"Beta decay of exotic fp shell nuclei, exotic decay of fp shell nuclei"

Berta Rubio
IFIC-Valencia
40-70 participants
25-30 talks
2.5 days

Physics of the proton rich side of the nuclear chart

Valencia

The formation and structure of r-process nuclei

Catania

Going to the limits of mass, temperature, spin and isospin with heavy radioactive ion beams

Krakow

Physics light exotic nuclei

Lisbon

B. Rubio, Eurisol 2014, Orsay
A possible schematic layout for a EURISOL facility.
ISOL Roadmap in EUROPE

TODAY

2014-2025

FROM 2025

B. Rubio, Eurisol 2014, Orsay
This is part of a series of experiments aimed at comparing CE reactions on stable targets with beta decay in proton rich nuclei,

Reaction on Stable target

GSI

GANIL

Rubio, Eurisol 2014, Orsay
Beta decay and Charge Exchange are two processes governed by the same operator

\[
B(GT) = \frac{1}{\sqrt{2}} \left| \langle \psi_f | \sum_{\mu} \sum_{k} \sigma^\mu \tau^\pm_k | \psi_i \rangle \right|^2
\]

\[
B(F) = \frac{1}{\sqrt{2}} \left| \langle \psi_f | \tau^\pm | \psi_i \rangle \right|^2
\]
Beta decay: Absolute Normalization of $B(GT)$.

$$B(GT) = \frac{1}{\sqrt{2}} \left| \langle \psi_f | \sum_{\mu} \sum_{k} \sigma_k^{\mu} \tau_k^{\pm} | \psi_i \rangle \right|^2$$

$$B(F) = \frac{1}{\sqrt{2}} \left| \langle \psi_f | \tau^\pm | \psi_i \rangle \right|^2$$

Charge Exchange Reactions: No restriction in excitation energy of Gamow-Teller states.
Fermi and GT strength observed in CE reactions

Fujita et al RCNP Nuclear Physics 66 (2011) 549–606

Radioactive initial nucleus

Typical beta decay range

Stable Target
Today
Radioactive nucleus
tomorrow

We need CE if we want to know What happens here

30/10/14
"Beta decay of exotic fp shell nuclei “
(exotic here=short half lifes)
We could compare them in mirror nuclei

If isospin symmetry exists, mirror nuclei should populate the same states with the same probability, in the daughter nucleus, in the two mirror processes.
Comparison of (p, n) and (\(^3\)He, t) \(^0\) spectra

\[ \text{Counts} \]

- \(^{58}\text{Ni}(p, n)^{58}\text{Cu} \]
  - \( E_p = 160 \text{ MeV} \)
  - J. Rapaport et al.
  - NPA (’83)

- \(^{58}\text{Ni}(^{3}\text{He}, t)^{58}\text{Cu} \]
  - \( E = 140 \text{ MeV/u} \)
  - Y. Fujita et al.,
  - EPJ A 13 (’02) 411.
  - H. Fujita et al.,
  - PRC 75 (’07) 034310

\( S_p \)

Excitation Energy (MeV)

Spectra courtesy Y. Fujita, quality of RCNP experiments with the Big Ridden spectrometer
Charge exchange reactions in inverse kinematics

Cannot achieve the same energy resolution, one possibility

Is to look at the gamma de-excitation of the levels with a setup with good Dopper correction
The first experiments on Tz=-1 nuclei were carried out at the GSI 2007
THE RARE ISOTOPE FACILITY AT GSI (no experiments of this kind possible anymore)

Primary beam HI
Cocktail beam
Fragment separator
Target
PRODUCTION TARGET
INJECTION FROM UNILAC
FRS Branches
ESR
ALADIN
LAND
SIS
Experimental area

B. Rubio, Eurisol 2014, Orsay
Beta Decay Experiments @ RISING

Beam 58Ni@680 MeV/u $10^9$ pps (part per spill) Target Be 4g/cm2

Separation in flight with the Fragment Separator (FRS)
RISING (Ge Array)
Detector Setup (Rising and DSSSD)

6 DSSSD detectors 1mm with 16 strips X and 16 strips Y, 1mm thick, 5 x 5 cm area

Implantations and Decay detectors

Logarithmic preamplifier linear up to 10 MeV.
Identification Plot for the $^{46}$Cr run. Implantation in M2.

<table>
<thead>
<tr>
<th>Run</th>
<th>Total Measurement Time</th>
<th>Total Number of Implantations</th>
<th>Counting rates in M2 [ions/sec]</th>
<th>Counting Rates per Pixel [ions/sec]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{54}$Ni</td>
<td>2151 min</td>
<td>$6.38 \times 10^6$</td>
<td>Imp. 50.4, Decay 62.9</td>
<td>$\sim 0.47$, $\sim 0.59$</td>
</tr>
<tr>
<td>$^{55}$Fe</td>
<td>1402 min</td>
<td>$2.80 \times 10^6$</td>
<td>Imp. 33.8, Decay 49.4</td>
<td>$\sim 0.23$, $\sim 0.38$</td>
</tr>
<tr>
<td>$^{45}$Cr</td>
<td>1140 min</td>
<td>$3.3 \times 10^6$</td>
<td>Imp. 45.3, Decay 74.2</td>
<td>$\sim 0.40$, $\sim 0.66$</td>
</tr>
<tr>
<td>$^{62}$Ti</td>
<td>531 min</td>
<td>$6.46 \times 10^5$</td>
<td>Imp. 20.7, Decay 32.8</td>
<td>$\sim 0.17$, $\sim 0.26$</td>
</tr>
</tbody>
</table>
Gamma Spectrum for the 46Cr run

Triton spectrum after (3He,t) at Osaka

511 keV

915.0 2+

993.2 1+

1432.5 1+

2459.8 1+

2697.4 1+

2977.8 1+

3867.6 1+

44Ti (5522.6)

527 keV

44Ti (5522.6)

B. Rubio, Eurisol 2014, Orsay
Are they really identical?

Find the difference
The $T_z = -1 \rightarrow 0$, $\beta$ decays of $^{54}$Ni, $^{50}$Fe, $^{46}$Cr, and $^{42}$Ti and comparison with mirror ($^3$He, t) measurements

F. Molina,$^1$,* B. Rubio,$^1$, † Y. Fujita,$^{2,3}$ W. Gelletly,$^4$ J. Agramunt,$^1$ A. Algora,$^{1,5}$ J. Benlliure,$^6$ P. Boutachkov,$^7$

\begin{itemize}
  \item Count \textbf{3He, t}
  \item \textbf{β-decay}
\end{itemize}
Are they really identical?

Even inside the Q window, we miss some strength at high energy.
The $T_z = -1 \rightarrow 0$, $\beta$ decays of $^{54}\text{Ni}$, $^{50}\text{Fe}$, $^{46}\text{Cr}$, and $^{42}\text{Ti}$ and comparison with mirror ($^3\text{He},t$) measurements

F. Molina, 1,* B. Rubio, 1 ,† Y. Fujita, 2,3 W. Gelletly, 4 J. Agramunt, 1 A. Algora, 1,5 J. Benlliure, 6 P. Boutachkov, 7 L. Cáreres, 7,8 R.B. Cakirli, 9 E. Casarejos, 6,10 C. Domingo-Pardo, 1,10 P. Doornenbal, 7 A. Gadea, 1,11 E. Ganoğlu, 9 M. Gascón, 6,8 H. Geissel, 7 J. Gerl, 7 M. Górski, 7 J. Grębosz, 7,12 R. Hoischen, 7,13 R. Kumar, 14 N. Kurz, 7 I. Kojouharov, 7 L. Amon Susam, 9 H. Matsubara, 3,11 A.I. Morales, 6 Y. Oktem, 9 D. Pauwels, 15 D. Pérez-Loureiro, 6 S. Pietri, 4 Zs. Podolyák, 4 W. Prokopowicz, 7 D. Rudolph, 13 H. Schaffner, 7 S.J. Steer, 4 J.L. Tain, 1 A. Tamii, 3 S. Tashenov, 7 J.J. Valiente-Dobón, 11 S. Verma, 6 and H-J. Wollersheim 7

PRC
(with the referees)

IFIC(Valencia)-Osaka-Surrey-Santiago de Compostela-Istanbul-Warsaw-Lund-Lueven Legnaro
We could compare them in mirror nuclei.

If isospin symmetry exists, mirror nuclei should populate the same states with the same probability, in the daughter nucleus, in the two mirror processes.
Only the day we can make both kind of experiments on the same radioactive target, we will have an answer.
"Exotic decay of fp shell nuclei"
Compare with Reaction on Stable target.
$^{58}\text{Ni}^{26+} (74.5 \text{ AMeV}) + \text{natNi} @ \text{GANIL 2010}$

**74.5 MeV / nucleon**  
Incoming $^{58}\text{Ni}^{26+}$ 3.7 eμA intensity

- Cyclotrons CSS1 and CSS2
- Ni target (natural) 200 μm thick
- Brho1
- Slits wedge
- Wien Filter
- DETECTORS
  - Cyclotrons CSS1 and CSS2
  - Ni target (natural) 200 μm thick
  - Slits wedge
  - Wien Filter
  - DETECTORS

**Detectors**
- LIS3 spectrometer
- DSSSD detector
- ImplantaVon and decay (β, p)
  - 16 strips X and 16 strips Y
  - 300 μm thick
  - 3 mm pitch

**4 EXOGAM gamma detectors**
As expected, the statistics are limited:

In 3 days:
Total $^{56}\text{Zn}$ implantations = 8861
0.033 imp/s
Expectations for the beta decay of $^{56}\text{Zn}$

Because $S_p$ is only 560 keV we expect most of the decay to proceed by proton emission.

- $^{55}\text{Ni}$, $T_Z = -1/2$
- $^{56}\text{Zn}$, $T_Z = -2$
- $^{56}\text{Cu}$, $T_Z = -1$

$T = 2$ IAS

$p$

$S_p = 560$ keV
This is indeed what we saw

Particle spectrum, mainly protons

300 µm DSSD detector
Constructing the level scheme, level energies very clear....

Naively one would assume that these intensities are proportional to the beta feeding.
Comparison of mirror transitions for $A = 56$

$^{56}\text{Zn} \rightarrow ^{56}\text{Cu} + \beta^+$

$E_x(^{56}\text{Cu}) = E_p + S_p$

Isospin symmetry holds well!

All the dominant transitions are observed in both $\beta$ decay and CE starting from mirror nuclei

Constructing the $^{56}\text{Zn}$ decay scheme...

The $p$-decay of the IAS is isospin forbidden.

$^{56}\text{Zn}$
$T_Z = -2$

$^{55}\text{Ni}$
$T_Z = -1/2$
$T = 1/2$

$^{56}\text{Cu}$
$T_Z = -1$

$T = 2$

The $p$-decay of the IAS is isospin forbidden

$B.\text{ Rubio, Eurisol 2014, Orsay}$
Indeed we observed the gamma transition deexciting the IAS

A γ ray at 1834.5 ± 1.0 keV is observed in the $^{56}$Zn-correlated γ-spectrum corresponding to the de-excitation of the IAS

$(\beta-\gamma)$-implant time correlations
$T_{1/2} = (27 \pm 8) \text{ ms}$

✓ In agreement with the β-implant time correlation value:
$T_{1/2} = (32.9 \pm 0.8) \text{ ms}$
This is the first observation of Beta-delayed gamma-proton decay in the fp shell.

"Exotic decay of fp shell nuclei"
We have observed for the first time beta-delayed gamma-proton emission in three cases!!
$^{56}$Zn decay scheme, another surprise

$Q_\beta = 12870(300)$ keV

$T_{1/2} = 32.9 (8)$ ms

$^{56}$Zn $(T_Z = -2)$

$B(GT)$ $B(F)$

2.7

$^{56}$Zn $(T_Z = -1)$

$T_{1/2} = 93$ ms

$B_p = (88.5 \pm 2.6)$ %

$S_p = 560 (140)$ (syst. AME2003)
But this is NOT the end of the story!!!

$^{56}$Fe($^3$He,t)$^{56}$Co

$E = 140$ AMeV

$\vartheta = 0^\circ$

The IAS is fragmented in the mirror!!
the fragmentation of the IAS is important for the Mass evaluation
And now we can compare with the Charge Exchange reaction in the mirror

\[ B_p = (88.5 \pm 2.6)\% \]

\[ \beta^+ \]

\[ {^{56}\text{Cu}} \ (T_z = -1) \]

\[ \beta^+ \]

\[ {^{56}\text{Zn}} \text{ B-decay} \]

\[ B(\text{GT}) \ B(\text{F}) \]

\[ 2.7(5) \]

\[ \leq 0.32 \]

\[ 1.3(5) \]

\[ \beta^+ \]

\[ {^{56}\text{Cu}} \ (T_z = -1) \]

\[ \beta^+ \]

\[ {^{56}\text{Zn}} \text{ B-decay} \]

\[ B(\text{GT}) \ B(\text{F}) \]

\[ 0.34(6) \]

\[ 0.30(9) \]

\[ \leq 0.32 \]

\[ 1.3(5) \]

\[ \beta^+ \]

\[ {^{56}\text{Cu}} \ (T_z = -1) \]

\[ \beta^+ \]

\[ {^{56}\text{Zn}} \text{ B-decay} \]

\[ B(\text{GT}) \ B(\text{F}) \]

\[ 2.7(5) \]

\[ \leq 0.32 \]

\[ 1.3(5) \]
Observation of the $\beta$-Delayed $\gamma$-Proton Decay of $^{56}$Zn and its Impact on the Gamow-Teller Strength Evaluation

S. E. A. Orrigo,$^{1,*}$ B. Rubio,$^{1}$ Y. Fujita,$^{2,3}$ B. Blank,$^{4}$ W. Gelletly,$^{5}$ J. Agramunt,$^{1}$ A. Algara,$^{1,6}$ P. Ascher,$^{4}$ B. Bilgier,$^{7}$ L. Cáceres,$^{8}$ R. B. Cakirli,$^{7}$ H. Fujita,$^{3}$ E. Ganioglu,$^{7}$ M. Gerbaux,$^{4}$ J. Giovannazzo,$^{4}$ S. Grévy,$^{4}$ O. Kamalou,$^{8}$ H. C. Kozer,$^{7}$ L. Kucuk,$^{7}$ T. Kurtukian-Nieto,$^{4}$ F. Molina,$^{1,9}$ L. Popescu,$^{10}$ A. M. Rogers,$^{11}$ G. Susoy,$^{7}$ C. Stodel,$^{8}$ T. Suzuki,$^{3}$ A. Tamii$^{3}$ and J C. Thomas$^{8}$
We were puzzled for some time....

\[ Q_{EC}^* = 12870(300) \text{ keV} \]

\[ B_p = 88.5(26) \% \]

\[ 56^{\text{Zn}} \left( T_z = -2 \right) \]

\[ T_{1/2} = 32.9(8) \text{ ms} \]

\[ E_x \left[ \text{keV} \right] \quad B(F) \quad B(GT) \]

| \( T=2, 0^+ \) | 3508(140) | 2.7(5) | \leq 0.32 |
| \( T=1, 0^+ \) | 3423(140) | 1.3(5) | 0 |
| \( T=1, 1^+ \) | 2661(140) | 0.34(6) | 0 |
| \( T=1, 2^+ \) | 2537(140) | 0.30(9) | 0 |

\[ 55^{\text{Ni}} \left( T_z = -1/2 \right) \]

\[ T_{1/2} = 209 \text{ ms} \]

\[ \beta^+ \]

\[ 56^{\text{Cu}} \left( T_z = -1 \right) \]

\[ T_{1/2} = 93 \text{ ms} \]

\[ S_p = 560(140) \text{ keV} \]

Aprox. 10^{-15} s

Aprox. 10^{-18} s
This neutron particle-hole excitation is well above the 55Ni ground state.
This proton particle-hole excitation is well above 55Ni ground state
On going understanding....by Piet van Isacker.

**Trying to understand the $\beta$-delayed proton and $\gamma$ decays of $^{58}\text{Zn}$**

1. Outline of the approach
We assume that the actors of this play are the nucleon holes in the $1f_{7/2}$ shell and the nucleon particles in the $2p_{3/2}$ shell. Basis states with good isospin are considered and this requires that the nucleons occupying the two shells can be neutrons or protons.

5. Proton decay
If we accept that the second $0^+$ state with $T = 1$ (see below for a problem with that) is the one that mixes with the isobaric analog state, then proton decay will remain hindered. Either a proton in the $2p_{3/2}$ shell is emitted to form a one-particle-two-hole excitation in $^{55}\text{Ni}$ or the proton is emitted from the $1f_{7/2}$ shell and the decay proceeds towards a two-particle-three-hole excitation in $^{55}\text{Ni}$. It can be expected (but should be checked) that these excitations occur above the energy window available for the proton decay from $^{56}\text{Cu}$.
Today (in principle) one can continue this kind of studies at RIKEN
Conclusion

Beta-decay studies are a powerful tool to understand nuclear structure far from the stability.

One needs intense radioactive beams if one wants to extract the real physics. Some of these experiments can be carried out at the Eurisol distributed facility.

Some experiments such as the one to one comparison between beta decay and Charge Exchange reactions on a shot living radioactive nucleus will probably demand EURISOL in full glory.