Two-proton radioactivity study and development of a Time Projection Chamber

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JRJC

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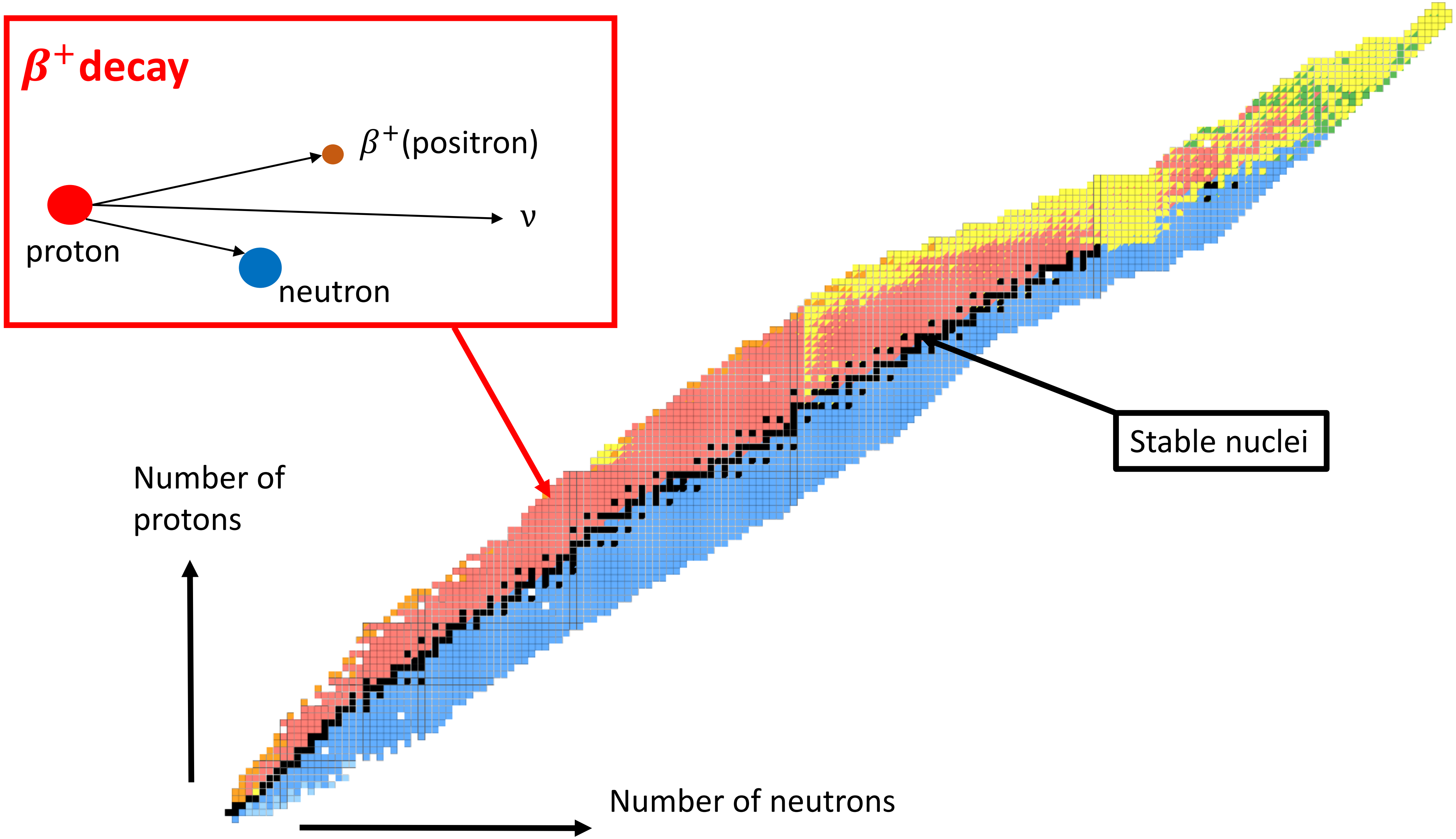
Summary

- The two-proton radioactivity
- RIBF4R1 experiment
- Results
- Time projection chamber
- Conclusion and outlook

The two-proton radioactivity

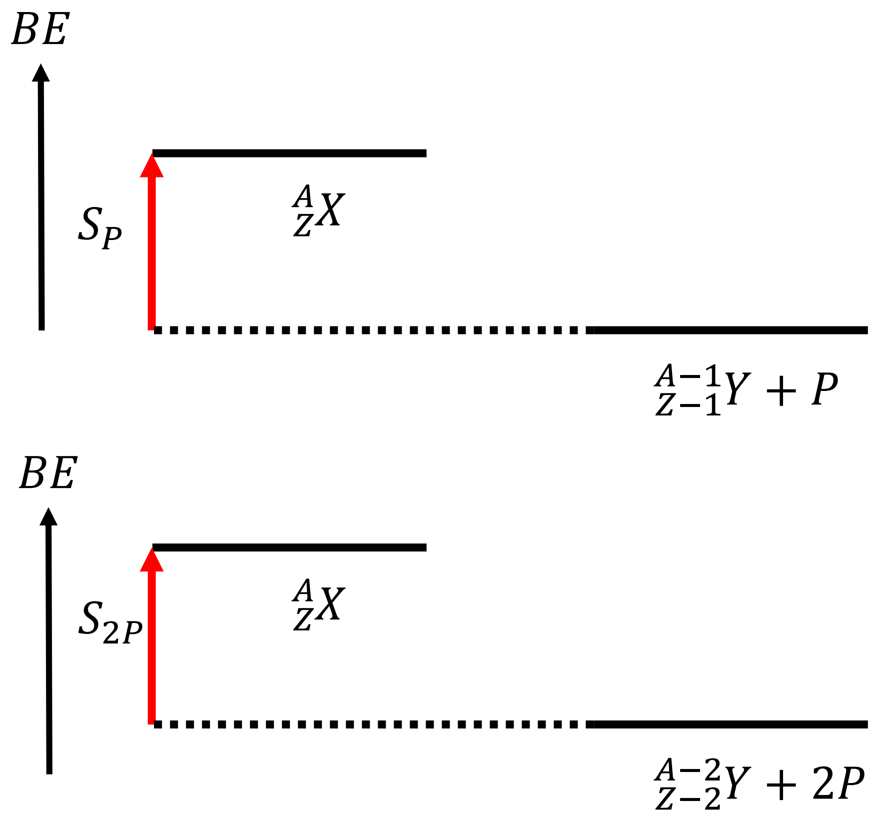
Decays and proton-rich nuclei physics

Most common radioactivity for proton-rich nuclei



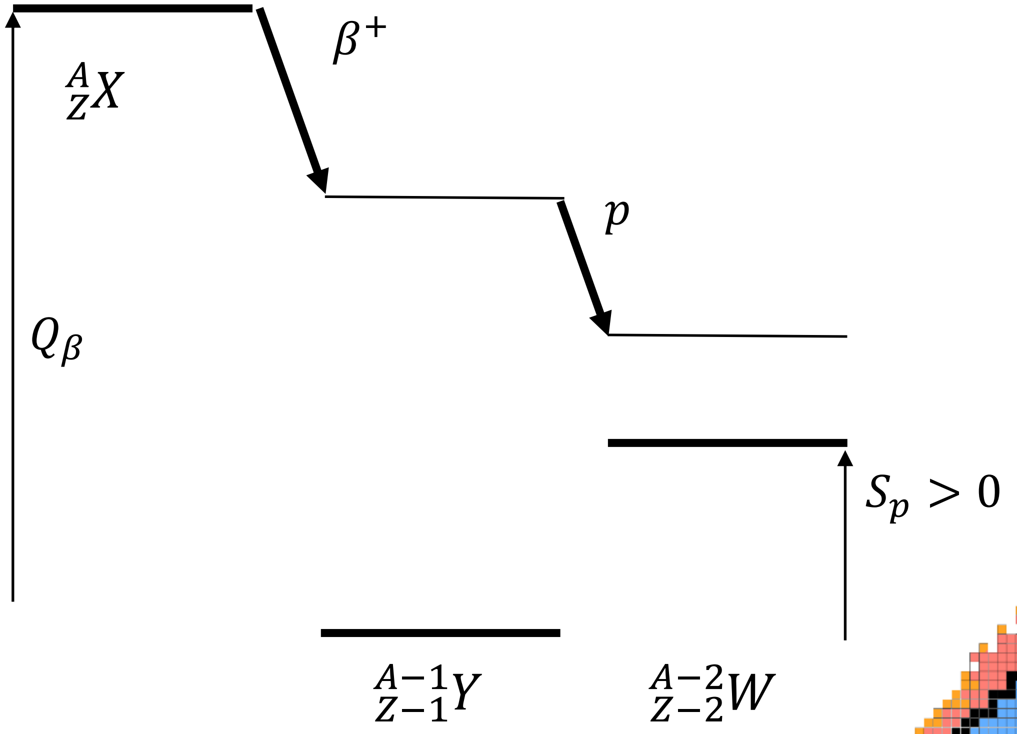
Decays of proton-rich nuclei

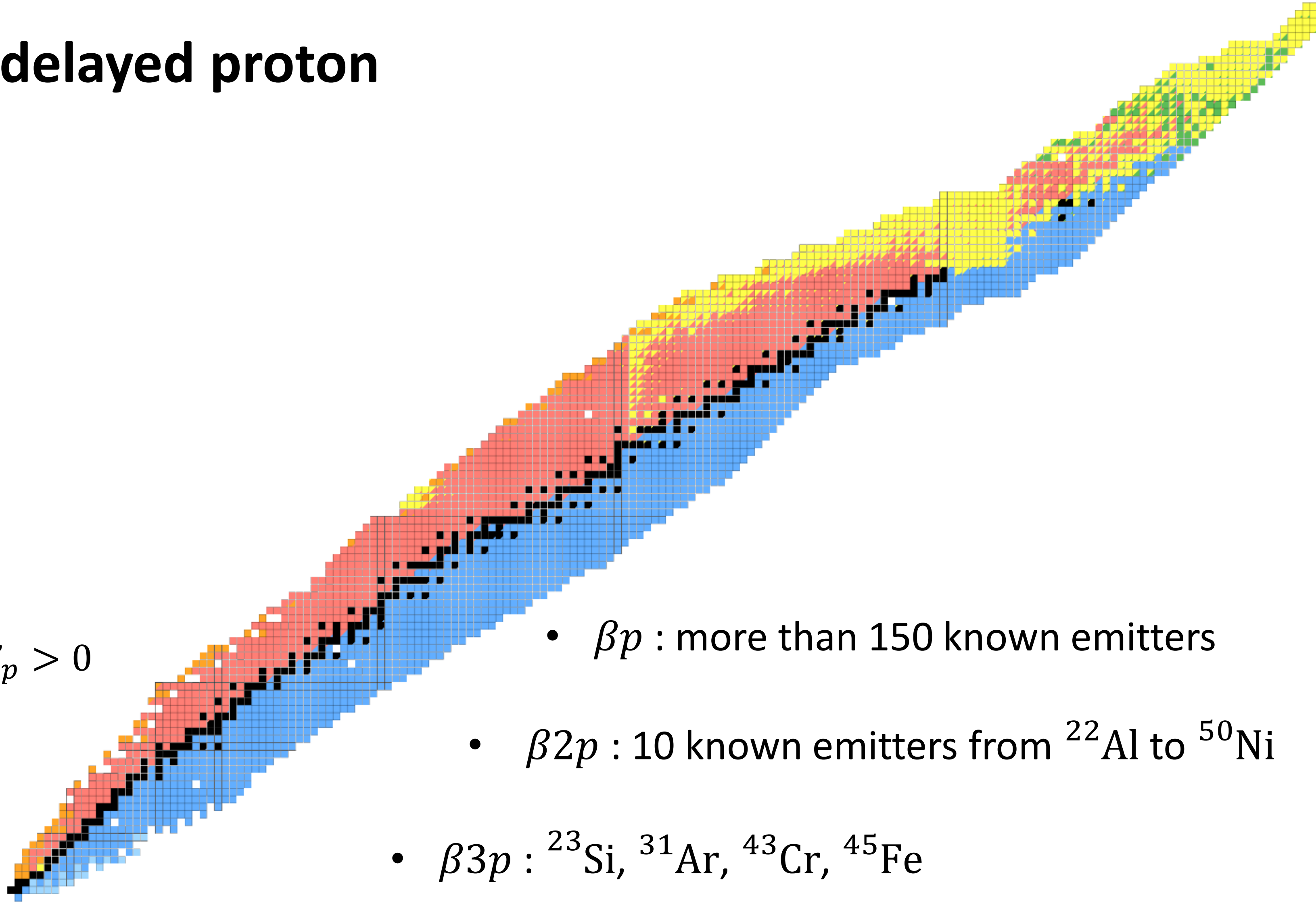
- Far from stability on proton-rich side, one and two proton separation energies decrease:
  - 1P: $S_P = BE\left({}^{A}_{Z}X\right) - BE\left({}^{A-1}_{Z-1}Y\right)$
  - 2P: $S_{2P} = BE\left({}^{A}_{Z}X\right) - BE\left({}^{A-2}_{Z-2}Y\right)$
- and the proton emission is more likely.
- When S_P (S_{2P}) is negative, the proton (2-proton) "drip-line" is crossed.



Decays of proton-rich nuclei

- Close to these driplines, ***β*-delayed proton** emission can be observed

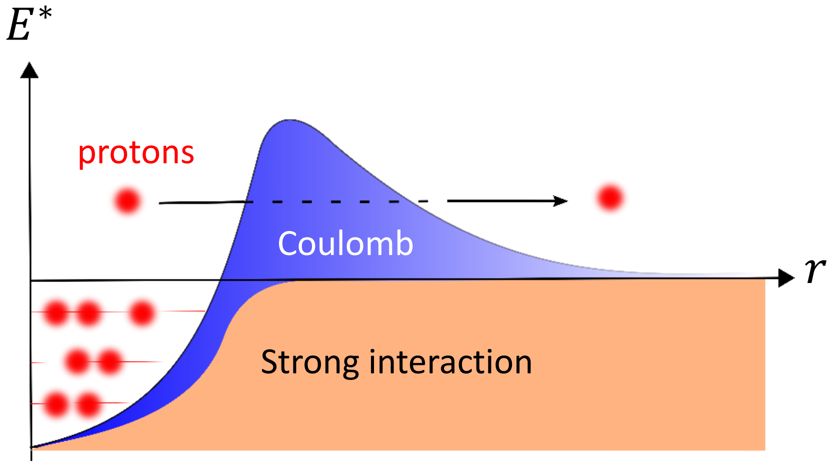


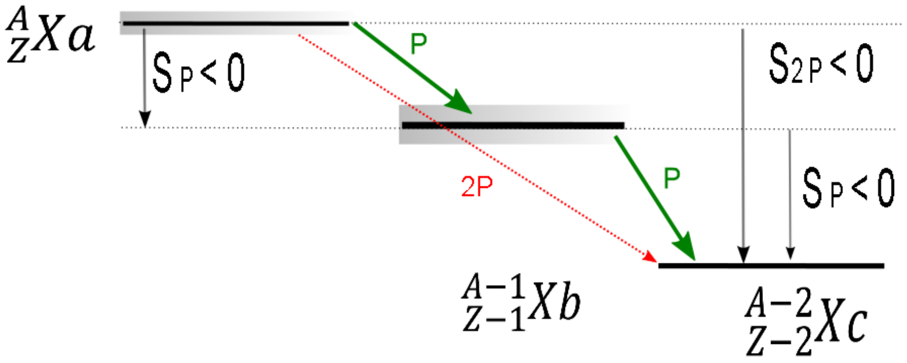


- βp : more than 150 known emitters
- $\beta 2p$: 10 known emitters from ^{22}Al to ^{50}Ni
- $\beta 3p$: ^{23}Si, ^{31}Ar, ^{43}Cr, ^{45}Fe

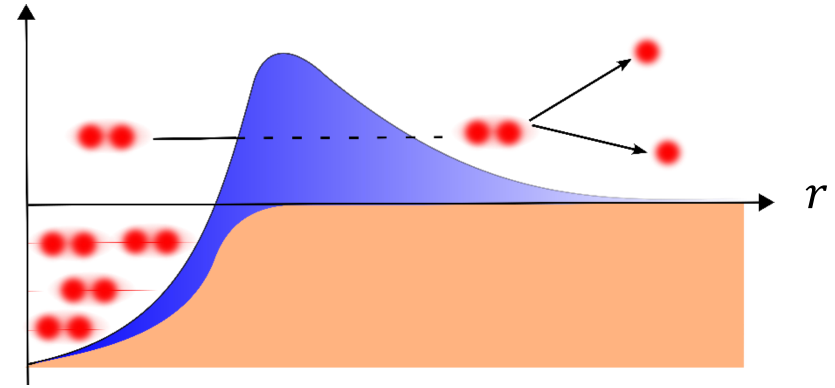
Direct proton emission

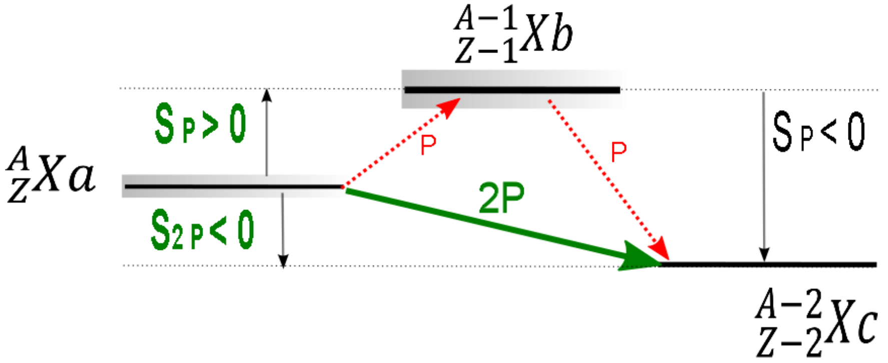
- Beyond the proton driplines (S_P or $S_{2P} < 0$) direct 1 and 2-proton emissions from ground-state allowed and can compete with β^+ decay.





Sequential emission favoured



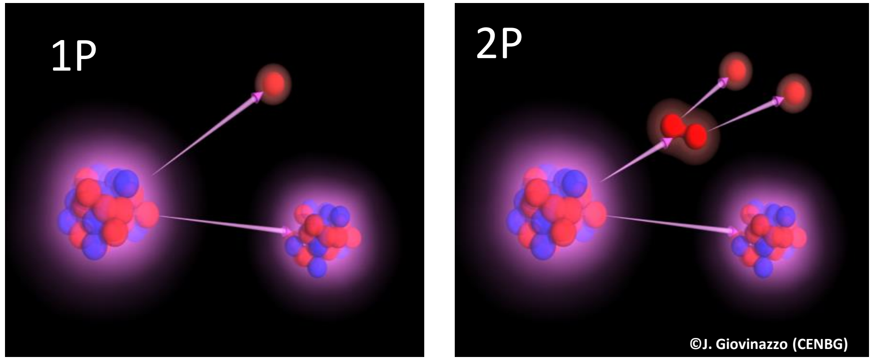


1P forbidden

=> "Real" two-proton radioactivity

Overview of 2-proton radioactivity

- 1 (odd-proton nuclei) and 2-proton (even-proton nuclei) radioactivities were predicted in the early **1960**s
  - 1-proton radioactivity was discovered in **1982** (^{151}Lu, ^{147}Tm)
  - 2-proton radioactivity only in **2002** (^{45}Fe)

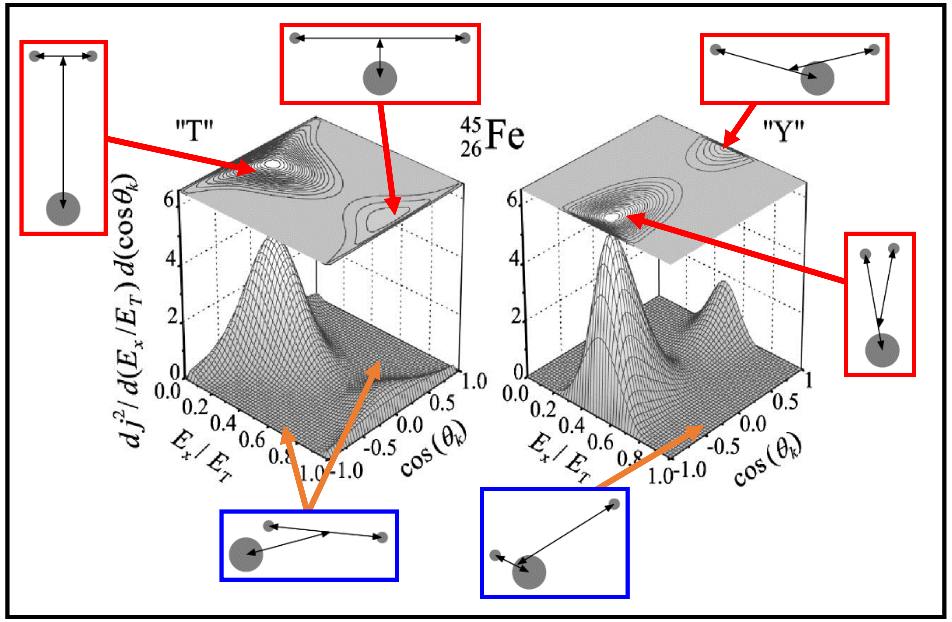


✓**Five cases known: ^{19}Mg, ^{45}Fe, ^{48}Ni, ^{54}Zn and recently ^{67}Kr**

Observables of 2P radioactivity given by models

- Overall observables:
  - Q_{2P} (released energy)
    - $Q_{2P} = -S_{2P} = M({}^{A-2}_{Z-2}Y) - M({}^{A}_{Z}X)$
      - ➢ Q_{2P} prediction based on mass models !
  - $T_{1/2}$ (half-life)
    - ➢ From probability of crossing potential barrier (depending on Q_{2P})
    - ➢ For higher barrier, a higher Q_{2P} required

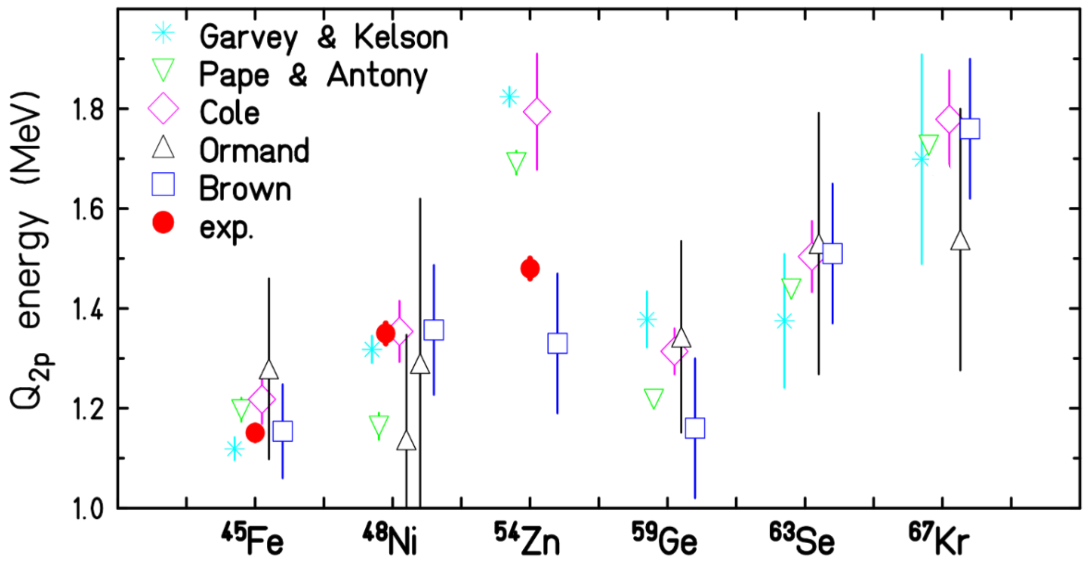
- Individual observables
  - Angular correlations
  - Energy correlations of emitted protons



^{45}Fe distributions

Grigorenko et al., PRC 68, 054005 (2003)

2-proton radioactivity: present knowledge



Expected emitters

Known emitters

Blank et al., PRL 94, 232501 (2005)

Dossat et al., PRC 72, 054315 (2005)
Pomorski et al., PRC 83, 061303(R) (2011)

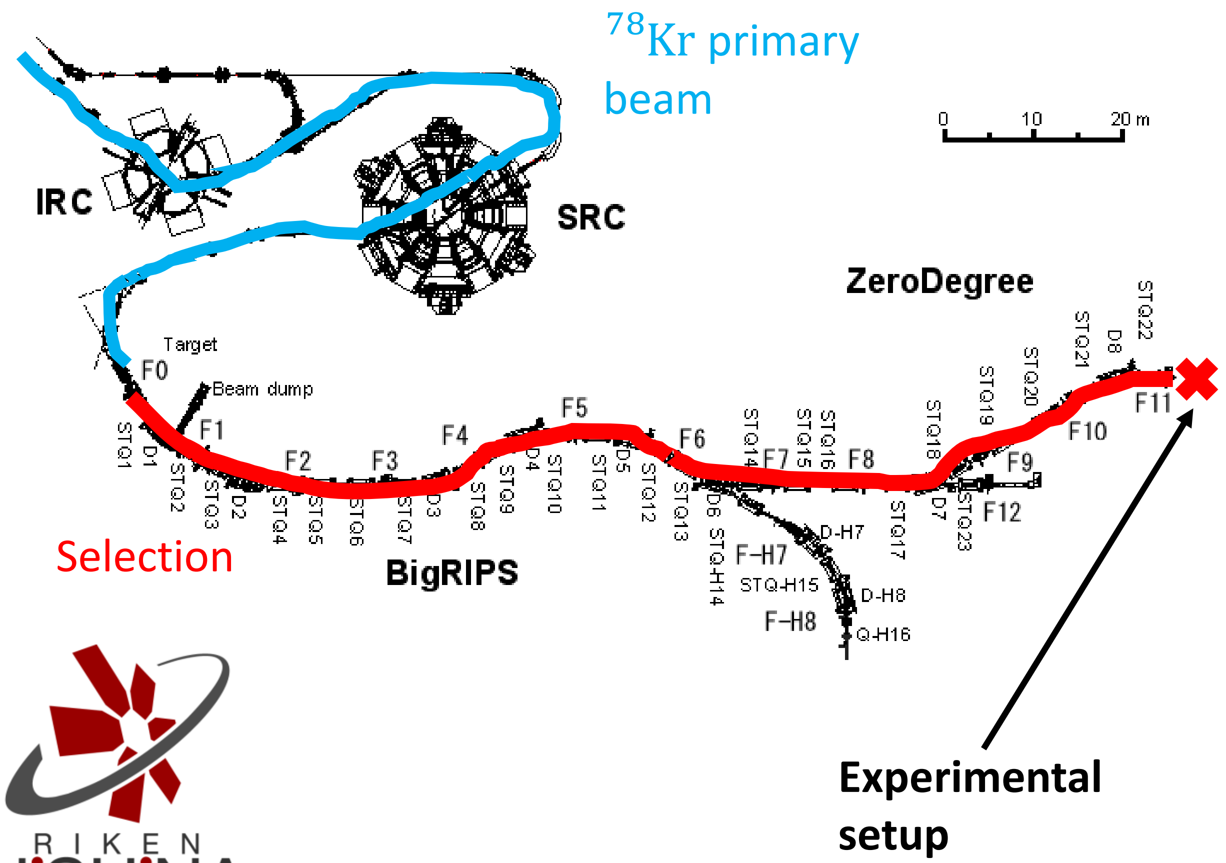
Giovinazzo et al., PRL 89, 102501 (2002)
Pfützner et al., EPJA 14, 3, 279–285 (2002)

RIBF4R1 experiment

The search for new 2P nuclei at the RIKEN Nishina Center

Production and selection

❖ Radioactive Isotope Beam Factory in Japan:



http://ribf.riken.jp

1. ^{59}Ge, ^{63}Se et ^{67}Kr created by fragmentation of a ^{78}Kr beam at 345 MeV/A on a ^{9}Be target.

2. Selection and identification
   - BigRIPS fragment separator
   - Zero Degree spectrometer.

3. Stop in our experimental setup

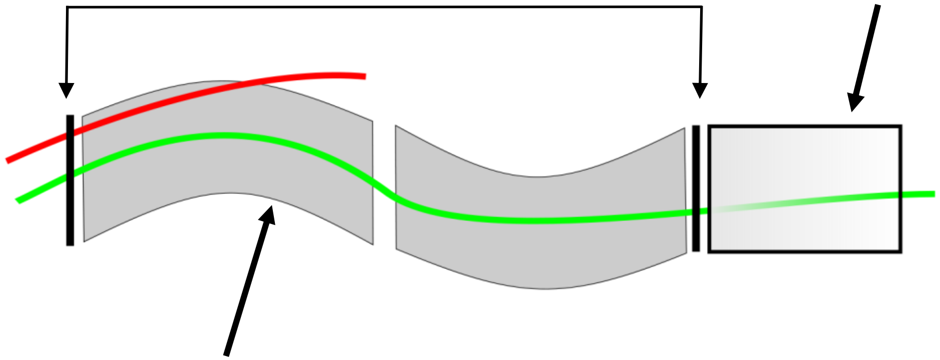
Selection and identification

Plastic scintillators
→ Time of flight (velocity $\boldsymbol{v}$)

&

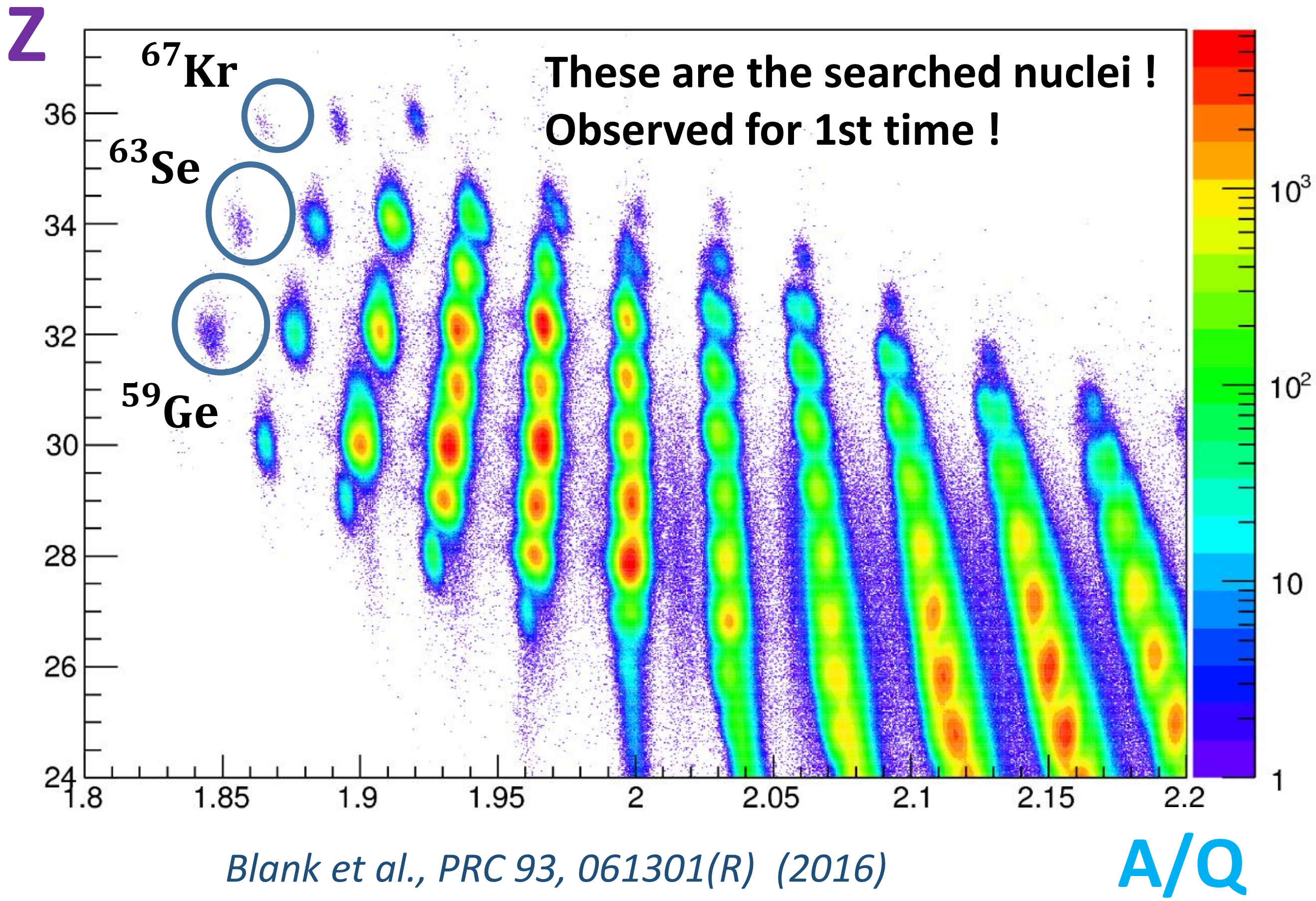
Ionisation chamber → Energy loss

$$-\frac{dE}{dx} \propto \frac{\boldsymbol{Z}^2}{\boldsymbol{v}^2}\left[\ln\left(\frac{m_e\gamma^2\boldsymbol{v}^2}{I}\right) - \frac{\boldsymbol{v}^2}{c^2}\right]$$



Magnetic dipoles
→ Reconstruction of trajectory curvature ρ,
→ set B field

$$B\rho = \frac{\|\vec{P}\|}{Q} \propto \frac{\boldsymbol{A}}{\boldsymbol{Q}}$$

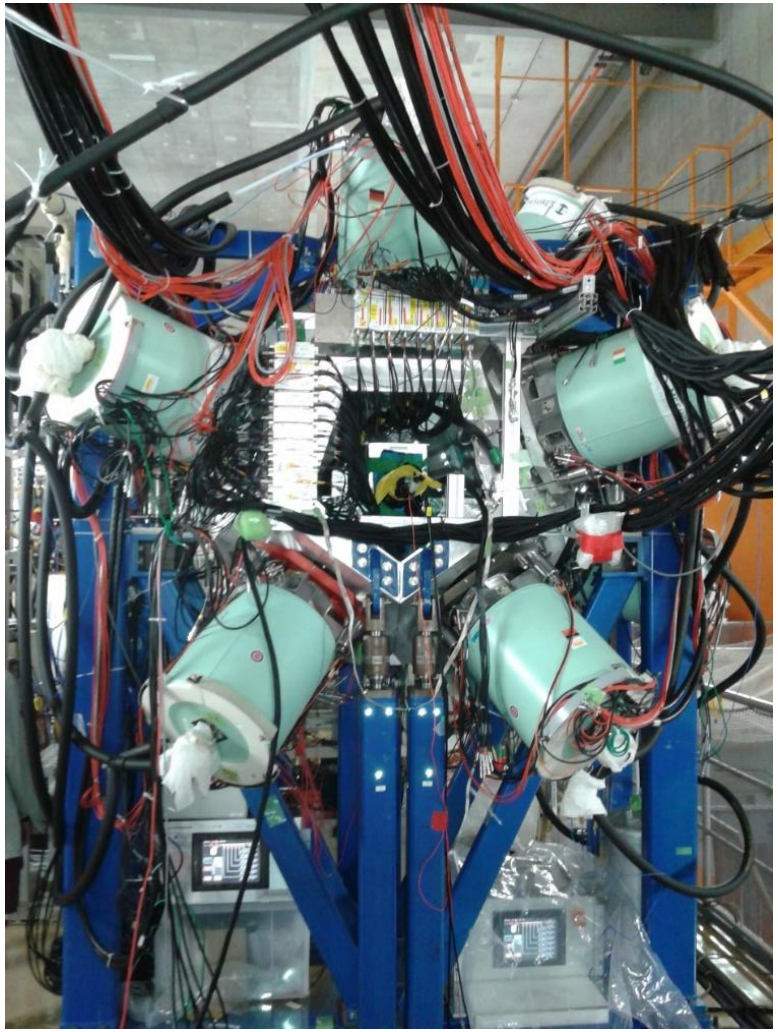


Blank et al., PRC 93, 061301(R) (2016)

Selection:

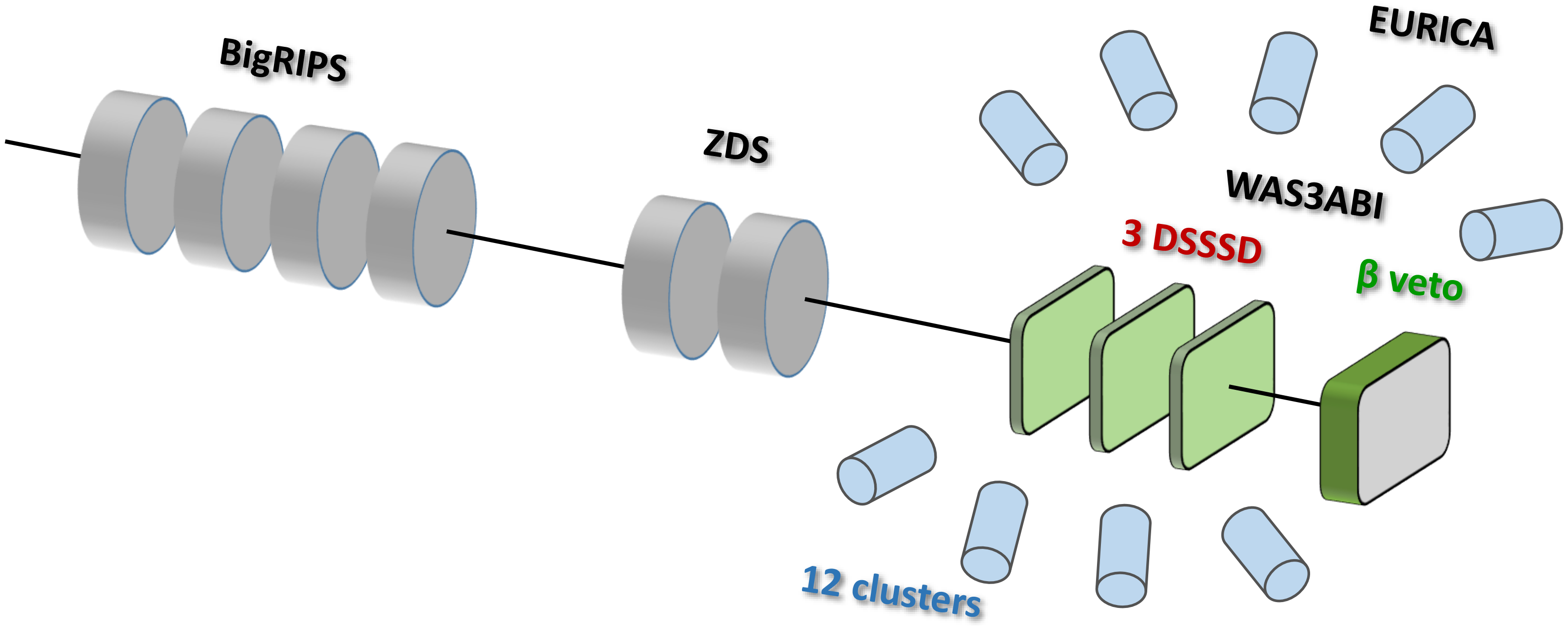
- Nuclei with too high or small $B\rho$ in respect with setting are lost.
- Selection of nuclei of interest

Setup dedicated to decays



- **WAS3ABi**: 3 Double-Sided Strip Silicon Detectors (DSSSD) & a plastic scintillator (β veto)
  - DSSSD: 1mm thick, 60x40 strips (1mm pitch)
  - ➢ Implantation of the nuclei
  - ➢ Detection of protons and β (positrons) from β decays and proton emissions

- Ge cluster array **EURICA**
  - 12 clusters of 7 crystals each
  - Detection of γ ray from deexcitation

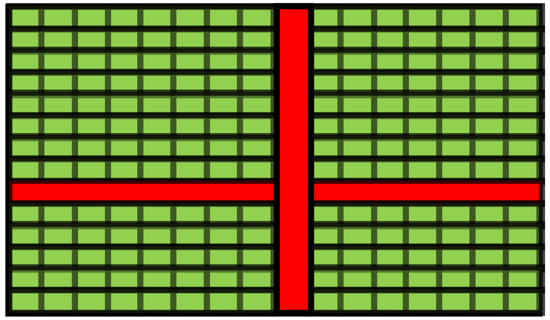


Implantation-decay correlations

1. Implantation

- Nucleus stopped in silicon detector
- Corresponding X and Y strips trigger

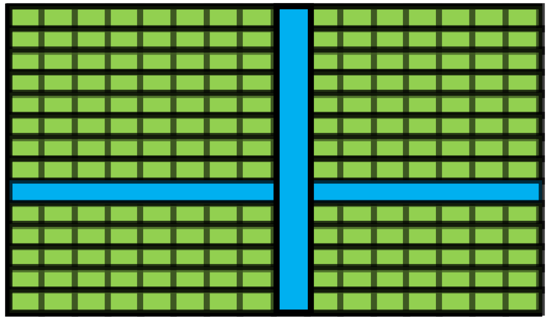
DSSSD



Implantation event

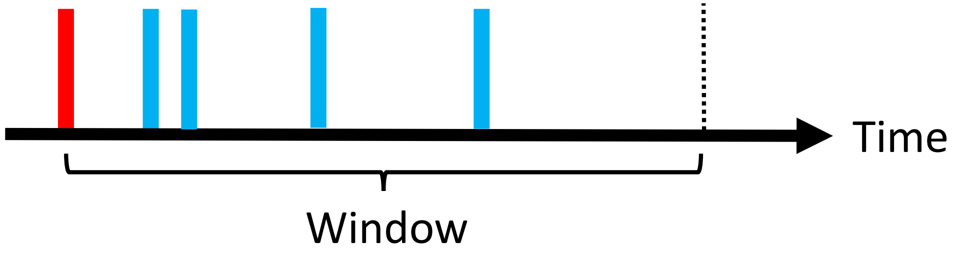
2. Decay

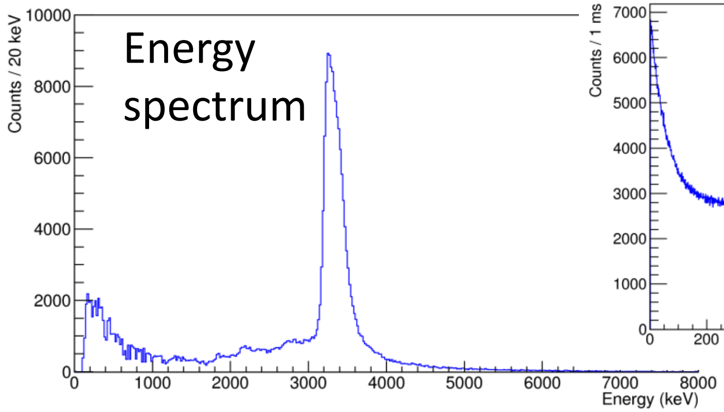
- Signal searched in pixel during a time window

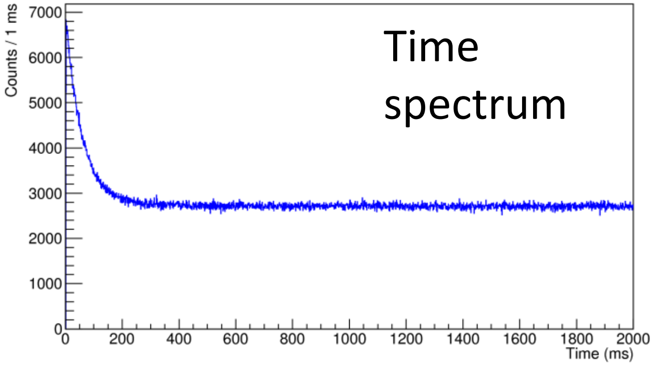


Decay event correlated

3. Correlations

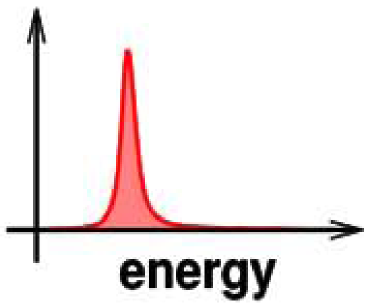




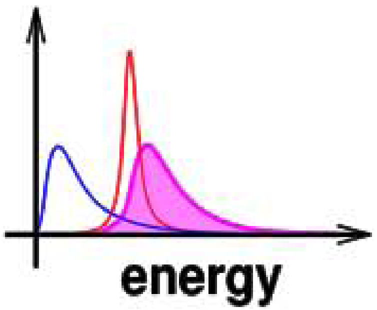


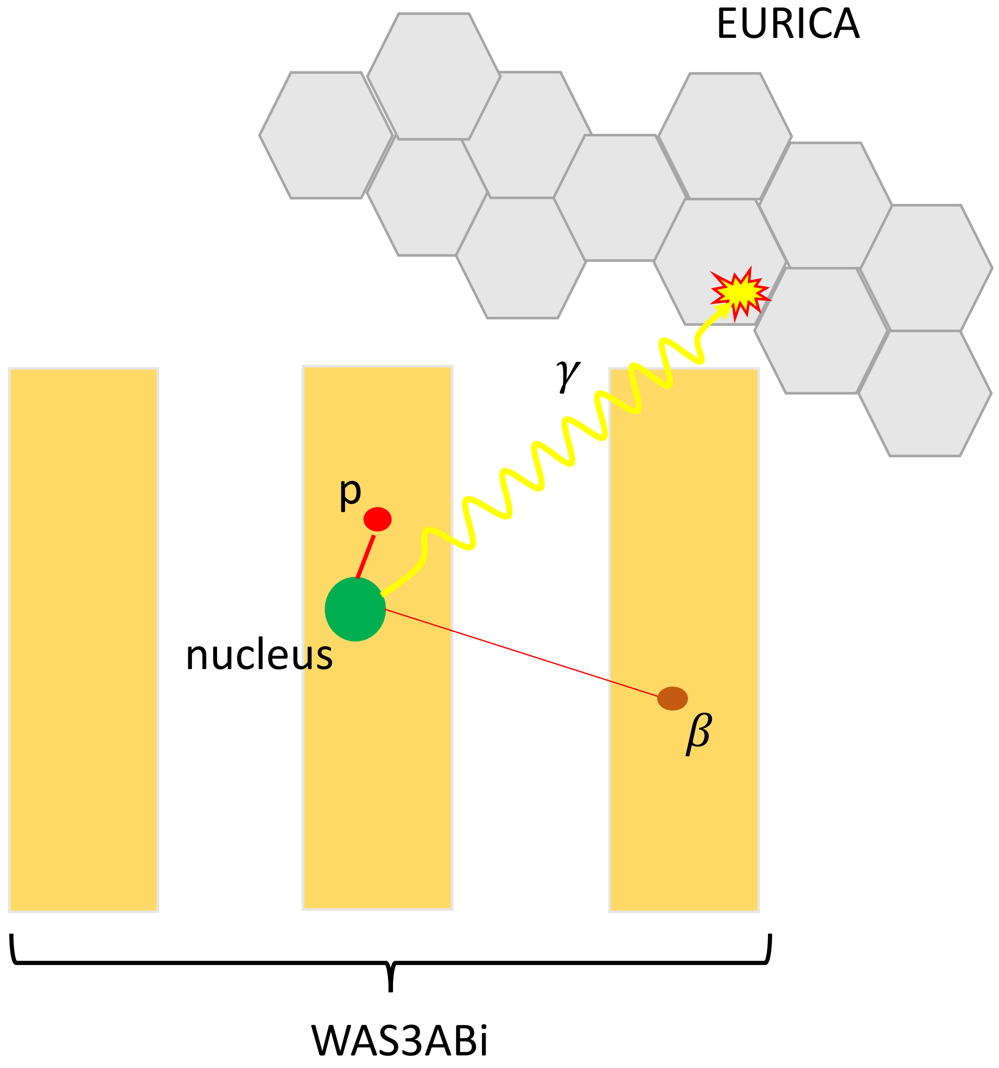
Spectra

- Energy deposited by protons and β (positrons)
- Two shapes of spectra:
  - Emission of proton: sharp peak because due to their small path in detector



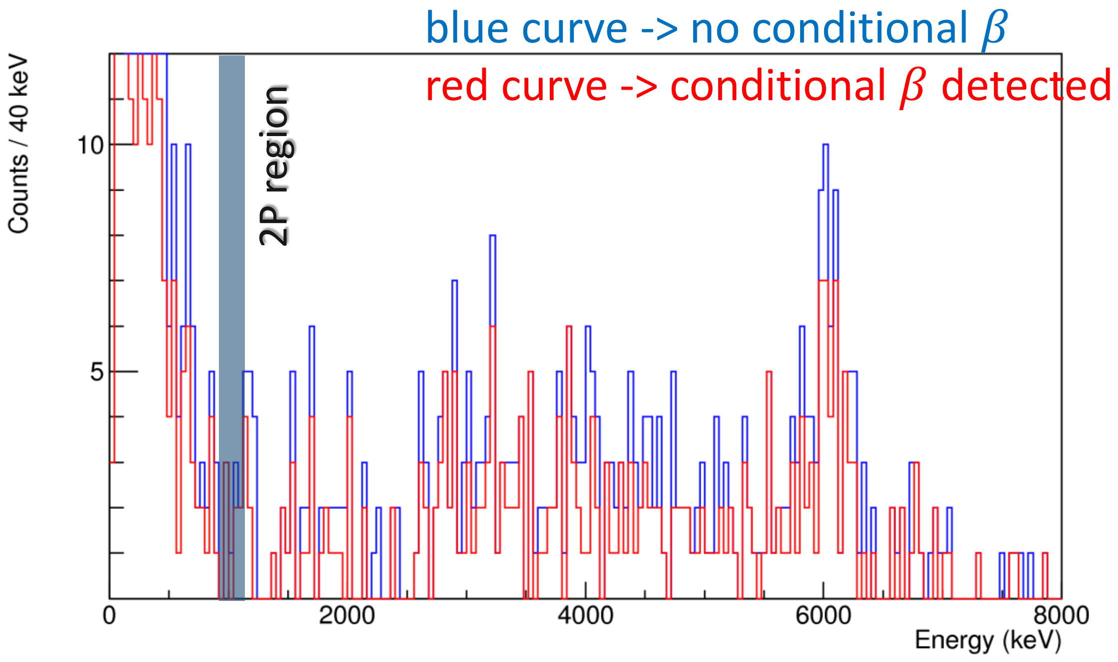
  - Simultaneous emission of β and proton(s): sum of 2 contributions because β have long path.

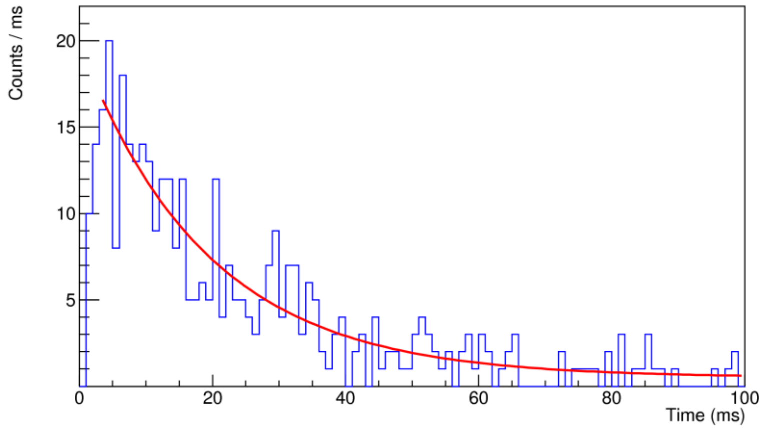




Results

Search of 2P: ^{59}Ge

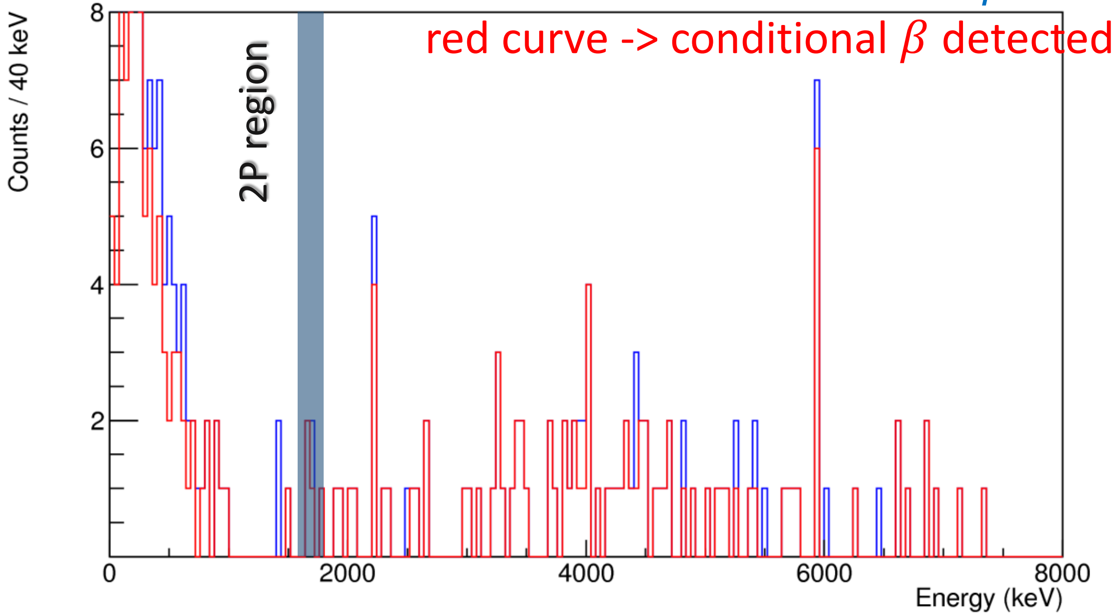


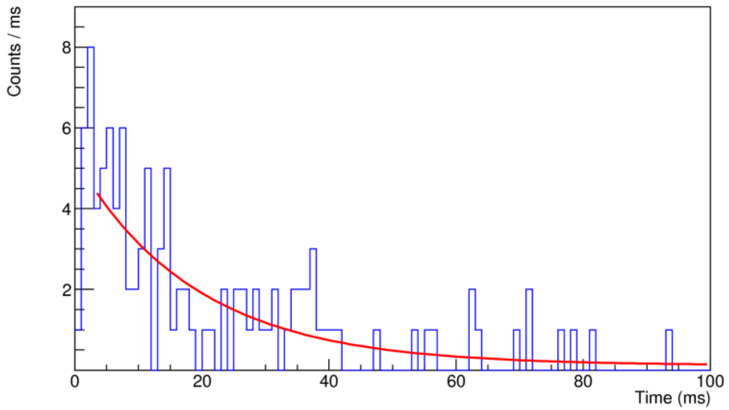


- No peak was seen without any β in coincidence in neighbouring DSSSDs
- $T_{1/2} = 13.3(17)\ ms$
  - ➢ Close to β Theory half-life: $10.9\ ms$
    http://wwwndc.jaea.go.jp/CN14/index.html
  - β decay dominates
- In 2p region (around 1.1 MeV)
  - One count without β coincidence observed
  - If a 2p event, BR_{2p} **< 0.2%**

No 2p radioactivity evidence

Search of 2P: ^{63}Se

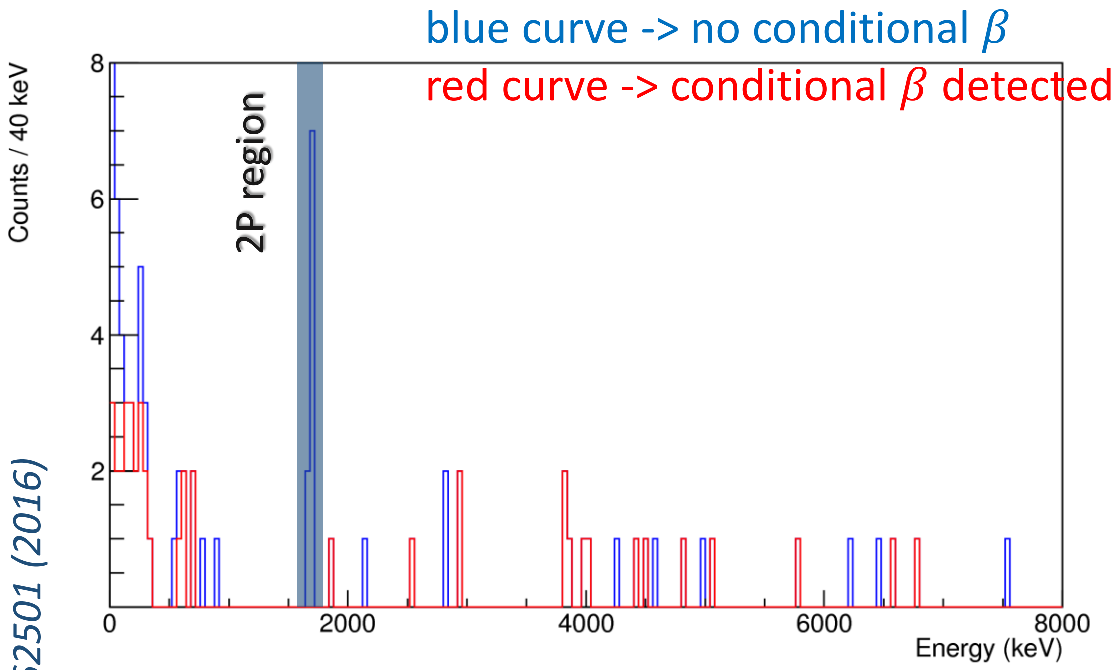


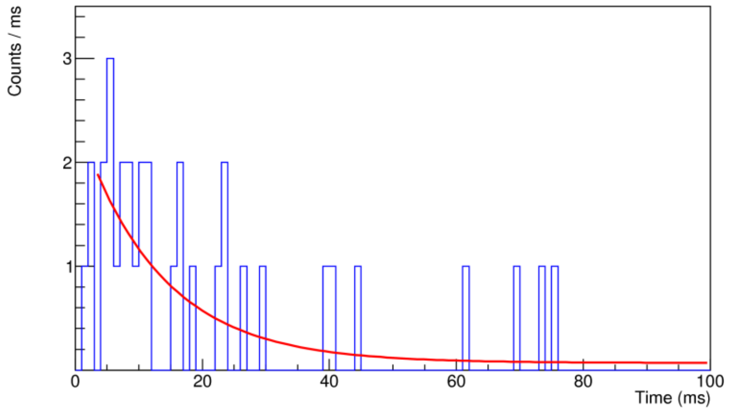


- No peak was seen without any β in coincidence in neighbouring DSSSDs
- $T_{1/2} = \mathbf{13.2(39)}\ \boldsymbol{ms}$
  - ➢ Close to β Theory half-life: $\mathbf{13.4}\ \boldsymbol{ms}$
  - β decay dominates
- In 2p region (around 1.5 MeV)
  - One count without β coincidence observed
  - If a 2p event, $\boldsymbol{BR_{2p}}$ **< 0.5%**

No 2p radioactivity evidence

Search of 2P: $^{67}\mathrm{Kr}$





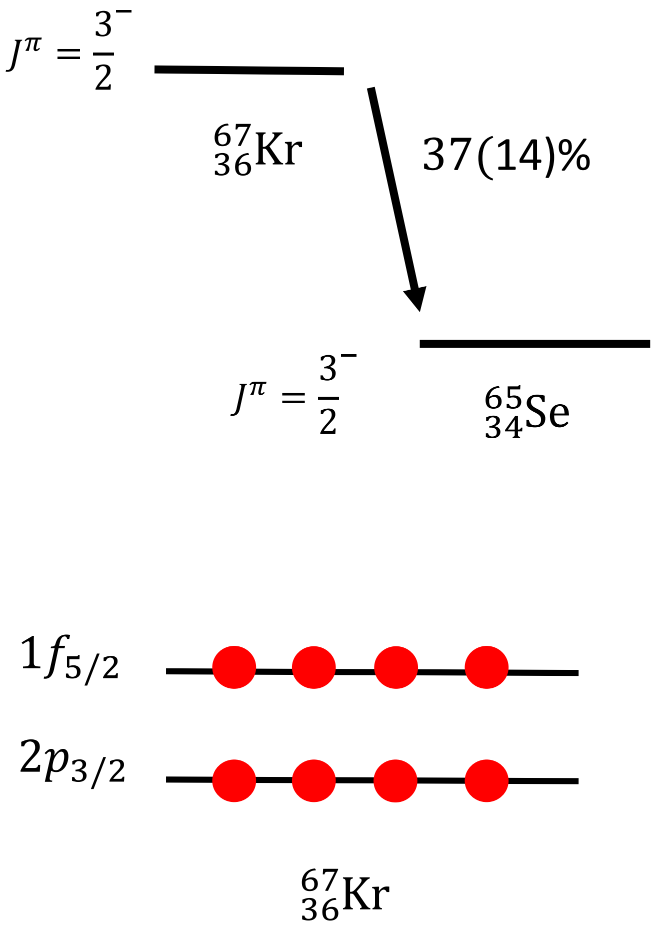
Goigoux et al., PRL 117, 162501 (2016)

- Prominent peak composed of 9 events at $\mathbf{1690(17)}$ $\boldsymbol{keV}$
- **The probability that we missed all $\boldsymbol{\beta}$ of the peak is less than $\mathbf{5.5 \times 10^{-6}}$**
- Also no $e^{-}e^{+}$annihilation γ was observed in coincidence with this peak: **8% probability of missing the 9 events.**
- $\boldsymbol{T_{1/2} = 7.4(30)\ ms}$
  - $\boldsymbol{BR_{2p}}$ **= 37(14)%**
    - 2p partial half-life $T_{1/2}^{2p} = 21(12)\ ms$
  - BR_{β} = 63(14)%
    - $\boldsymbol{T_{1/2}^{\beta} = 10(6)\ ms}$
    - Compatible with β Theory value: $\mathbf{11.1}\ \boldsymbol{ms}$

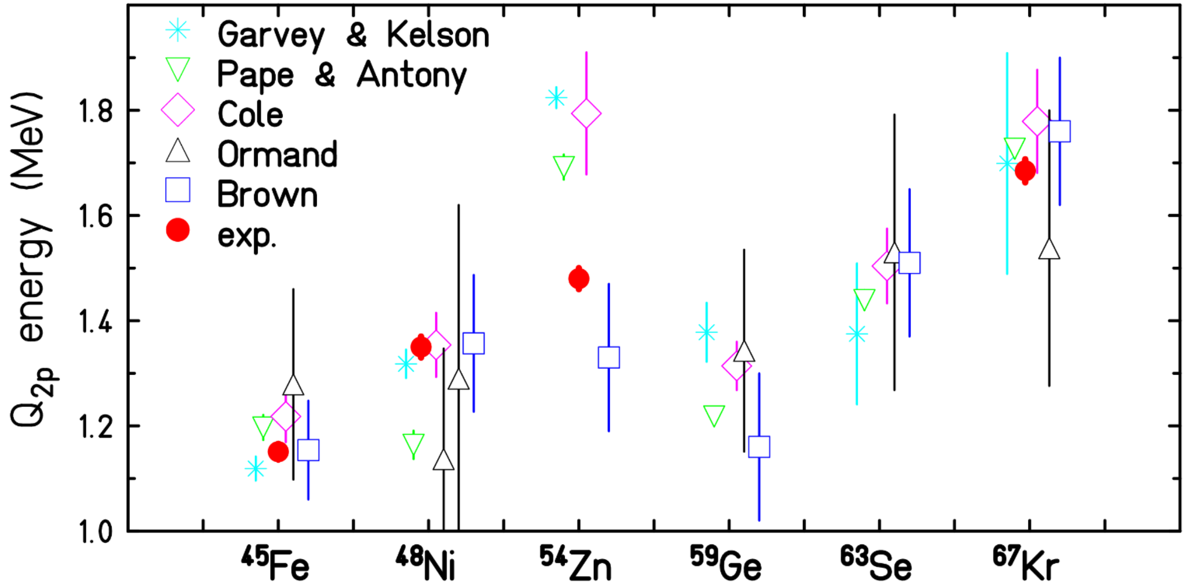
$^{67}\mathrm{Kr}$ confirmed as a new 2p emitter !

Comparison with Theory

- Assumed decay scheme:



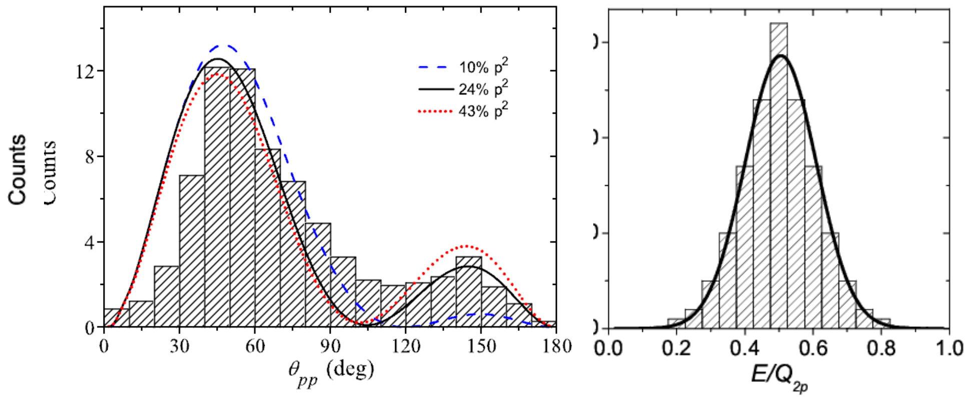
- $T_{1/2}$:
  - Smallest half-life given by models is 0.28 s
    - Still a factor 10 from our value (0.021(12)s)
- Q_{2P}:
  - Good fit with theory



Time Projection Chamber

2P study with a Time Projection Chamber

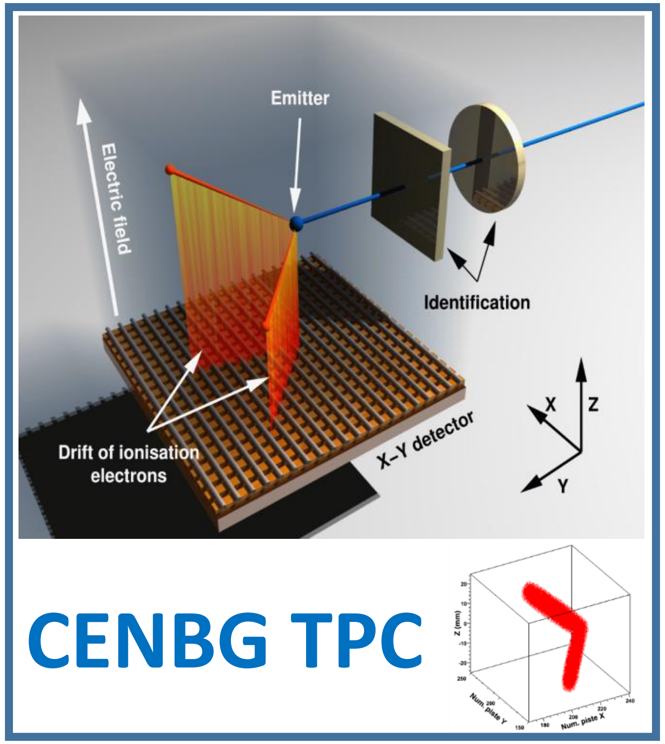
- Individual properties of the protons:
  - Emission relative angles
  - Individual energies
  - Comparison with structure models

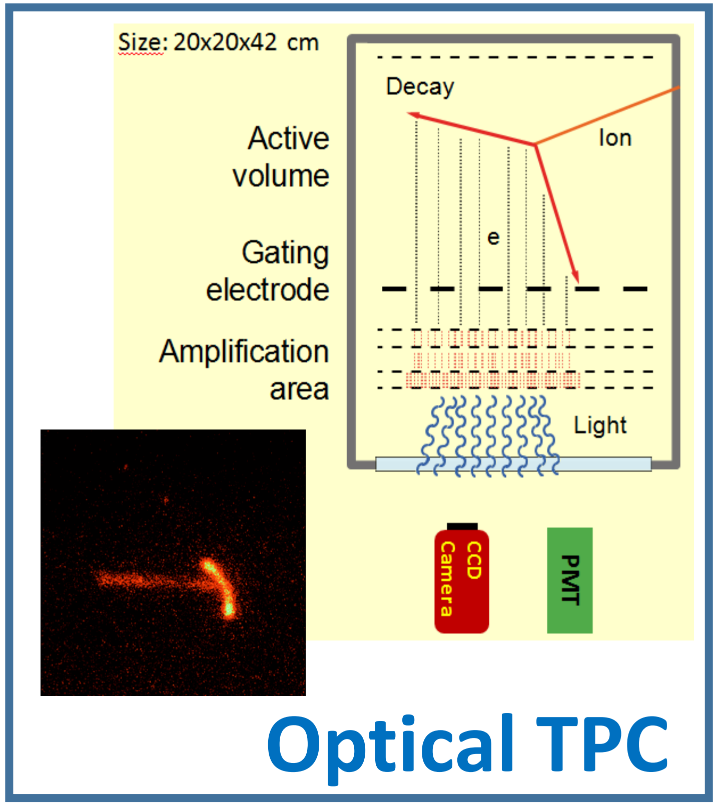


^{45}Fe results

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

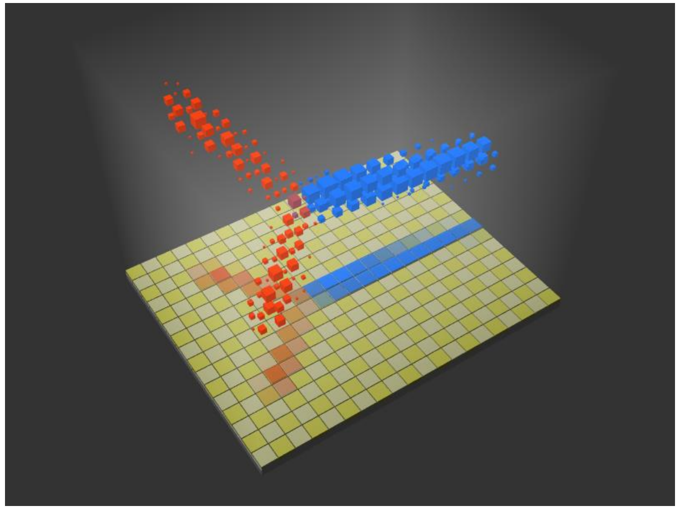
- Former TPCs used to observed the 2P

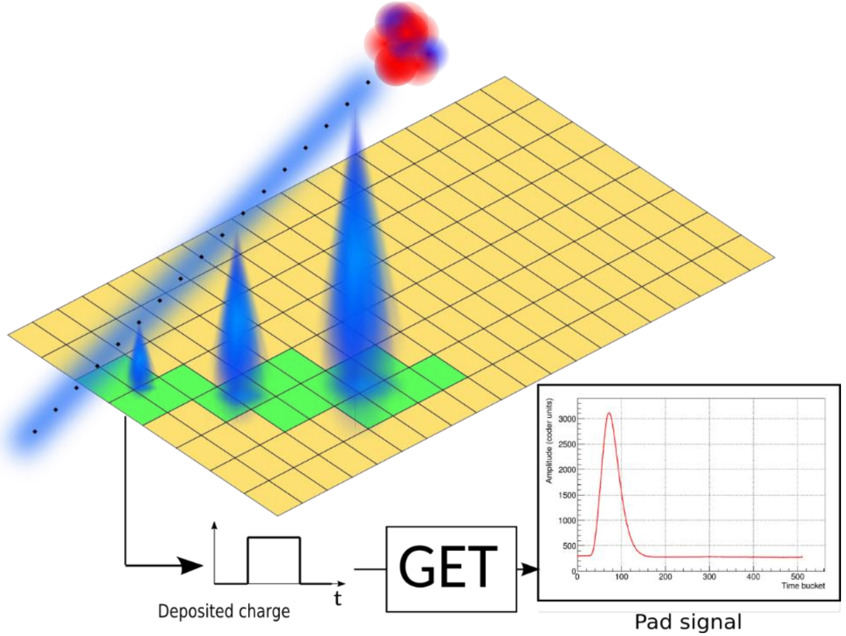




New generation of TPC

- ACTAR TPC
  - Pads instead of strips
    - →Real 2D decomposition
  - Dedicated mode to 2P → better dead time
  - Electronics GET (General Electronics for TPC)



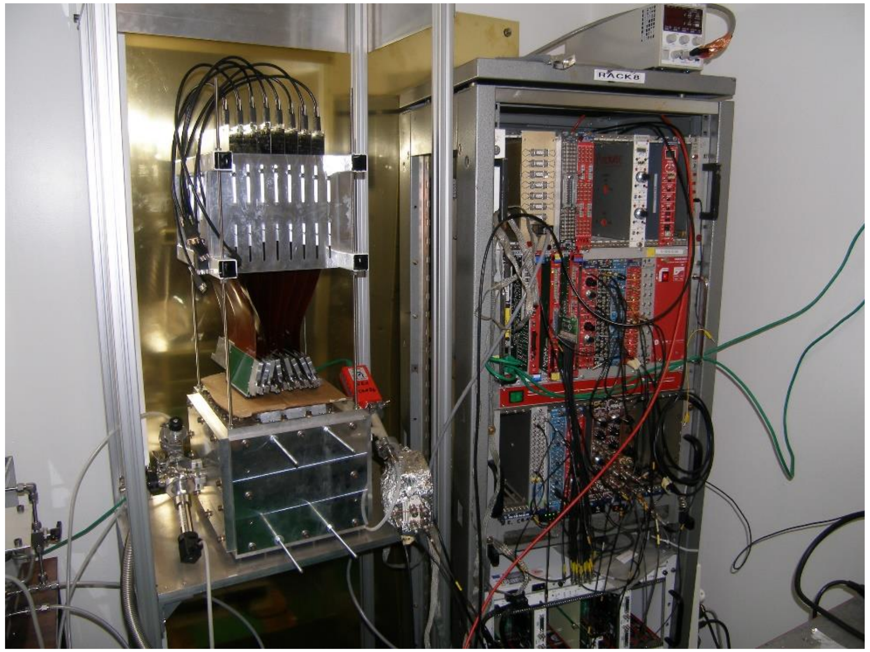


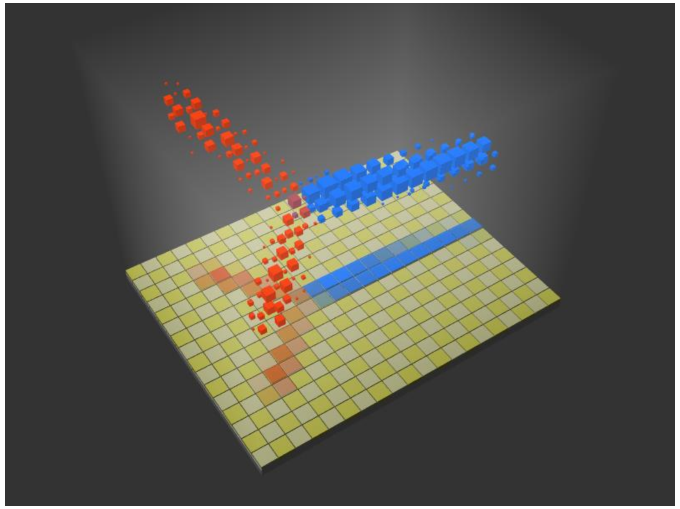
- Prototype tests:
  - Charge signal reconstruction:
    - Collected charge per pad→ energy loss
    - Timing information → z position

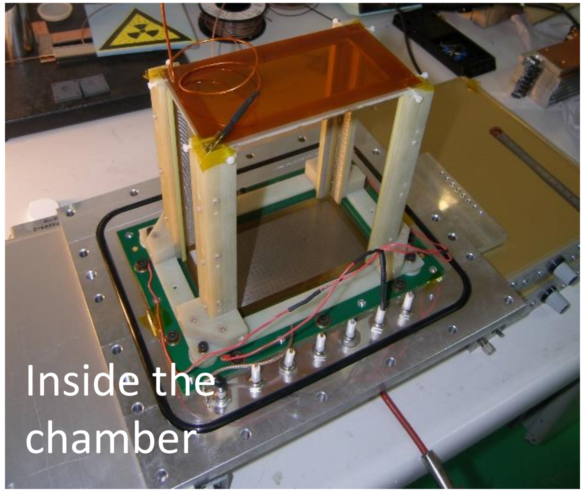
Giovinazzo et al., NIMA, 840, 15 (2016)

- Energy resolution tests

New generation of TPC







- Prototype tests:
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Giovinazzo et al., NIMA, 840, 15 (2016)

  - Energy resolution tests

Conclusion

Conclusions and perspectives

- A new 2P emitter was observed: $^{67}\mathrm{Kr}$
- Disagreement of our $T_{1/2}$ with theoretical calculations

- Outlook
  - Direct observation of $^{67}\mathrm{Kr}$ → correlations measurement
    - Development of a new TPC (ACTAR TPC collaboration) coupling to the General Electronics for TPCs (GET).
    - Final detector assembled in 2017 with a test experiment in summer.
  - Need of new 2P calculation models in this mass region

Thank you for your attention !