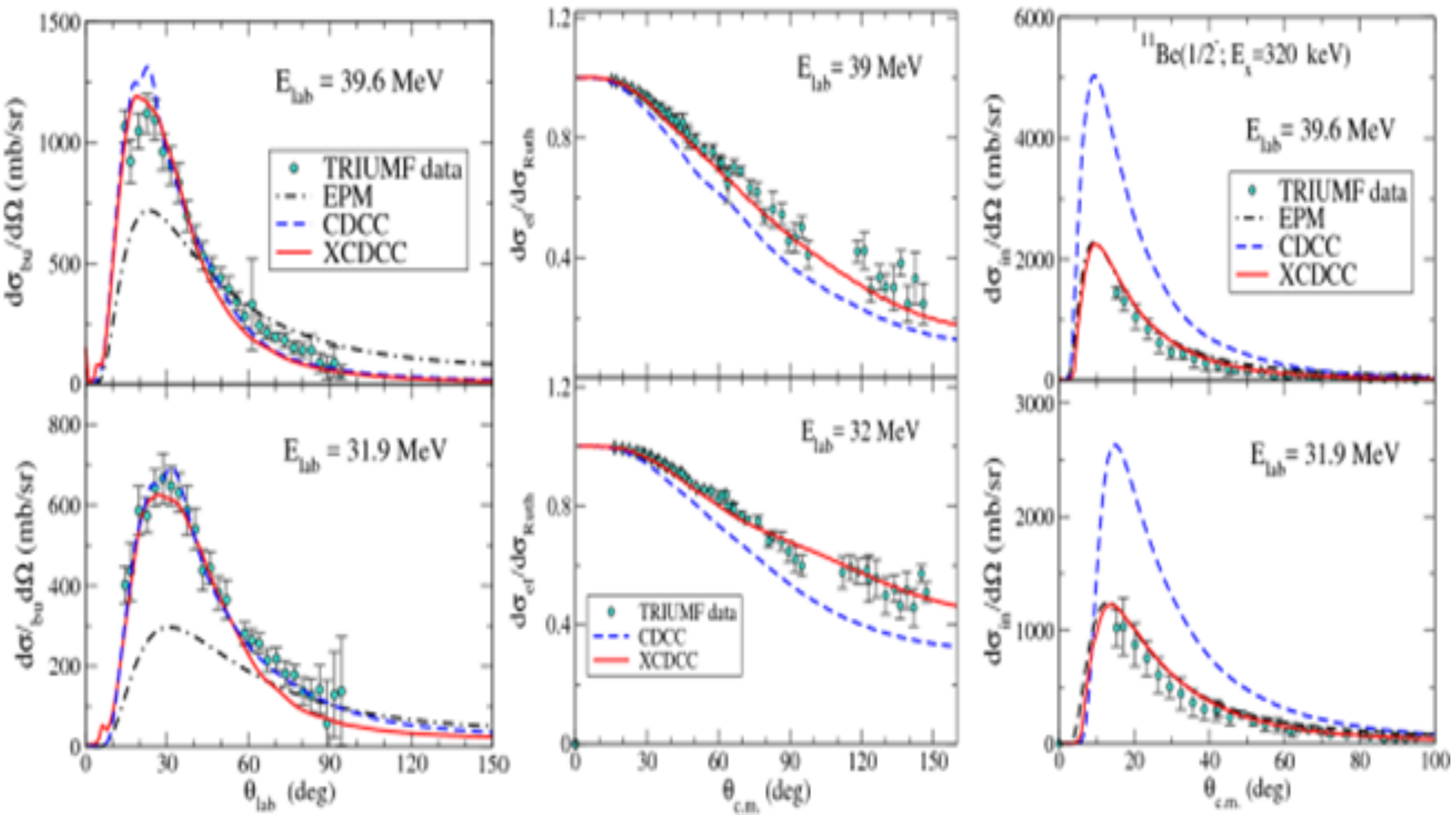
V. Morcelle[a,b], K.C.C. Pires[c,d], M. Rodríguez-Gallardo[e], R. Lichtenthäler[d,*], A. Lépine-Szily[d], V. Guimarães[d], P.N. de Faria[b], D.R. Mendes Junior[b], A.M. Moro[e], L.R. Gasques[d], E. Leistenschneider[d], R. Pampa Condori[d], V. Scarduelli[d], M.C. Morais[f], A. Barioni[g], J.C. Zamora[i],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





^{11}Be is a 1 neutron halo nucleus

These data and calculations show that the the ^{10}Be core is excited during the reaction

Experimental differential cross sections compared to theoretical calculations of the elastic scattering of **^{11}Be+^{197}Au** (figures in the central column), of the **^{11}Be** breakup (figures in the column to the left), of the inelastic scattering of **^{11}Be** (figures in the column to the right). **Exclusive measurements**

V. Pesudo, et al, Phys. Rev. Lett. 118, 152502 (2017)

Present and future plans at RIBRAS for nuclear reactions:

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

Perform exclusive measurements: coincidence between the clusters emitted in breakup and the scattered particle, or measure the breakup in coincidence with γ-rays.

Total reaction cross section can be deduced from elastic scattering analysis.

$$\sigma_{reac} = 2\pi \int_{\theta_0}^{180} [\sigma_{Ruth}(\theta) - \sigma(\theta)] \sin\theta d\theta$$

This information is useful to investigate the role of breakup (or other reaction mechanisms) for weakly-bound / exotic nuclei.

To compare total reaction cross sections of systems with different projectiles and targets, including halo nuclei,a reduction is introduced

reduced energy

$$E_{cm}^{red} = E_{cm}\left(\frac{A_p^{1/3}+A_a^{1/3}}{Z_p Z_a}\right)\frac{MeV}{fm}$$

reduced reaction cross section

$$\sigma_R^{red} = \frac{\sigma_R}{\left(A_p^{1/3}+A_a^{1/3}\right)^2}(mb)$$

Removes: Geometrical differences arising from sizes and charges

PHYSICAL REVIEW C 71, 017601 (2005)

Uncertainties in the comparison of fusion and reaction cross sections of different systems involving weakly bound nuclei

P. R. S. Gomes, J. Lubian, I. Padron, and R. M. Anjos
Instituto de Física, Universidade Federal Fluminense, Av. Litorânea, s/n, Gragoatá, Niterói, R.J., 24210-340, Brazil

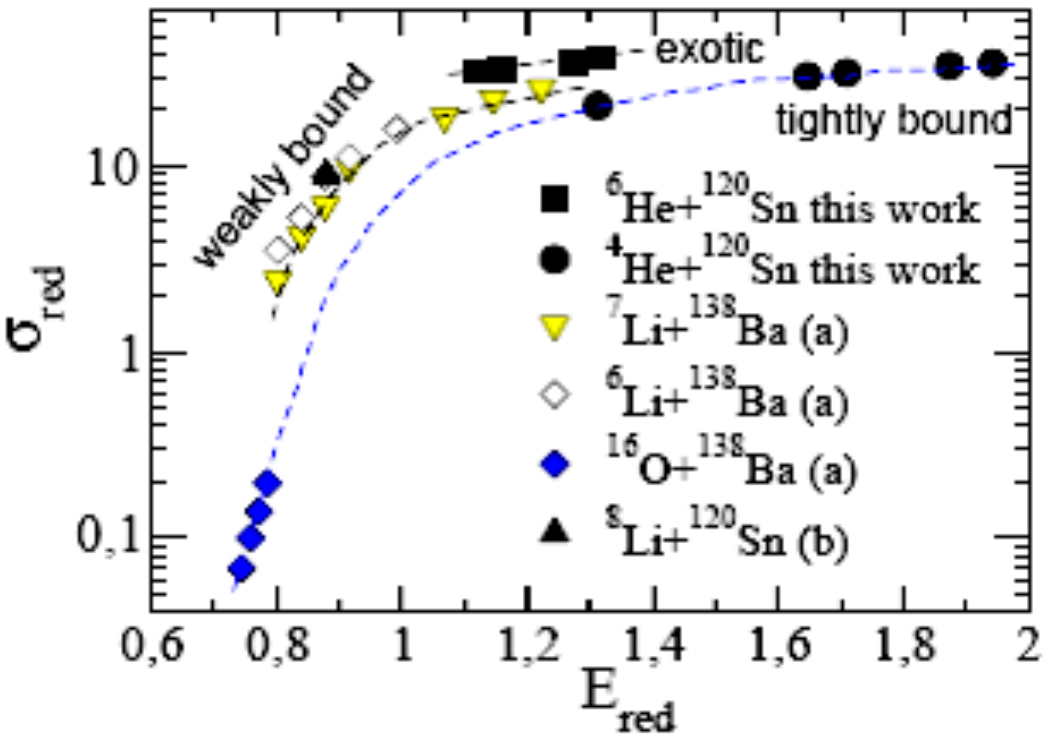
Total reaction cross sections on A~120 targets

Reduction or scaling:

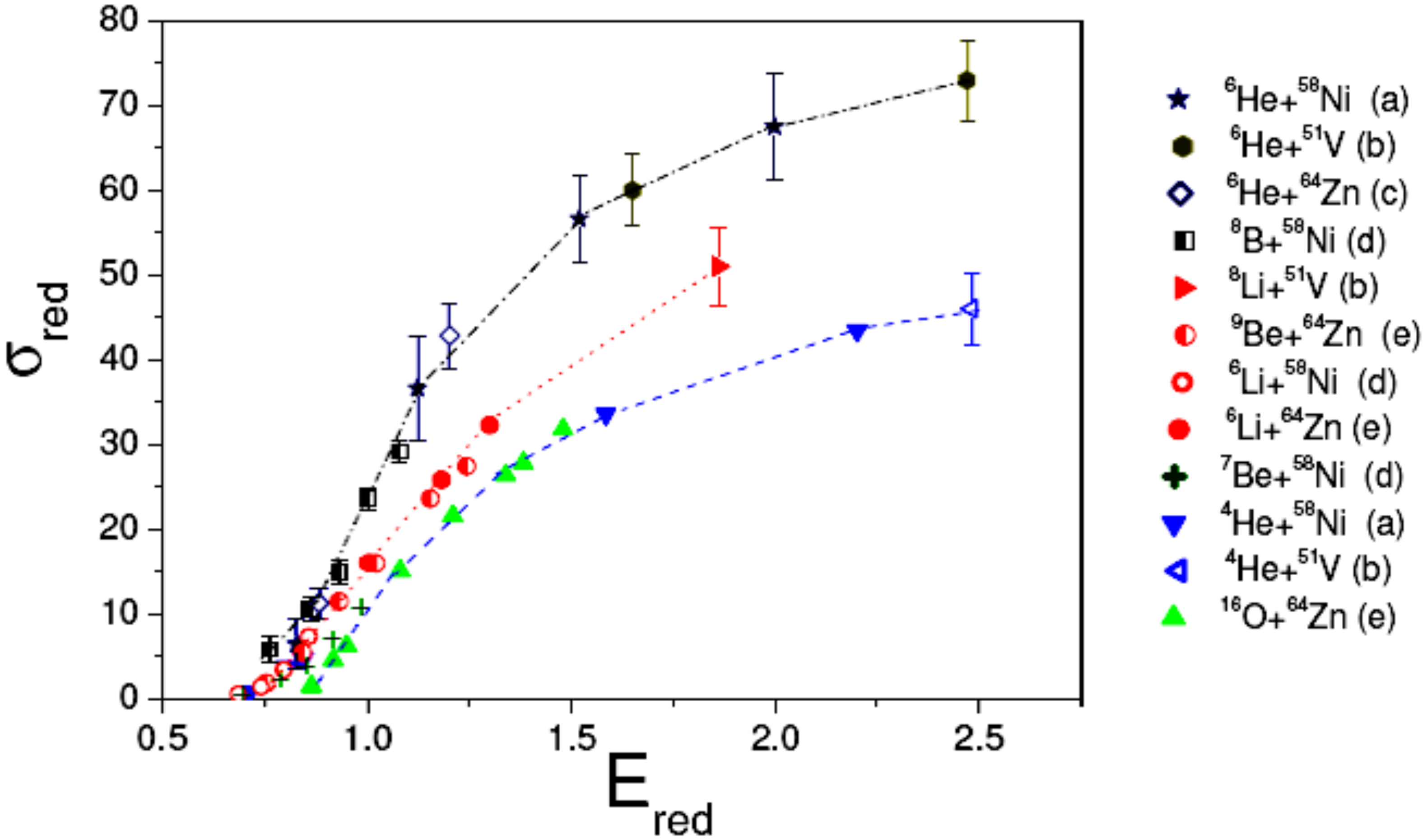
σ_{red} (^6He +^{120}Sn): enhancement of ~ 50% over σ_{red} (^7Li+^{138}Ba)

The scaling yields 3 trends:

Lowest σ_{red} -> tightly bound
Higher σ_{red} -> weakly bound
Highest σ_{red} -> halo projectile



Total reaction cross sections on A~60 targets

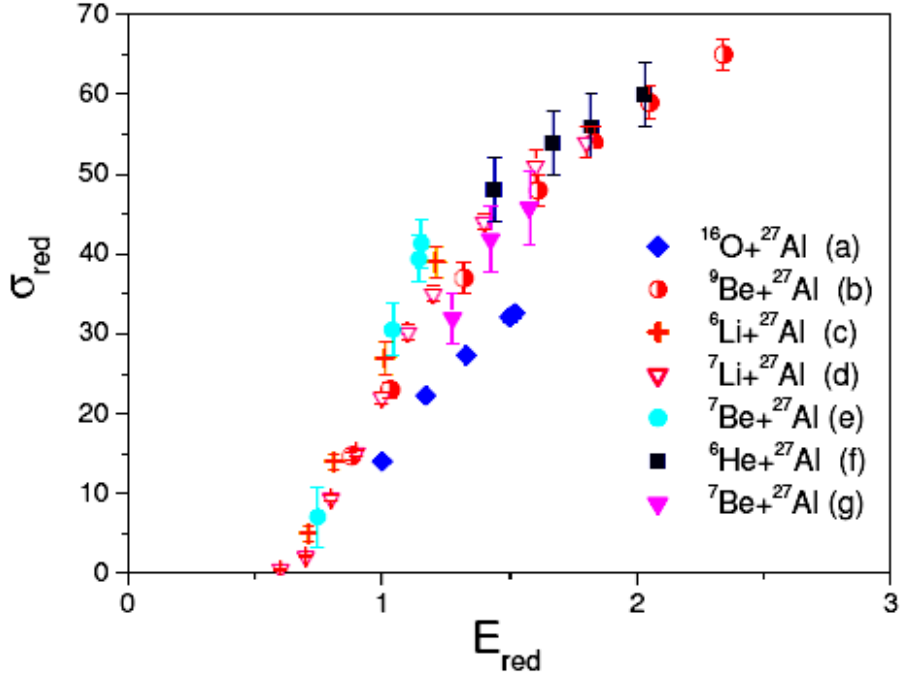


σ_{red} (^{6}He + ^{58}Ni,^{51}V,^{64}Zn, ^{8}B+^{60}Ni): enhancement

of ~ 40 - 50% over σ_{red} (^{6,7,8}Li + A~60 targets)

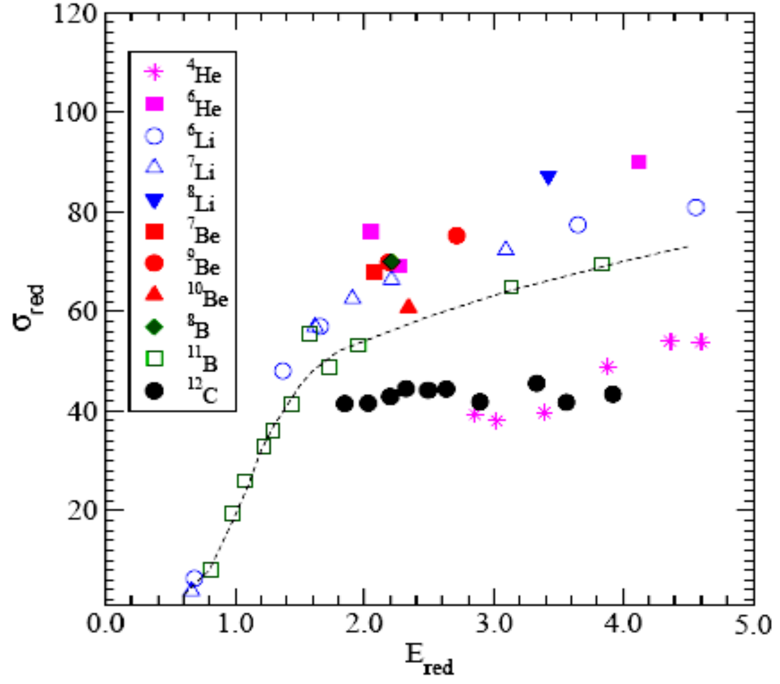
Total reaction cross sections on ^{27}Al target

No enhancement for halo nuclei over weakly bound but over tightly bound



Total reaction cross sections on ^{12}C target

Slight enhancement (15%)
for halo nuclei over weakly bound.
At low energies, strongly bound (^{11}B) and weakly bound (^{6}Li) have similar behaviour

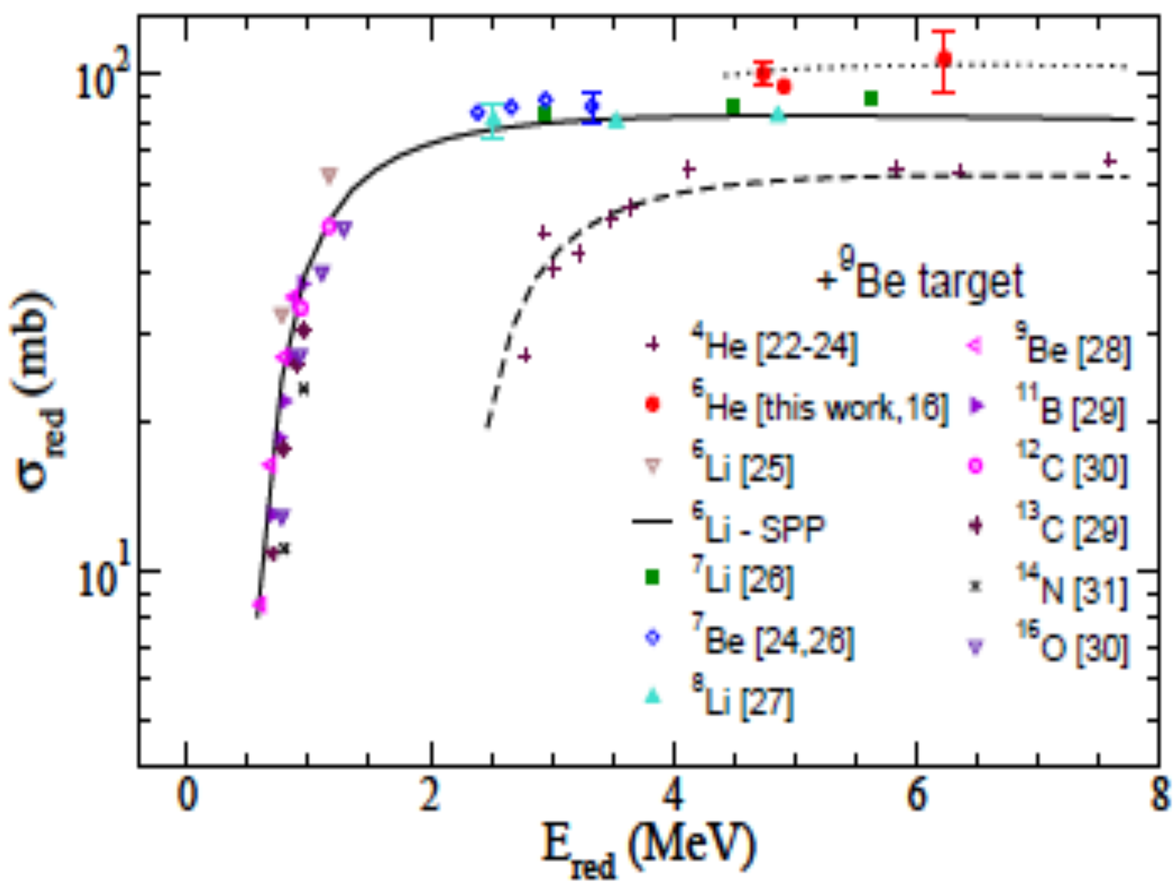


Total reaction cross sections on ^{9}Be target

At high energies large enhancement for the ^{6}He projectile over ^{4}He.

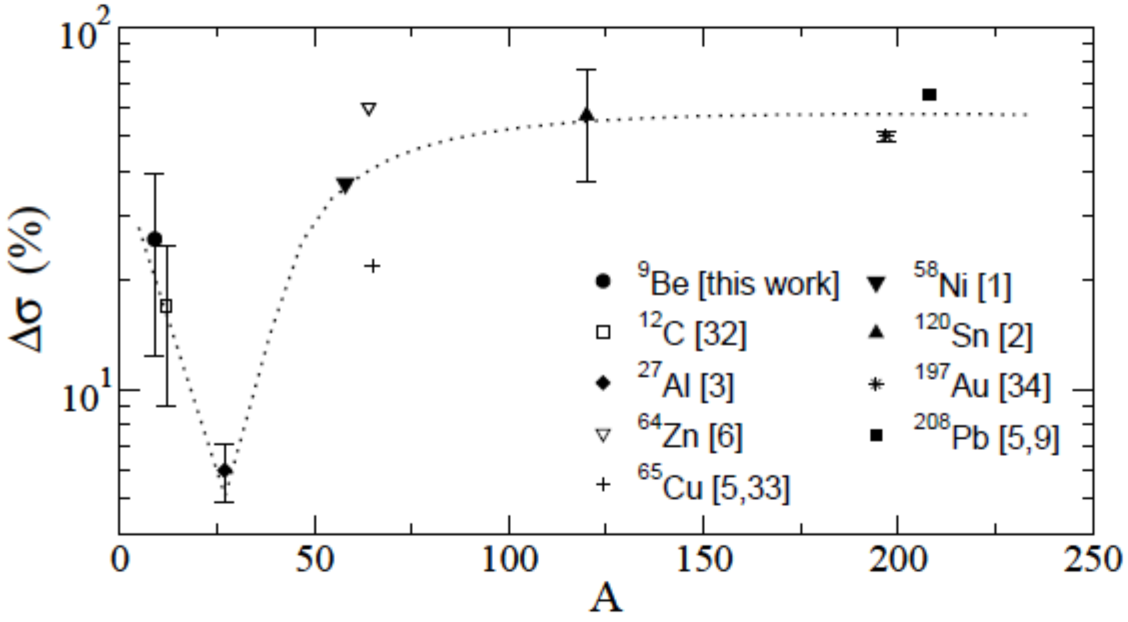
Some enhancement over weakly bound as ^{7}Li

At low energies, some strongly bound (^{11}B,^{12}C, ^{14}N,^{16}O)and weakly bound (^{6}Li, ^{9}Be) have similar behaviour



Total reaction cross sections of ^{6}He projectile as a function of A of target

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



Comparison of σ_{reac} of ^{6}He and ^{6}Li at the same energy (E_{red}>1.1MeV).
It can yield information on effects which are not purely geometrical.
Its understanding is challenging.

Measurements with purified radioactive beams:

Elastic scattering and transfer reactions on hydrogen target

Interest of $^{8}Li(p,\alpha)^{5}He$, $^{8}Li(p,p)^{8}Li$ and $^{8}Li(p,d)$ reactions:

Nuclear Physics:

- Provide spectroscopic information on ^{9}Be states near the p+^{8}Li threshold (16.88 MeV)

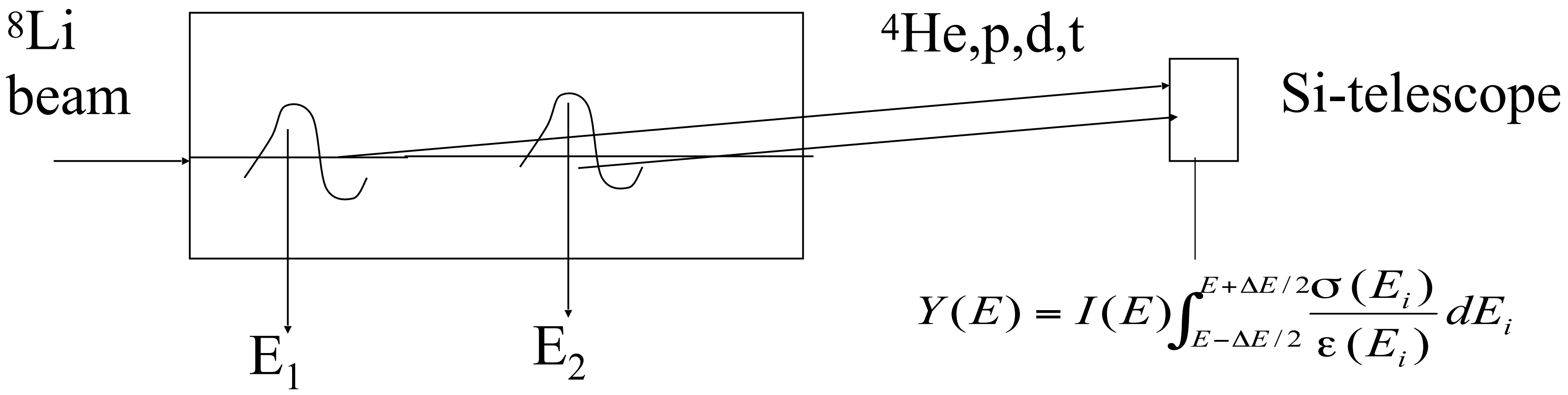
Astrophysics:

- The reaction $^{8}Li(p,\alpha)^{5}He$ destroys the ^{8}Li, preventing the access to higher mass nuclei.
- Important to measure and compare its strength with the branch $^{8}Li(\alpha,n)^{11}B$

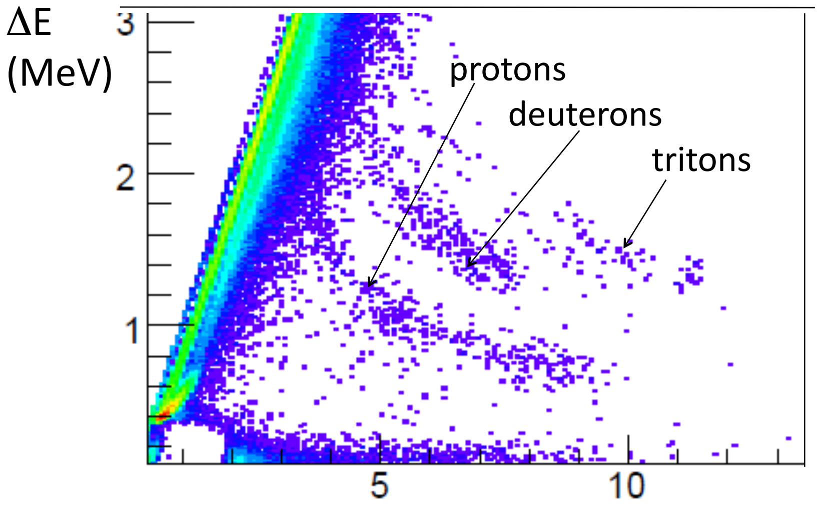
➔Previously we have measured the excitation function for
$^{8}Li(p,\alpha)^{5}He$ reaction between E_{cm}=0.2 -2.12 MeV,

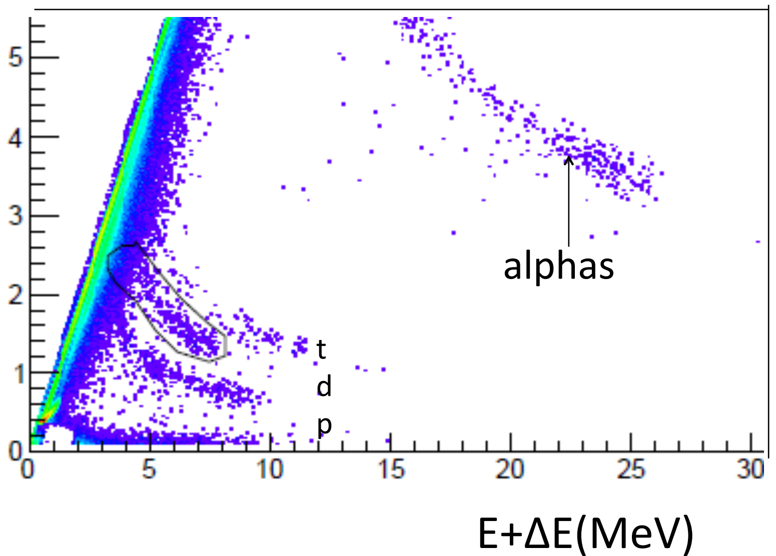
D.R.Mendes Jr. et al. Phys. Rev. C 86, 064321 (2012)

Method: Thick Target Inverse Kinematics (TTIK) : ^{8}Li beam hitting a thick (6.7 mg/cm^2) $[CH_2]_n$ target . ^{8}Li beam looses energy, stops in the target



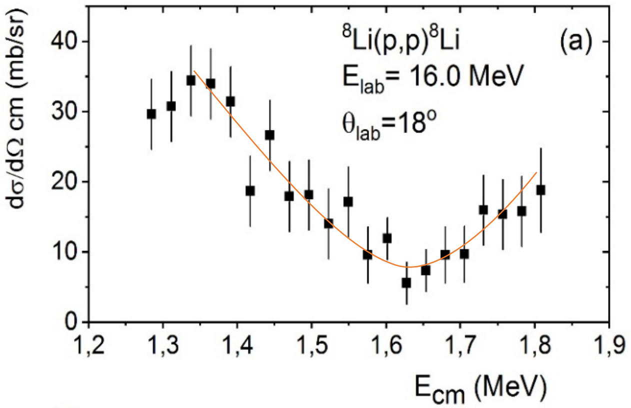
$$Y(E) = I(E)\int_{E-\Delta E/2}^{E+\Delta E/2} \frac{\sigma(E_i)}{\varepsilon(E_i)} dE_i$$; ,



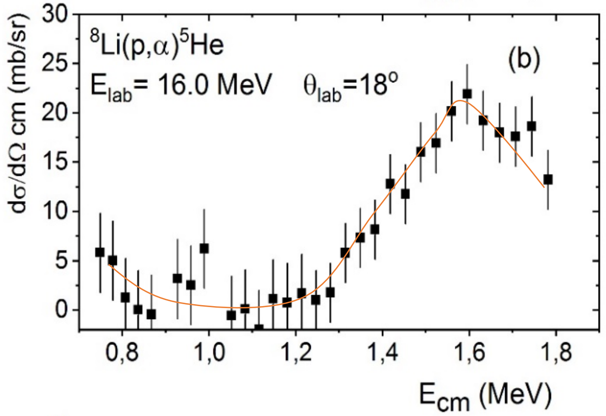


Results at θ_{lab} = 18°

The excitation function of the elastic scattering $^{8}Li(p,p)$ was measured in our recent experiment. At E_{cm}=1.65 MeV there is a strong minimum.

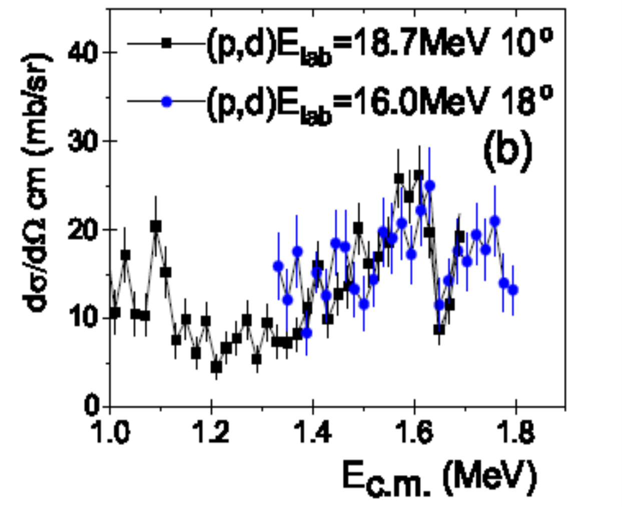


$^{8}Li(p,p)^{8}Li$



$^{8}Li(p,\alpha)$

In our recent measurements we could measure the excitation function of the transfer reaction $^{8}Li(p,d)^{7}Li$. We see 2 peaks, due to the excitation of the ^{7}Li.



$^{8}Li(p,d)^{7}Li$

R-matrix calculation

Procedure:

1. Inputs for each resonance: ,
2. Calculation of the R-matrix for each J values
3. From R-matrices: calculation of the scattering matrices U_J for each J
4. From the scattering matrices U_J : elastic and transfer cross sections

Several reactions with the same entrance channel → constraints

Energy , proton width are common → constraints

$^{8}Li(p,p)^{8}Li$:

$^{8}Li(p,\alpha)^{5}He$:

$^{8}Li(p,d)^{7}Li$:

5-channels:

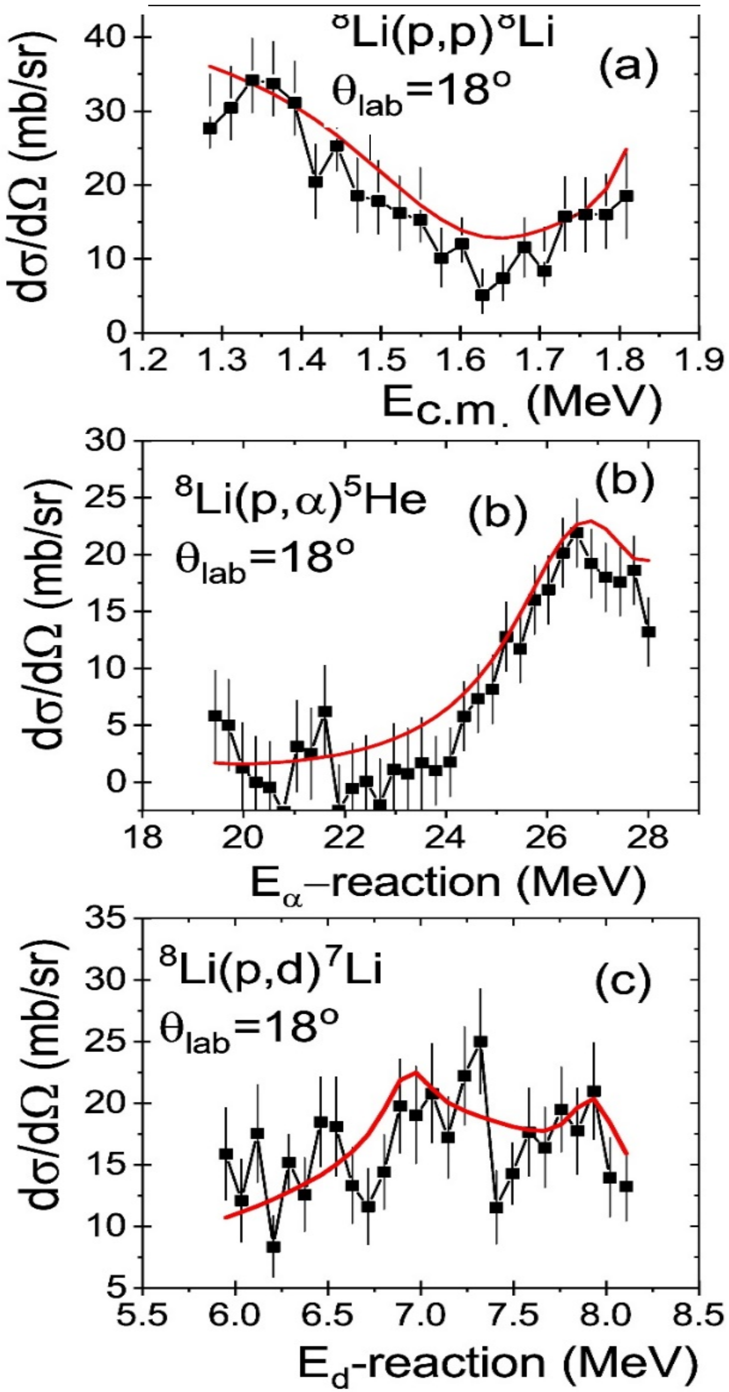
$^{8}Li + p$

$^{5}He + \alpha$

$^{5}He^{*}(1/2^{-}) + \alpha$

$^{7}Li_{gs} + d$

$^{7}Li^{*}(1/2^{-}) + d$



Present					
E_r	J^π	Γ_p	Γ_α	Γ_d	$\Gamma_{d'}$
0.42	$5/2^-$	40	20	150[b]	
0.61	$7/2^+$	1.0	39	7	
1.10 ± 0.03	$3/2^+$	10		30	10
1.65 ± 0.04	$7/2^-$	185	185	95	30
1.80 ± 0.04	$5/2^-$	20	14	25	20

[a] Fitted on the ^{8}Li(d,p)^{7}Li integrated cross section [31] near the resonance.

Literature [27]		
E_r	J^π	Γ
0.40	$(5/2)^-$	200
0.605	$(7/2)^+$	47
1.13		
1.69 ± 0.04		
1.76 ± 0.05	$(5/2^-)$	300 ± 100

E. Leistenschneider, A. Lépine-Szily et al, Physical Review C 98, 064601 (2018)

Conclusions:

- A low-energy, light, radioactive beam facility, as RIBRAS, can make competitive contribution in nuclear reaction studies. RIBRAS has 2n halo beam (^{6}He) and 1 proton halo beam (^{8}B).

- Need for constant upgrade in electronics and detection capacity to be able to perform exclusive measurements. There are still very few data since they demand long measurement times. RIBRAS has the advantage of beam time availability.