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

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

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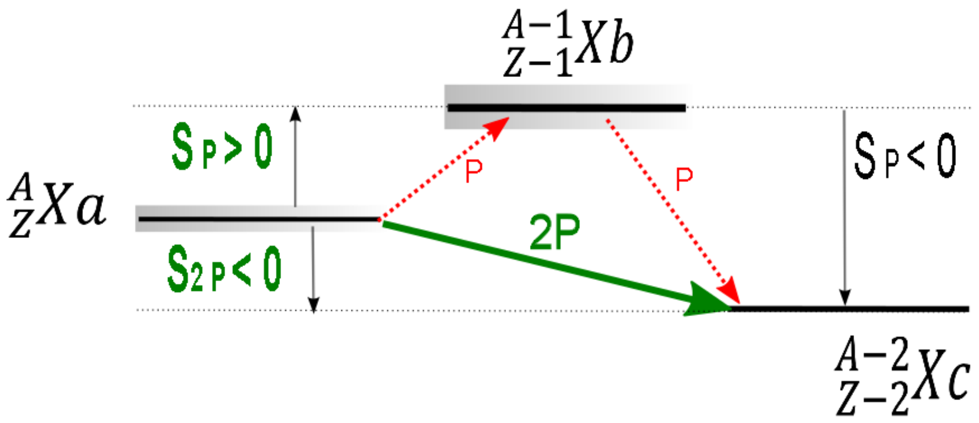
Summary

- Introduction
- Previous studies of two-proton radioactivity
- Study of $^{67}\mathrm{Kr}$ at RIKEN Nishina Center
- Conclusions and perspectives

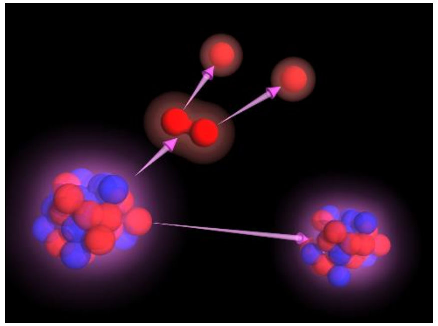
Two-proton radioactivity

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

- Predicted in 1960.
  Goldansky, Nucl. Phys. 19, 482-495 (1960)
- Discovered in 2002 ($^{45}\mathrm{Fe}$)
  Giovinazzo et al., PRL 89, 102501 (2002) (GANIL)
  Pfützner et al., EPJA 14, 3, 279–285 (2002) (GSI)



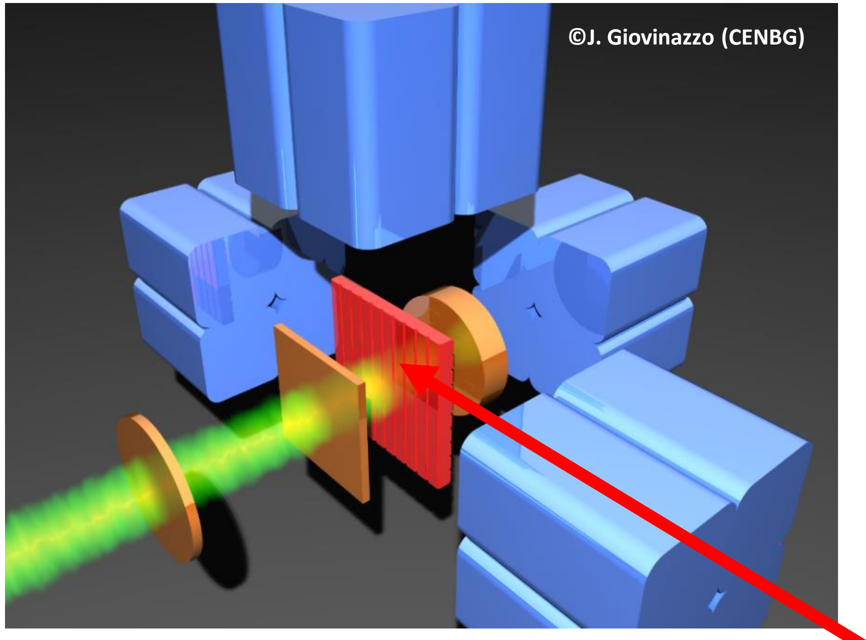
✓ **Four medium-mass cases known: $^{45}\mathrm{Fe}$, $^{48}\mathrm{Ni}$, $^{54}\mathrm{Zn}$ and $^{67}\mathrm{Kr}$**



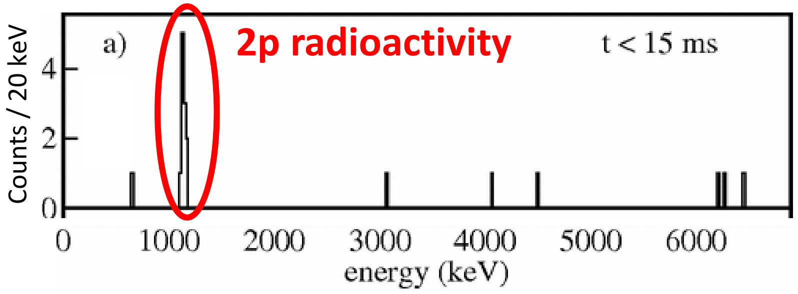
Previous studies of two-proton radioactivity

Discoveries of the 2p emitters: indirect observations

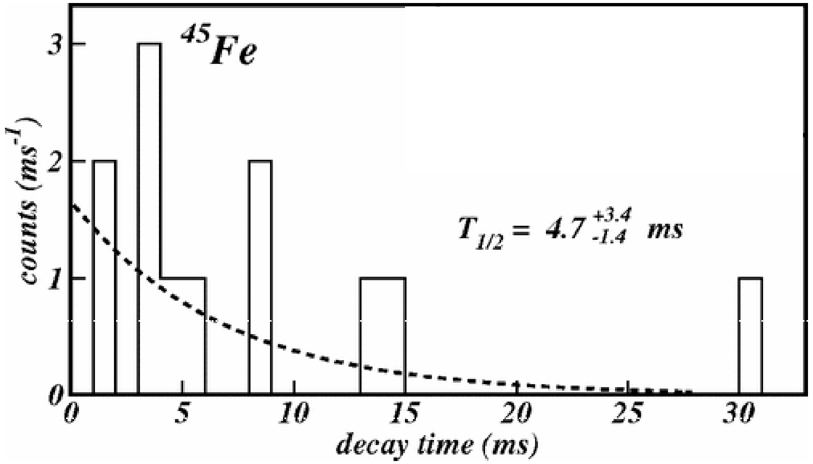
- ^{45}Fe : GANIL /GSI (2002)
- ^{48}Ni : Indication at GANIL (2005)
- ^{54}Zn : GANIL (2005)



- 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)*)

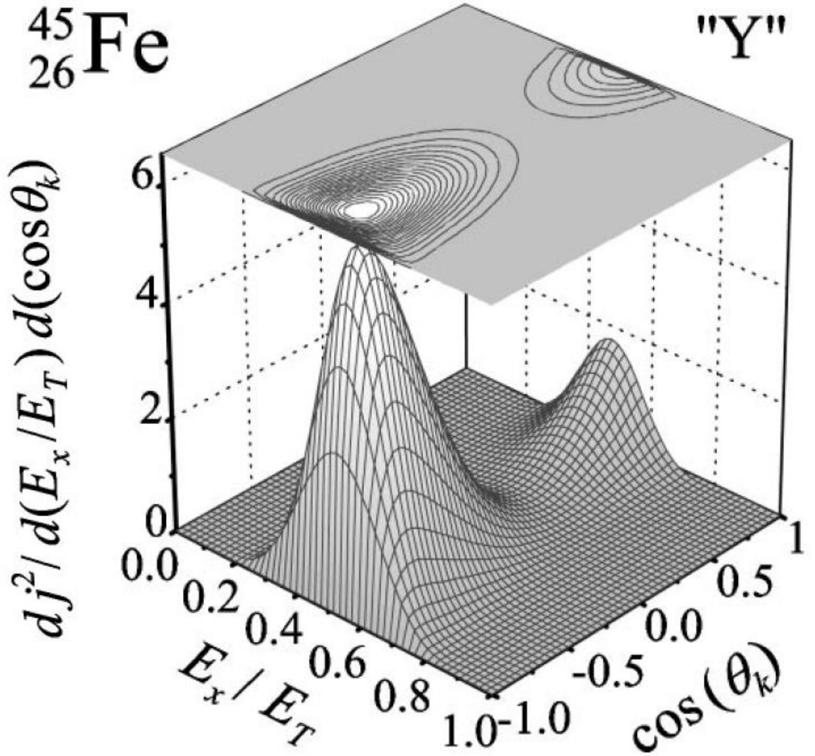


Previous studies of two-proton radioactivity

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)

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- Emission relative angles
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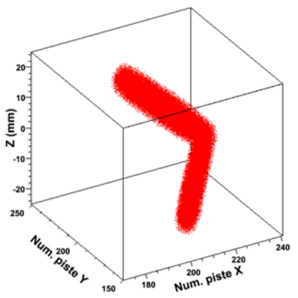
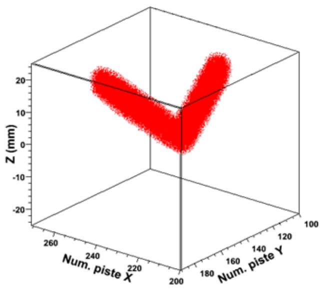
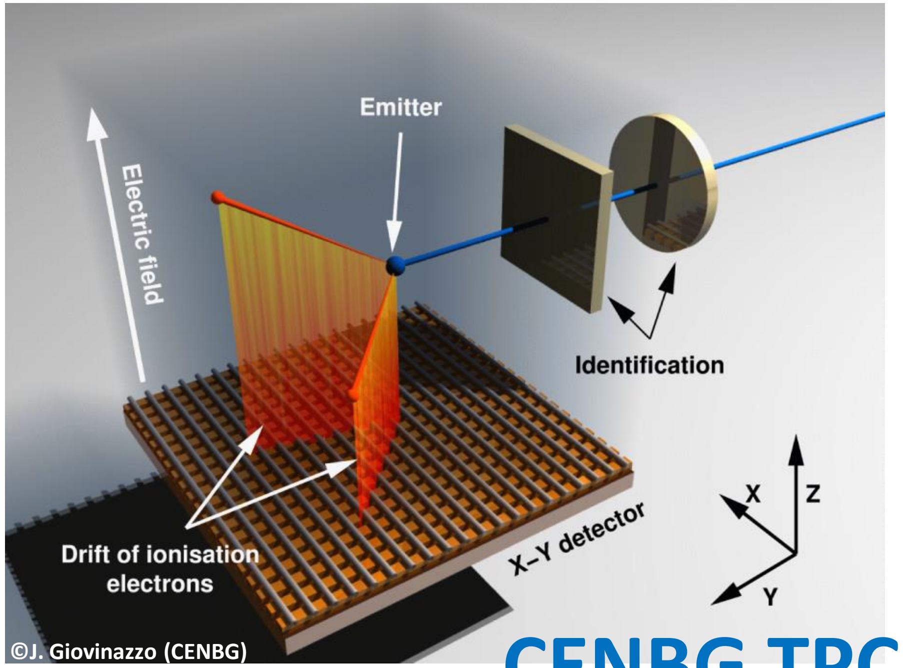
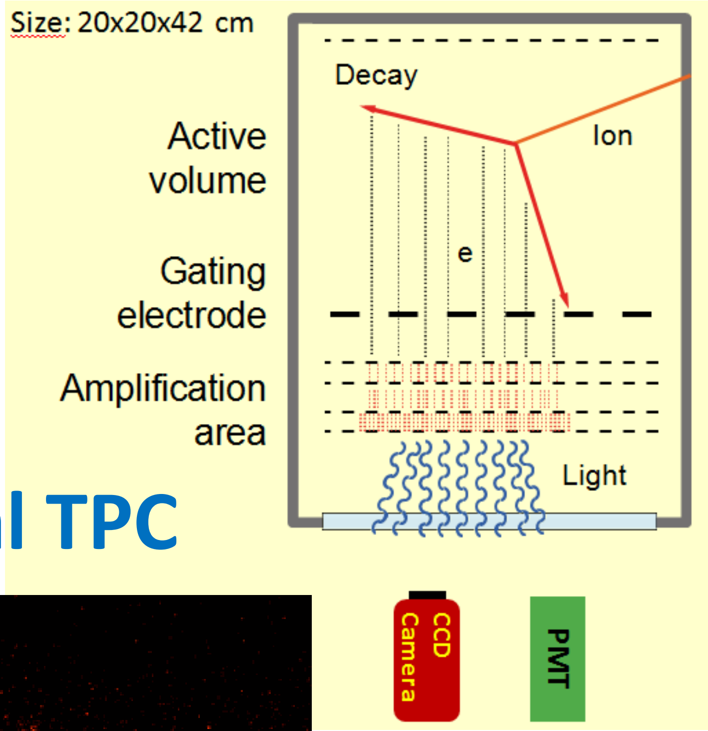
- ^{45}Fe, ^{54}Zn @ GANIL : CENBG TPC *Blank et al., NIM B, 266, 19-20, 4606–4611 (2008)*
- ^{45}Fe, ^{48}Ni @ MSU : Optical TPC *Miernik et al., NIM A, 581, 1–2, 194–197 (2007)*



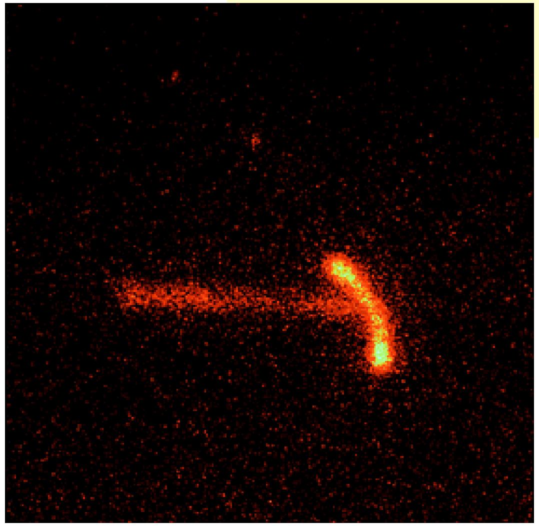




CENBG TPC



Optical TPC

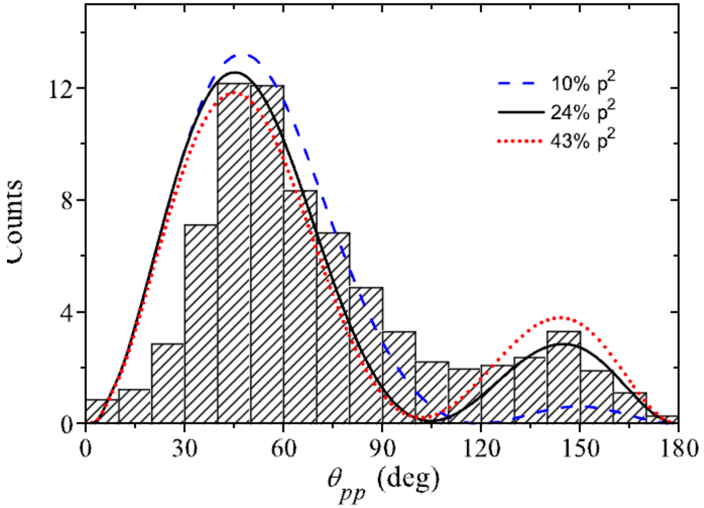


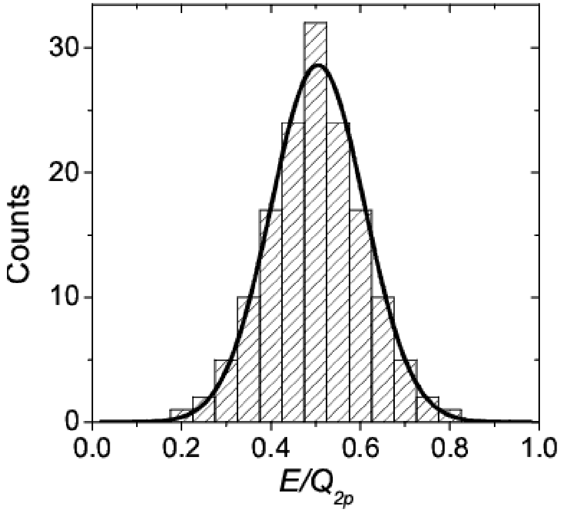
Miernik et al., PRL 99, 192501 (2007)

TPC experiments status

^{45}Fe first and most studied case

- since 2002 (GANIL / GSI)
- first direct observation (2006, TPC CENBG/GANIL)
- angular correlation → structure (2007, OTPC Warsaw/MSU)





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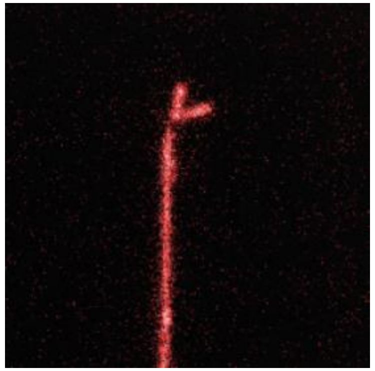


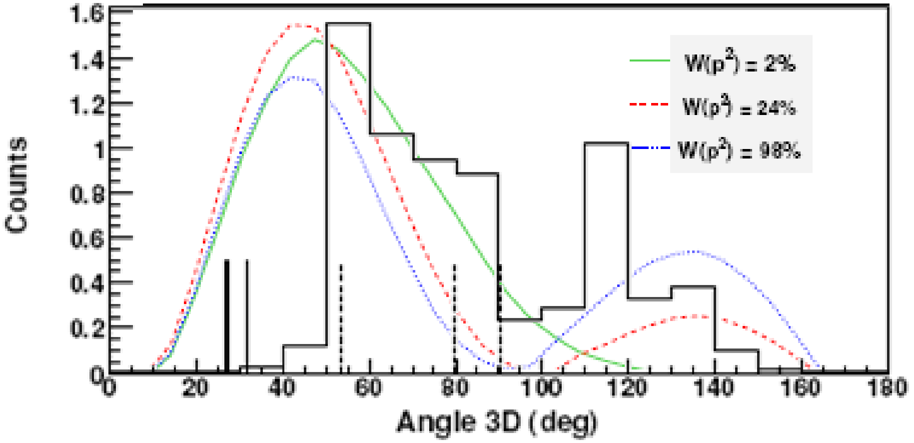
Pomorski et al., PRC 83, 061303(R) (2011)

^{48}Ni few counts only

- first indication (2004, indirect) – only 1 event
- few direct observation events (2011, OTPC Warsaw/MSU)

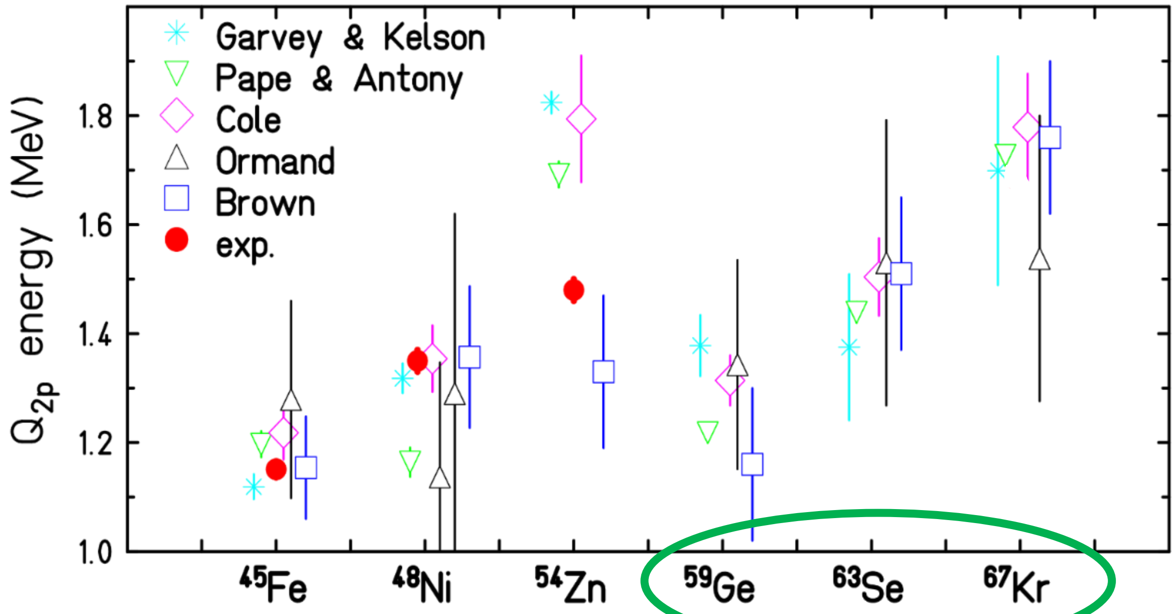
^{54}Zn low statistics, decay scheme well established

- indirect observation (2004, GANIL)
- limited angular distribution (2011, CENBG TPC / GANIL)



Ascher et al., PRL 107, 102502 (2011)

Search for new emitters



^{78}Kr beam

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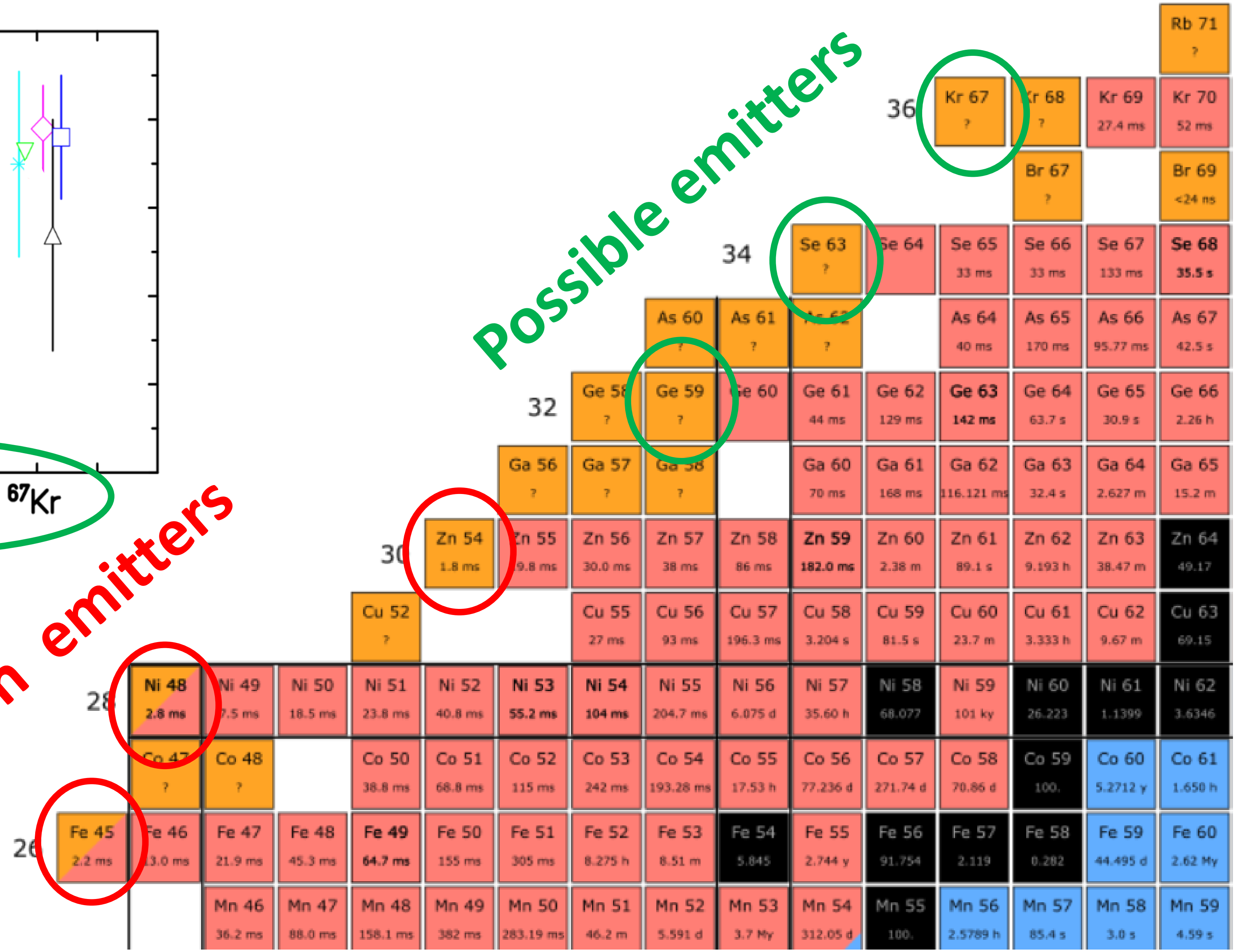
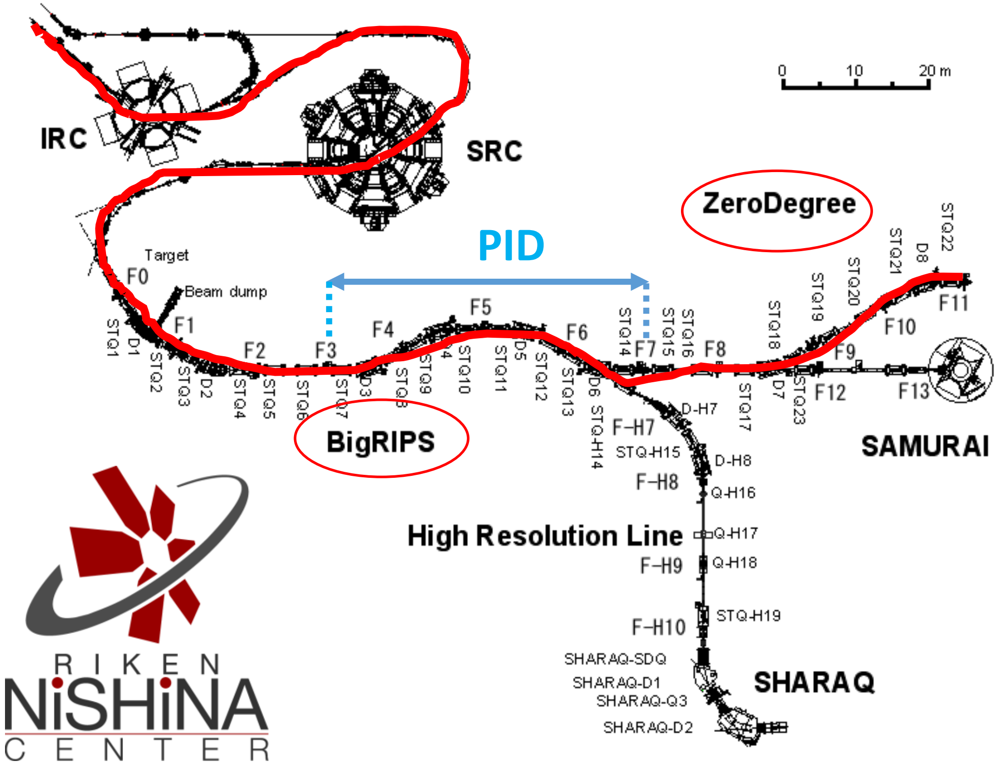


RIBF4R1 experiment (2015)

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)



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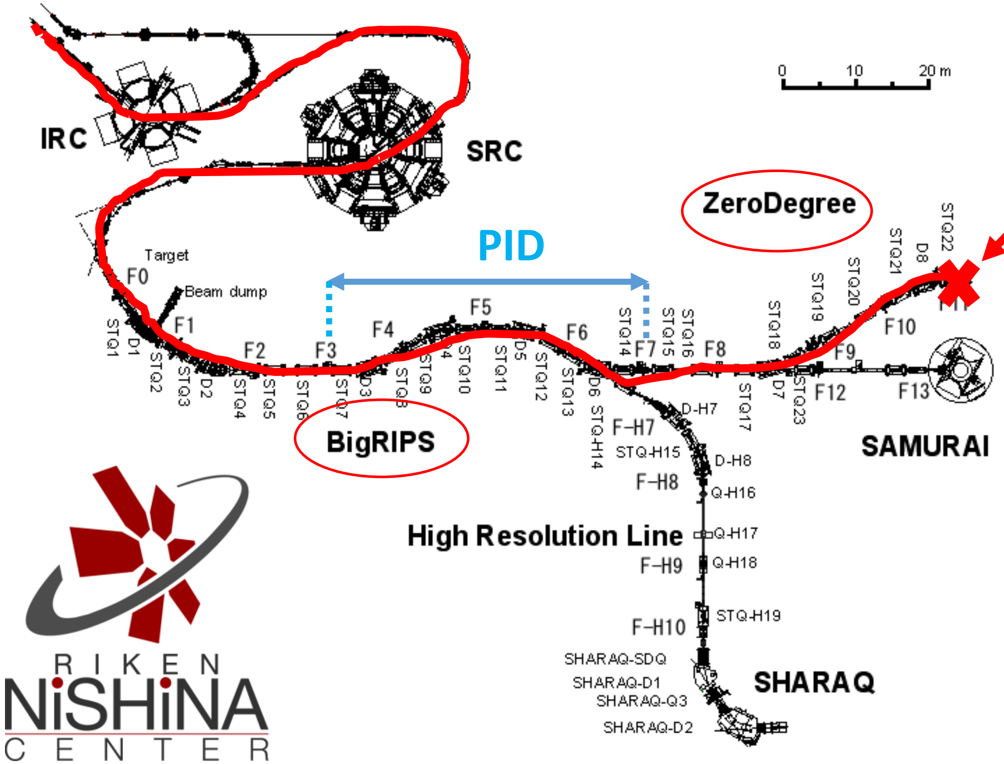

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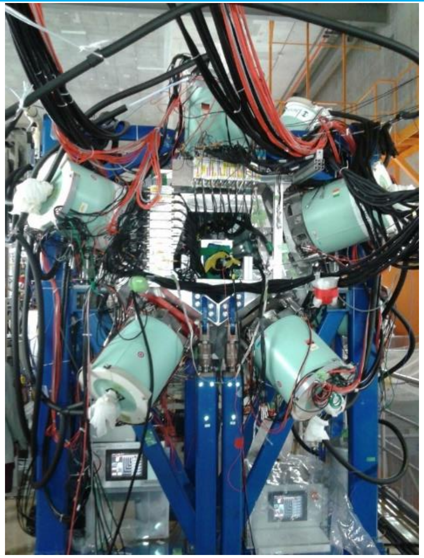
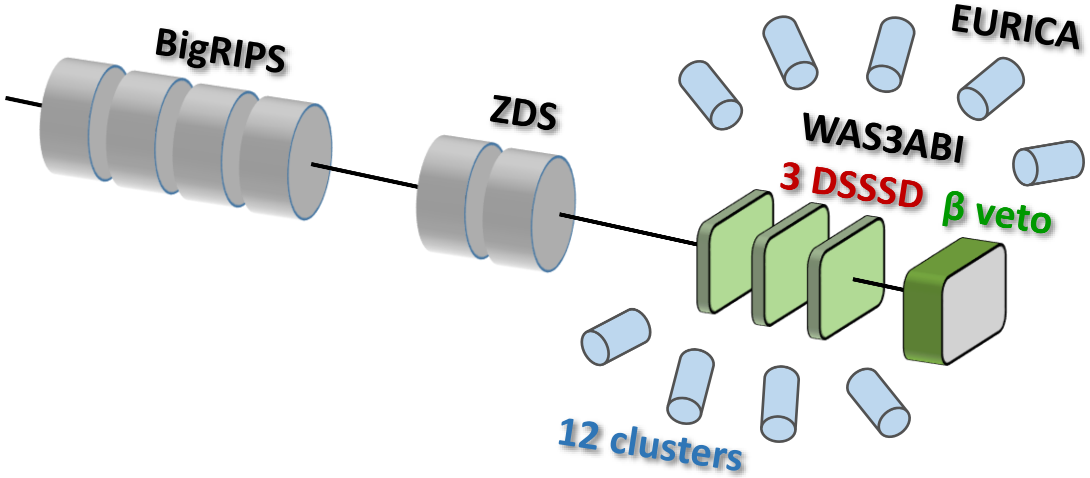
3. **Decay study**
   - WAS3ABi (proton and β decay)
     - DSSSD: 1mm thick, 60x40 strips (1mm pitch)
     - ➢ Implantation of the nuclei
     - ➢ Correlation implantation-decay (in position and time)
   - EURICA (γ-ray decays)
     - 12 EUROBALL clusters of 7 crystals each
     - 8% efficiency at 1.3 MeV

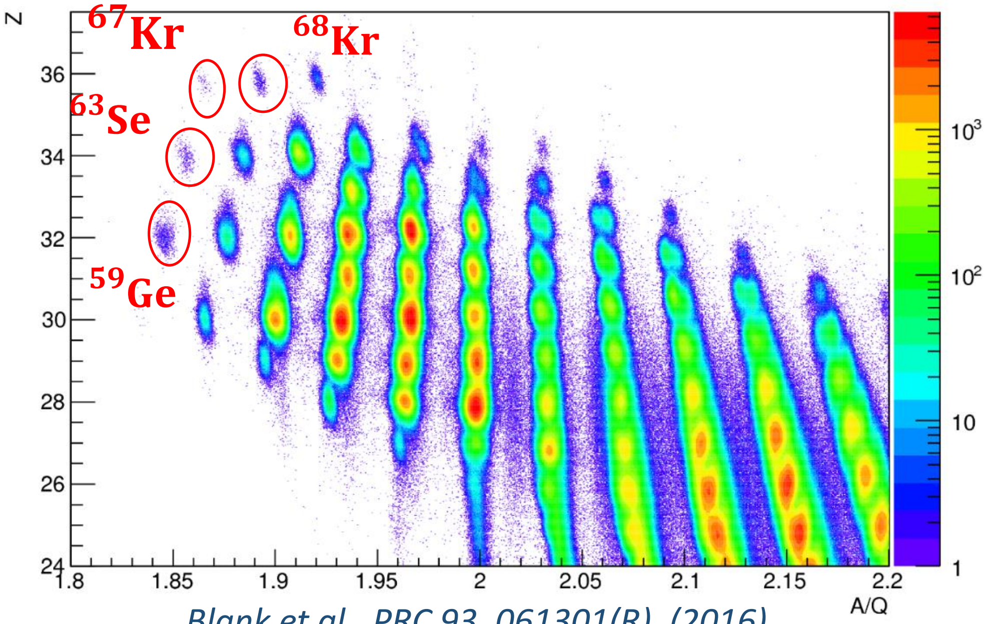




Results

- ^{63}Se, ^{67}Kr and ^{68}Kr were produced and identified for the first time
- Second time for ^{59}Ge after an experiment at NSCL (4 counts)

  Ciemny et al., PRC 92, 014622 (2015)



Blank et al., PRC 93, 061301(R) (2016)

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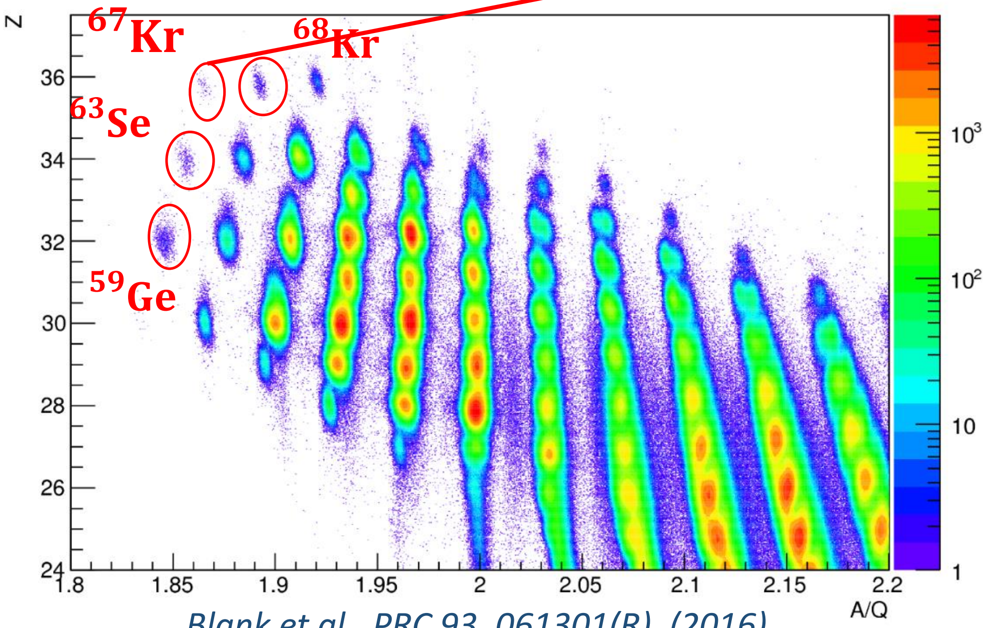
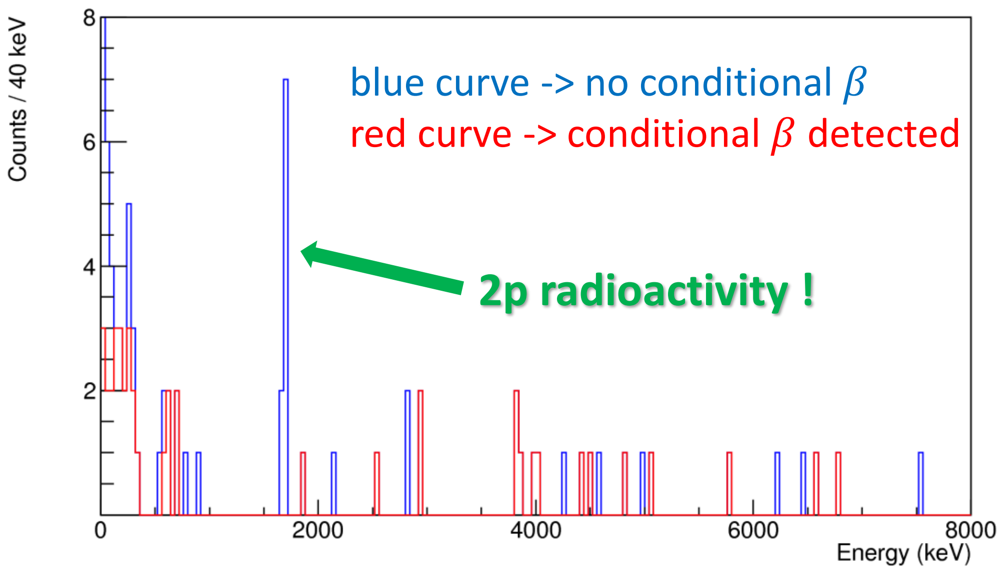


Blank et al., PRC 93, 061301(R) (2016)

Decay

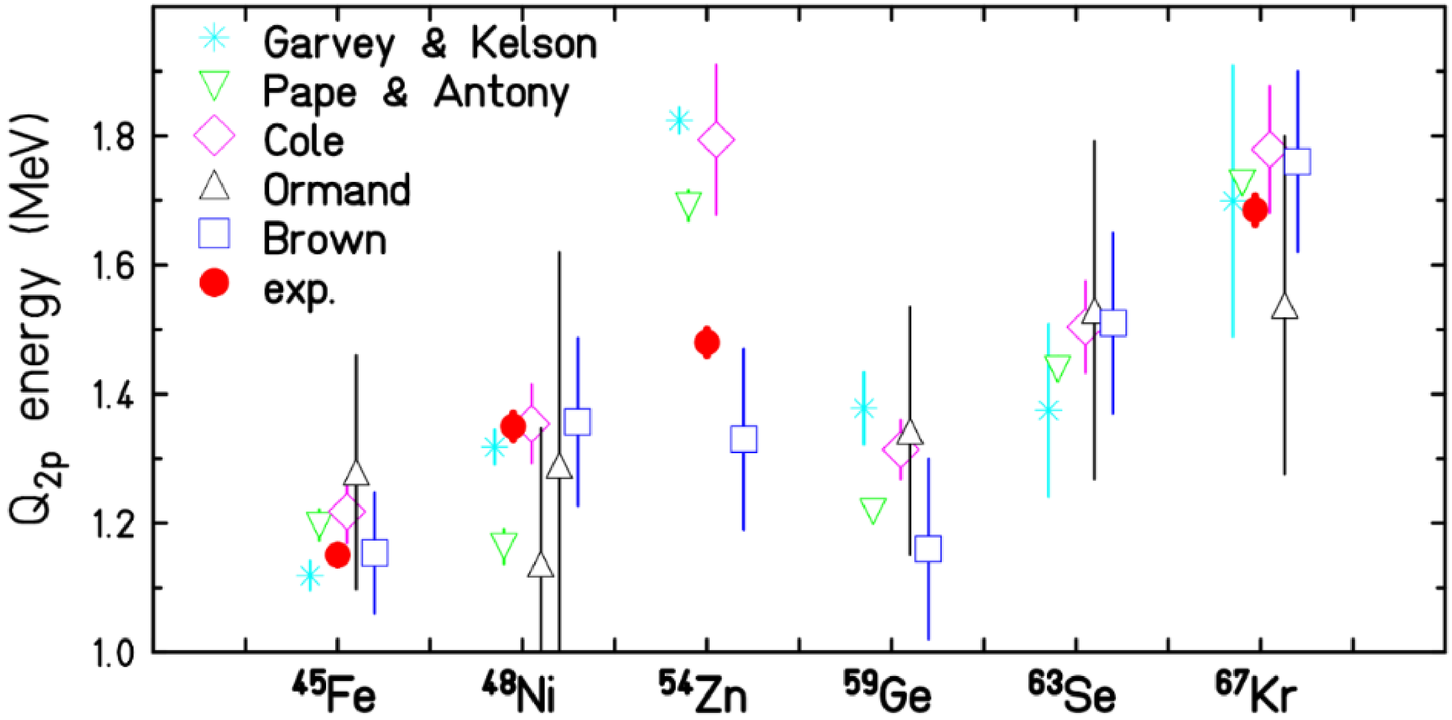
^{67}Kr



Goigoux et al., PRL 117, 162501 (2016)

- Peak composed of 9 events at $\mathbf{1690(17)}\ \boldsymbol{keV}$
- **β-detection efficiency of 67(1)% → probability of missing 9 counts: $\mathbf{5.5 \times 10^{-6}}$**
- No γ observed in coincidence with the peak: **8% probability of missing the 9 events (at 511 keV)**.
- **Global $T_{1/2} = 7.4(30)\ ms$**
  - $\boldsymbol{BR_{2p}} = \mathbf{37(14)\%}$ → 2p partial half-life $T_{1/2}^{2p} = 20(11)\ ms$
  - $BR_{\beta} = 63(14)\%$ → $\boldsymbol{T_{1/2}^{\beta} = 10(6)\ ms}$ (Gross theory: $\mathbf{11.1}\ \boldsymbol{ms}$)

Comparison with theory: decay energy



✓ **Good agreement with local mass models**

Comparison with theory: half-life

Three-body half-life (Grigorenko 2003)

- Pure f^2configuration: 13.5 s
- Pure p^2configuration: 0.28 s

Shell model's removal amplitude (Brown)

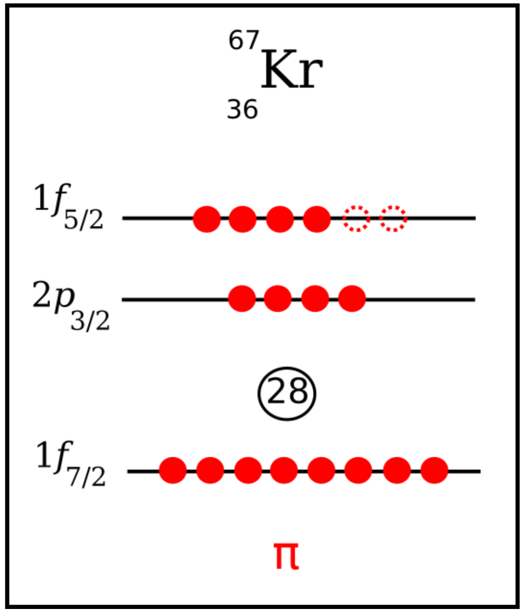
- Pure f^2configuration: 0.655
- Pure p^2configuration: 0.556

Shell-model corrected half-lives:

$$T_{1/2}(f^2) = \frac{13.5}{(0.655)^2} = 31.5 \text{ s}$$

$$T_{1/2}(p^2) = \frac{0.28}{(0.556)^2} = 0.9 \text{ s}$$

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

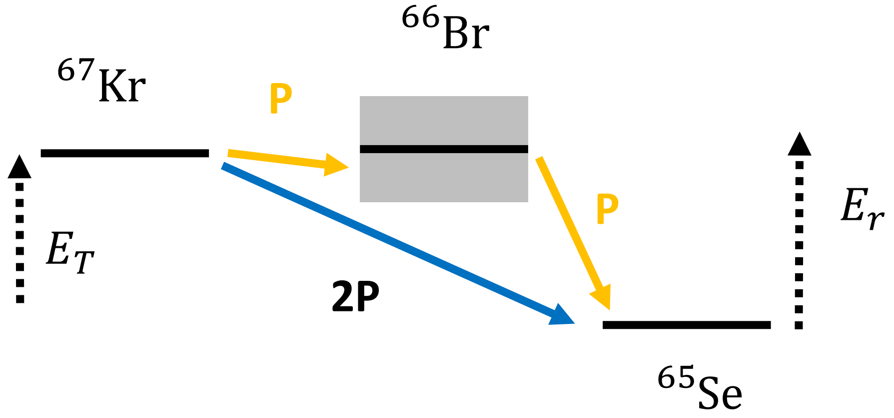


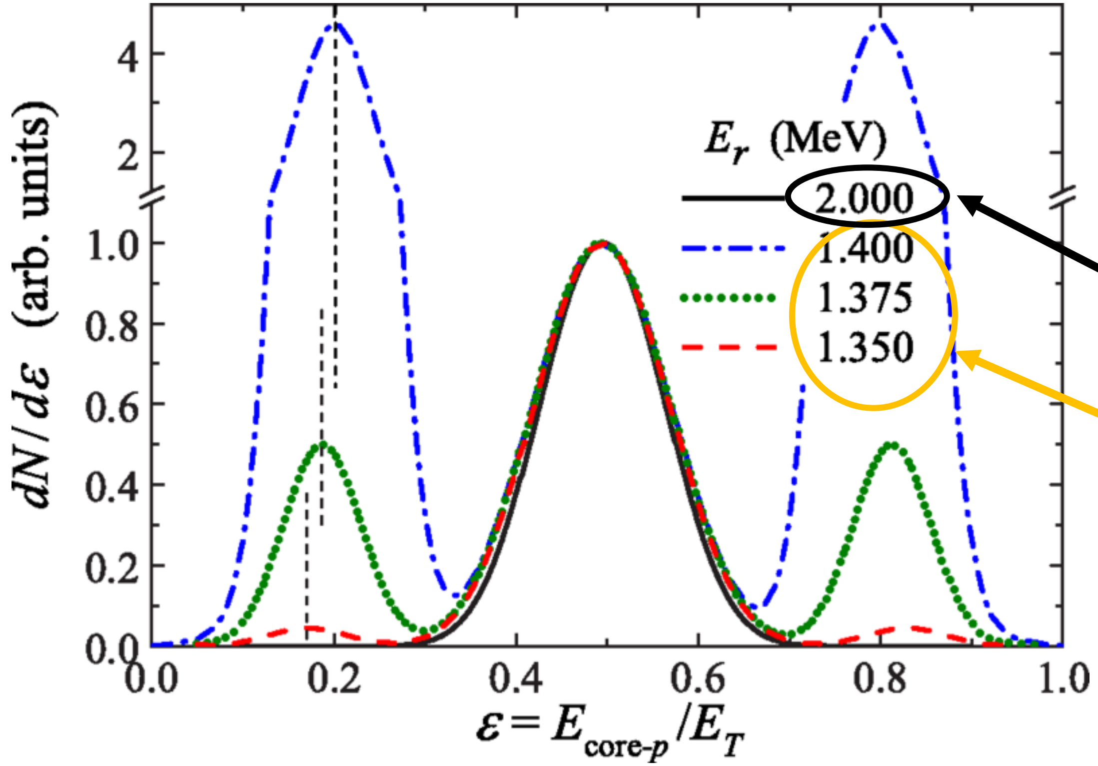
Nucleus	Calculation (ms)	Experiment (ms)
^{45}Fe	2.7	3.76(26)
^{54}Zn	1.6	$1.98^{+0.73}_{-0.41}$
^{67}Kr	**660**	**20(11)**

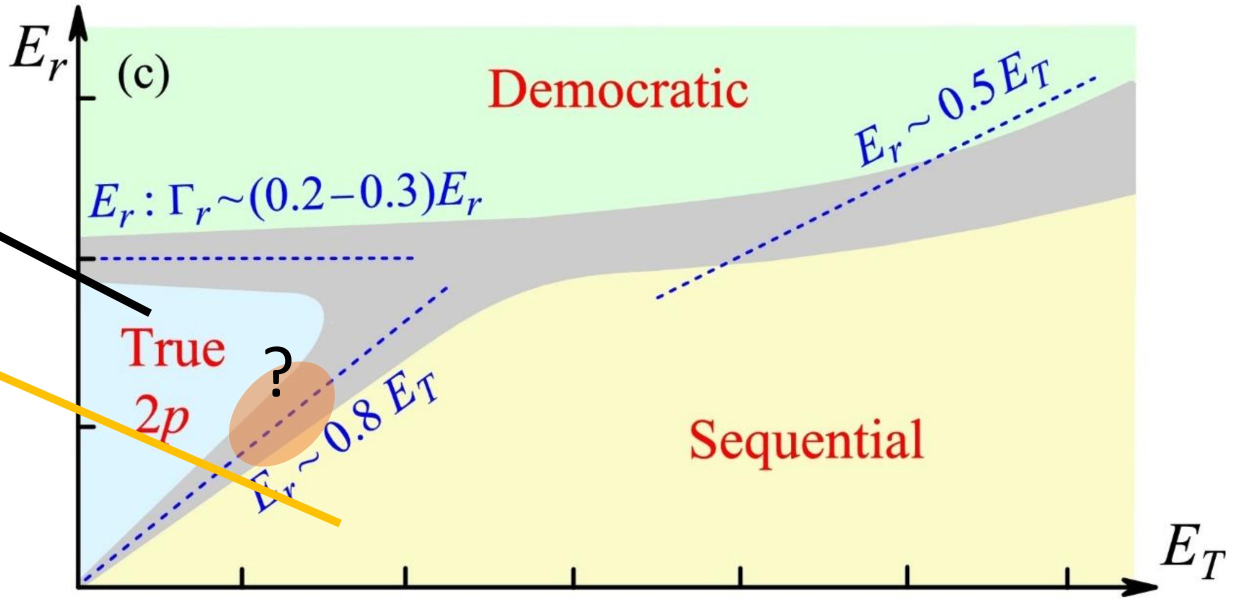
Strong disagreement with experimental value

Comparison with theory

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







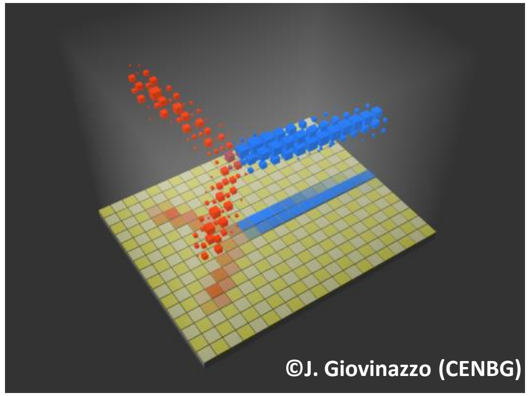
Grigorenko et al., PRC 95, 021601(R) (2017)

Conclusions and perspectives

- A new 2P emitter was observed: $^{67}\mathrm{Kr}$
  - 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 $^{48}\mathrm{Ni}/^{54}\mathrm{Zn}$ (GANIL, accepted)
➢ Direct observation of $^{67}\mathrm{Kr}$ to get energy correlations (RIBF, accepted)



Thank you for your attention

Collaboration

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