Two-proton radioactivity and $\alpha$ decay

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M. Pfützner, Alpha decay as a probe of nuclear structure, Stockholm, September 12-13, 2013
Landscapes of Two-Proton Radioactivity

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The proton drip-line is close and almost fully delineated. In most cases, however, it is „invisible” when we cross it. The decay spectroscopy may stretch far beyond it.

The questions: how far beyond the proton drip-line we have to go to see the difference? How far is the limit?

The neutron drip-line is far from present experimental reach. It represents the real limit of decay spectroscopy – the region beyond, if accessible, is a domain of reactions.
Beyond the proton drip-line

Competition between two decay modes

➢ The $\beta^+$ decay

Probability of transition:

$$\lambda \sim Q^5$$

Decay energy may be large, but the weak interaction is really weak

$\Rightarrow T_{1/2} > 1 \text{ ms}$

➢ The emission of particles

The Coulomb barrier hampers emission of an unbound charged particle ($\alpha, p, 2p, \ldots$)

$$\lambda \sim \exp \left\{ -\frac{2}{\hbar} \cdot \int_{r_{\text{in}}}^{r_{\text{out}}} \sqrt{2\mu [V(r) - Q]} \cdot dr \right\}$$

➢ To find where the drip-line actually is and to predict which decay will happen, we need: a) atomic masses, b) decay models

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The limit of stability for even-Z elements is determined by two-proton emission.

- For a true simultaneous two-proton emission, $Q_p < 0$ and $Q_{2p} > 0$.
- For a sequential two-proton emission, $Q_p > 0$ and $Q_{2p} > 0$.

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

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First 2p candidates

Light and medium masses can be precisely predicted by a trick based on the IMME:

\[ BE(T_z = -T) = BE(T_z = T) - 2bT \]

Binding energy of the neutron-deficient nuclide is calculated from the measured mass of its neutron-rich analogue and from the calculated coefficient \( b \) (shell-model, systematics...)

\[
\begin{align*}
S_{1p} & = -2.0 \\
S_{2p} & = -1.5 \\
45\text{Fe} & \quad 48\text{Ni} \\
54\text{Zn} &
\end{align*}
\]

- Brown, PRC 43 (91) R1513
- Ormand, PRC 55 (97) 2407
- Cole, PRC 54 (96) 1240
- Brown et al., PRC 65 (02) 045802

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TPC with optical readout

- Counting gas at atmospheric pressure
- Ionization electrons
- HD electrodes
- Gating electrode
- Charge amplification
- Light
- Recording system
- CCD PMT

- Trigger
- incoming ion
- Identified ion

- Decay event $^6\text{He} \rightarrow \alpha + d$
- seen on the background of about $10^4$ beta rays

$\beta^2\alpha$ decay of $^8\text{Li}$
$\beta^3\alpha$ decay of $^{12}\text{N}$

M. Pfützner, Euroschool on Exotic Beams, Dubna 2013, Lecture 1/2
Three cases around $Z=28$

$^{45}\text{Fe}$

$^{48}\text{Ni}$

$^{54}\text{Zn}$

K. Miernik et al., PRL 99 (07) 192501

Pomorski et al., PRC 83 (2011) 061303(R)

Ascher et al., PRL 107 (2011) 102502

Grigorenko et al., PLB 677 (2009) 30

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$^6\text{Be}$ and $^{19}\text{Mg}$

$^7\text{Be} + \text{Be} \rightarrow ^6\text{Be}$ @ NSCL

$^{20}\text{Mg} + \text{Be} \rightarrow ^{19}\text{Mg}$ @ GSI

Egorova et al., PRL 109 (2012) 202502

Mukha et al., PRL 99 (2007) 182501
Mukha et al., EPJA 42 (2009) 421

$T_{1/2} = 4.0(15)$ ps

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The current status of 2p emission

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

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

- Below $^{19}\text{Mg}$ 2p are emitted from broad resonances, like $^{6}\text{Be}$
Heavier 2p candidates

- Proton drip-line calculations for the rp-process:
  - the measured masses combined with the Coulomb displacement energies calculated by HF with the SkX Skyrme force

Strontium (Z=38) is the heaviest element for which the precise $Q_{2p}$ predictions were made

Brown et al., PRC 65 (2002) 045802
Global mass predictions using density functional theory with 6 different Skyrme interactions.

There are 6900 ± 500 nuclei bound with $Z \leq 120$.

Erler et al., Nature 486 (2012) 509
Diproton model

- By simplifying interactions in the core+p+p system, the three-body decay can be reduced to the combination of two-body processes.

Jacobi T system ➔ diproton model

The WKB approximation

\[
\Gamma_{2p,\text{dipr}} = \theta^2_{\text{dipr}} N \frac{\hbar^2}{4\mu} \exp \left[ -2 \int_{r_{in}}^{r_{out}} k(r) \, dr \right]
\]

\[
N \int_{r_{in}}^{r_{out}} \frac{dr}{2k(r)} = 1 \quad \quad k(r) = \sqrt{2\mu \left| Q_{2p} - 2V_p(r) \right|}
\]

\[
\theta^2_{\text{dipr}} = \frac{(2n)!}{2^{2n} (n!)^2} \left[ \frac{A}{A-2} \right]^{2n} O^2 \quad n \approx (3Z)^{1/3} - 1
\]

The value of proton overlap function determined from the experimental half-lives of known 2p emitters: $^{19}\text{Mg}$, $^{45}\text{Fe}$, $^{48}\text{Ni}$, and $^{54}\text{Zn}$

\[O^2 = 0.015\]
Direct model

Jacobi Y system \(\rightarrow\) direct model

\[
\Gamma_{2p,\text{dir}} = \frac{Q_{2p}}{2\pi} \left( Q_{2p} - 2E_p \right)^2 \int_0^1 d\varepsilon \frac{\Gamma_x (\varepsilon Q_{2p})}{\left( \varepsilon Q_{2p} - E_p \right)^2 + \Gamma_x (\varepsilon Q_{2p})^2} \frac{\Gamma_y ((1-\varepsilon)Q_{2p})}{((1-\varepsilon)Q_{2p} - E_p)^2 + \Gamma_y ((1-\varepsilon)Q_{2p})^2} / 4
\]

\(\Gamma_i\) is the width of the two-body subsystem: \(\Gamma_i (E) = 2\gamma_i^2 P_{l_p} (E, R, Z_i)\)

penetrability: \(P_{l_p} (E, R, Z_i) = \frac{kR}{F_{l_p}^2 (\eta, kR) + G_{l_p}^2 (\eta, kR)}\)

reduced width: \(\gamma_i^2 = \frac{\hbar^2}{2\mu_i R^2} \theta_i^2\)

The value of spectroscopic factor determined from the experimental half-lives of known 2p emitters: \(^{19}\text{Mg}, ^{45}\text{Fe}, ^{48}\text{Ni},\) and \(^{54}\text{Zn},\) assuming \(l_p = 0\)

\[\theta_x^2 = \theta_y^2 = 0.173\]

Grigorenko and Zhukov, PRC 76 (07) 014009
2p-emission half-lives

Direct model

\[ \Gamma_{2p,dir} \approx \frac{8Q_{2p}}{\pi(Q_{2p} - 2E_p)^2} \int_0^1 d\varepsilon \Gamma_x (\varepsilon Q_{2p}) \Gamma_y ((1-\varepsilon)Q_{2p}) \]

Diproton model

\[ \Gamma_{2p,dipr} = \theta_{dipr}^2 N \frac{\hbar^2}{4\mu} \exp \left[ -2 \int_{r_{in}}^{r_{out}} k(r) dr \right] \]

The comparison of predicted half-lives with experiment

\[ T_{1/2} = \frac{\ln 2 \hbar}{\Gamma} \]

\[ l_p = 0 \]

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>Experiment</th>
<th>Direct</th>
<th>Diproton</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{19}\text{Mg}) [7]</td>
<td>4.0(15) ps</td>
<td>6.2 ps</td>
<td>12.3 ps</td>
</tr>
<tr>
<td>(^{45}\text{Fe}) [10]</td>
<td>3.7(4) ms</td>
<td>1.1 ms</td>
<td>8.7 ms</td>
</tr>
<tr>
<td>(^{48}\text{Ni}) [8]</td>
<td>3.0(^{+2.2}_{-1.2}) ms</td>
<td>6.8 ms</td>
<td>5.3 ms</td>
</tr>
<tr>
<td>(^{54}\text{Zn}) [9]</td>
<td>1.98(^{+0.73}_{-0.41}) ms</td>
<td>1.0 ms</td>
<td>0.8 ms</td>
</tr>
</tbody>
</table>
In the direct model we can investigate how the proton’s energy spectrum depends on the position of the intermediate state.

\[ Q_{2p} = 1.15 \text{ MeV}, \quad Q_{1p} = -0.05 \text{ MeV} \]

True 2p decay (simultaneous)
In the direct model we can investigate how the proton’s energy spectrum depends on the position of the intermediate state.

\[ Q_{2p} = 1.15 \text{ MeV}, \quad Q_{1p} = 0.17 \text{ MeV} \]

Still simultaneous 2p!
In the direct model we can investigate how the proton’s energy spectrum depends on the position of the intermediate state.

\[ Q_{2p} = 1.15 \text{ MeV}, \quad Q_{1p} = 0.23 \text{ MeV} \]

Sequential emission shows up! Simultaneous component still visible.
Simultaneous vs. sequential

In the direct model we can investigate how the proton’s energy spectrum depends on the position of the intermediate state.

\[ Q_{2p} = 1.15 \text{ MeV}, \quad Q_{1p} = 0.31 \text{ MeV} \]

Sequential 2p emission dominates

Rough criterion: for \( Q_p < 0.2 \, Q_{2p} \) true, simultaneous 2p decay

for \( Q_p > 0.2 \, Q_{2p} \) sequential 2p emission
Predictions

- **Nuclear binding energies**: deformed DFT with six effective Skyrme interaction plus density-dependent zero-range pairing term (Erler et al., *Nature* 486 (2012) 509)

- **The half-lives for 2p emission**: estimated with the direct and diproton models. The $\alpha$ decay half-lives calculated using global, fenomenological formula by Koura, *J. Nucl. Science and Tech.* 49 (2012) 816

- **The adopted decay-time criterion (arbitrary)**:
  we consider a nucleus to be a 2p decay candidate predicted by a given mass (and decay) model when $100 \text{ ns} < T_{1/2} < 100 \text{ ms}$. Longer half-life will loose competition with $\beta$ decay. Shorter will be difficult to detect using in-flight separation and implantation technique.

- **Counting**:
  a candidate has the model multiplicity $m(Z,N) = k$ when it is predicted by $k$ mass models.
Nickel and zinc in the direct model

Nickel isotopes (Z=28)

![Graph showing decay energy vs neutron number for nickel isotopes.]

Zinc isotopes (Z=30)

![Graph showing decay energy vs neutron number for zinc isotopes.]

Experimental reach 2012

100 ns < $T_{1/2}$ < 100 ms
Germanium isotopes (Z=32)

- We predict $^{57}$Ge to be 2p radioactive ($m=2$)
- Taking decay energies from Brown, the 2p half-life of $^{58}$Ge comes shorter than 100 ns and that of $^{59}$Ge longer than 100 ms

Brown et al., PRC 65 (2002) 045802
Predictions of the direct model

- Simultaneous 2p emission:
  \[ Q_{2p} > 0, \quad Q_p < 0.2 \quad Q_{2p} \]
  \[ 100 \text{ ns} < T_{1/2}^{2p} < 100 \text{ ms} \]
Predicted candidates relative to the 2p dripline

$100 \text{ ns} < T_{2p} < 100 \text{ ms}$
Global fenomenological formula for $\alpha$ decay half-lives: H. Koura 2012

Tellurium isotopes, Z=52

- Tellurium isotopes, Z=52

- Halflife [s]
- 2p decay
- 2p seq.
- α decay
- Exp.

- Decay energy [MeV]
- Q_α
- Q_{2p}
- Q_{1p}
- Exp. Qα

- Neutron number
- 48 49 50 51 52 53 54 55 56 57 58
- 10^8 10^7 10^6 10^5 10^4 10^3 10^2 10^1 10^0 10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9} 10^{-10} 10^{-11} 10^{-12} 10^{-13} 10^{-14} 10^{-15} 10^{-16}

- At $^{103}$Te a transition from the simultaneous 2p to the sequential emission occurs
- In addition, in $^{103}$Te both decays, α and 2p may be observable!
When the energy condition for the true 2p decay is fulfilled, the predicted half-life is extremely long.

When the fast proton emission becomes possible, it proceeds as the sequential 2p decay.
Between tellurium and lead

Predictions of the direct model

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

- $T_{pp}/10 < T_\alpha < 10 \cdot T_{pp}$
Full 2p landscape

Model averaged path of 2p emission

\[ N_{av}(Z) = \frac{\sum_N N m(Z, N)}{\sum_N m(Z, N)} \]
The direct (simultaneous) ground-state \(2p\) emission established for \(^{6}\text{Be}, \; ^{19}\text{Mg}, \; ^{45}\text{Fe}, \; ^{48}\text{Ni},\) and \(^{54}\text{Zn}\).

The hunt for other cases continues: \(^{30}\text{Ar}, \; ^{59}\text{Ge},\ldots\).

For every even-Z element between zinc and tellurium (Z=52) the isotopes decaying by \(2p\) radioactivity in the time window \(100 \text{ ns} < T_{1/2} < 100 \text{ ms}\) are predicted.

In \(^{103}\text{Te}\) the competition between simultaneous \(2p\), sequential \(pp\), and \(\alpha\) emission may occur. For \(^{145}\text{Hf}\) the competition between \(\alpha\) and sequential \(pp\) is predicted.

Above tellurium the limit of decay spectroscopy is represented by sequential \(pp\) emission, except for xenon (Z=54) where \(\alpha\) decay dominates.

Above lead (Z=82) \(\alpha\) decay dominates, no \(2p\) emission is expected to be observed.
Thank you!