Two-proton radioactivity studies

- two-proton radioactivity
- discovery of two-proton radioactivity
- Experimental results with TPC
- future studies
alpha emission of $^4\text{He}$
2 protons + 2 neutrons

beta +
proton $\rightarrow$ neutron
+ light particles

beta -
neutron $\rightarrow$ proton
+ light particles

fission
break-up of a nucleus
$\rightarrow$ two light nuclei

"classical" radioactivities
One-proton radioactivity
nucleus → proton
+ nucleus - 1

Two-proton radioactivity
nucleus → two protons
+ nucleus - 2
Two-proton radioactivity studies

Sequential emission:

Three-body decay

$^2$He emission:

Measurement of protons and recoil
Primary beam:
$^{58}$Ni @ 75 MeV/A
intensity: 3 - 4 μAe

SISSI target:
nat Ni 200 mg/cm$^2$

detector Be (50 μm)
Wien filter

detection setup

spectrometer LISE3:
RF cyclotron

silicon telescope
identification of implanted fragments
DSSSD (X-Y): 2 x 16 x 3 mm

- veto for light particles
- residual energy, x-y position
- energy loss
- time of flight:
  micro-channel plate detectors
RF cyclotron
two-proton decay of iron-45 from GANIL 2000

Giovinazzo et al., 2002
**GSI / FRS experiment: 2001**

- **beam intensity** (SEETRAM)
- **primary beam** 650 MeV/u $^{58}$Ni
- **target** 4 g/cm$^2$ Be
- **TOF 1, 2, 3** (scintillators)

**in flight identification**
- $B_p$ 2 $\Rightarrow p/Z$
- $\Delta E$ $\Rightarrow Z$
- $\text{ToF 1,2,3} \Rightarrow A/Z$

- **S1 degrader** 3.2 g/cm$^2$ Al
- **S2 degrader** 3.6 g/cm$^2$ Al
- **Nal barrel**
  - identified ions
  - 511 keV trigger, $\Delta E$
  - 300 $\mu$m Si
  - Si-telescope 7 x 300 $\mu$m

**M. Pfützner et al. (2002)**
identification: 6 implantations of $^{45}\text{Fe}$

$T_{1/2} = 3.4^{+3.4}_{-1.1} \text{ ms}$
$Q_{2p} = 1.1 \pm 0.1 \text{ MeV}$

four 2p decay events

M. Pfützner et al., 2002
two-proton radioactivity of zinc-54

$^{54}\text{Zn}$
second decay
β detected

Energy (keV)

Counts

$^{54}\text{Zn}$
second decay

$T_{1/2} = 3.2^{+1.8}_{-0.8} \text{ ms}$

time (ms)

Counts

nickel-48 from GANIL 2004

energy (MeV)

counts

energy (MeV)

12

0 5 10 15 20 25 30 35 40

time (ms)

1 2

0 1 2 3 4 5 6 7 8
agreement with 3-body model, SMEC, and R-matrix model with p-p resonance
agreement with 3-body Model, SMEC, and R-matrix model with p-p resonance

Grigorenko et al.
Brown and Barker
Rotureau et al.
However:
- only total decay energy, half-life, no beta, daughter decay
- no individual energies
- no proton-proton angle
aim
measurement of individual proton energies and proton-proton angle
→ distinction between correlated $^2$He or uncorrelated 3-body decay

principle of detection
implantation in gas volume
traces in 3D of protons
→ X-Y detector
→ Z from time projection

technology: MGMS + GEMs
electronics: ASICs
1500 electronics channels

GEM: Gas electron multiplier

2D detector

Hybrid boards

Daughter boards

beam
Results for Chromium-43 and Iron-45

$^{43}$Cr: $\beta^{2p}$

$^{45}$Fe: $2p$

J. Giovinazzo et al.
Run 410

X implantation

Y implantation
Run 1155

- X: Implantation
- Y: Implantation
- X: Decay
- Y: Decay
Warsaw time projection chamber

technology: CCD camera + PM

K. Miernik et al.
Two-proton correlations

M. Pfützner et al.
Conclusions

- two-proton radioactivity is discovered
- first direct observation of two protons in 2p radioactivity
- need for microscopic interpretation
- new candidates exist, but are they sufficiently 2p unbound...???
collaborations

**GANIL experiments**
- CEN Bordeaux-Gradignan (France)
- GANIL Caen (France)
- IAP Bucharest (Romania)
- Warsaw University (Pologne)
- NSCL-MSU (USA)
- University of Santiago di Compostella (Spain)
- IPN Orsay (France)
- LPC Caen (France)
- KU Leuven (Netherlands)

**GSI experiment**
- Warsaw University (Poland), GSI Darmstadt (Allemagne),
- CEN Bordeaux-Gradignan (France), GANIL Caen (France),
- ORNL (Tennessee / USA), Edinburg University (UK)

**MSU experiment**
- Warsaw University (Poland), MSU (USA),
- ORNL (Tennessee / USA), University of Tennessee (USA)
time projection chamber

TPC chamber
Electronics card
Detector mount

Strip-strip matrix

GEM

$\Phi = 70 \, \mu m$

$d = 100 \, \mu m$

$\phi = 70 \, \mu m$

50 $\mu m$
Double-sided micro-strip gas detector

Anodes:
- 768 microstrips of copper on a capton substrate (2x100μm)
- Epoxi frame

Cathodes:
- 768 microstrips of copper (200μm)
Mother board
+ detector (15x15 cm²)
+ 2-3 GEMs
Detector: double-sided microstrip detector (CERN)

GEM: Gas electron multiplier (CERN)

Detector gas: P10 at 1atm

Active detection volume: 15 x 15 x 15 cm³

ASICS: VAT/TAT by IDEAS, Norway

  TAC window: 10 μs
  
  channels per chip: 32 time and energy

Electronics and data acquisition: PXI - VME
Run 1163
Accelerator laboratories
Two-proton radioactivity of $^{45}$Fe observed in three independent experiments:

**Branching ratio for 2p decay: 60 %**

competition between $\beta$p and 2p

predictions for $\beta$ decay half-life:

- $T_{1/2} = 11.7$ ms (Gross theory)
- 7 ms (Ormand et al.)
- 7 – 30 ms (Hirsch et al.)

$T_{1/2} \approx 3.8$ ms

$T_{1/2} \approx 6$ ms
Daughter decay: Chrome-43
Daughter decay: Nickel-52

The graph illustrates the half-lives of various isotopes related to the decay of Nickel-52. The half-life values are plotted on a logarithmic scale. The isotopes represented include:

- 52Ni
- 53Ni
- 52Co
- 54Fe
- 57Mn
- 59Cr

The graph highlights the experimental data and theoretical predictions for the decay of 54Zn, indicating the daughter half-lives.
Candidates for future studies

- **$^{45}$Fe**: $T_{1/2} = 1.75^{+0.49}_{-0.28}$ ms, $E_{2p} = 1.151(15)$ MeV, BR = 59(7)%
  
  $E_{2p} = 1.279(181)$ MeV (O), 1.218(49) MeV (C), 1.154(94) MeV (B)

- **$^{48}$Ni**: $T_{1/2} = 2.2^{+2.2}_{-0.7}$ ms, $E_{2p} = 1.35(2)$ MeV, BR = 25(+29 -19)%
  
  $E_{2p} = 1.137(210)$ MeV (O), 1.290(330) MeV (O), 1.354(61) MeV (C)
  
  1.357(130) MeV (B)

- **$^{54}$Zn**: $T_{1/2} = 3.2^{+1.8}_{-0.8}$ ms, $E_{2p} = 1.48(2)$ MeV, BR = 87 (+10 -17)%
  
  $E_{2p} = 1.794(116)$ MeV (C), 1.33(14) MeV (B)

- **$^{59}$Ge**: $E_{2p} = 1.16(14)$ MeV (B.A. Brown), 1.314(46) MeV (Cole), 1.343(192) MeV (Ormand)

- **$^{63}$Se**: $E_{2p} = 1.51(14)$ MeV (B.A. Brown), 1.504(71) MeV (Cole), 1.530(262) MeV (Ormand)

- **$^{67}$Kr**: $E_{2p} = 1.76(14)$ MeV (B.A. Brown), 1.779(98) MeV (Cole), 1.538(262) MeV (Ormand)

- **$^{58}$Ge**: $E_{2p} = 2.38(14)$ MeV (B.A. Brown)

- **$^{62}$Se**: $E_{2p} = 2.76(14)$ MeV (B.A. Brown)
Two-proton radioactivity experiments at the Big RIPS

- **Nuclei of interest:** $^{59}\text{Ge}$, $^{63}\text{Se}$, $^{67}\text{Kr}$
- **Production:** $^{78}\text{Kr}$ fragmentation at 360 MeV/u, 100 pnA
- **Separation:** BigRIPS
- **Detection:** standard BigRIPS detection + silicon telescope with DSSSD (1mm) + Germanium detectors

- **Settings:** $^{59}\text{Ge}$, rate = 9 ppd (CENBG, Stolz et al. + EPAX2)
- **Settings:** $^{63}\text{Se}$, rate = 6 ppd (Stolz et al. + EPAX2)
- **Settings:** $^{67}\text{Kr}$, rate = 4 ppd (Stolz et al. + EPAX2)
- **New isotopes:** $^{59}\text{Ge}$, $^{63}\text{Se}$, $^{68,67}\text{Kr}$