Two-proton radioactivity of $^{67}$Kr

Results of the $^{78}$Kr campaign (2015) at the Radioactive Isotope Beam Factory (RIKEN)

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Summary

• Introduction

• Previous studies of two-proton radioactivity

• Study of $^{67}$Kr at RIKEN Nishina Center

• Conclusions and perspectives
Two-proton radioactivity

When $S_{2p} < 0$, 2-proton emission from ground-state allowed.

- Predicted in 1960.
  
  \textit{Goldansky, Nucl. Phys. 19, 482-495 (1960)}

- Discovered in 2002 ($^{45}\text{Fe}$)
  
  \textit{Giovinazzo et al., PRL 89, 102501 (2002) (GANIL)}
  

✓ Four medium-mass cases known: $^{45}\text{Fe}$, $^{48}\text{Ni}$, $^{54}\text{Zn}$ and $^{67}\text{Kr}$
Previous studies of two-proton radioactivity

Discoveries of the 2p emitters: indirect observations

- $^{45}$Fe: GANIL /GSI (2002)
- $^{48}$Ni: Indication at GANIL (2005)
- $^{54}$Zn: GANIL (2005)

- Only access to overall properties of the decay
  - $Q_{2p}$ value
  - 2-Proton branching ratio $BR_{2p}$
  - Half-life $T_{1/2}$

Giovinazzo et al., PRL 89, 102501 (2002)
(similar results at GSI Pfützner et al., EPJA 14, 3, 279–285 (2002))

Counts / 20 keV

$^{45}$Fe

$T_{1/2} = 4.7^{+3.4}_{-1.4}$ ms
Previous studies of two-proton radioactivity

**Direct observation with Time Projection Chamber (TPC)**
- Emission relative angles
- Individual energies
- Comparison with dynamic models (three-body model)

Three-body model calculations

Grigorenko et al., PRC 68, 054005 (2003)
Previous studies of two-proton radioactivity

Direct observation with Time Projection Chamber (TPC)

- Emission relative angles
- Individual energies
- Comparison with dynamic models (three-body model)

- $^{45}$Fe, $^{54}$Zn @ GANIL: CENBG TPC  

- $^{45}$Fe, $^{48}$Ni @ MSU: Optical TPC  

Optical TPC

CENBG TPC

Miernik et al., PRL 99, 192501 (2007)
**TPC experiments status**

\(^{45}\text{Fe}\) first and most studied case
- since 2002 (GANIL / GSI)
- first direct observation (2006, TPC CENBG/GANIL)
- angular correlation → structure (2007, OTPC Warsaw/MSU)

\(^{48}\text{Ni}\) few counts only
- first indication (2004, indirect) – only 1 event
- few direct observation events (2011, OTPC Warsaw/MSU)

\(^{54}\text{Zn}\) low statistics, decay scheme well established
- indirect observation (2004, GANIL)
- limited angular distribution (2011, CENBG TPC / GANIL)

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

Miernik et al., PRL 99, 192501 (2007)

Ascher et al., PRL 107, 102502 (2011)
Search for new emitters

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Known emitters

Possible emitters

78Kr beam

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Thomas Goigoux
1. **Production**
   - $^{78}$Kr primary beam: 345 MeV/A, up to 250 pnA
   - $^9$Be target (5 mm)

2. **Identification (PID):** $\Delta E - ToF - B\rho$

   *Fukuda et al., NIM B 317B, 323-332 (2013)*
1. **Production**
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Fukuda et al., *NIM B* 317B, 323-332 (2013)

3. **Decay study**
- WAS3ABi (proton and $\beta$ decay)
  - DSSSD: 1mm thick, 60x40 strips (1mm pitch)
  - Implantation of the nuclei
  - Correlation implantation-decay (in position and time)

- EURICA ($\gamma$-ray decays)
  - 12 EUROBALL clusters of 7 crystals each
  - 8% efficiency at 1.3 MeV
• $^{63}\text{Se}$, $^{67}\text{Kr}$ and $^{68}\text{Kr}$ were produced and identified for the first time

• Second time for $^{59}\text{Ge}$ after an experiment at NSCL (4 counts)

_Ciemny et al., PRC 92, 014622 (2015)_

_Blank et al., PRC 93, 061301(R) (2016)_
Results

- $^{63}\text{Se}$, $^{67}\text{Kr}$ and $^{68}\text{Kr}$ were produced and identified for the first time

- Second time for $^{59}\text{Ge}$ after an experiment at NSCL (4 counts)

$^{59}\text{Ge}$ detected after an experiment at NSCL (4 counts)

$\text{Ciemny et al., PRC 92, 014622 (2015)}$

- Peak composed of 9 events at $1690(17)$ keV
- $\beta$-detection efficiency of $67(1)\% \rightarrow$ probability of missing 9 counts: $5.5 \times 10^{-6}$
- No $\gamma$ observed in coincidence with the peak: 8% probability of missing the 9 events (at 511 keV).

- Global $T_{1/2} = 7.4(30)$ ms
  - $BR_{2p} = 37(14)\% \rightarrow$ 2p partial half-life $T_{1/2}^{2p} = 20(11)$ ms
  - $BR_\beta = 63(14)\% \rightarrow T_{1/2}^\beta = 10(6)$ ms (Gross theory: 11.1 ms)
Comparison with theory: decay energy

![Graph showing decay energy comparison with theory for various isotopes.]

- Good agreement with local mass models.
Comparison with theory: half-life

Three-body half-life (Grigorenko 2003)
- Pure $f^2$ configuration: 13.5 s
- Pure $p^2$ configuration: 0.28 s

Shell model’s removal amplitude (Brown)
- Pure $f^2$ configuration: 0.655
- Pure $p^2$ configuration: 0.556

Shell-model corrected half-lives:
\[
T_{1/2}(f^2) = \frac{13.5}{0.655^2} = 31.5 \text{ s}
\]
\[
T_{1/2}(p^2) = \frac{0.28}{0.556^2} = 0.9 \text{ s}
\]

\[
\frac{1}{(T_{1/2}^{2p})^{1/2}} = \frac{1}{[(T_{1/2}(f^2))^{1/2}]^{1/2}} + \frac{1}{[(T_{1/2}(p^2))^{1/2}]^{1/2}}
\]

Nucleus | Calculation (ms) | Experiment (ms) |
--- | --- | --- |
$^{45}$Fe | 2.7 | 3.76(26) |
$^{54}$Zn | 1.6 | 1.98$^{+0.73}_{-0.41}$ |
$^{67}$Kr | 660 | 20(11) |

Strong disagreement with experimental value
Comparison with theory

• Possible explanations:
  • Deformation
  • New calculations from Grigorenko
    ➢ Transitional case between sequential and true 2P

\[ E_r : \Gamma_r \sim (0.2 - 0.3)E_r \]

\[ E_r \sim 0.5E_T \]

\[ E_r \sim 0.8E_T \]
Conclusions and perspectives

• A new 2P emitter was observed: $^{67}$Kr
  • Agreement with theoretical Q value
  • Disagreement with shell-model corrected half-life
    • Deformation ?
    • Transitional case between sequential and true 2P emission ?

• Perspectives
  • New TPC (ACTAR TPC collaboration) coupling to the General Electronics for TPCs (GET) → previous talk (T. Roger)
    • Specific mode for short-lived decays
  
  ➢ New measurement of $^{48}$Ni/$^{54}$Zn (GANIL, accepted)
  ➢ Direct observation of $^{67}$Kr to get energy correlations (RIBF, accepted)
Thank you for your attention
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Collaboration

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