Charged-particle spectroscopy with the Optical TPC

Marek Pfützner

Nuclear Physics Division
University of Warsaw

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Outline

- Nuclei at the proton drip-line and beyond
  - Two-proton radioactivity
- Optical TPC
- Decay study of $^{45}\text{Fe}$ (and $^{43}\text{Cr}$)
- Decay study of $^{48}\text{Ni}$ (and $^{46}\text{Fe}$, $^{44}\text{Cr}$)
- Beta-delayed 3p emission from $^{31}\text{Ar}$
- Rare decay of $^{6}\text{He}$
- Beta decay of $^{8}\text{He}$
- New TPC for ELI-NP
Beyond the proton drip-line

The $\beta^+$ decay

Probability of transition:

$$\lambda \sim Q^5$$

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

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

The emission of particles

There is a potential barrier which hampers emission of an unbound proton ($\alpha$, 2p, $^{14}$C,..)

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

To find where the drip-line actually is and to predict which decay will happen, precise estimates of atomic masses are required!

To study particle radioactivity fast techniques are needed!
When the $\beta$ decay energy is large, many exotic channels are available.
The limit of „existence” beyond the proton drip-line is determined by emission of protons.

Visually, the emissions are categorized as:
- **Simultaneous (2p)**: Where both protons are emitted simultaneously, denoted by \( Q_p < 0, Q_{2p} > 0 \), indicated by the label „true” simultaneous.

- **Sequential (pp)**: Where the protons are emitted one after the other, denoted by \( Q_p > 0, Q_{2p} > 0 \), indicated by the label sequential.

Graphs illustrate the separation energy [MeV] as a function of the neutron number for different proton numbers (Z).

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

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Global prediction based on EDF theory with 6 Skyrme forces and simple models of 2p emission

New terra incognita

Model averaged path of 2p/pp emission


OLSEN ET AL., PRL 110 (2013) 222501; PRL 111 (2013) 139903 (E)
TPC detector

Time projection chamber with optical readout (OTPC)

- Combination of the CCD image with the PMT waveform allows to fully reconstruct the track in three dimensions
Raw data and ion ID

CCD

ID data

Experimental data
Slope fit
TAC fit
Zero point

ΔE
TOF

PMT

Ion implantation
Decay

PMT voltage [mV]

Time [ms]

Number of events

ΔE [V]
TOF [V]
A track is reconstructed by comparing the data with the SRIM simulation.

\[ E_p = 1393 (50)(6) \text{ keV} \]
\[ \Theta = 28 (4)(1) \text{°} \]

Pomorski et al., PRC 90 (14) 014311
Study of $^{45}$Fe

- NSCL/MSU, February 2007: $^{58}$Ni at 161 MeV/u + natNi $\rightarrow$ $^{45}$Fe

![Diagram of experimental setup]

![Energy loss vs. time-of-flight plot]

2p decay of $^{45}$Fe

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p-p momentum correlations for $^{45}$Fe

Proton-proton momentum correlations measured for $^{45}$Fe are complex and indicate a genuine 3-body phenomenon.

Good agreement with the 3-body model of Grigorenko et al.

Miernik et al., PRL 99 (07) 192501  Grigorenko et al., PLB 677 (2009) 30  MP, Karny, Grigorenko, Riisager, RMP 84 (12) 567
Decays of $^{45}$Fe and $^{43}$Cr

$^{45}$Fe and $^{43}$Cr

$Q_{EC} = 18.7$ MeV

$T_{1/2} = 7$ ms

$\beta^+ + \beta^+ + \beta^2 p$

$45$Mn$+ p$

$45$Fe

$\beta^2 p$

$\beta^3 p$

$44$Mn$+ p$

NSCL/MSU, 2007

$\beta^3 p$

$0.08\%$

$\beta^2 p$

$11\%$

$\beta^p$

$\approx 70\%$

$\approx 30\%$

$\approx$ 70%

$\approx$ 30%

$40$Ca$+ 3p$

$41$Sc$+ 2p$

$42$Ti$+ p$

$43$V

$45$Mn

$44$Cr$+ p$

$44$Cr$+ 2p$

$43$V$+ 2p$

$42$Ti$+ 3p$

$41$Sc$+ 4p$

Pomorski et al., Phys. Rev. 83 (2011) 014306

Miernik et al., PRL 99 (07) 192501

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Study of $^{48}\text{Ni}$

- NSCL/MSU, March 2011: $^{58}\text{Ni}$ at 160 MeV/u + $^{\text{nat}}\text{Ni}$ → $^{48}\text{Ni}$

10 events of $^{48}\text{Ni}$ in 10 days

Cross section: $\sigma = 150(50)$ fb!

Pomorski et al., PRC 90 (14) 014311
2p decay of $^{48}$Ni

Four 2p events of $^{48}$Ni

$Q_{2p} = 1.29 (4) \text{ MeV}$

Pomorski et al., PRC 90 (14) 014311
\[ \beta\text{-delayed protons from }^{44}\text{Cr} \]

5542 identified ions of \(^{44}\text{Cr}\)
4098 properly stopped
183 decays observed
\[ b_p = 10(1)\% \]
Dossat: \[ b_p = 14.0(9)\% \]

A clear new line at 740(20) keV
\[ I_p = 0.6(2)\% \]

Pomorski et al., PRC 90 (14) 014311
β-delayed protons from $^{46}$Fe

471 identified ions of $^{46}$Fe  
269 properly stopped  
148 decays observed  

$\Rightarrow b_p = 66(4)\%$  
Dossat: $b_p = 79(4)\%$


19 reconstructed protons

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Pomorski et al., PRC 90 (14) 014311
β2p channel in $^{46}$Fe

One good event!

![CCD Image](Image)

![PMT Image](Image)

![Energy-Time Spectrum](Image)

![Energy-TOF Spectrum](Image)
Both protons escaped the detector. From the length of tracks we know only that:

\[ E_1 > 1.96 \text{ MeV} \]
\[ E_2 > 1.67 \text{ MeV} \]
\[ E_1 + E_2 > 3.63 \text{ MeV} \]

This cannot go through the IAS!
Decay scheme of $^{48}\text{Ni}$

$Q_{2p} = 1.29 (4) \text{ MeV}$

$T_{1/2} = 2.1^{+1.4}_{-0.6} \text{ ms}$
β3p in $^{31}$Ar

**Decay modes of $^{31}$Ar and first observation of β-delayed three-proton radioactivity**

D. Bazin,* R. Del Moral, J. P. Dufour, A. Fleury, F. Hubert, and M. S. Pravikoff

*Centre d’Etudes Nucléaires de Bordeaux – Gradignan, Le Haut Vigneau 33175 Gradignan CEDEX, France*

**31Ar examined: New limit on the β-delayed three-proton branch**

H. O. U. Fynbo,1 L. Axelsson,2 J. Åystö,3 M. J. G. Borge,4 L. M. Fraile,4 A. Honk4 A. Jokinen,3 B. Jonson,1 I. Martel,3,7 I. Mukha,1,2 T. Nilsson,5,8 G. Nyman,2 M. Oinio4 M. H. Smedberg,2 O. Tengblad,4 F. Wenander,2 and the ISOLDE
\[ \beta 3p \text{ in } ^{31}\text{Ar} \]

- Experiment at FRS, August 2012

Confirmed at ISOLDE

Lis et al., to be published

Koldste et al., PRC 89 (2014) 064315
Decay of $^6\text{He}$ into $\alpha + d$

- $^6\text{He}$ has a very weak decay branch to $\alpha + d$

Due to $\beta$-background, it was not possible to determine the spectrum below $E_{\text{CM}} \approx 400$ keV!

No model has succeeded in satisfactory description of both the shape and the intensity of the $\alpha+d$ spectrum!

Due to $\beta$-background, it was not possible to determine the spectrum below $E_{\text{CM}} \approx 400$ keV!

A bunch of $\approx 10^3$-$10^4$ $^6\text{He}$ ions, accelerated to 3 MeV/u by REX-Isolde, is implanted into the OTPC. The difference in the depth of implantation corresponds to the energy loss of $^6\text{He}$ in a layer of 5 $\mu$m of Cu + 2 $\mu$m of Au.

Data are taken for 650 ms exposure. Light from many beta decays is seen as a smeared cloud around the implantation points.

The difference in the depth of implantation corresponds to the energy loss of $^6\text{He}$ in a layer of 5 $\mu$m of Cu + 2 $\mu$m of Au.
Decay of $^6\text{He}$ with OTPC at ISOLDE

CCD image, 650 ms exposure

PMT slow sampling, 1 MHz (rough history of what happened)

PMT fast sampling, 100 MHz (fine details of events)

Bunch of $10^3$-$10^4$ $^6\text{He}$ ions

> Practically no background in the PMT traces
Event reconstruction

Horizontal length: 23 mm
Vertical length: 62 mm
Total length = 66 mm
Angle = 69°
Energy = 1000 ± 30 keV
Event reconstruction

Horizontal length: 3 mm  
Vertical length: 16 mm  
Total length = 16 mm  
Angle = 80°  
Energy = 150 ± 10 keV
The spectrum

317 events collected in 12 h

Full statistics should be up to 6 times larger
The previous experiment on $^8$He $\beta$ decay:

**ISOLDE (1992)**
M. Borge et al., NP A 560 (1993) 664

- Observation of strong $\beta$-delayed triton channel

$$^8\text{He} \rightarrow ^8\text{Li}^* \rightarrow \alpha + t + n$$

The branching: $(8.0 \pm 0.5) \times 10^{-3}$

$B_{GT} \geq 5.2$, $\log ft = 2.9$!

Essentially, this is the tetra-neutron decay to a triton and a neutron! (If the clustering approximation is the good one).
Decays to particle bound states of $^8$Li

Dubna, Acculinna, 2009/2012
Final-state continuum in $^8$Li $\rightarrow 2\alpha$ decay

Mianowski, PhD thesis
Bhattacharya et al. PRC73(2006) 055802

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Reconstruction of $\alpha$-t-n decay event

$Q = 4.3$ MeV

$E_a = 1150$ keV
$E_t = 2570$ keV
$E_n = 610$ keV

We see about 400 triton events. The branching for the $\beta t$ is 0.9%
Feeding of $\alpha$-$t$-$n$ decaying states

$E_n$ (MeV)

$^{8}\text{He}$

$^{8}\text{Li}$

$B_{\text{GT}}$ evaluation is in progress

Mianowski, Janas, to be published
Mianowski, PhD thesis
Understanding the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ reaction is still one of the key open questions in nuclear astrophysics. It determines the carbon/oxygen ration which determines the fate of massive stars and the light curve of SN Ia ("standard candles").
The proposed solution is to measure the reverse reaction: \( \gamma + ^{16}\text{O} \rightarrow ^{12}\text{C} + \alpha \) using photon beams at ELI-NP.

Advantages: very clean signal, no background issues, angular correlations allows E1/E2 decomposition

To have the full freedom of gas selection, a new detector with electronic readout is developed at University of Warsaw

Other reactions planned:
\( ^{19}\text{F}(\gamma, p)^{18}\text{O} , \quad ^{22}\text{Ne}(\gamma, \alpha)^{18}\text{O} , \)
\( ^{24}\text{Mg}(\gamma, \alpha)^{20}\text{Ne} , \ldots \)

See a talk by Jan Bihałowicz on Thursday!
The OTPC detector is a very efficient tool to search for very rare multiparticle decays or to investigate particle decays obscured by beta background.

Can provide precise branching ratios for $\beta$-delayed particle channels. Although the energy resolution is worse than for Si detectors, yields complementary data for low-energy particles.

Non-trivial 3-body character of 2p decay of $^{45}$Fe discovered. 2p decay of $^{48}$Ni discovered.

New decay channels, like $\beta$3p ($^{45}$Fe, $^{43}$Cr, $^{31}$Ar), observed for the first time. $\beta$2p emission discovered in $^{46}$Fe based on one atom decay!

Low-energy part of d-spectrum will shed light on the halo structure of $^6$He

Strong $\beta$-delayed triton emission confirmed for $^8$He. Will provide the $B_{GT}$ strength for the t-emitting states.

A new TPC with electronic read-out being developed for ELI-NP to solve the helium burning problem.
Thank you!