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STUDIES OF CHARGED PARTICLE EMISSION IN THE DECAY OF ^{45}Fe*

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The decay of extremely neutron-deficient isotope ^{45}Fe has been studied by using a new type of gaseous detector in which a technique of optical imaging is used to record tracks of charged particles. The two-proton radioactivity and the β-decay channels accompanied by proton(s) emission were clearly identified. For the first time, the angular and energy correlations between two protons emitted from the ^{45}Fe ground-state were measured. The obtained distributions were confronted with predictions of a three-body model. Studies of β-decay channels of ^{45}Fe provided first unambiguous evidence for the β-delayed three proton emission.

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1. Introduction

The phenomenon of two-proton ($2p$) radioactivity was considered for the first time by Goldansky in 1960's [1]. He suggested that extremely neutron-deficient nuclei can decay by simultaneous emission of two protons from a narrow nuclear ground state while emission of a single proton is forbidden due to a higher mass of neighbouring nuclide. First experimental evidence for the $2p$ decay was reported more than 40 years later for the case of ^{45}Fe, the $2p$ emitter predicted already by Goldansky. In the pioneering experiments [2,3]

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the decay of ^{45}Fe was observed after deep implantation of ions into a thick silicon detector. This commonly used technique allowed to measure the ^{45}Fe lifetime and the total $2p$ decay energy. However, the observation of the two protons independently, which is a key to understand the mechanism of the $2p$ emission, was not possible. To overcome this limitation we have developed a new type of a gaseous detector based on a technique of time projection chamber combined with optical imaging (OTPC) [4]. Details of the operation of the OTPC detector were described in Refs. [5, 6].

In this contribution we present results of an experiment performed with the use of our detector at the National Superconducting Cyclotron Laboratory at Michigan State University, USA. First results from this measurement were presented in Refs. [7, 8]. The tracks of individual protons emitted in the $2p$ decay of ^{45}Fe were recorded providing an unambiguous experimental proof of this decay mode. The three-dimensional reconstruction of the $2p$ decay events allowed us to determine for the first time the angular and energy correlations between the emitted protons. Although the ground state $2p$ emission is a dominating decay mode of ^{45}Fe, there is also a considerable probability of its β-decay. High energy available in this process opens exotic β-delayed multiparticle decay channels. Here we report on a first observation of the β-delayed three-proton decay ($\beta 3p$) of ^{45}Fe.

2. Experimental setup

The experiment was performed at the National Superconducting Cyclotron Laboratory at Michigan State University, USA. The primary beam of ^{58}Ni was accelerated to the energy of 161 MeV/nucleon and fragmented on the 800 mg/cm^2 thick target made of natural nickel. The ^{45}Fe ions were separated by means of the A1900 fragment separator and identified using time-of-flight (TOF) and energy loss (ΔE) information. At the focal plane of the separator the ^{45}Fe ions were slowed down in an aluminium degrader and stopped in the active volume of the OTPC detector. The chamber consists of several parallel wire-mesh electrodes forming uniform electric field regions. Ions and their charged decay products are stopped within a conversion volume filled with a gas mixture of 66% of He, 32% of Ar, 1% N_2, and 1% CH_4 at atmospheric pressure. The primary ionisation electrons are transported with a drift velocity of 0.97 cm/μs and are multiplied in two amplification sections. At the final multiplication stage ultraviolet photons are emitted. They are transformed to visible light by a wavelength shifter foil and recorded by an electron-multiplying CCD 2/3" 1M pixel camera [9] and a 5" photomultiplier (PMT).

While waiting for a ^{45}Fe ion, the chamber was operated in the low gain mode suitable for registration of tracks of heavy ions (fragments) entering the active volume of the detector. Whenever the ion of interest was identified by using the TOF signal, the OTPC was (within $100\,\mu$s) switched to the high sensitivity mode, the 25 ms CCD exposure gate was opened, and the beam from the separator was turned off to prevent other ions to arrive in the chamber. At the end of the exposure time the CCD image, the digitized (50 MHz) PMT signal and the TOF and ΔE information of the triggering ion were saved on a hard disk.

Recorded TOF and ΔE information unambiguously identify decaying nucleus. The camera image represents the two-dimensional projection of the particles' tracks on the image plane while the time profile of the signal from the PMT yields information on the track projection in the direction normal to the image plane. The combination of the camera image with the recorded drift time profile allows the three-dimensional reconstruction of the decay kinematics.

3. Results

During 9 days of experiment 125 decays of ^{45}Fe were recorded. 87 of them were identified as $2p$ decays and remaining 38 as β^+ decays followed by charged particle(s) emission. Since the probability that β-decay of ^{45}Fe is accompanied by proton(s) emission is expected to be 100%, the branching ratio for the $2p$ decay amounts to 0.70 ± 0.04. The decay time analysis of the $2p$ events yields the half-life of $T_{1/2} = 2.6 \pm 0.2$ ms, in agreement with previous results [10].

Fig. 1 shows an example of a $2p$ decay event. The two bright, short tracks visible on the CCD image are protons of 0.6 MeV each. Since the camera exposure was started 100 μs after ion implantation, its track was not recorded. The energy of protons was derived from the ratio of light intensity recorded in the CCD for each proton track under the constraint that the energy sum equals to the $2p$ decay Q-value of 1.151 MeV [10]. The angle between the tracks representing the projection of the angle between the two protons on the image plane was found to be $\varphi = 82 \pm 5°$.

The right top panel of Fig. 1 shows the time profile of light recorded by the PMT during the exposure time. The decay event seen occurred about 3.72 ms after ion arrival. The right bottom plot shows magnified part of the light intensity distribution which was used to determine angles of the protons tracks with respect to the axis normal to the image plane. A reconstruction procedure taking into account ionizing density along the tracks and detector response gave for an event shown in Fig. 1 values of $\vartheta_1 = 52 \pm 7°$ and $\vartheta_2 = 60 \pm 8°$. These angles combined with the φ value yield the opening angle $\theta_{pp} = 66 \pm 6°$.

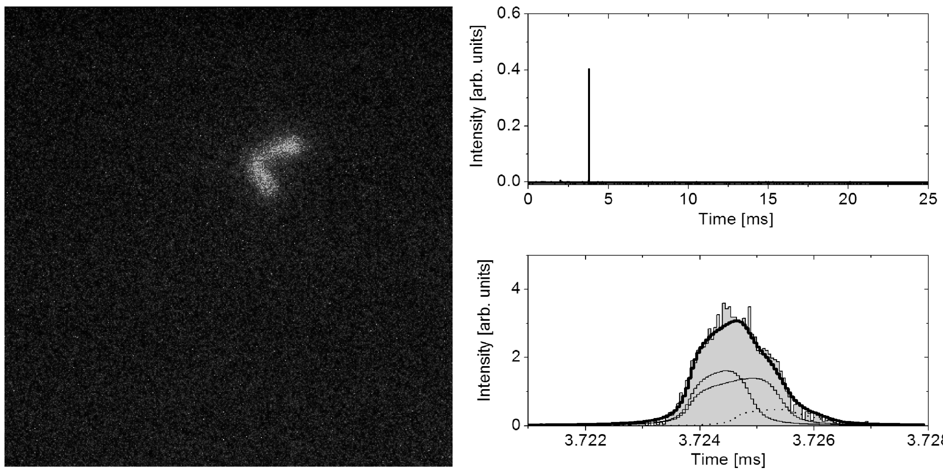

Fig. 1. An example of a $2p$ decay of ^{45}Fe. The CCD image (left) is taken with exposure time of 25 ms. The two bright tracks are protons of about 0.6 MeV each, emitted approximately 3.72 ms after ion implantation. The right top plot shows the time profile of light recorded by the PMT during the camera exposure. The right bottom plot shows a magnified part of the PMT data for the decay event (gray histogram). The thick black line shows the result of the reconstruction procedure and represents the sum of two protons profiles (thin black lines) and after-pulse signal (dashed line).

The reconstruction procedure was applied to all recorded $2p$ decay events and for 75 of them it yielded reliable and unambiguous results. Fig. 2 shows the measured distributions (hatched histograms) for the opening angle and energy of protons in comparison with theoretical predictions (solid lines) of a 3-body model [11]. In the calculations it was assumed that the initial state of the decaying nucleus is a mixture of p^2 and f^2 states with a ratio of $p^2/f^2 \sim 30/70$. For the sake of comparison the predicted energy distribution was folded with a Gaussian function describing resolution of the OTPC which is about 20% for 0.5 MeV protons. As it can be seen in Fig. 2, the results of the 3-body model calculations are in remarkable agreement with the measured angular and energy distribution.

The energy available in the β-decay of ^{45}Fe amounts to about 18.7 MeV [12] and in consequence many decay modes involving β-delayed particle emission are possible. Besides the βp and $\beta 2p$ channels also $\beta 3p$, $\beta 4p$ and $\beta\alpha p$ branches are energetically allowed. High energy particles emitted after the β-decay have a range in the OTPC gas mixture large enough to escape from the detector and could be easily distinguished from the $2p$ decay events. During the experiment we have observed 38 β decays of ^{45}Fe followed by the

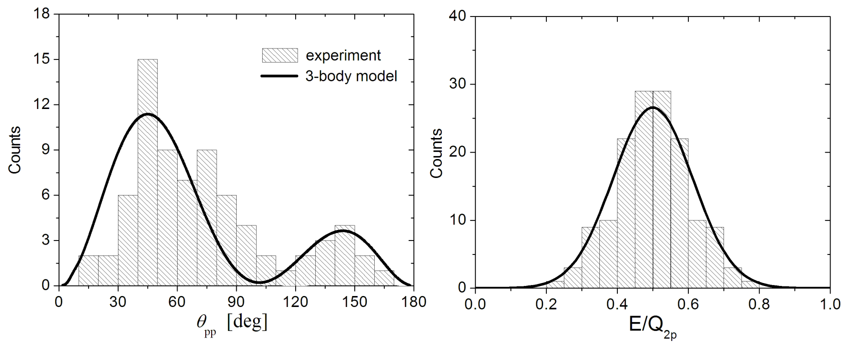

Fig. 2. The proton–proton correlations in the $2p$ decay of ^{45}Fe. Histograms show measured values while solid lines represent the predictions of the 3-body model. The left plot shows the opening angle between two protons emitted in the decay of ^{45}Fe. The right plot shows the energy of individual protons as a part of the total $2p$ decay energy.

emission of high energy protons. 24 of them were identified as βp decays, 10 as $\beta 2p$ decays and 4 as β decays followed by three proton emission. An example of the latter decay type is shown in Fig. 3. Our observation of the $\beta 3p$ decay of ^{45}Fe represents the first unambiguous evidence for such a disintegration mode.

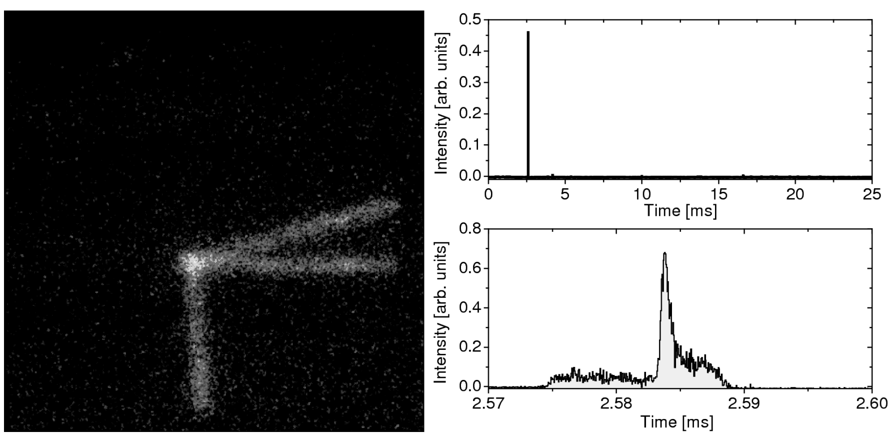

Fig. 3. An example of $\beta 3p$ decay of ^{45}Fe. The CCD image (left) is taken with exposure time of 25 ms. Three bright tracks are protons emitted simultaneously approximately 2.58 ms after ion implantation. The right top plot shows the time profile of light recorded by the PMT during the camera exposure. The right bottom plot shows a magnified part of the PMT data for the decay event.

4. Summary

A novel type of the detector — the Optical Time Projection Chamber — was used to study the decay of ^{45}Fe. More than 120 decay events of this extremely neutron-deficient isotope were recorded, most of them proceeded via $2p$ emission. Using the capability of the OTPC to fully reconstruct the decay kinematics we were able to determine angular and energy correlation between protons emitted in this exotic decay. The measured distributions agree very well with the predictions of the 3-body model assuming that the protons are emitted from the ^{45}Fe ground state characterized by a significant mixture of p^2 and f^2 configurations.

In addition to the $2p$ emission studies, the β^+ decay channels accompanying by proton(s) emission were investigated. The βp, $\beta 2p$ and $\beta 3p$ branches in the decay of ^{45}Fe were clearly identified. Our observation of the $\beta 3p$ emission represents the first direct evidence for such a decay type.

The results of the decay studies of ^{45}Fe illustrate the capabilities of a new detection technique based on optical imaging of the particle tracks. The remarkable sensitivity of this method makes it ideally suited to studies of rare nuclear decay modes involving charged particle emission and to explore variety of nuclear landscape at and beyond the proton drip-line.

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