STUDIES OF ^{48}Ni USING THE OPTICAL TIME PROJECTION CHAMBER*

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The decay of the extremely neutron deficient ^{48}Ni was studied by means of an imaging time projection chamber which allowed recording tracks of charged particles. Four decays with two-proton tracks clearly corresponding to two-proton radioactivity were registered, providing the first direct evidence for this decay mode in ^{48}Ni. The half-life of ^{48}Ni is determined to be $T_{1/2} = 2.1^{+1.4}_{-0.4}$ ms. The measured decay energy is 1.28(6) MeV.

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1. Introduction

Studies of $2p$ radioactivity represent the youngest branch in nuclear spectroscopy. This task is quite challenging due to very small rates available in current accelerator facilities. When one adds to that the necessity to register individual protons separately, the challenge is even greater.

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To allow for such studies new detectors were constructed, one of which is the Optical Time Projection Chamber developed at University of Warsaw [1]. This detector has already provided the first data on $2p$ correlations in ^{45}Fe [2] as well as the first observations of β-delayed three proton emissions from ^{45}Fe [2] and ^{43}Cr [3]. In this paper we report on the latest experiment devoted to study ^{48}Ni.

2. Experiment

The experiment was conducted at National Superconducting Cyclotron Laboratory at Michigan State University, East Lansing, USA, in 2011. The primary beam of ^{58}Ni at energy of 160 AMeV hit natural nickel target of 580 mg/cm^2 thickness with average beam intensity of approx. 20 pnA. In order for the target to survive this intensity, a rotating target assembly was developed in cooperation with University of Tennessee, Knoxville, and Oak Ridge National Laboratory. The products of fragmentation reaction were separated in the A1900 separator. The ions were identified in-flight using the Time-of-Flight (TOF) and the energy-loss (ΔE) information for each ion. The identified ions were slowed down in an aluminium foil and stopped inside the active volume of the OTPC detector.

In short, the OTPC is a gaseous detector with optical readout. The ions are implanted in the detector, where after short time the decay takes place. Primary ionisation electrons are travelling in electric field with a known velocity towards amplification stages. After the amplification, the signal is converted to visible light and registered with a CCD camera and a photomultiplier tube (PMT) read out by an oscilloscope. The CCD image provides information on event's 2D projection, while PMT records light intensity as a function of time, giving information on 3rd dimension as well as timing information of registered events. More information on recent improvements in the OTPC chamber and more details about the experiment were presented in Ref. [4].

3. Results

The experiment lasted 156 hours. The OTPC acquisition system was triggered 1.5 times every minute on average, mostly with ions of ^{46}Fe and ^{44}Cr. The ID plot of all ions registered with OTPC acquisition system is presented in Fig. 1. In total 10 events were identified as ^{48}Ni.

In order to calculate the cross-section for the production of ^{48}Ni we used a procedure described in Ref. [6]. The cross-section is given by

$$\sigma = \frac{N_f}{N_p}\frac{A_t}{N_A d_t}\frac{1}{t_1 t_2}\,, \qquad (1)$$

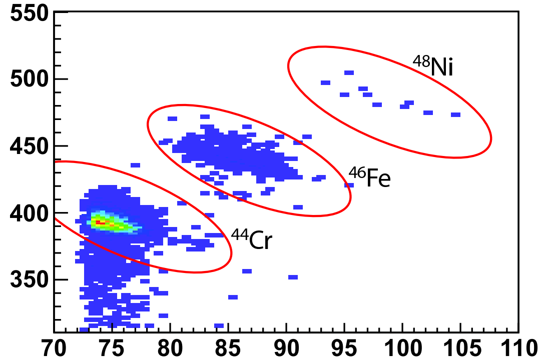

Fig. 1. (colour on-line) Identification spectrum of ions which triggered the OTPC acquisition system.

where N_p, N_f is the number of beam particles on target, and the number of observed ^{48}Ni ions, respectively, $A_{\rm t}$ is the atomic mass of the target, $N_{\rm A}$ is the Avogadro's constant, $d_{\rm t}$ is the target thickness, t_1 is transmission to the final focus of the A1900, taking into the account losses in target and degrader, the t_2 factor is the transmission through the beam line to the detector.

In this experiment, N_p was determined by a Faraday cup placed in front of the target. This number was found to be $N_p = 8 \times 10^{16}$ (taking into the account 90% efficiency of the Faraday cup). The t_1 factor was determined using LISE code [7] to be $t_1 = 0.54$, using effective target and degrader thickness. The t_2 factor was determined experimentally to be $t_2 = 0.4 \pm 0.05$. Using above values we arrive at the final result of $\sigma = 0.1 \pm 0.03$ pb. The error comes mainly from statistical uncertainty. In Table I we compare determined cross-section with the value measured previously by Blank *et al.* [5] and with the EPAX parametrisation [8]. We note that in Ref. [5] the same reaction was used but the beam energy was 74.5 AMeV.

TABLE I

Cross-section for the production of ^{48}Ni by fragmentation of a ^{58}Ni on a natural nickel target.

This work	Blank *et al.* [5]	EPAX [8]
0.1 ± 0.03 pb	0.05 ± 0.02 pb	0.06 pb

Two of the registered ^{48}Ni ions passed through the chamber and were stopped outside the active volume, so that their decays could not be observed.

Two events represented β-delayed (βp) proton emission, which can be recognised by a proton with sufficient energy to leave active volume of the chamber. In these cases the energy of protons cannot be reconstructed, as most of the protons energy is lost outside of detectors active volume, but we can still extract timing signal from the PMT for the half-life measurement.

In the case of four events, two short proton tracks can be seen on the CCD image — they represent $2p$ radioactivity events. The $2p$ decay of ^{48}Ni leads to ^{46}Fe which has the half-life of 13(2) ms and the branching ratio for the βp emission of 79(4)% [9]. It follows that there is a high probability that within the observation time of 30 ms the βp decay of the ^{46}Fe daughter nucleus will be recorded after the $2p$ decay of ^{48}Ni. Indeed, we observe such a chain of decays in two cases, where in addition to the track of the ^{48}Ni ion and the two short tracks resulting from $2p$ emission a longer track representing the βp proton is visible. Example of such event is presented in Fig. 2.

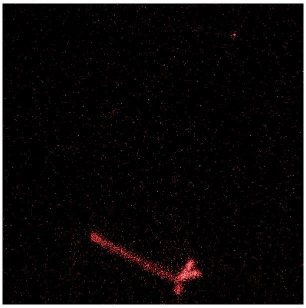

Fig. 2. (colour on-line) An example of the CCD image of the $2p$ decay of ^{48}Ni followed by βp decay from the daughter ^{46}Fe.

Finally, in two events of ^{48}Ni implantation no decay signal was observed. This implies that either the decay occurred outside the observation window, or it proceeded with no proton emission, see discussion in Ref. [4].

Based on the 6 decays, we were able to calculate the half-life of ^{48}Ni to be $T_{1/2} = 2.1^{+1.4}_{-0.6}$ ms, using maximum likelihood analysis [10]. This is in agreement with previous findings by Dossat *et al.* [11]. Using a test described in [12] the data is consistent with an assumption of a single radioactive decay and with the assumption that the full time range was covered in the experiment on a 90% confidence level.

The branching ratios for the $2p$ and the βp channels are $b_{2p} = 0.7(2)$ and $b_{\beta p} = 0.3(2)$, respectively. From this, one can compute partial half-lives as $T^{2p}_{1/2} = 3.0^{+2.2}_{-1.2}$ ms and $T^{\beta}_{1/2} = 7.0^{+6.6}_{-5.1}$ ms for $2p$ and β decays, respectively.

One can reconstruct the total length of a given track and its direction utilising a fact, that the image represents a 2D projection of tracks on a plane, while the PMT signal gives a projection on the direction perpendicular to that plane. The drift velocity of free electrons in active volume of the OTPC, necessary for these calculations, was measured during the experiment and found to be $v_{\rm drift} = 6\pm0.6\,{\rm mm}/\mu{\rm s}$. Simulating energy loss in a gas filling the OTPCs active volume by the SRIM code [13], one can infer energy from tracks length, and such a procedure was carried out for all 4 cases of $2p$ decays of ^{48}Ni. The resulting proton energies, angles between protons, and the total decay energy values, including the nucleus recoil, are presented in Table II. The mean decay energy is $Q_{2p} = 1.28(6)$ MeV, which is consistent with theoretical predictions [14, 15, 16].

TABLE II

Registered energies of individual protons, the angle between protons Θ_{pp} and full decay energies Q_{2p} for the $2p$ decay events of ^{48}Ni.

p_1 energy [keV]	p_2 energy [keV]	Θ_{pp} [deg]	Q_{2p} [MeV]
652 ± 63	649 ± 61	37 ± 10	1.35 ± 0.12
660 ± 69	624 ± 87	36 ± 4	1.34 ± 0.16
643 ± 35	587 ± 67	72 ± 4	1.27 ± 0.10
630 ± 30	553 ± 67	91 ± 4	1.21 ± 0.13

With the kinematic data collected in Table II one can reconstruct $2p$ events in the Jacobi "T" system, as described in Ref. [17]. The resulting energy distribution for the four $2p$ events is shown in Fig. 3 (a). Since the predictions for this distribution for ^{48}Ni are not yet available, we have plotted the predictions for ^{45}Fe for reference, expecting similar behaviour for both nuclei. We also compare the partial half-life and the Q_{2p} value with the predictions of Grigorenko and Zhukov [17], as shown in Fig. 3 (b).

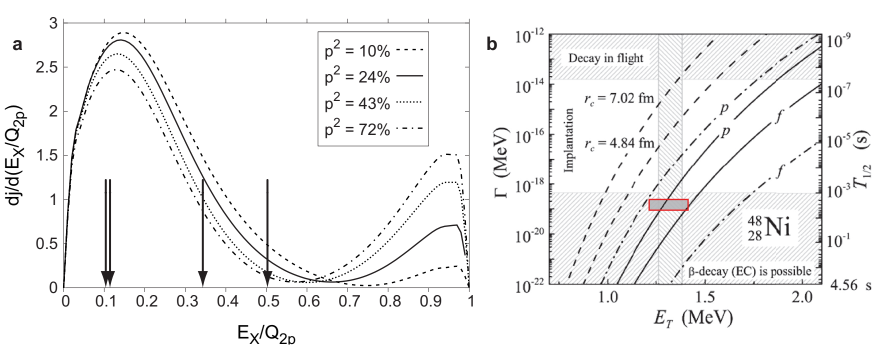

Fig. 3. (a) Energy distribution in the "T" Jacobi system of the $2p$ decay events from ^{48}Ni (arrows) superimposed on the 3-body predictions for the ^{45}Fe [17]. (b) Correlation of the partial half-life for the $2p$ decay of the ^{48}Ni with the decay energy as predicted by the 3-body model [17]. The experimental results are shown by the grey box.

4. Summary

In this paper we have presented results of an experiment on ^{48}Ni using the OTPC detector. For the first time we have observed the $2p$ radioactivity of this nucleus by detecting two tracks of individual protons. We have measured individual proton energies, the Q_{2p} value and proton–proton correlations. The half-life and branching ratios were also determined. During the experiment we have successfully used a new rotating target assembly, which allowed us to accept beam intensities of up to 40 pnA. Data on ^{46}Fe an ^{44}Cr collected in this experiment will be soon analysed as well.

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