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First observation of β-delayed three-proton emission in ^{45}Fe

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The decay of extremely neutron deficient ^{45}Fe has been studied by means of a new type of a gaseous detector in which a technique of digital imaging was used to record tracks of charged particles. The β^+ decay channels accompanied by proton emission were clearly identified. In addition to β-delayed one-proton and β-delayed two-proton decays, β-delayed three-proton emission was recorded which represents the first direct and unambiguous observation of this decay channel. The branching ratio for the β decay of ^{45}Fe and the corresponding partial half-life are found to be 0.30 ± 0.04 and $T_{1/2}(\beta) = 8.7 \pm 1.3$ ms, respectively.

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A characteristic feature of the β-decay of very neutron-deficient nuclei is the possibility of proton emission from highly excited states populated in the daughter nucleus. This phenomenon becomes particularly important when the proton-drip line is approached. Due to increasing decay energy and decreasing proton separation energy, many decay channels open, including multiparticle emission. The β-delayed two-proton emission was observed already in 1983 in the decays of ^{22}Al and ^{26}P [1,2]. Later, several other cases of such decay mode were identified [3]. The first observation of β-delayed three-proton emission was claimed by Bazin *et al.* [4] who studied the decay of ^{31}Ar implanted into a segmented silicon telescope at GANIL Caen. However, later experiment performed at ISOLDE at CERN with a silicon detector array of much larger granularity and efficiency, failed to confirm this claim [5]. Only the upper limit for the β-delayed three-proton branch from the isobaric analog state in ^{31}Cl to the ground state of ^{28}Si could be determined to be 1.1×10^{-3} [5]. Thus, β-delayed three-proton emission remained to be observed.

In this Rapid Communication, we present the first direct and unambiguous evidence for the β-delayed three-proton emission in the decay of ^{45}Fe. This extremely neutron-deficient nucleus ($T_z = -7/2$) has attracted experimental interest as a main candidate for the two-proton emission ($2p$) from the ground state [6]. Indeed, this new type of radioactivity was discovered after decay studies of ^{45}Fe at GSI Darmstadt [7] and GANIL [8]. The conclusions were based on measurements of the decay time and the total decay energy of ^{45}Fe ions implanted into a thick silicon detector. The particles emitted during the decay were not identified. However, already these pioneering experiments were able to show that although the $2p$ emission is the dominant decay mode of ^{45}Fe, there is a considerable probability for the β^+ decay channel. The estimated branching ratio for β decay ranged between 20% [7] and 45% [8]. Later experiment performed at GANIL with the same method confirmed the previous results with increased accuracy [9]. The average over results from three experiments yielded for ^{45}Fe a half-life value of $1.75^{+0.49}_{-0.28}$ ms and the β^+ decay branching ratio of 0.41 ± 0.07 [9].

To study the decay of ^{45}Fe in more detail, in particular to detect emitted protons, we have developed a new type of a gaseous detector—the Optical Time Projection Chamber (OTPC) in which digital photography is used to record tracks of ionizing particles [10,11]. We have applied this detector in the experiment performed at the National Superconducting Cyclotron Laboratory at Michigan State University, East Lansing, USA. The main goal of this measurement was an investigation of correlations between protons emitted in the $2p$ radioactivity of ^{45}Fe. Results on this subject will be published separately [12]. We have successfully recorded also the β decay channels of ^{45}Fe accompanied by emission of protons. Here, we report on these results.

Ions of ^{45}Fe were produced in the fragmentation reaction of a ^{58}Ni beam at 161 MeV/nucleon, with average intensity of 15 pnA, impinging on a 800 mg/cm^2 thick natural nickel target. The ^{45}Fe fragments were separated using the A1900 fragment separator [13] and identified in-flight by using time-of-flight (TOF) and energy-loss (ΔE) information for each ion. The TOF was measured between a plastic scintillator located in the middle focal plane of the A1900 separator and a thin silicon detector mounted at the end of the beam-line. The silicon detector also provided the ΔE signal. Identified ions were slowed down in an aluminium foil and stopped inside the active volume of the OTPC detector.

In short, the principles of operation of the OTPC detector are as follows. Ions and their charged decay products are stopped in a volume of $20 \times 20 \times 42$ cm^3 filled with a counting gas at atmospheric pressure. The counting gas is a mixture of helium (66%), argon (32%), nitrogen (1%), and methane (1%). The primary ionization electrons drift in a uniform electric field, with a velocity of 0.97 cm/μs, toward a double-stage amplification structure formed by parallel-mesh flat electrodes. In the second multiplication stage, emission of UV photons occurs. After conversion of their wavelength to the visual range by a thin luminescent foil, these photons are recorded by a CCD camera and by a photomultiplier tube (PMT). The camera image represents the projection of particles' tracks on the luminescent foil. The camera exposure time was 25 ms per image. The signals from the PMT are digitized with a 50 MHz sampling frequency yielding the time dependence of the total light intensity. This provides information on the timing of events and on the projection of the particle's track on the axis normal to the image plane. By changing the potential of an auxiliary gating electrode, the chamber can be switched between a low sensitivity mode in which tracks of highly ionizing heavy ions can be recorded, and a high sensitivity mode used to detect light particles emitted during the decay.

The acquisition system was triggered selectively when a ^{45}Fe ion was identified. In this way, the corresponding CCD image and the PMT time profile could be assigned unambiguously to individual ions. The trigger signal was also used to switch the OTPC to the high sensitivity mode and to turn the beam off for a period of 75 ms to prevent other ions from entering the detector while waiting for the decay of the stopped ion. Most of the data presented below (except for the left panel in Fig. 5) were collected while the camera exposure was started about 100μs after the trigger, thus the track of the triggering ion was not recorded.

The two protons ejected in the $2p$ decay of ^{45}Fe share the total Q_{2p} decay energy of 1.151 ± 0.015 MeV [9]. Assuming equal energy sharing, the proton track in the counting gas of the OTPC is expected to have the length of about 2.3 cm. In contrast, the energy available for β decay channels is much larger, see Fig. 1. According to shell model calculations of Ormand [14] the β decay of ^{45}Fe proceeds predominantly to states in ^{45}Mn with excitation energy above 2 MeV. The largest feeding is predicted for the isobaric analogue state (IAS) whose location, based on the systematics of Coulomb displacement energies [15], is predicted to be 8.44 MeV below the ground state of ^{45}Fe. Taking the masses of relevant nuclei from the latest mass evaluation [16], we estimate that for the transition leading the IAS state, the energy window opened for the βp, $\beta 2p$, and $\beta 3p$ emission is 11.31 MeV, 8.58 MeV, and 8.40 MeV, respectively. Thus, it can be safely assumed that each β decay of ^{45}Fe is accompanied by emission of at least one proton. Moreover, since already a 2 MeV proton has a range of about 17 cm in the OTPC gas, protons emitted after the β decay are expected to have long tracks, which allows to distinguish them from the particles emitted in the $2p$ radioactivity. In fact, β-delayed protons are expected to escape the active volume of the OTPC detector in most cases.

In addition to ^{45}Fe ions, a few other nuclei, produced with much higher rate, were transmitted by the A1900 spectrometer and stopped inside the OTPC detector during the experiment. It could happen that a decay of such a contaminant ion is recorded by a random coincidence in an event triggered by a ^{45}Fe ion. We estimate that the highest probability for such a random coincidence appeared for ^{43}Cr which has a half-life of 21.6 ms and a 90% probability for β-delayed proton emission [17]. The ^{43}Cr was stopped in the OTPC detector with a rate of 8 ions/minute. It follows that the probability of a random β-delayed proton decay of ^{43}Cr within an event triggered by ^{45}Fe was less than 2×10^{-3}. Therefore, in the following we consider such random coincidences as negligible.

An example of a decay event, interpreted as a β-delayed one-proton emission from ^{45}Fe, is shown in Fig. 2. The long

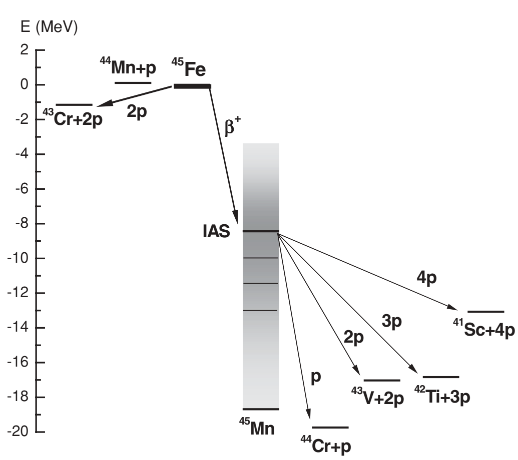

FIG. 1. Partial decay scheme of ^{45}Fe showing some of the opened β-delayed particle emission channels. The energy scale is shown relative to the ground state of ^{45}Fe. The mass values were taken from Ref. [16].

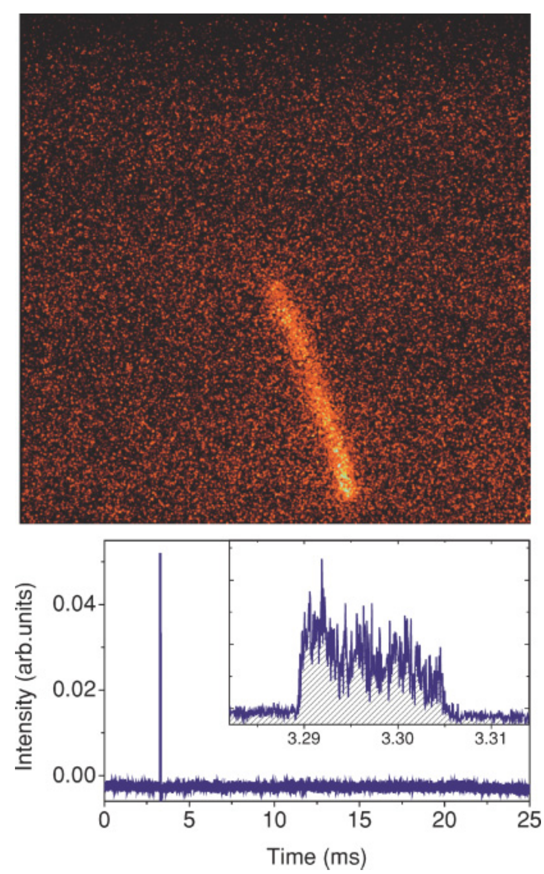

FIG. 2. (Color online) An example of a registered β-delayed proton emission from ^{45}Fe. Top: An image recorded by the CCD camera. The observed track is consistent with a high energy proton. The ionizing power of the positron is too small to see its track. Bottom: The time profile of the total light intensity measured by the PMT. In the inset, a magnified part is plotted, showing in detail the decay event.

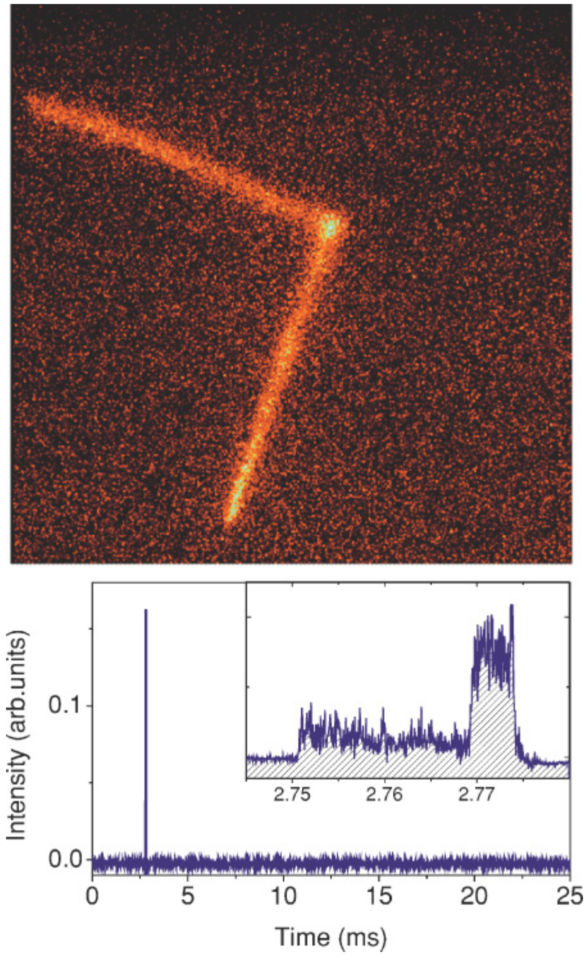

FIG. 3. (Color online) An example event of a β-delayed two-proton emission from ^{45}Fe. The description of panels is the same as in the Fig. 2.

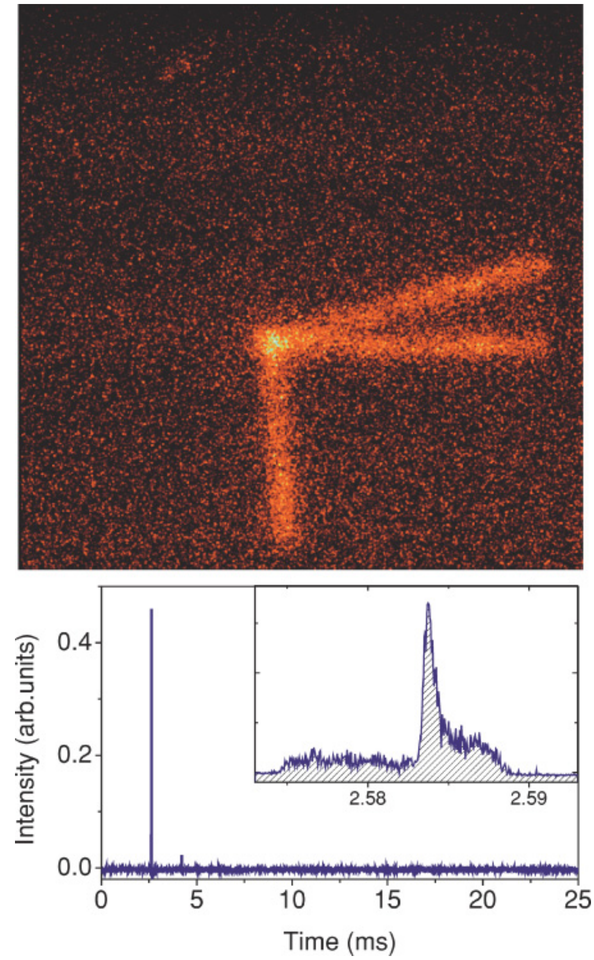

FIG. 4. (Color online) An example event of a β-delayed three-proton emission from ^{45}Fe. The description of panels is the same as in the Fig. 2.

track visible on the CCD image, which occurred about 3.3 ms after implantation of a ^{45}Fe ion, is consistent with a proton leaving the detector volume. The projection of the track on the image plane has the length of about 10 cm. The inset to the lower panel in Fig. 2 shows that the drift-time duration of this track was about 15μs, so its length in the direction perpendicular to the image plane was about 15 cm. Combining these two projections, we estimate that the proton passed about 18 cm in the chamber. Thus, its energy must have been larger than 2 MeV.

Figures 3 and 4 present events where two and three protons were emitted after implantation of ^{45}Fe, respectively. In both cases, the long tracks correspond to protons escaping the detector volume. From the shortest track in the image plane we may infer that their energies were larger than 1.2 MeV. The inset to the lower panel in Fig. 3 shows clearly two components corresponding to the two protons—one was emitted toward the camera (broad drift time profile), the other was ejected more parallel to the image plane (narrow drift time profile). Similarly, the drift-time profile shown in Fig. 4 has three components corresponding to three particles emitted in different directions. We conclude that in both cases the particles were emitted in a single decay event. Therefore, these events are interpreted as evidence for β-delayed two-proton and a β-delayed three proton decay of ^{45}Fe, respectively. The event shown in Fig. 4 represents the first observation of such a decay channel. In total, four such events were detected—the CCD images of the remaining three are shown in Fig. 5.

During the experiment, 125 decays of ^{45}Fe were observed, 87 of them proceeding by the direct $2p$ emission and 38 by β-decay followed by proton emission. Under assumption that each β decay of ^{45}Fe is accompanied by proton emission, this yields the branching ratio for the β decay of 0.30 ± 0.04 which is consistent with the results reported previously [7–9]. The decay-time analysis of $2p$ decay events yielded a half-life value of 2.6 ± 0.2 ms [12]. When the analysis is restricted only to β decay events, it yields the value of 2.8 ± 0.4 ms consistent with the above. The decay times of four events interpreted as $\beta 3p$ transitions lead to a value of 3.0 ± 1.4 ms, also consistent with the half-life of ^{45}Fe. Finally, the partial half-life for the β decay of ^{45}Fe is $T_{1/2}(\beta) = 8.7 \pm 1.3$ ms which is in good agreement with the theoretical value of 7 ms calculated by Ormand [14]. Out of 38 recorded β decay events, ten were of the $\beta 2p$ type and four represented the $\beta 3p$ category. The remaining 24 events were of the βp type. It follows that the relative branching ratios for the different β decay channels

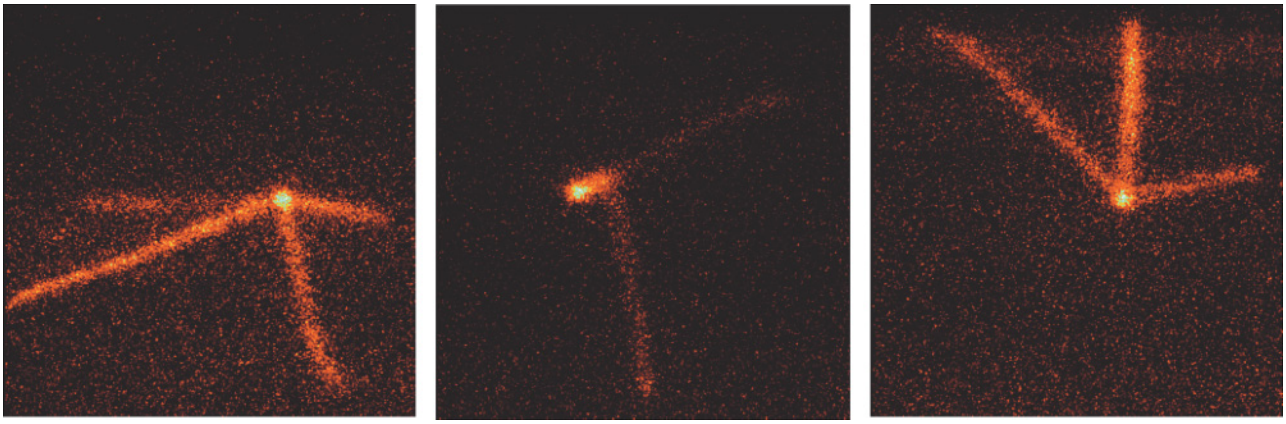

FIG. 5. (Color online) The CCD images of remaining three events of β-delayed three-proton emission from ^{45}Fe. The left image was taken in the mode in which a track of a ^{45}Fe ion, entering the detector horizontally from the left, can be seen.

are equal to 0.63 ± 0.08, 0.26 ± 0.07, and 0.11 ± 0.05, for the βp, $\beta 2p$, and $\beta 3p$ transition, respectively.

In summary, we have applied a newly developed ionization chamber, in which the optical imaging technique is used to record tracks of charged particles, to the detailed decay study of ^{45}Fe. Although the experimental conditions, like active detector volume and the gas density, were optimized for detection of low-energy protons emitted in the $2p$ radioactivity of ^{45}Fe [12], the events associated with the β^+ decay branch could be clearly identified. It was possible because protons following β transitions in this case have significantly larger energies than protons resulting from the $2p$ decay. In consequence, most of the recorded β-delayed protons escaped the active volume of the detector. This was sufficient to establish the occurrence of various β-delayed proton emission channels and to determine their probabilities. However, the detailed kinematical characterization of these processes, like the decay energy, was not possible in the present experimental conditions. Identification of the β-delayed three-proton emission represents the first direct evidence for such a decay type. The results illustrate the advantages of a new detection technique based on digital photography. The remarkable sensitivity of this method makes it ideally suited to studies of rare nuclear decays with emission of charged particles.

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