Investigating proton drip-line nuclei with Optical Time Projection Chamber

Marcin Pomorski

University of Warsaw

May 30, 2013

Contents

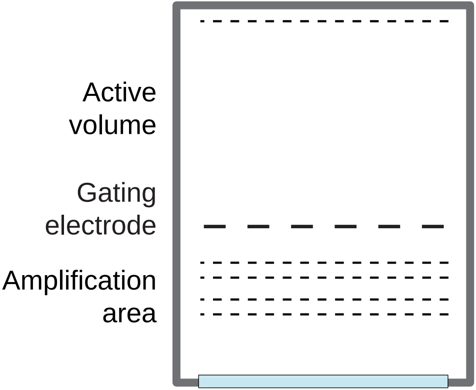
- Motivation
- The Optical Time Projection Chamber
- β-decay of ^{43}Cr
- Two-proton decay of ^{48}Ni
- The β-delayed emitters: ^{44}Cr and ^{46}Fe

Motivation

- Study of very neutron deficient nuclei at and beyond proton drip-line
- Characteristic phenomena
  - Large β-decay energies $\rightarrow$ emission of delayed particles (p, $2p$, $3p$, α, d, t, ...)
  - Proton radioactivity (odd-Z)
  - Two-proton radioactivity (even-Z)
- Need to detect charged particles
- Detection of multi-particle decays and low-energy particles with Si detectors is difficult
- Gaseous detectors (TPC) offer a possible solution

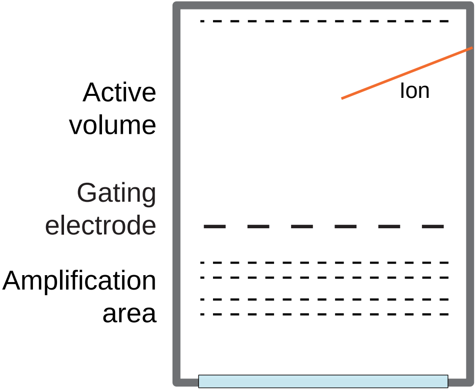
Optical Time Projection Chamber - OTPC

- Chamber is filled with a gas mixture



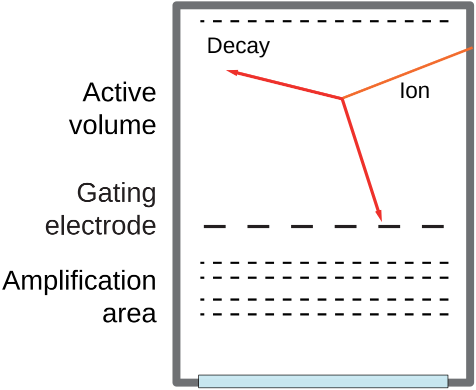
Optical Time Projection Chamber - OTPC

- Chamber is filled with a gas mixture
- Ion is implanted in the active volume



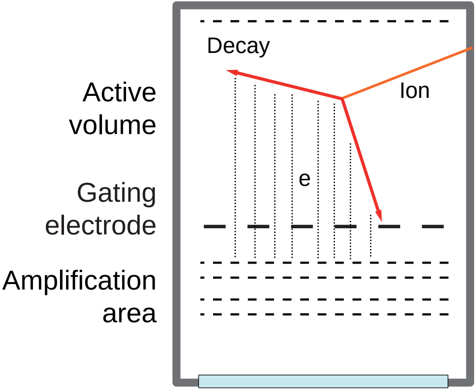
Optical Time Projection Chamber - OTPC

- Chamber is filled with a gas mixture
- Ion is implanted in the active volume
- Decay occurs



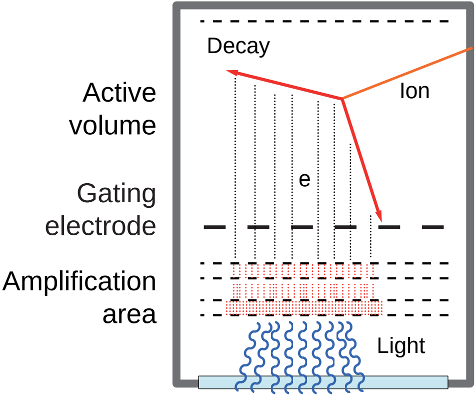
Optical Time Projection Chamber - OTPC

- Chamber is filled with a gas mixture
- Ion is implanted in the active volume
- Decay occurs
- Ionization electrons drift with the constant velocity



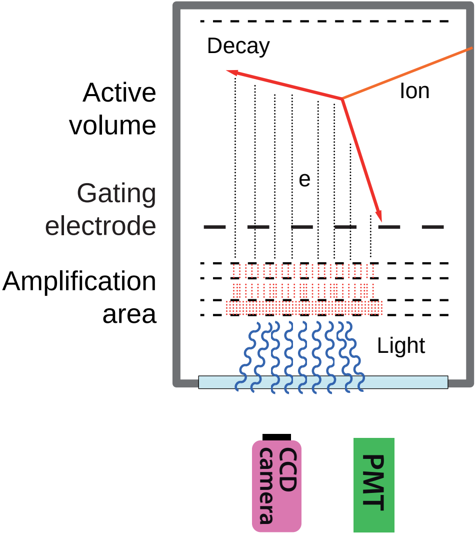
Optical Time Projection Chamber - OTPC

- Chamber is filled with a gas mixture
- Ion is implanted in the active volume
- Decay occurs
- Ionization electrons drift with the constant velocity
- The electric signal is amplified and converted to light



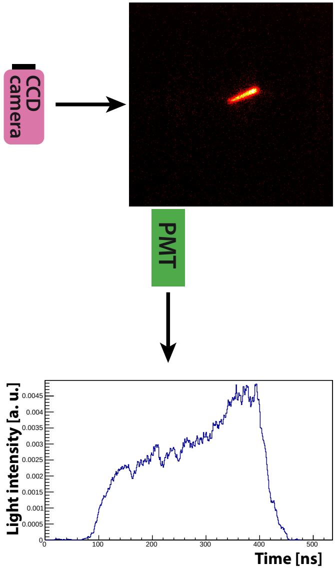
Optical Time Projection Chamber - OTPC

- Chamber is filled with a gas mixture
- Ion is implanted in the active volume
- Decay occurs
- Ionization electrons drift with the constant velocity
- The electric signal is amplified and converted to light
- Light is registered in a CCD camera and a fast photomultiplier



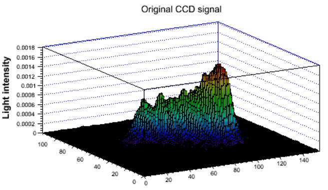
OTPC readout

- We use LabView environment
- Each event consists of a CCD image and...
- ... a trace from PMT sampled by a fast oscilloscope, yielding light intensity as a function of time
- ID data of the ion can be also saved



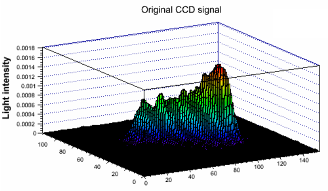
Reconstruction

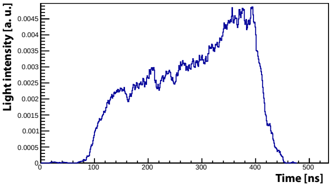
- The CCD image gives information about the event in the XY plane



Reconstruction

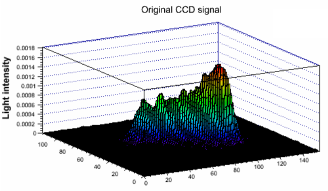
- The CCD image gives information about the event in the XY plane
- The PMT trace provides information along Z axis

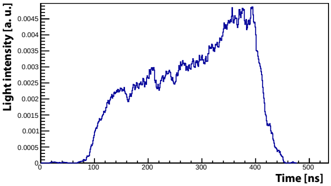




Reconstruction

- The CCD image gives information about the event in the XY plane
- The PMT trace provides information along Z axis
- Combining the two yields the full 3D reconstruction

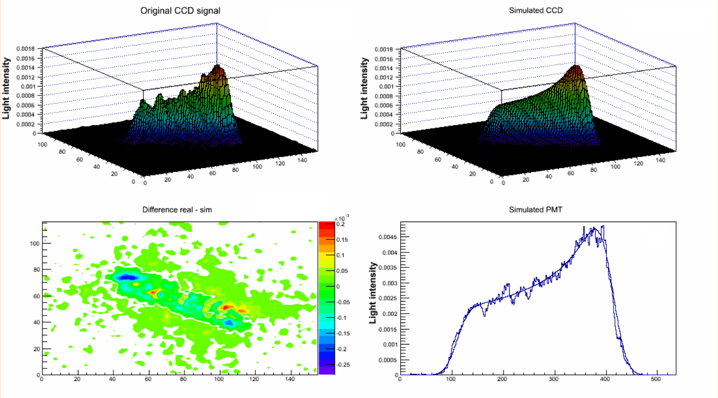




Reconstruction

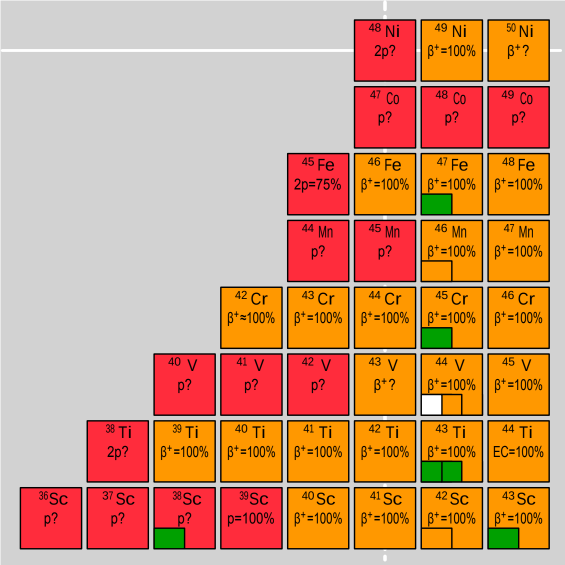
Reconstructed alpha event

Example reconstruction of an α particle registered in OTPC. It yields the energy and the direction of the emitted particle.



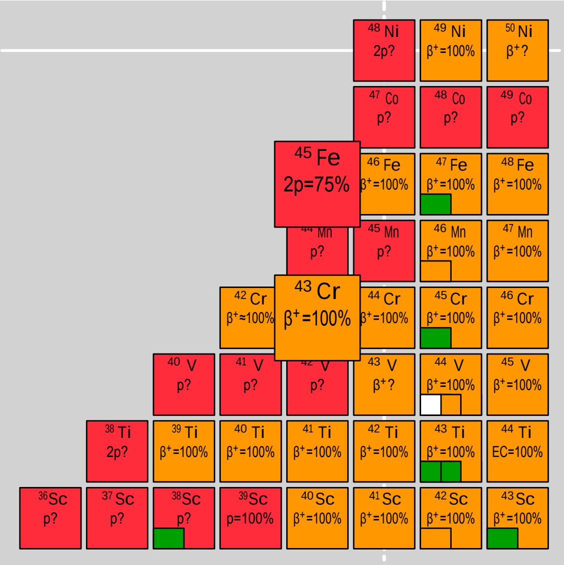
The region

We concentrate on a region in vicinity of ^{45}Fe and ^{48}Ni, where two-proton radioativity is known to occur.



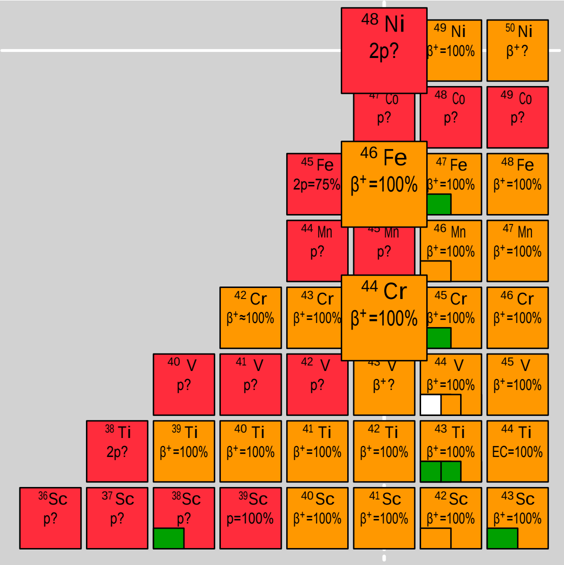
The region

We concentrate on a region in vicinity of ^{45}Fe and ^{48}Ni, where two-proton radioativity is known to occur.



The region

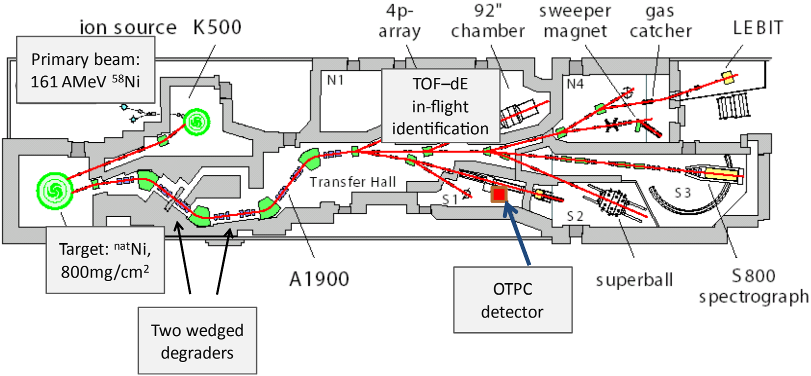
We concentrate on a region in vicinity of ^{45}Fe and ^{48}Ni, where two-proton radioativity is known to occur.



^{43}Cr experiment

NSCL/MSU - 2007

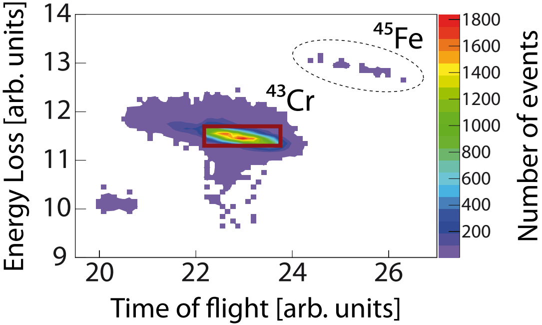
The main goal of the experiment was 2p-decay study of ^{45}Fe. However about 40 000 events of ^{43}Cr were collected during the run.



^{43}Cr experiment

Identification

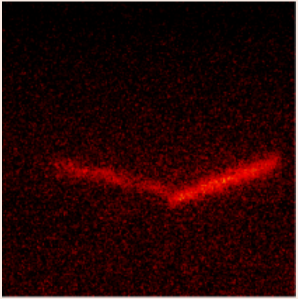
- The identification was performed using standard TOF-$\Delta\mathrm{E}$ method, using A1900 detectors
- These signals were registered independently by MSU and our setups.
- ID data were stored by the OTPC only for selected ions. Their ID spectrum is shown below

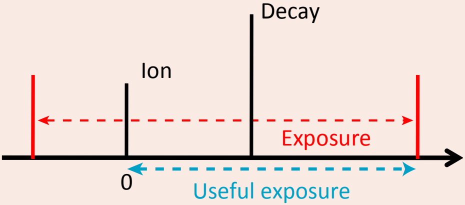


^{43}Cr experiment

CCD asynchronous mode

In this mode the exposures are taken one after another, but only frames co-inciding with identification trigger are saved. As a result the photo contains the implantation track, but useful exposure length is random.

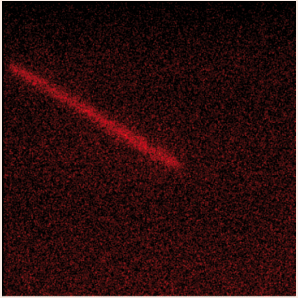


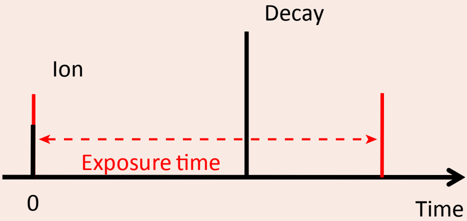


^{43}Cr experiment

CCD synchronous mode

In this mode the exposure is started by the trigger. As a result ion trace is not registered, but the exposure time is always the same.

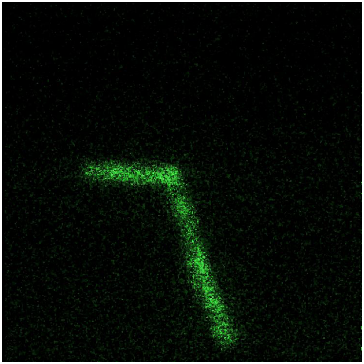


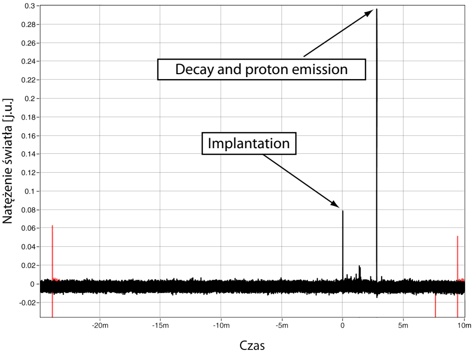


Decays of ^{43}Cr

β1p decays

Over 11 000 of registered ^{43}Cr events corresponded to β-delayed emission of 1 proton. Below is an example taken in the asynchronous mode.

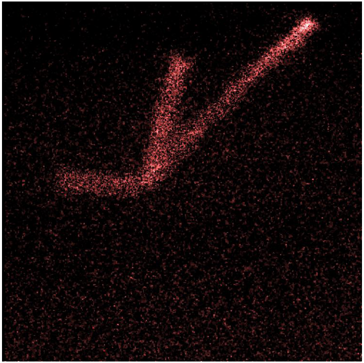


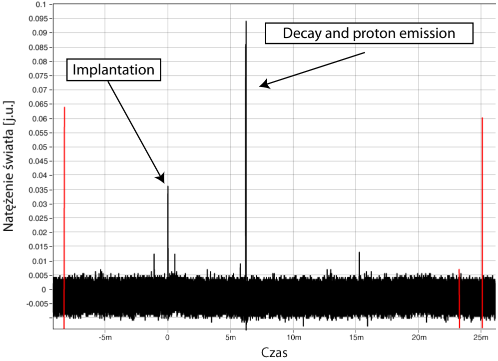


Decays of ^{43}Cr

β2p decays

About 1000 β-decays were followed by emission of 2 protons. Below an example of such a decay.

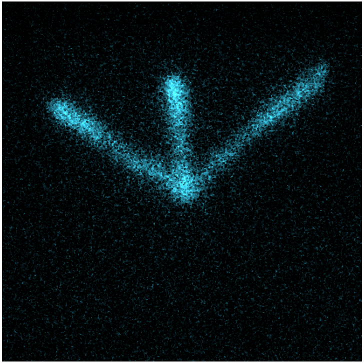


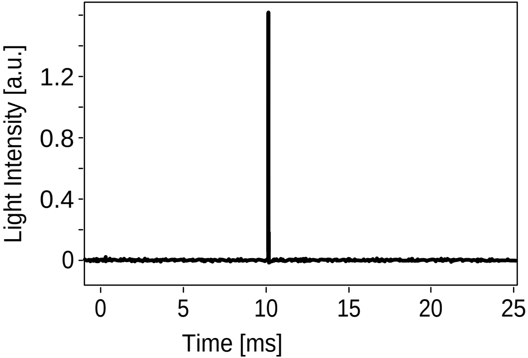


Decays of ^{43}Cr

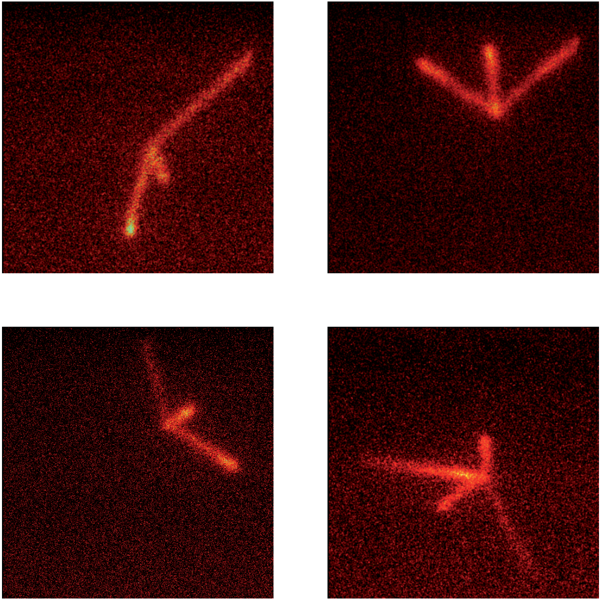
First observations of β3p emission from ^{43}Cr

This extremely rare decay channel is very hard to detect using silicon detectors, and was observed for the first time in this experiment. Only 13 events showed β3p emission. Below an example in the synchronous mode.





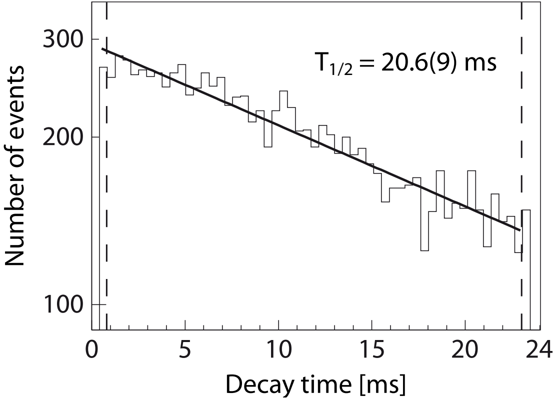
Decays of ^{43}Cr



^{43}Cr results

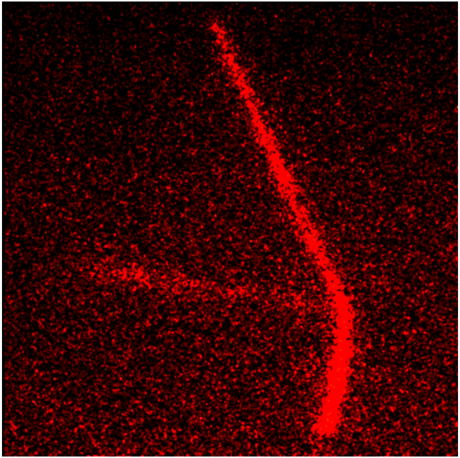
Half-life of ^{43}Cr

The half-life of ^{43}Cr was determined to be $T_{1/2} = 20.6(9)$ ms. Previously ^{43}Cr was studied by Dossat *et. al.*[1], where half life was reported to be $T_{1/2} = 21.1(4)$ ms.



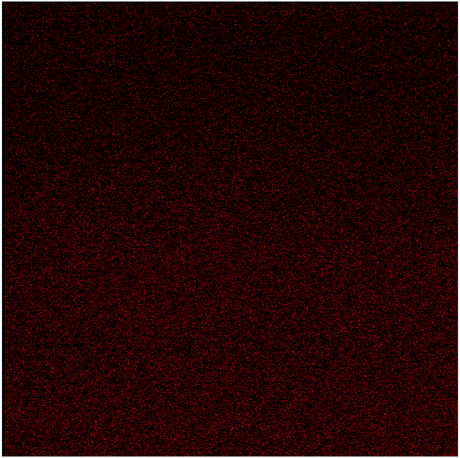
Branching ratios

- The number of emitted protons can be easily counted from CCD images



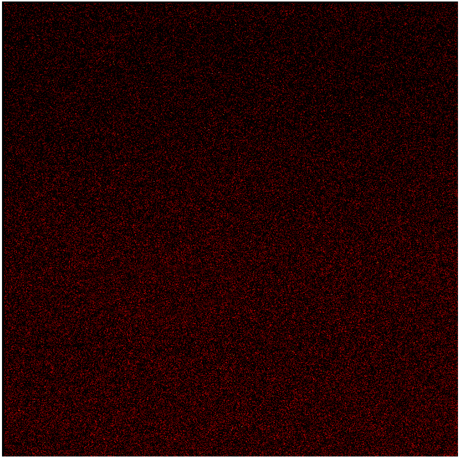
Branching ratios

- The number of emitted protons can be easily counted from CCD images
- Not all ions of ^{43}Cr were properly implanted in the OTPC - some of them stopped in the window



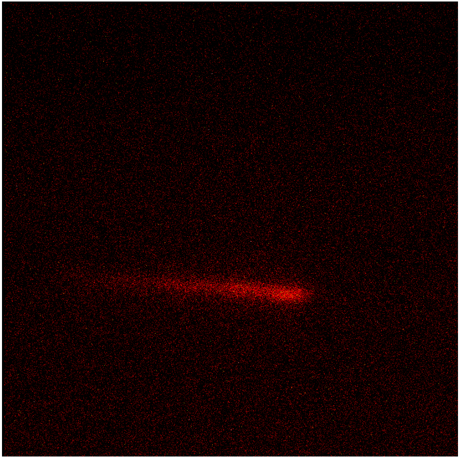
Branching ratios

- The number of emitted protons can be easily counted from CCD images
- Not all ions of ^{43}Cr were properly implanted in the OTPC - some of them stopped in the window
- In the synchronous mode we don't know if an ion was properly implanted



Branching ratios

- The number of emitted protons can be easily counted from CCD images
- Not all ions of ^{43}Cr were properly implanted in the OTPC - some of them stopped in the window
- In the synchronous mode we don't know if an ion was properly implanted
- In case of the asynchronous mode we see good implantations. However, the detector is not sensitive to β particles.



Branching ratios

Problem:

The β-decay without proton emission is indistinguishable from no decay during exposure.

Branching ratios

Problem:

The $\beta\text{-decay}$ without proton emission is indistinguishable from no decay during exposure.

Solution:

Using maximum likelihood method we can construct a function describing probability of measured data taking above situation into account.

Branching ratios

Problem:

The β-decay without proton emission is indistinguishable from no decay during exposure.

Solution:

Using maximum likelihood method we can construct a function describing probability of measured data taking above situation into account.

Maximum likelihood function

$$\mathscr{L}(b_e) = \prod_{i=0}^{N_e} \left\{ b_e \left[1 - \exp\left(-\lambda \tau^i \right) \right] \right\} \prod_{j=0}^{N_{ne}} \left\{ \exp\left(-\lambda \tau^j \right) + (1 - b_e) \left[1 - \exp\left(-\lambda \tau^j \right) \right] \right\}$$

Branching ratios

Branching ratios of ^{43}Cr

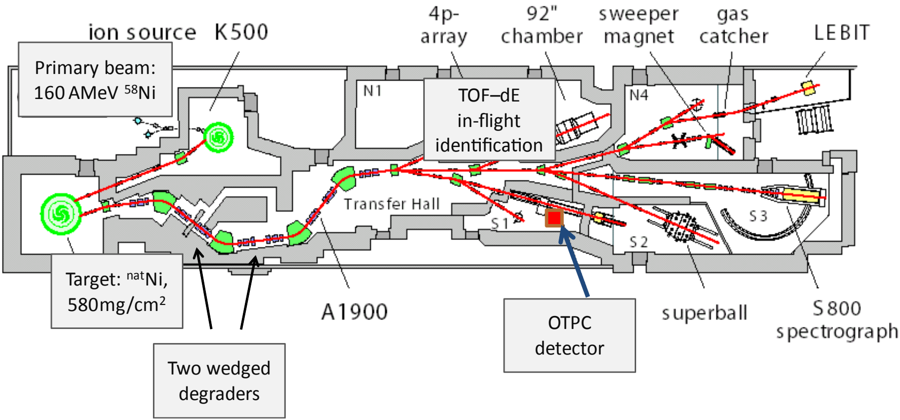
Resulting branching ratios are presented in table below, together with the data of Dossat *(et al.)*[1]. Note, that data from [1] were collected using Si detectors, where number of emitted protons was assigned only to strong lines in proton energy spectrum.

No. of emitted protons	Branching ratio [%]	Branching ratios of Dossat *et al.*[%]
0	12(4)	7.5(3)
1	81(4)	28(1)
2	7.1(4)	5.6(7)
3	0.08(3)	-

^{48}Ni experiment

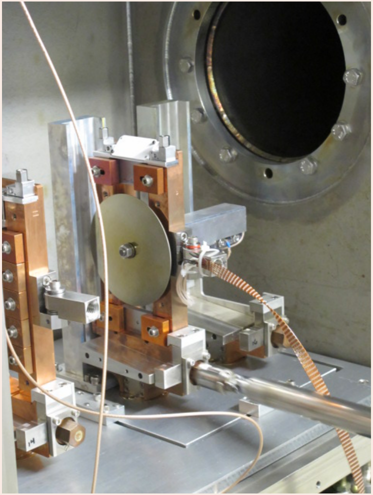
NSCL/MSU - 2011

This experiment was very similar to the previous one. The main difference was much more intense beam - necessary to produce very exotic ^{48}Ni.



^{48}Ni experiment

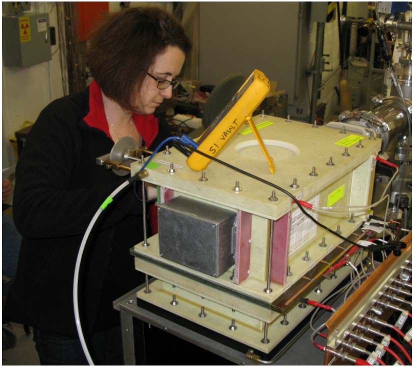
Rotating target



A rotating target was developed in cooperation with Oak Ridge National Laboratory and University of Tennessee, Knxoville. It allowed us to work with beam currents as high as 40 pnA, which would destroy our stationary target.

OTPC improvements

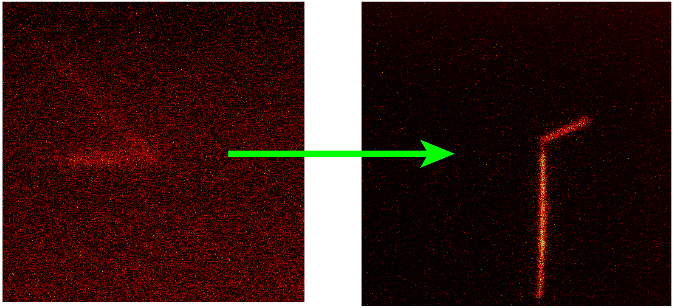
- New camera (90% quantum efficiency)
- New electron multiplying stage based on GEM foils
- Larger active volume (20cm x 33cm x 14cm)



OTPC improvements

- New camera (90% quantum efficiency)
- New electron multiplying stage based on GEM foils
- Larger active volume (20cm x 33cm x 14cm)

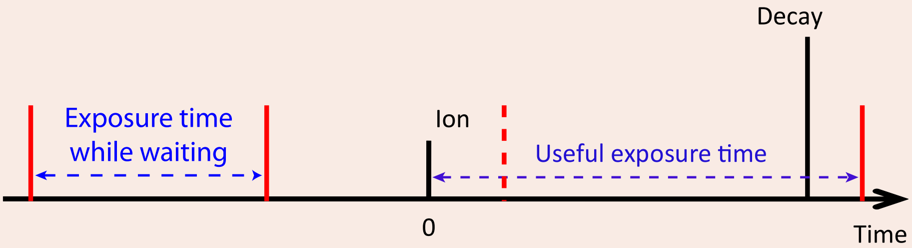
Result:



OTPC improvements

Extended exposure mode

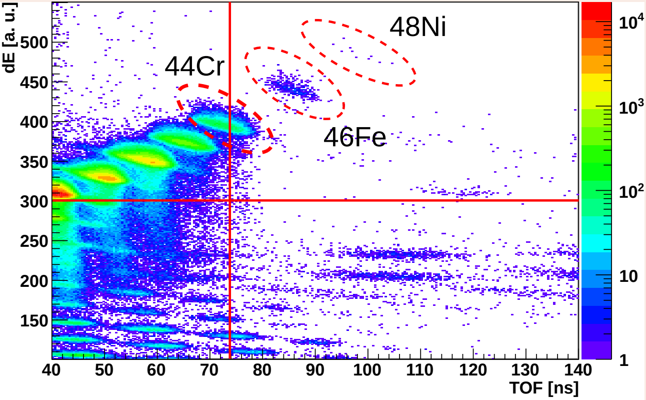
- Camera is exposing short frames
- Upon an ion arrival exposition is extended for a preset amount of time
- Only extended frames are saved to disk
- The resulting frames show implantation trace (as in asynchronous mode)...
- ... and exposure time is fixed (as in synchronous mode)



^{48}Ni experiment

NSCL ID spectrum

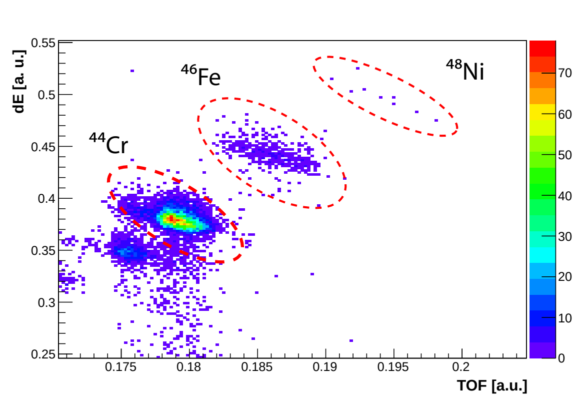
All ions arriving to the detector were identified with $\Delta\mathrm{E}$ - TOF signals. Only ions above and to the right of red lines triggered the acquisition system of the OTPC.



^{48}Ni experiment

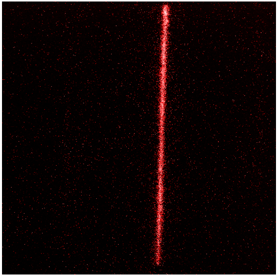
OTPCs ID spectrum

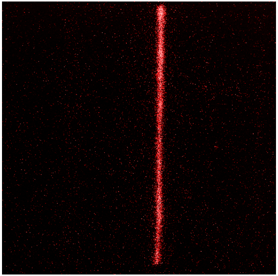
The picture below shows only events recorded by the OTPC. 9 events of ^{48}Ni can be seen, together with many events of ^{46}Fe and ^{44}Cr.



The 0.45$ worth of Nickels

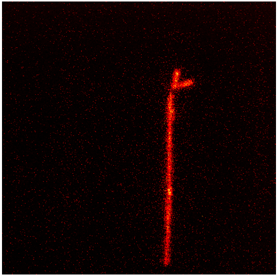
- Two of the ^{48}Ni punched through the OTPC

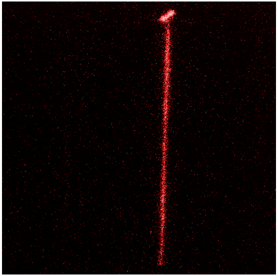




The 0.45$ worth of Nickels

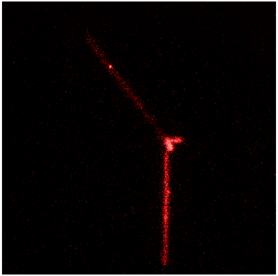
- Two of the ^{48}Ni punched through the OTPC
- Two have undergone 2p decay

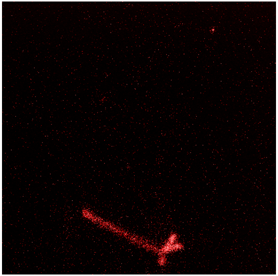




The 0.45$ worth of Nickels

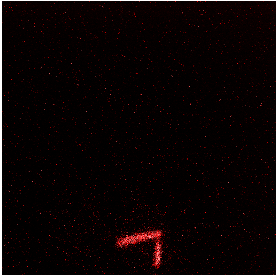
- Two of the ^{48}Ni punched through the OTPC
- Two have undergone 2p decay
- Two have undergone 2p decay followed by β1p

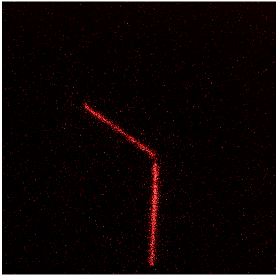




The 0.45$ worth of Nickels

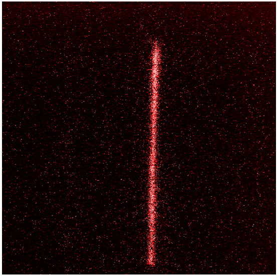
- Two of the ^{48}Ni punched through the OTPC
- Two have undergone 2p decay
- Two have undergone 2p decay followed by β1p
- Two have decayed by β1p





The 0.45$ worth of Nickels

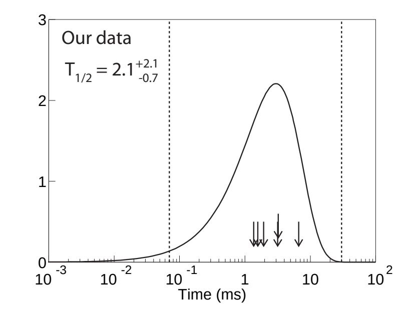
- Two of the ^{48}Ni punched through the OTPC
- Two have undergone 2p decay
- Two have undergone 2p decay followed by β1p
- Two have decayed by β1p
- One has been implanted and did not decay during the exposure.

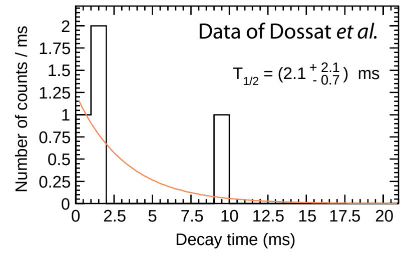


^{48}Ni results

Half-life of ^{48}Ni

The half-life, based on 6 events, was found to be $T_{1/2} = 2.1^{+1.4}_{-0.6}$ ms. The only other measurement of this value was done by Dossat *et al.*[3] which reported $T_{1/2} = 2.1^{+2.1}_{-0.7}$ ms.





^{48}Ni results

Cross-section of ^{48}Ni

The cross-section for production of ^{48}Ni on ^{nat}Ni target with the beam of ^{58}Ni at $160 \mathrm{AMeV}$ was determined to be $\sigma = 90 \pm 30$ fb. Below this value is compared with data from [4] and EPAX v2.1 predictions [5].

This work	B. Blank *et al.*[4]	EPAX v2.1 [5]
90 ± 30 fb	50 ± 20 fb	60 fb

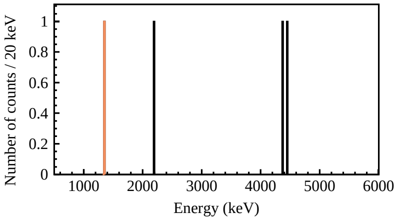
We would like to note, that this is extremely low cross-section for production, comparable with super-heavy elements.

^{48}Ni results

Branching ratios

The branching ratios are compared with results of Dossat *et al.*[3]. Note, that in case of the [3], only the total decay energy was measured.

Channel	Branching	Branching by [3]	Partial $T_{1/2}$	Partial $T_{1/2}$ by [3]
$2p$	67(17)%	25^{+25}_{-19}%	$3.0^{+2.2}_{-1.2}$ ms	$8.4^{+12.8}_{-7.0}$ ms
βp	33(23)%	75(−)%	$7.0^{+6.6}_{-5.1}$ ms	-



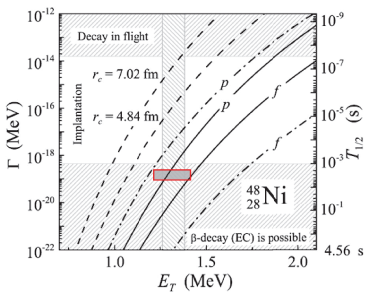
^{48}Ni results

2p decay

We estimated the total energy of both emitted protons to be $E = 1.28(6)\mathrm{MeV}$. This can be compared with theoretical predictions (all values in MeV):

This work (exp)	Dossat *et al.*[3] (exp)	Brown[6]	Cole [7]	Ormand [8]
1.28(6)	1.35(2)	1.36(13)	1.35(6)	1.29(33)

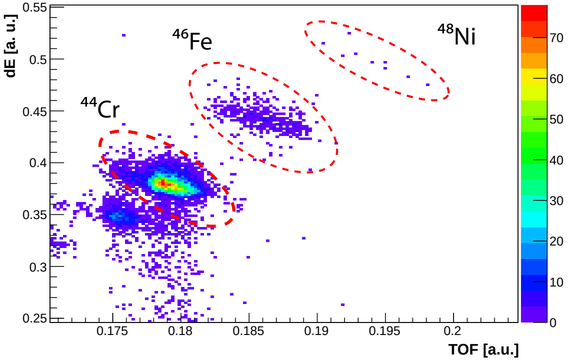
We can also compare our data against predictions of "three-body model" by Grigorenko and Zhukov [9].



Extra data from ^{48}Ni experiment

^{44}Cr and ^{46}Fe

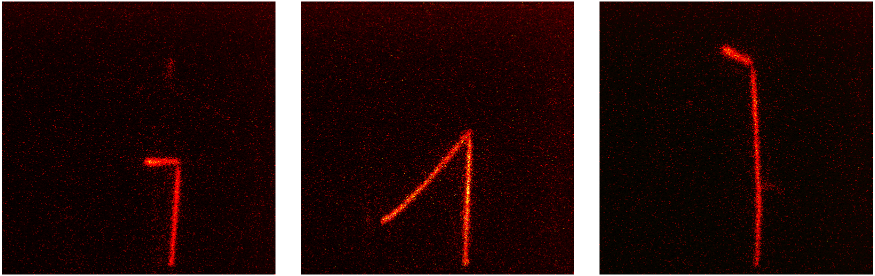
Same as in 2007 experiment, OTPC have collected large number of events in order to monitor the work of the setup. Both ^{44}Cr and ^{46}Fe are β-delayed proton emitters.



Extra data from ^{48}Ni experiment

^{44}Cr data

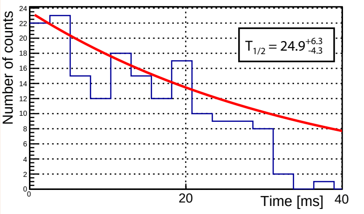
About 5500 ions of ^{44}Cr were collected. Of those 183 events pictured β1p decay. This number is so low due to short exposure time (optimized for ^{48}Ni) compared to half-life of ^{44}Cr.



Extra data from ^{48}Ni experiment

Results for ^{44}Cr

- Half-life was determined to be $T_{1/2} = 24.9^{+6.3}_{-4.3}$ ms. This is within 3σ of Dossat *et al.*[1] value of $T_{1/2} = 43.1 \pm 1.7$ ms.
- The error bars on this value are so large due to short time of exposition window (32 ms).
- For determining branching ratios $T_{1/2}$ of Dossat *et al.*[1] was used, as it is more precise.

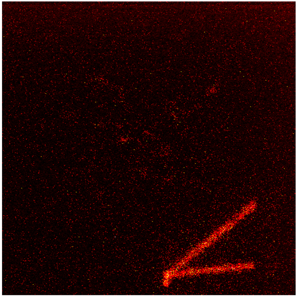


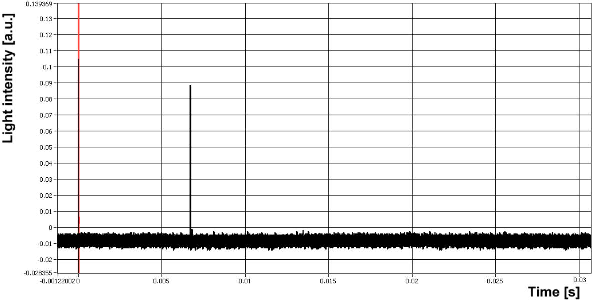
#p	Branching [%]	Branching from [1] [%]
0	90(1)	86.0(9)
1	10(1)	3.4(5)

Extra data from ^{48}Ni experiment

^{46}Fe data

We have collected 471 events of ^{46}Fe. Of those 164 events pictured β1p decay and at least one showed β2p decay. This is the first time this channel is observed for ^{46}Fe.

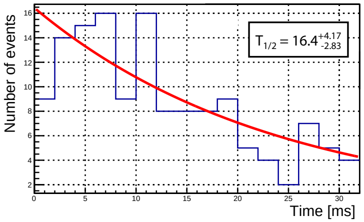




Extra data from ^{48}Ni experiment

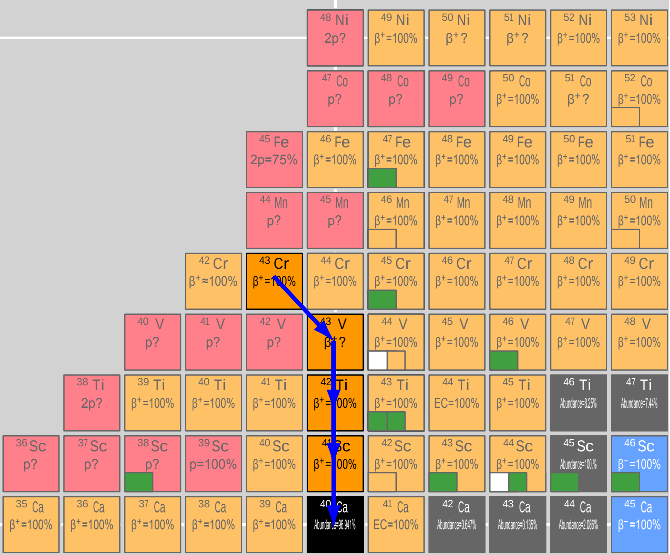
Results from ^{46}Fe

- We determine half-life of ^{46}Fe as $T_{1/2} = 16.4^{+4.2}_{-2.8}$ ms. The value of Dossat *et al.*[1] is $T_{1/2} = 13.0 \pm 1.7$ ms. Combining these two values we get 14.0(1.3) ms.
- Only one clear, and one possible, cases of β2p were registered, thus we present only lower limit for β2p branching.

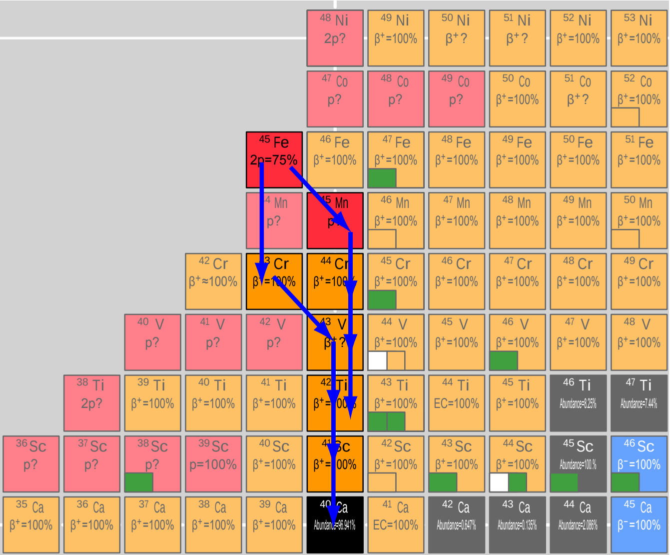


#p	Branching [%]	Branching from [1] [%]
0	66(1)	78.7(38)
1	34(1)	28(6)
2	> 0.2	-

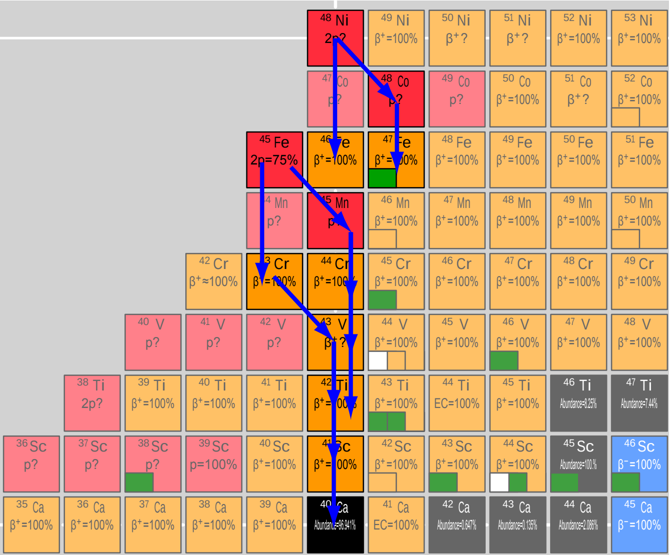
To sum up


48 Ni 2p?
49 Ni β+=100%
50 Ni β+?
51 Ni β+?
52 Ni β+=100%
53 Ni β+=100%
47 Co p?
48 Co p?
49 Co p?
50 Co β+=100%
51 Co β+?
52 Co β+=100%
45 Fe 2p=75%
46 Fe β+=100%
47 Fe β+=100%
48 Fe β+=100%
49 Fe β+=100%
50 Fe β+=100%
51 Fe β+=100%
44 Mn p?
45 Mn p?
46 Mn β+=100%
47 Mn β+=100%
48 Mn β+=100%
49 Mn β+=100%
50 Mn β+=100%
42 Cr β+≈100%
43 Cr β+=100%
44 Cr β+=100%
45 Cr β+=100%
46 Cr β+=100%
47 Cr β+=100%
48 Cr β+=100%
49 Cr β+=100%
40 V p?
41 V p?
42 V p?
43 V β+?
44 V β+=100%
45 V β+=100%
46 V β+=100%
47 V β+=100%
48 V β+=100%
38 Ti 2p?
39 Ti β+=100%
40 Ti β+=100%
41 Ti β+=100%
42 Ti β+=100%
43 Ti β+=100%
44 Ti EC=100%
45 Ti β+=100%
46 Ti Abundance=8.25%
47 Ti Abundance=7.44%
36 Sc p?
37 Sc p?
38 Sc p?
39 Sc p=100%
40 Sc β+=100%
41 Sc β+=100%
42 Sc β+=100%
43 Sc β+=100%
44 Sc β+=100%
45 Sc Abundance=100.%
46 Sc β−=100%
35 Ca β+=100%
36 Ca β+=100%
37 Ca β+=100%
38 Ca β+=100%
39 Ca β+=100%
40 Ca Abundance=96.941%
41 Ca EC=100%
42 Ca Abundance=0.647%
43 Ca Abundance=0.135%
44 Ca Abundance=2.086%
45 Ca β−=100%

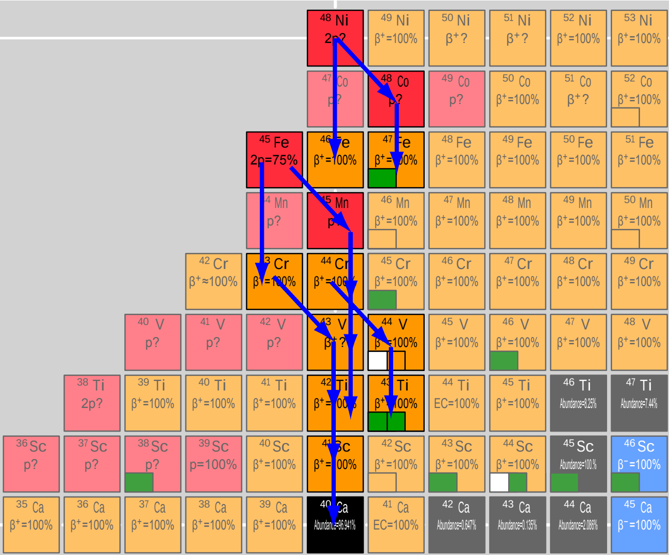
To sum up


48 Ni 2p?
49 Ni β+=100%
50 Ni β+?
51 Ni β+?
52 Ni β+=100%
53 Ni β+=100%
47 Co p?
48 Co p?
49 Co p?
50 Co β+=100%
51 Co β+?
52 Co β+=100%
45 Fe 2p=75%
46 Fe β+=100%
47 Fe β+=100%
48 Fe β+=100%
49 Fe β+=100%
50 Fe β+=100%
51 Fe β+=100%
46 Mn β+=100%
47 Mn β+=100%
48 Mn β+=100%
49 Mn β+=100%
50 Mn β+=100%
42 Cr β+≈100%
45 Cr β+=100%
46 Cr β+=100%
47 Cr β+=100%
48 Cr β+=100%
49 Cr β+=100%
40 V p?
41 V p?
42 V p?
44 V β+=100%
45 V β+=100%
46 V β+=100%
47 V β+=100%
48 V β+=100%
38 Ti 2p?
39 Ti β+=100%
40 Ti β+=100%
41 Ti β+=100%
43 Ti β+=100%
44 Ti EC=100%
45 Ti β+=100%
46 Ti Abundance=8.25%
47 Ti Abundance=7.44%
36 Sc p?
37 Sc p?
38 Sc p?
39 Sc p=100%
40 Sc β+=100%
42 Sc β+=100%
43 Sc β+=100%
44 Sc β+=100%
45 Sc Abundance=100.%
46 Sc β−=100%
35 Ca β+=100%
36 Ca β+=100%
37 Ca β+=100%
38 Ca β+=100%
39 Ca β+=100%
41 Ca EC=100%
42 Ca Abundance=0.647%
43 Ca Abundance=0.135%
44 Ca Abundance=2.086%
45 Ca β−=100%

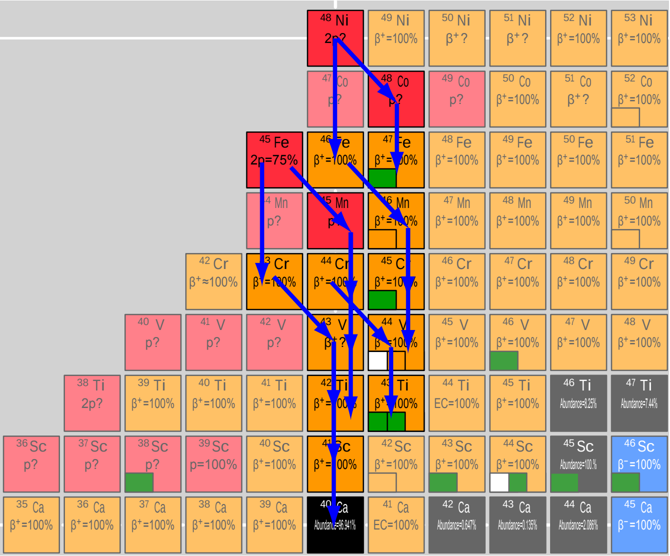
To sum up


48 Ni 2p?
49 Ni β+=100%
50 Ni β+?
51 Ni β+?
52 Ni β+=100%
53 Ni β+=100%
47 Co p?
48 Co p?
49 Co p?
50 Co β+=100%
51 Co β+?
52 Co β+=100%
45 Fe 2p=75%
46 Fe β+=100%
47 Fe β+=100%
48 Fe β+=100%
49 Fe β+=100%
50 Fe β+=100%
51 Fe β+=100%
44 Mn p?
45 Mn p?
46 Mn β+=100%
47 Mn β+=100%
48 Mn β+=100%
49 Mn β+=100%
50 Mn β+=100%
42 Cr β+≈100%
43 Cr β+=100%
44 Cr β+=100%
45 Cr β+=100%
46 Cr β+=100%
47 Cr β+=100%
48 Cr β+=100%
49 Cr β+=100%
40 V p?
41 V p?
42 V p?
43 V β+?
44 V β+=100%
45 V β+=100%
46 V β+=100%
47 V β+=100%
48 V β+=100%
38 Ti 2p?
39 Ti β+=100%
40 Ti β+=100%
41 Ti β+=100%
42 Ti β+=100%
43 Ti β+=100%
44 Ti EC=100%
45 Ti β+=100%
46 Ti Abundance=8.25%
47 Ti Abundance=7.44%
36 Sc p?
37 Sc p?
38 Sc p?
39 Sc p=100%
40 Sc β+=100%
41 Sc β+=100%
42 Sc β+=100%
43 Sc β+=100%
44 Sc β+=100%
45 Sc Abundance=100%
46 Sc β−=100%
35 Ca β+=100%
36 Ca β+=100%
37 Ca β+=100%
38 Ca β+=100%
39 Ca β+=100%
40 Ca Abundance=96.941%
41 Ca EC=100%
42 Ca Abundance=0.647%
43 Ca Abundance=0.135%
44 Ca Abundance=2.086%
45 Ca β−=100%

To sum up


48 Ni 2p?
49 Ni β+=100%
50 Ni β+?
51 Ni β+?
52 Ni β+=100%
53 Ni β+=100%
47 Co p?
48 Co p?
49 Co p?
50 Co β+=100%
51 Co β+?
52 Co β+=100%
45 Fe 2p=75%
46 Fe β+=100%
47 Fe
48 Fe β+=100%
49 Fe β+=100%
50 Fe β+=100%
51 Fe β+=100%
Mn p?
Mn
46 Mn β+=100%
47 Mn β+=100%
48 Mn β+=100%
49 Mn β+=100%
50 Mn β+=100%
42 Cr β+≈100%
Cr
44 Cr
45 Cr β+=100%
46 Cr β+=100%
47 Cr β+=100%
48 Cr β+=100%
49 Cr β+=100%
40 V p?
41 V p?
42 V p?
43 V
44 V
45 V β+=100%
46 V β+=100%
47 V β+=100%
48 V β+=100%
38 Ti 2p?
39 Ti β+=100%
40 Ti β+=100%
41 Ti β+=100%
42 Ti
Ti
44 Ti EC=100%
45 Ti β+=100%
46 Ti Abundance=8.25%
47 Ti Abundance=7.44%
36 Sc p?
37 Sc p?
38 Sc p?
39 Sc p=100%
40 Sc β+=100%
41 Sc
42 Sc β+=100%
43 Sc β+=100%
44 Sc β+=100%
45 Sc Abundance=100%
46 Sc β−=100%
35 Ca β+=100%
36 Ca β+=100%
37 Ca β+=100%
38 Ca β+=100%
39 Ca β+=100%
40 Ca
41 Ca EC=100%
42 Ca Abundance=0.647%
43 Ca Abundance=0.135%
44 Ca Abundance=2.086%
45 Ca β−=100%

To sum up


48 Ni 2p?
49 Ni β+=100%
50 Ni β+?
51 Ni β+?
52 Ni β+=100%
53 Ni β+=100%
47 Co p?
48 Co p?
49 Co p?
50 Co β+=100%
51 Co β+?
52 Co β+=100%
45 Fe 2p=75%
46 Fe β+=100%
47 Fe
48 Fe β+=100%
49 Fe β+=100%
50 Fe β+=100%
51 Fe β+=100%
44 Mn p?
45 Mn
46 Mn
47 Mn β+=100%
48 Mn β+=100%
49 Mn β+=100%
50 Mn β+=100%
42 Cr β+≈100%
43 Cr
44 Cr
45 Cr
46 Cr β+=100%
47 Cr β+=100%
48 Cr β+=100%
49 Cr β+=100%
40 V p?
41 V p?
42 V p?
43 V
44 V
45 V β+=100%
46 V β+=100%
47 V β+=100%
48 V β+=100%
38 Ti 2p?
39 Ti β+=100%
40 Ti β+=100%
41 Ti β+=100%
42 Ti
43 Ti
44 Ti EC=100%
45 Ti β+=100%
46 Ti Abundance=8.25%
47 Ti Abundance=7.44%
36 Sc p?
37 Sc p?
38 Sc p?
39 Sc p=100%
40 Sc β+=100%
41 Sc
42 Sc β+=100%
43 Sc β+=100%
44 Sc β+=100%
45 Sc Abundance=100.%
46 Sc β−=100%
35 Ca β+=100%
36 Ca β+=100%
37 Ca β+=100%
38 Ca β+=100%
39 Ca β+=100%
40 Ca Abundance=96.941%
41 Ca EC=100%
42 Ca Abundance=0.647%
43 Ca Abundance=0.135%
44 Ca Abundance=2.086%
45 Ca β−=100%

To sum up

- OTPC was first used in 2007 in a pioneering experiment devoted to ^{45}Fe [11]
- The data on ^{43}Cr collected in the same experiment showed new decay channel and proved the OTPC to be a very useful tool for study of β-delayed emissions
- In 2011 the improved chamber was used in an experiment devoted to ^{48}Ni. This was the first time, when two proton decay was directly observed for ^{48}Ni
- In addition β-delayed emitters ^{44}Cr and ^{46}Fe were studied. β2p decay channel was observed for ^{46}Fe
- We are constantly improving OTPC system

References:

[1] C. Dossat et al., Nucl. Phys. A 792, 18 (2007).

[2] K.H. Schmidt et al., Z. Phys. A 316, 19 (1984).

[3] C. Dossat et al., Phys. Rev. C 72, 054315 (2005).

[4] B. Blank et al., Phys. Rev. Lett. 84 , 11161119 (2000).

[5] K. Sümmerer and B. Blank, EPAX version 2.1, http://www-w2k.gsi.de/hellstr/asp/gsi/epaxv21m.asp

[6] B. A. Brown, Phys. Rev. C 43, R1513 (1991).

[7] B. J. Cole, Phys. Rev. C 54, 1240 (1996).

[8] W. E. Ormand, Phys. Rev. C 55, 2407 (1997).

[9] L.V. Grigorenko, M.V. Zhukov, Phys. Rev. C68, 054005 (2003).

[10] R. Barlow Asymmetric Statistical Errors http://arXiv.org/abs/physics/0406120v1

[11] K. Miernik et al., Phys. Rev. Lett. 99, 192501 (2007).