Recent results with radioactive ion beams in São Paulo, Brazil (RIBRAS)

Alinka Lépine-Szily
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Nuclear Physics today

stable nuclei = valley of β-stability (less than 300 !!!)

«known» nuclei

TERRA INCognita
( > 5000 !!!)
Nuclear Chart

• 3000 known nuclei
• 300 stables, others decay (radioactive)
• Terra Incógnita (radioactive nuclei yet not observed)
• $T_{1/2}$ from $\mu$sec to billions of years.
• Nuclei with very short half-life do not exist on Earth.
• They can be continuously produced and decay in Universe (important role in stellar processes)

• Applications: 1. Radioactive isotopes in medicine
   2. Nuclear Astrophysics
   3. Hybrid Reactors and Transmutation of nuclear waste
Unstable or radioactive nuclei

Are $\beta^-$ or $\beta^+$ emitters with half-lives: $T_{1/2}\sim1\text{ms to years}$

→ possibility to produce

Unstable or radioactive nuclear beams

Exotic nuclei : close to the drip-line,

often present exotic features

Crossing the Drip Line the nuclear system becomes unbound:

but emission of protons can be hindered by the Coulomb barrier and of neutrons by centrifugal barrier.
Some fundamental questions:
What are we looking for?

1. What are the limits for the existence of nuclei?
   Where are the proton and neutron drip lines situated?
   Where ends the Mendeleyev table?

2. How does nuclear force depend on proton-to-neutron ratios?

3. How to explain collective phenomena from individual motion?

4. How are complex nuclei built from their basic constituents?
“Basic Truths” revisited:

1. Nuclear radii don’t go as $A^{1/3}$
2. Magic Z and N numbers depend on N and Z, respectively
3. Many more bound nuclei exist than anticipated
Surprises

“halo” nuclei

Number of neutrons

12Be

11Li
Halo Nuclei

\[ ^{11}\text{Li} \rightarrow ^{9}\text{Li} + 2n \]
\[ ^{11}\text{Be} \rightarrow ^{10}\text{Be} + n \]
\[ ^{6}\text{He} \rightarrow ^{4}\text{He} + 2n \]

2 neutron halo

core of \(^{9}\text{Li}\)

\(^{11}\text{Li}\)

4 fm

16 fm
$^{11}$Li: Borromean Halo Nucleus  
$^{19}$C: The Heaviest Known Halo Nucleus  
$^{208}$Pb: Well Bound Heavy Nucleus  
The Borromean Rings
Nuclear radii: neutron and proton skins

FIG. 2. The rms neutron radii ($\bar{r}_n$) [open circles from case (a), open triangles from case (b)] and the rms proton radii ($\bar{r}_p$) [solid circles] from Ref. [5] as a function of the neutron number of Na isotopes. The error bars for the $\bar{r}_n$ are shown only for case (b). The dashed (solid) line is the calculated $\bar{r}_n$ ($\bar{r}_p$) by the RMF model.
Limit of Stability

Energy loss (MeV)

Time of flight (ns)

first observation of $^{48}$Ni

H        D        T        $^4$H        $^5$H        $^6$H ? $^7$H ?

Dubna 2001

GANIL 2001
Mass Measurements

Measured masses (1995)

N (Z=50)

Mass difference (MeV)

S Liran and N Zeldes, At Data Nucl. Data Tables 17 (1976) 431
T Tachibana et al., At Data Nucl. Data Tables 39 (1988) 251
P Moeller et al., At Data Nucl. Data Tables 59 (1995) 185
H von Grote et al., At Data Nucl. Data Tables 17 (1976) 418
Various astrophysical processes on the nuclear chart:
i) Primordial nucleosynthesis (red),
ii) Normal slow stellar evolution (dark-blue),
iii) Slow neutron capture (s-process, brown),
iv) fast neutron capture (r-process, green)
v) rapid proton capture (rp process light blue).

Ciel pendant le burst de rayons X GRB 971214. Sur la partie droite le p-process peut avoir lieu.

Vue du ciel avant (gauche) et après (droite) l'explosion de la supernovae SN1987a. Sur la droite, le r-process peut avoir lieu.
How we can study nuclei far from stability?

Production of radioactive ion beams

- projectile fragmentation
- Spallation
- Fission
- Fusion
- Transfer reactions
Main Process at $E > 30\text{MeV/nucleon}$.

Fragment with $N/Z$ similar to the projectile.
Projectile fragmentation in flight separation produces radioactive beams with velocity close to the primary projectile, rapid process.

- Production methods of radioactive beams at primary E > 30 MeV/nucleon
- Projectile fragmentation in flight separation
  - ISOL (isotope separation on line)
  - Radioactive species produced in spallation, stopped, ionized, separated, re-accelerated
Unsufficient energy for projectile fragmentation, use fusion or transfer reactions
Two superconducting solenoids

foto Orly Camargo
Production system (primary target)

- Primary target
- Secondary beam
- Acceptance from 2 deg to 6 deg
- Acceptance from 2 deg to 15 deg maximum
- 7Li
- Solenoid bore 30cm
- Berilium foil 12μm
- Havar foil
- Gas target
- Faraday cup
- Colimators

Diagram shows the layout of the production system with the primary beam, secondary beam, and the acceptance range.
## Production reactions

<table>
<thead>
<tr>
<th>Secondary particle</th>
<th>production reactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^6\text{He}$</td>
<td>$^9\text{Be}(^7\text{Li},^6\text{He})$</td>
</tr>
<tr>
<td>$^8\text{Li}$</td>
<td>$^9\text{Be}(^7\text{Li},^8\text{Li})$</td>
</tr>
<tr>
<td>$^7\text{Be}$</td>
<td>$^3\text{He}(^6\text{Li},^7\text{Be})$</td>
</tr>
<tr>
<td>$^7\text{Be}$</td>
<td>$^3\text{He}(^7\text{Li},^7\text{Be})$</td>
</tr>
<tr>
<td>$^8\text{B}$</td>
<td>$^3\text{He}(^6\text{Li},^8\text{B})$</td>
</tr>
<tr>
<td>$^{18}\text{Fm}$</td>
<td>$^{12}\text{C}(^{17}\text{O},^{18}\text{Fm})$</td>
</tr>
</tbody>
</table>
Selection with solenoids

\[ B \rho = \frac{mv}{q} = \frac{\sqrt{2mE}}{q} = k \frac{\sqrt{2AE}}{q} \]
Trajectory for $^8\text{Li}$

- Primary target
- Secondary target
- Colimadores
crossover mode

Primary target
7,6Li

Primary beam
9Be,3He

Faraday cup

Solenoid 1

Colimator

Solenoid 2

PPAC

E-DeltaE

Secondary target

tof 3.2 m

1 meter
Detection system

Beam → Target

PPAC 1
PPAC 2

50 cm

z

y

Secondary target

lollipop

ΔE-E

tof
Reaction: \( ^9\text{Be}(^7\text{Li},^8\text{Li}) \)

5 mm beam spot
Angular divergence: 1-2 deg

Parallel Plate Avalanche Counter (PPAC)
X-Y position sensitive gas detector
Secondary beam contaminants

$^7\text{Li} + ^9\text{Be}$

$^7\text{Li}$
$^8\text{Li}$
$^6\text{He}$
$^4\text{He}$
$t$
$d$

$\Delta E = E - E_{\text{res}}$

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

$\sim 10^5 \text{p/s}$

$^7\text{Li}$ primary beam $I = 300 \text{ nAe}$

2004 J.A Swieca Summer School
\[ \text{\(^6\)He} \]

\[ \text{\(^{14}N + \text{\(^3\)He}) \]

\[ \text{\(^9\)Be(\(^7\)Li,\(^6\)He)} \]

\[ \sim 10^4 \text{p/s} \]
production reaction

$^3\text{He}(^6\text{Li},^7\text{Be})$

production reaction

$^3\text{He}(^7\text{Li},^7\text{Be})$
Present beams at RIBRAS

<table>
<thead>
<tr>
<th>Ion</th>
<th>primary beam energy (MeV)</th>
<th>reaction</th>
<th>production rate (/ 1μA of primary beam)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^6$He</td>
<td>30.</td>
<td>$^9$Be($^7$Li,$^6$He)</td>
<td>$10^{+6}$ p/s</td>
</tr>
<tr>
<td>$^6$He</td>
<td>20.</td>
<td>$^9$Be($^7$Li,$^6$He)</td>
<td>$10^{+5}$ p/s</td>
</tr>
<tr>
<td>$^8$Li</td>
<td>30</td>
<td>$^9$Be($^7$Li,$^8$Li)</td>
<td>$10^{+6}$ p/s</td>
</tr>
<tr>
<td>$^7$Be</td>
<td>30</td>
<td>$^3$He($^6$Li,$^7$Be)</td>
<td>$4\times10^{+5}$ p/s</td>
</tr>
<tr>
<td>$^7$Be</td>
<td>30</td>
<td>$^3$He($^7$Li,$^7$Be)</td>
<td>$2\times10^{+5}$ p/s</td>
</tr>
<tr>
<td>$^8$B</td>
<td>30</td>
<td>$^3$He($^6$Li,$^8$B)</td>
<td>(?)</td>
</tr>
</tbody>
</table>

present primary beam $^6,^7$Li intensities $\sim$ 300 nAe

First measurements: Elastic scattering
Elastic scattering of $^6$He on $^{27}$Al

Motivation: Obtain information on the effect of the nuclear break-up of the $^6$He on the reaction cross-section at energies close to the Coulomb barrier

Method: Determine the reaction cross-section of $^6$He+$^{27}$Al at energies close to the Coulomb barrier from the elastic scattering angular distributions.
Experimental method:

Radioactive $^6$He beam produced by reaction
$^9$Be($^7$Li,$^6$He)$^{10}$B \quad Q = - 3.38 \text{ MeV}

Primary beam $^7$Li, intensity 300 nAe,
at energies: 19, 20.5 and 21 MeV

Production target 16 microns $^9$Be foil

Radioactive beam intensity: $10^5$ pps
Detection: E-ΔE silicon telescope with 300 mm$^2$
ΔE 20 microns, E 150 microns

Targets: $^{27}$Al of 7 mg cm$^{-2}$
$^{197}$Au of 5 mg cm$^{-2}$

Secondary beam energies: calculated by energy losses and confirmed by energy calibration of the detectors: 9.54, 11, 12 MeV

Normalization and secondary beam intensity determination: using $^{197}$Au target (Rutherford scattering)
Elastic scattering of $^6$He beam on Au and Al targets

Energy spectra measured at 20 degrees

$^4$He not stopped in the E detector, comes from scattered contaminant $^4$He beam, from 2n transfer and from $^6$He break-up. Repeat measurements with thicker E detector.
Average scattering angle and detection solid angles:

- Calculated by Monte-Carlo simulation
- Secondary beam spot size on secondary target (4-5mm)
- Secondary beam divergency (1-2 degr)
- Rutherford scattering angular distribution at forward angles in the detector modifies average angle
Rutherford scattering on gold with and without average angle corrections
Angular distributions at 9.54, 11, 12 MeV for $^6$He+$^{27}$Al

optical model São Paulo potential
L.C. Chamon et al.

- Imaginary part reduced, fit improved
Reaction cross sections

obtained from elastic scattering angular distributions

\(^{16}\text{O} + ^{27}\text{Al} - \text{D. Pereira et al}\)

\(^{9}\text{Be} + ^{27}\text{Al} - \text{P.R.S. Gomes et al}\)

\(^{6}\text{He} + ^{27}\text{Al}\) and \(^{7}\text{Be} + ^{51}\text{V} - \text{RIBRAS}\)

\[\sigma = \sigma/(A_{1}^{1/3} + A_{2}^{1/3})^{2}\]

reduced reaction cross-section

(P.R.S. Gomes)

\[E_{\text{red}} = E_{\text{cm}}(A_{1}^{1/3} + A_{2}^{1/3}) / Z_{p}Z_{t}\]
**Conclusion:** The reaction cross-sections of the $^{6}\text{He}+^{27}\text{Al}$ system are similar to $^{9}\text{Be}+^{27}\text{Al}$. $^{6}\text{He}$ is a radioactive 2n halo nucleus, $^{9}\text{Be}$ is stable but weakly bound.

They are enhanced when compared to strongly bound projectile as $^{16}\text{O}$ on $^{27}\text{Al}$.

The size of the halo nucleus $^{6}\text{He}$, as well as its low binding energy produce an enhancement of the reaction cross-section also when the reaction partner has low Z value (no Coulomb, only nuclear break-up).
What’s next?

- Measurements of elastic scattering of $^8\text{Li}$, $^6\text{He}$, $^7\text{Be}$, $^8\text{B}$ on targets: $^{208}\text{Pb}$, $^{120}\text{Sn}$, $^{58}\text{Ni}$, $^{27}\text{Al}$ at energies around the Coulomb barrier

- Accomplish the setup by mounting the secondary scattering chamber after the second solenoid

- Experiments with transfer reactions of astrophysical interest type (alpha,p), (alpha,n)