Particle emission at the proton drip-line

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When the $\beta$ decay energy is large, many exotic channels are available.

Blank and Borge, Progress in Part. Nucl. Phys. 60 (2008) 403
p drip-line is not a limit!

- The limit of „existence” beyond the proton drip-line is determined by emission of protons.

V.I. Goldanskii, Nucl. Phys. 19 (60) 482

NN2015, June 21-26, Catania, Italy
The current status of 2p emission

- Ground-state 2p radioactivity first observed in $^{45}$Fe. Later also in $^{54}$Zn, $^{48}$Ni and $^{19}$Mg.

- In lighter nuclei due to small Coulomb barrier 2p emission is fast, $T_{1/2}^{(19)}$Mg $= 4$ ps!

- Below $^{19}$Mg 2p are emitted from broad resonances, like $^6$Be.

True 2p emitters:
- expected/discussed
- established
- $p-p$ correlations determined

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Predictions of a simple model  

\[ \Omega_{2p} > 0 , \quad \Omega_{p} < 0.2 \Omega_{2p} \]

\[ 100 \text{ ns} < T_{1/2}^{2p} < 100 \text{ ms} \]
Between tellurium and lead

- Predictions of a simple model

- Sequential pp emission
  \[ Q_{2p} > 0, \quad Q_p > 0.2 Q_{2p} \]
  \[ 100 \text{ ns} < T_{1/2}^{pp} < 100 \text{ ms} \]
  \[ T_{pp} < 10 \cdot T_{\alpha} \]

- \[ T_{pp} / 10 < T_{\alpha} < 10 \cdot T_{pp} \]
Combination of the CCD image with the PMT waveform allows to fully reconstruct the track in three dimensions.
Decays of $^{45}$Fe and $^{43}$Cr

NSCL/MSU, 2007

Pomorski et al., Phys. Rev. 83 (2011) 014306

Miernik et al., PRL 99 (07) 192501

$\beta^3p$ 0.08%

$\beta^2p$

$\beta^p$

$^{40}$Ca+$3p$

$^{41}$Sc+$2p$

$^{42}$Ti+$p$

$^{43}$V

$^{44}$Mn+$p$

$^{45}$Fe

$2p$

$\beta^+$

$IAS$

$^{43}$Cr+$2p$

$\approx 70\%$

$Q_{EC} = 18.7$ MeV

$T_{1/2} = 7$ ms

$\beta^3p$ 11%

$\beta^2p$

$\beta^p$

$^{43}$V+$2p$

$^{42}$Ti+$3p$

$^{45}$Mn

$4^{4}$Cr+$p$

$\beta^4p$

$\beta^3p$

$\beta^2p$

$^{41}$Sc+$4p$

$^{40}$Ti+$p$

$\beta^p$
p-p momentum correlations for $^{45}$Fe

- Proton-proton momentum correlations measured for $^{45}$Fe are complex and indicate a genuine 3-body phenomenon

- Good agreement with the 3-body model of Grigorenko et al.

Miernik et al., PRL 99 (07) 192501  Grigorenko et al., PLB 677 (2009) 30  MP, Karny, Grigorenko, Riisager, RMP 84 (12) 567

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Study of $^{48}$Ni

- NSCL/MSU, March 2011: $^{58}$Ni at 160 MeV/u + natNi $\rightarrow$ $^{48}$Ni

Cross section: $\sigma = 150(50)$ fb!

10 events of $^{48}$Ni in 10 days

Pomorski et al., PRC 90 (14) 014311
2p decay of $^{48}\text{Ni}$

- Four 2p events of $^{48}\text{Ni}$
- $Q_{2\text{p}} = 1.29 (4) \text{ MeV}$

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Pomorski et al., PRC 90 (14) 014311
5542 identified ions of $^{44}\text{Cr}$
4098 properly stopped
183 decays observed

$\Rightarrow b_p = 10(1)\%$

Dossat: $b_p = 14.0(9)\%$

A clear new line at 740(20) keV

$I_p = 0.6(2)\%$


103 reconstructed protons

No beta background!

<table>
<thead>
<tr>
<th></th>
<th>Dossat et al.</th>
<th>This work</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_p$ (keV)</td>
<td>$I_p$ (%)</td>
<td>$I_p$ (%)</td>
</tr>
<tr>
<td>1</td>
<td>908(11)</td>
<td>1.7(3)</td>
</tr>
<tr>
<td>2</td>
<td>1384(12)</td>
<td>1.1(3)</td>
</tr>
<tr>
<td>3</td>
<td>1741(15)</td>
<td>0.6(3)</td>
</tr>
</tbody>
</table>

Pomorski et al., PRC 90 (14) 014311
$\beta^2p$ channel in $^{46}$Fe

One good event!

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Decay scheme of $^{48}\text{Ni}$

$Q_{2p} = 1.29(4) \text{ MeV}$

$T_{1/2} = 2.1^{+1.4}_{-0.6} \text{ ms}$
β3p in $^{31}$Ar?

Decay modes of $^{31}$Ar and first observation of β-delayed three-proton radioactivity

D. Bazin, R. Del Moral, J. P. Dufour, A. Fleury, F. Hubert, and M. S. Pravikoff
Centre d’Etudes Nucléaires de Bordeaux–Gradignan, Le Haut Vigneau 33175 Gradignan CEDEX, France

$^{31}$Ar examined: New limit on the β-delayed three-proton branch

$^{31}\text{Ar}$ at the FRS

- Experiment at GSI-FRS, August 2012
  "Search for two-proton decay of $^{30}\text{Ar}$ in flight by the tracking technique" by I. Mukha

- Many $^{31}\text{Ar}$ ions pass to the S4
  An idea: stop them in the OTPC and search for $\beta3p$ channel of $^{31}\text{Ar}$

- With the beam of $10^{10}$ proj./spill we hoped for one $^{31}\text{Ar}$ atom/spill stopped.
  If spill every 4 s $\Rightarrow$ 20 000/day
For effective stopping, the thickest gas mixture was chosen: 98% Ar + 2% N₂

We could not stop the beam upon arrival of a triggering ion.

Simulation of the range vs. hor. position

OTPC thickness: 50 mg/cm²

triggers

53 000 in five days

all ions during high sensitivity mode
Yes, $\beta 3p$ in $^{31}\text{Ar}$!

- A new acquisition mode – a series of shorter expositions („movie”)

- Selection of events: in the first frame no other ions than well stopped $^{31}\text{Ar}$ present

21 000 events, all inspected individually by Ola Lis
13 events of $\beta^3p$ decay of $^{31}\text{Ar}$ was observed

<table>
<thead>
<tr>
<th>Channel</th>
<th>Events</th>
<th>Branching [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta^0p$</td>
<td>5984</td>
<td>22.6(3)$^a$</td>
</tr>
<tr>
<td>$\beta^1p$</td>
<td>13157</td>
<td>68.3(3)</td>
</tr>
<tr>
<td>$\beta^2p$</td>
<td>1729</td>
<td>9.0(2)</td>
</tr>
<tr>
<td>$\beta^3p$</td>
<td>13</td>
<td>0.07(2)</td>
</tr>
</tbody>
</table>

Only 3 cases of $\beta^3p$ known:
- $^{45}\text{Fe}$ (Miernik et al., PRC76, 2007)
- $^{43}\text{Cr}$ (Pomorski et al., PRC83, 2011)
- $^{31}\text{Ar}$ (Lis et al., PRC, 2015)

All discovered with the OTPC!
β3p in $^{31}$Ar

- β3p decay channel of $^{31}$Ar confirmed by ISOLDE using Si Cube

Koldste et al., PRC 89 (2014) 064315

- The estimated β3p branching: 0.08(4)%
- The β3p transitions responsible for 30% of the total Gamow-Teller strength in $^{31}$Ar!
60\textsuperscript{Ge} discovered at NSCL/MSU in 2004


A1900: 78\textsuperscript{Kr} @ 140 MeV/u + Be

Lower cross section for the production of 60\textsuperscript{Ge} than expected \(\Rightarrow\) does it indicate very short half-life?
Ten years after...

- Experiment at NSCL/MSU, September 2014

A1900 schematic

A1900: \(^{78}\text{Kr} \at 150 \text{ MeV/u} + \text{Be}\)

- 73 atoms of \(^{60}\text{Ge}\) identified!
  Delayed protons observed, analysis in progress

- Cross section measured for \(^{60,61,62}\text{Ge}\)

- Search for \(^{59}\text{Ge}\)
First observation of $^{59}\text{Ge}$

Ciemny et al., submitted to PRC as RC

NN2015, June 21-26, Catania, Italy
Cross section for Ge isotopes

- Decay studies of $^{59}$Ge possible. Perhaps at RIKEN one can go even further...?

$^{78}$Kr + Be $\rightarrow ^{A}$Ge

$^{70}$Ge @ 70 A·MeV on $^{nat}$Ni target produces $^{60}$Ge with larger cross section ($\times 2$)!

Blank et al., EPJ A 31 (2007) 267
Summary

• Beyond proton drip-line there is a large territory of beta decaying nuclei waiting for discovery (*terra incognita nova*).

• The OTPC detector is a very efficient tool to search for very rare multiparticle decays or to investigate particle decays obscured by beta background.

• Can provide precise branching ratios for $\beta$-delayed particle channels. Although the energy resolution is worse than for Si detectors, yields complementary data for low-energy particles.

• Non-trivial 3-body character of 2p decay of $^{45}$Fe discovered. 2p decay of $^{48}$Ni discovered.

• New decay channels, like $\beta$3p ($^{45}$Fe, $^{43}$Cr, $^{31}$Ar), observed for the first time. $\beta$2p emission discovered in $^{46}$Fe based on one atom decay!

• New neutron-deficient isotope $^{59}$Ge identified, first decay data for $^{60}$Ge collected.
Thank you!