First Direct Observation of Two Protons in the Decay of ^{45}Fe with a Time-Projection Chamber

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The decay of the ground-state two-proton emitter ^{45}Fe was studied with a time-projection chamber and the emission of two protons was unambiguously identified. The total decay energy and the half-life measured in this work agree with the results from previous experiments. The present result constitutes the first direct observation of the individual protons in the two-proton decay of a long-lived ground-state emitter. In parallel, we identified for the first time directly two-proton emission from ^{43}Cr, a known β-delayed two-proton emitter. The technique developed in the present work opens the way to a detailed study of the mechanism of ground state as well as β-delayed two-proton radioactivity.

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Since the advent of facilities capable of producing atomic nuclei far away from the valley of nuclear stability, β-delayed particle emission and direct one-proton emission were among the tools most efficiently used to elucidate the structure of the atomic nucleus close to the proton drip line. The study of these decay modes allowed one to investigate the nuclear mass surface, to determine half-lives, to establish the sequence of single-particle levels, and to improve the modeling of astrophysical processes.

For the most proton-rich nuclei with an even number of protons, Goldansky [1] predicted the occurrence of a new nuclear decay mode, which he termed two-proton ($2p$) radioactivity. He suggested that, at the proton drip line and due to the pairing of protons, nuclei exist which are bound with respect to one-proton emission but unbound to two-proton emission. In the early 1960's, it was not clear which nuclei would be good candidates for this new decay mode. It is interesting that the list of possible $2p$ emitters proposed by Goldansky [2] contained already ^{45}Fe, for which ground-state two-proton radioactivity was indeed discovered [3,4] only recently.

This new type of radioactivity was observed in projectile-fragmentation experiments at the LISE3 separator of GANIL [3] and at the FRS of GSI [4]. These experiments allowed an unambiguous identification of this decay mode by measuring the decay energy, which nicely fits modern decay Q-value predictions [5–7], and the half-life, which is in agreement with models linking decay energy and Coulomb and centrifugal barrier penetration half-lives [8–10]. In addition, both experiments could demonstrate that, with a very large likelihood, there was no accompanying β-particle emission. This conclusion was achieved by a direct search for positrons [3] or for the 511 keV photons from positron annihilation [4] as well as by the width of the $2p$ emission peak, which was too narrow for pileup of protons and β particles. The most convincing piece of evidence is certainly the observation of the daughter decay with a half-life in agreement with the half-life of ^{43}Cr, the $2p$ daughter of ^{45}Fe [11]. All other possible daughters (e.g., the β-delayed proton emission daughter) could be excluded based on the measured daughter-decay half-life.

After the observation of $2p$ radioactivity for ^{45}Fe, this decay mode was also identified for ^{54}Zn [12] and evidence has been found for $2p$ radioactivity of ^{48}Ni [13]. However, in both experiments the decay was observed in a silicon detector. This allows only a determination of the total decay energy, the half-life, the branching ratio, and to demonstrate the absence of coincident β radiation, as in the case of ^{45}Fe. In none of these experiments, the two protons were identified separately. Emission of two protons has been observed directly only from excited states (see, e.g., [14–16]) or from very short lived resonances [17–19]. In the present work, we report for the first time on the direct observation of two protons emitted by ^{45}Fe. This is the first case of a direct two-proton observation of a long-lived ground-state two-proton emitter.

The technique developed in the present work, the purpose of which is to determine the complete kinematics for two protons in three dimensions, paves the way for a detailed study of ground-state and β-delayed two-proton emission. It will enable us to investigate the decay dynamics, i.e., whether the decay is an ordinary three-body decay or whether the two protons are correlated in energy and in angle. However, this nuclear structure information can only be extracted by a comparison to theoretical models. Therefore, a development of nuclear structure and reaction models is essential.

The ^{45}Fe nuclei were produced at the SISSI-ALPHA-LISE3 facility of GANIL. A primary $^{58}Ni^{26+}$ beam with an energy of 75 MeV/nucleon and an average intensity of 3 μA was fragmented in a ^{nat}Ni target (200 μm) in the SISSI device. The fragments of interest were selected by a magnetic-rigidity, energy-loss, and velocity analysis by means of the ALPHA spectrometer and the LISE3 separator including an energy degrader (500 μm of beryllium) in the LISE3 dispersive focal plane and transported to the LISE3 final focal plane. Time-of-flight, energy-loss, and residual energy measurements allowed an event-by-event identification of individual fragments. Details of the identification procedure can be found in Ref. [20].

Fragments transmitted to the LISE3 final focal plane were finally implanted in the center of a newly developed time-projection chamber (TPC) [21], which allows a visualization in three dimensions of implantation and decay events (see Fig. 1). For this purpose, the charges created by the primary ionizing particles (protons or heavy ions) in the gas [argon (90%)—methane (10%)] drift in an electric field towards a set of four gas electron multipliers [22] and are finally detected by two sets of orthogonal strips.

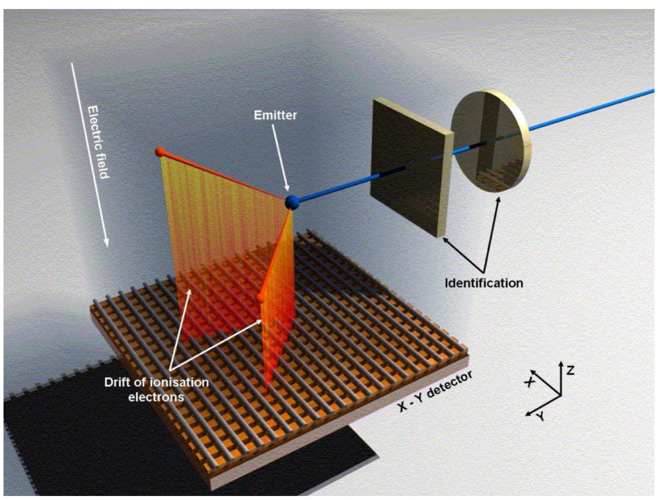

FIG. 1 (color online). Schematic representation of the time-projection chamber developed at the CEN Bordeaux-Gradignan. The nuclei of interest traverse first two silicon detectors (one standard detector with a thickness of 150 μm and a second position-sensitive detector (150 μm) with resistive readout) and are then implanted in the active volume of a gas-filled chamber, where they decay by emission of charged particles. The charge cloud created by the energy loss of either the heavy ions or the decay products drifts in the electric field of the chamber towards a set of four GEMs (not shown), where the charges are multiplied. The electric potential finally directs the charges onto a two-dimensional detection plane, where two orthogonal sets of 768 strips (pitch of 200 μm) allow a measurement of the charges deposited on each strip. Every second strip is equipped with an ASIC readout yielding signal height and time stamp. The other half of the strips is connected in groups of 64 strips to standard preamplifiers and shapers.

The front-end electronics, based on ASIC technology, allows the measurement of the charge deposited on each strip and of the arrival time of the charge on each strip with respect to a start triggered by the first strip that fires. The ASICs were readout by VME multiplexed analog to digital convertors. This readout mode yielded a dead time per event of about 1.3 ms. The dead time was determined event by event by sending the signals from a 1 MHz clock in coincidence with the "busy" signal from the data acquisition to a scaler.

The signals from different strips were gain-matched first by injecting a pulser signal into the last gas electron multiplier (GEM) thus creating an image charge on each single strip. This gain matching was refined by means of primary and fragment beams traversing the whole chamber with sufficient energy so that the energy loss can be assumed constant over the chamber. The strips parallel to the beam direction were gain-matched by rotating the chamber by 90°. The TPC was extensively tested offline with α sources and online with different beams. Details of this new instrument will be published elsewhere [21].

After a setting on ^{52}Ni, a well-known β-delayed proton emitter with decay energies around 1.2 MeV (see, e.g., [20]), the main setting of the SISSI-ALPHA-LISE3 facility was optimized for the production and selection of ^{45}Fe. In addition to ^{45}Fe, a large number of ^{43}Cr nuclei were also produced and implanted in the TPC in the same setting. ^{43}Cr is a β-delayed two-proton ($\beta 2p$) emitter, for which, however, the two protons were never directly observed [20,23,24].

In this Letter, we present only results obtained from the energy signals, which allows an unambiguous identification of the two protons emitted by ^{45}Fe. The analysis of the time signals, which will give rise to a three-dimensional reconstruction of the proton tracks, is much more complicated and beyond the scope of the present Letter. The complete analysis and the final results of the present experiment will be published in a subsequent paper.

In order to accept a pair of implantation and decay events, the decay tracks in X and Y have to start where the implantation tracks end. Figure 2 shows an implantation event for ^{45}Fe. The beam enters parallel to the X strips and stops at a certain Y depth in the active volume of the TPC (see Fig. 2). There, the tracks of the two protons emitted have to start.

In the present experiment, we observed a total of 10 ^{45}Fe implantations, which could be correlated with decays. Five other decay events are lost to a large extent due to the data acquisition dead time mentioned above and the short half-life of ^{45}Fe ($T_{1/2} = 1.75^{+0.49}_{-0.28}$ ms) [13]. In these cases, the treatment of the ^{45}Fe implantation event prevents the registration of its decay.

Four ^{45}Fe decay events are shown in the lower part of Fig. 2 and in Fig. 3. We will explain briefly the event in Fig. 2 in the following. On the lower left panel (X strips),

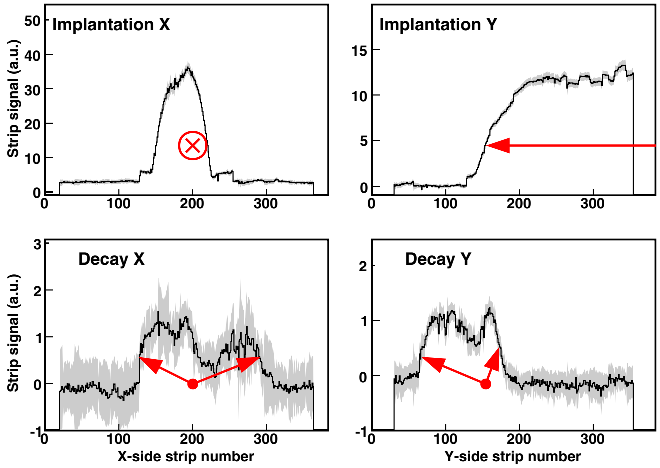

FIG. 2 (color online). Upper part: The figure shows a typical implantation event for ^{45}Fe. The ion enters parallel to the X strips (left figure) and stops at a certain depth in the Y direction (right figure). This plot allows one to determine the stopping position of the ion, where then the decay has to occur. Lower part: The decay of ^{45}Fe takes place by two-proton emission. The decay tracks start, within the position resolution of about 6–7 mm (FWHM), at the stopping point of the implantation event described above. The arrows are indicative only of the tracks of the two protons. A horizontal arrow means that the proton propagates perpendicular to the strips, whereas a vertical arrow indicates that the proton track is parallel to the strips. The shaded zone corresponds to the error bars due to the gain matching procedure.

one sees the starting point of the two protons around channel 200, in agreement with the maximum of the implantation event in the upper left part of Fig. 2. The traces extend to the left and the right of this point, testimony of the two protons being emitted across a number of strips. The lower right panel indicates a starting point around strip 160. One observes a large bump on which is superimposed a narrower one. The former indicates that one proton is emitted more or less perpendicular to the Y strips, whereas the second proton has a trajectory parallel to these strips. Therefore, this figure clearly proves the presence of two charged particles in the decay of ^{45}Fe. There is no other explanation possible for such a decay pattern.

This is the first direct observation of the emission of two protons in the ground-state decay of a long-lived two-proton emitter. As mentioned above, all previous evidence was indirect. Although the third coordinate Z is not yet determined—it will follow from the drift-time analysis—one can already state that a variety of decay configurations is observed and not only one type, e.g., a back-to-back emission.

After background subtraction, the charges deposited by decay events on the different strips can be integrated and are proportional to the energy of the decay event. Charges on X and Y strips were integrated separately. In addition, the different GEMs yield also the total decay energy. Therefore, the charge signal from the GEMs is sent to a charge-sensitive preamplifier and a shaper. In Fig. 4(a), we

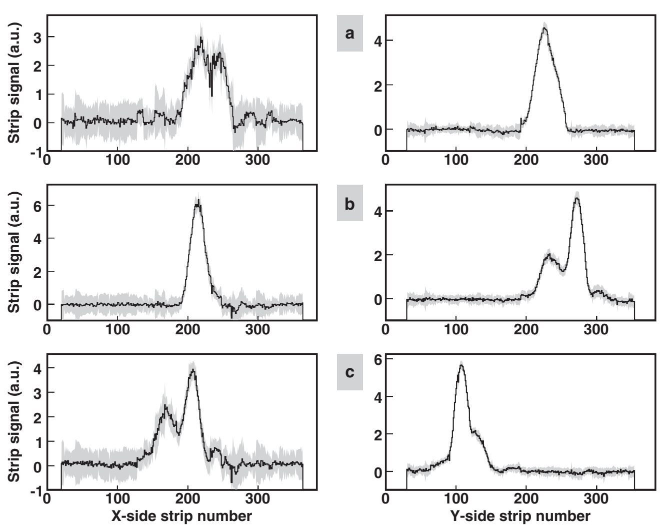

FIG. 3. The figure shows three of the ten decay events observed after implantation of ^{45}Fe. We have chosen here events where the two protons can be clearly identified. For two of the ten events, the two protons cannot be separated, as they fire the same strips.

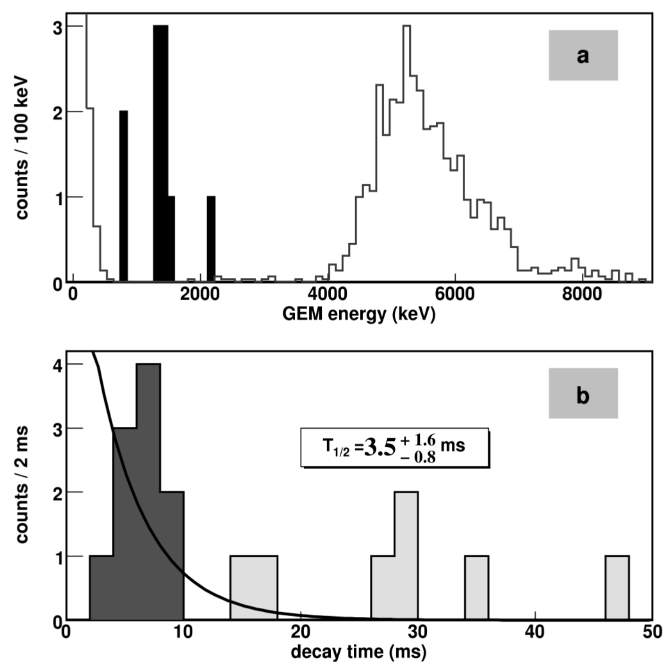

FIG. 4. (a) Total decay energy of the ^{45}Fe events as determined with the last GEM. The low-energy events (in black) show the ^{45}Fe decay, whereas the high-energy events are from a triple-α source. The energy of the ^{45}Fe events corresponds roughly to the expected decay energy of 1.15 MeV [13]. (b) Half-life of ^{45}Fe as determined from the time difference of the implantation events and the decay events (black events). The half-life is $3.5^{+1.6}_{-0.8}$ ms. The events in gray are the daughter-decay events which were not included in the fit.

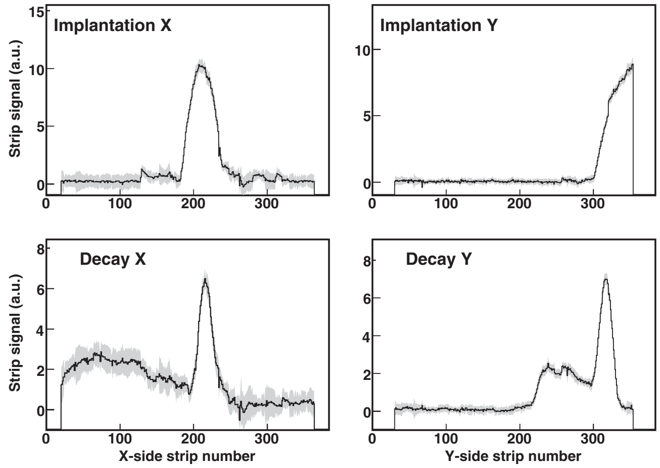

FIG. 5. Upper part: Implantation event of a ^{43}Cr nucleus in the TPC. The nucleus is identified by means of energy loss and time-of-flight measurements. Lower part: Decay of ^{43}Cr as observed with the TPC. The traces of the two protons can be seen in the X and Y directions.

plot this charge signal from the last GEM (energy resolution of 500–600 keV). A rough energy calibration was achieved by means of a triple α source. The decay energy thus determined corresponds roughly to the expected decay Q value of 1.15 MeV [13].

The time difference between an implantation event and its subsequent decay event allows a determination of the half-life of ^{45}Fe. This spectrum is shown in Fig. 4(b). We used the procedure proposed by Schmidt *et al.* [25] to determine the half-life of ^{45}Fe from these events. For this purpose, we shifted the time by the dead time. This procedure was tested with Monte Carlo simulations. It yields a half-life of $3.5^{+1.6}_{-0.8}$ ms. This value is in fair agreement with the average value from previous experiments of $1.75^{+0.49}_{-0.28}$ ms [13].

As outlined above, the setting of LISE3 on ^{45}Fe allowed us also to study the decay of ^{43}Cr, a known β-delayed two-proton emitter, for which the $\beta 2p$ decay was only identified by means of the total decay energy [20,23,24]. The present experiment with the TPC enabled us for the first time also to visualize the emission of two protons from this nucleus. Although the active volume of the present version of the TPC is too small to stop all the protons in this decay due to their much higher energy (up to about 2 MeV for each proton), the two protons are nonetheless clearly observable for most of the decay events. One of these decay events together with its preceding implantation is shown in Fig. 5. The two-proton tracks are visible in both directions.

A detailed study of this decay and the search for a possible angular correlation between the two protons can be envisaged either by increasing the active volume of the TPC or by working at higher pressure. In this way, many other $\beta 2p$ emitters could be identified and studied.

In summary, we have performed the first experiment, which demonstrates unambiguously that ^{45}Fe emits indeed two protons in most of its decays. This is the first time that ground-state two-proton emission of a long-lived (longer than 10^{-21} s) isotope is observed directly. Thus, ground-state two-proton radioactivity is definitively established as a nuclear decay mode.

A more detailed analysis will determine how the two protons share the energy and thus to elucidate the decay mechanism which governs two-proton radioactivity. The complete analysis of the energy and of the time signals should give access to the decay kinematics. However, to establish a detailed picture of the decay process, higher-statistics data (50–100 implantation and decay events) are needed, which can be obtained in a future experiment.

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