Risultati Recenti sulla Sperimentazione con Fasci di Ioni Radioattivi Leggeri in Italia

Marco Mazzocco

Dipartimento di Fisica e Astronomia,
Università degli Studi di Padova
INFN – Sezione di Padova

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III. Summary
I. Introduction
198 (284) “stable” nuclei
(86 nuclei with $T_{1/2} \sim 10^9$ years)
3600 known radioactive nuclei
6000 nuclei of “possible” existence
The **weak interaction** let nuclei slide down along isobaric chains towards the bottom of the **β-stability valley**.
Half-lives of radioactive nuclei

The half-lives for $\beta$-decays get smaller and smaller as we move apart from the stability valley.
RIB Production Requirements

The global production scheme for RIBs should:

1. be fast (because of the short half-lives of the produced nuclear species);

2. warranty the largest possible production cross section by optimizing the production mechanism (projectile-target combination, bombarding energy, primary beam intensity, power dissipation into the target);

3. by efficient (because of the low production rates);

4. by selective (because contaminations might be several orders of magnitude larger than the nuclear species of interest).
RIBs Production Mechanisms

a. **Projectile/Target Fragmentation**
   (neutron-deficient nuclei)

b. **Projectile/Target Fission**
   (neutron-rich nuclei)

c. **Nuclear Fusion**
   (proton-rich nuclei and super-heavy)

d. **Direct Processes in Inverse Kinematics**
   (light RIBs)
Radioactive Nuclei Produced

a. Fragmentation

b. Fission

c. Nuclear Fusion

d. Direct Reactions in Inverse Kinematics
RIB Factories in Europe

ISOL
In-Flight

LISE, France
SPIRAL, France
SPIRAL2, France (Project)

REX-ISOLDE, CERN

FRS, Germany
Super FRS, Germany (Project)

IGISOL, Finland

SPES, Italy (Project)
EXOTIC, Italy
EXCYT, Italy
FRIBS, Italy
II. Recent Results in Italy
IIa. FRIBs: $^{18}$Ne 2p-decay
IIa. Motivations

The simultaneous emission of two protons was proposed in ‘60s as a decay mode for even-Z nuclei close or beyond the proton drip-line (V. Goldansky, Nucl. Phys. 19, 482 (1960))

Three different decay modes for the 2p emission:

1. **democratic emission** (3-body direct breakup);
2. **di-proton emission** (\(^2\)He cluster emitted in a quasibound 1S configuration and then breakup);
3. **sequential decay** through (correlated scattering continuum of) the intermediate Z-1 nucleus.
IIa. Experiment

2p-decay energetically possible from the 1- state at 6.15 MeV

\(^{18}\text{Ne}\) produced via fragmentation of a 45 AMeV \(^{20}\text{Ne}\) beam on a \(^{9}\text{Be}\) target, 500 um thick. Properly identified by means of the \(\Delta E\)-ToF technique.

Coul-ex on \(^{\text{nat}}\text{Pb}\).

G. Raciti et al., NIM B 266, 4632 (2008)
IIa. Experimental Set-Up

Two Si-CsI hodoscopes (G. Raciti et al., PRL 100, 192503 (2008))

1. **Hodo Small:**
   
   81 twofold 1 x 1 cm$^2$: 300 um (Si) – 10 cm CsI(Tl)

2. **Hodo Big:**
   
   89 threefold 3 x 3 cm$^2$: 50 um (Si) – 300 um (Si) – 6 cm CsI(Tl)
IIa. Results

Competition between $1p$- and $2p$-decay modes

Democratic 3-body: $64 \pm 7\%$
Actual Sequential: $30 \pm 4\%$
Di-proton emission: $6 \pm 2\%$

Democratic 3-body: $66 \pm 9\%$
Virtual Sequential: $3 \pm 2\%$
Di-proton emission: $31 \pm 7\%$

G. Raciti et al., PRL 100, 192503 (2008)
IIb. EXCYT: Big Bang Experiment
IIb. Motivations

1. Production of $A>8$ elements during the Big Bang
These elements are observed in the oldest stars. Can their existence be traced back to the Big Bang?

The candidate reaction chain is

$$ ^1\text{H}(n,\gamma)^2\text{H}(n,\gamma)^3\text{H}(^2\text{H},n)^4\text{He}(^3\text{H},\gamma)^7\text{Li}(n,\gamma)^8\text{Li}(^4\text{He},n)^{11}\text{B}(n,\gamma)^{12}\text{B}(\beta)^{12}\text{C} $$

2. Heavy-element nucleosynthesis in Supernova explosion

r-process: rapid neutron capture on seed nuclei that are made through $\alpha$-captures, starting with the two reaction chains:

$$ ^4\text{He}(^4\text{He} \, n,\gamma)^9\text{Be}(^4\text{He},n)^{12}\text{C} $$

$$ ^4\text{He}(^3\text{H},\gamma)^7\text{Li}(n,\gamma)^8\text{Li}(^4\text{He},n)^{11}\text{B} $$

The latter significantly enhances the production of seed nuclei → constraints on models for the r-process.

Courtesy of A. Del Zoppo
IIb. Experiment

4π threshold-less capture-time measurement of neutrons from the $^8\text{Li}(^4\text{He},n)^{11}\text{B}$ reaction at EXCYT (G. Cuttone et al., NIM B 266, 4108 (2008) and D. Rifuggiato et al., JoP: CS 267, 012007 (2011))

1. **Start** detector: microchannel plate (MCP)
2. **Stop** detector: thermalization counter

12 $^3\text{He}$ tubes $\rightarrow$ neutrons detected by means of the $^3\text{He}(n,p)^3\text{H}$ reaction capture times ($t \sim 100 \mu s$) compatible with low intensity beams ($< 10^3$ pps)

$E_{\text{cm}} = 1.05$ MeV

Courtesy of A. Del Zoppo
IIb. Results

$^8\text{Li} (^4\text{He},n)^{11}\text{B}$ reaction cross section

Factor of 5 discrepancy at $r$-process energies solved


The result has been recently selected by A. Coc et al. [ApJ 744, 158 (2012)] to estimate the recommended rate in the frame of an improved extended nuclear network for the Big Bang nucleosynthesis (BBN).

Courtesy of A. Del Zoppo
IIc. EXCYT: Resonant Scattering
IIc. Motivations

Matter density distribution in Boron isotopes ground states

For $^{12}$B cluster configurations of $^8$Li + $^4$He type are expected near the $\alpha$-decay threshold

Kanada En’yo et al PRC 52 (1995) 647

Courtesy of D. Torresi
IIc. Experiment

$^8\text{Li}$ beam delivered by **EXCYT**

$E_{\text{beam}} = 30.6$ MeV $\quad I = 5 \times 10^4$ pps

$p = 700$ mbar $\quad T = 295$ K

D. Torresi et al., *IJMPE* 20, 1026 (2011)

$\Delta E \ [\text{Si (50 um) 4 pads}]$

$E \ [\text{DSSD (Si 1 mm), 16 x 16 strips}]$

*Courtesy of D. Torresi*
IIc. Results

Preliminary results in agreement with those obtained for the reaction $^9\text{Be} + ^7\text{Li} \rightarrow 2\alpha + ^8\text{Li}$


Courtesy of D. Torresi
IIId. FRIBs: n-Transfer Reactions
IId. Motivations

Study of elastic scattering and transfer reactions of light nuclei on p,d targets to investigate halo or other nuclear structure effects by means of kinematic coincidences and measuring both reaction partners in binary reactions.

Courtesy of G. Cardella

$^{10}\text{Be} + d \rightarrow ^{11}\text{Be} + p$
IIId. Experimental Set-Up

2. $\Delta E(Si) - E(CsI)$
Charge $Z$ for particles punching through the Si detector

3. PSD in CsI(Tl)
$Z$ and $A$ for light charged particles

4. $\Delta E(Si)$-ToF
Mass for particles stopping in the Si detector

5. $E(Si)$-Rise time
Charge $Z$ for particle stopping in Si detectors (NEW)

1. $\Delta E(Si) - E(CsI)$
Charge $Z$ and $A$ for light ions ($Z<9$) punching through the Si detector
IId. Results

\[ ^8\text{Li} + p \rightarrow ^8\text{Li} + p \]

\[ ^9\text{Li} + p \rightarrow ^9\text{Li} + p \]

\( \Delta \Phi \) angle between events where two detectors were fired in coincidence, setting some constraints on the complete event reconstruction

(\textbf{Multiplicity} = 2, \( Z_{\text{tot}} = Z_{\text{beam}} + 1 \))

\( ^{10}\text{Be} + p \rightarrow ^9\text{Be}_{\text{g.s.}} + d \)

detection efficiency + beam spread

Courtesy of G. Cardella
IIe. EXOTIC: Reactions Dynamics
IIe. Motivations

Reaction dynamics induced by light weakly-bound/halo RIBs at Coulomb barrier energies.

Being the projectile very loosely bound and, sometimes with a pronounced cluster/halo structure, the reaction dynamics scenario is more “colorful” than for reactions induced by stable well-bound nuclei.

New direct reaction channels, i.e. breakup process.

Experiments performed with $^6,^8\text{He}$, $^8,^9\text{Li}$, $^{7,11}\text{Be}$, $^8\text{B}$, $^{17}\text{F}$, … showed an enhancement of the cross sections for direct processes (transfer and breakup) at near-barrier energies.
IIe. Facility and Experimental Set-Up

EXODET (2005-2009)

DINEX (2009-2010)

EXPADES (2012-)

Quadrupole Triplet

Wien Filter

30° Dipole Magnet

Slit Systems
IIe. Experiments

Three RIBs have been produced up to now:

1. $^{17}\text{F} \ (S_p = 600 \ \text{keV})$: $^1\text{H}(^{17}\text{O},^{17}\text{F})\text{n} \quad \text{Q}_{\text{value}} = -3.54 \ \text{MeV}$;
2. $^8\text{B} \ (S_p = 137.5 \ \text{keV})$: $^3\text{He}(^6\text{Li},^8\text{B})\text{n} \quad \text{Q}_{\text{value}} = -1.97 \ \text{MeV}$;
3. $^7\text{Be} \ (S_\alpha = 1.586 \ \text{MeV})$: $^1\text{H}(^7\text{Li},^7\text{Be})\text{n} \quad \text{Q}_{\text{value}} = -1.64 \ \text{MeV}$.

F. Farinon et al., NIM B 266, 4097 (2008)

Experiments:

$^{17}\text{F} + ^{208}\text{Pb}$ [Quasi-Elastic Scattering and Breakup]
C. Signorini et al., EPJ A 44, 63 (2010)

$^{17}\text{F} + ^{58}\text{Ni}$ [Quasi-Elastic Scattering]
M. Mazzocco et al., PRC 82, 054604 (2010)

$^{17}\text{F} + ^1\text{H}$ [Elastic Scattering]
N. Patronis et al., PRC 85, 024609 (2012)

$^7\text{Be} + ^{58}\text{Ni}$ [Elastic Scattering, Direct Processes]
M. Mazzocco et al., Proc. Inter. Conf. NN 2012

$^6\text{Li},^7\text{Be},^8\text{B} + ^{28}\text{Si}$ [Total Reaction, Fusion]
A. Pakou et al., (in preparation)
IIe. Results

The collected data were analyzed within the framework of the optical model with the coupled-channel code FRESCO to extract the reaction cross sections and to investigate the relevance of direct reaction mechanisms.

At the lower $^{17}$F energy the reaction probability is moderately-rather small enhanced with respect to the “reference” systems $^{16}$O + $^{58}$Ni - $^{17}$O + $^{58}$Ni. M. Mazzocco et al., PRC 82, 054604 (2010)
3. Summary

Italy is a leading country in the development of RIBs. There exist already 3 facilities fully operational:

1. **EXCYT** at LNS: $^{15}$O beam development;
2. **FRIBS** at LNS: recently upgraded, RIB intensity increased by a factor 10;
3. **EXOTIC** at LNL: upgrade in progress to increase RIB intensity (+30%) and energy (+15%);
4. A 4th facility is ready to be constructed: **SPES** at LNL.

Several experiments have been already performed, covering several different fields of nuclear physics: new radioactive decay modes, nuclear astrophysics, resonant scattering, n-transfer reactions at intermediate energies and reaction dynamics studies at Coulomb barrier energies.
Thank you for the Attention!!!
IF e ISOL

In Flight (IF)
- Heavy Ions
- Thin Target
- Fragment Separator
- Storage Ring

Isotope Separation On Line (ISOL)
- Light and Heavy Ions, n, e
- Thick Target at High Temperature
- Ion Source
- Mass Selector
- Post-Acceleration
- Gas Cell (ms)

Experiments
- Detectors
- Spectrometers

Energy ~ MeV-GeV
- μs
- high emittance

Energy: meV - 100 MeV/u
- ms - s
- high quality
Studies with RIBs

**Existence** of nuclei;

Synthesis of **superheavy** nuclei ($Z = 118$);

**Mass Measurements**;

New radioactive decays: **p-decay** (1982), **2p-decay** (2002);

**Shape coexistence**, isomeric states;

**Shell closures** far from stability;

Reactions of **Astrophysical Interest** (r-process, rp-process, Big-Bang nucleosynthesis);

**New Reaction Mechanisms** (Breakup).