First direct observation of two protons in the decay of $^{45}$Fe with a TPC

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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 $^{45}$Cr, a known $\beta$-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 $\beta$-delayed two-proton radioactivity.

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Since the advent of machines to produce atomic nuclei far away from the valley of nuclear stability, $\beta$-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 or to improve the modeling of astrophysical processes.

For the most proton-rich nuclei with an even number of protons, Goldanskiï [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 for 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 Goldanskiï [2] in the 1960’s 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 [5] and at the FRS of GSI [4]. These experiments allowed for an unambiguous identification of this decay mode by measuring the decay energy, which nicely fits modern decay $Q$ value predictions [3, 6, 7], and the half-life, which is in agreement with models linking decay energy and Coulomb and centrifugal barrier penetration half-lives [8, 9]. In addition, both experiments could demonstrate that, with a very large likelihood, there was no $\beta$ particle emission. This conclusion was achieved by a direct search for positrons [3] or for the 511 keV photons from positron annihilation [3] as well as by the width of the 2p emission peak, which is too narrow for a pile-up event of protons and $\beta$ particles. The most convincing piece of evidence is certainly the observation of the daughter decay with a half-life in nice agreement with the half-life of $^{45}$Cr, the 2p daughter of $^{45}$Fe [10]. All other possible daughters (e.g. $\beta$-delayed proton emission daughter) can be excluded based on the experimentally measured daughter half-life.

After the observation of 2p radioactivity for $^{45}$Fe, this decay mode was also identified for $^{54}$Zn [11] and evidence has been found for 2p radioactivity of $^{48}$Ni [12]. However, in both experiments the decay was observed in a silicon detector, which allows only for a determination of the total decay energy, the half-life, the branching ratio, and the absence of $\beta$ radiation, as in the case of $^{45}$Fe. In none of these experiments, the two protons were explicitly identified. Emission of two protons has been observed directly only from excited states (see e.g. [13, 14, 15]) or from very short lived resonances [16, 17, 18]. 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 $\beta$-delayed two-proton emission. It will enable us to investigate the decay dy-

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namics, i.e. whether the decay is an ordinary three-body decay or whether the two protons are correlated in energy and in angle, the sequence of single-particle levels beyond the drip line and more. However, this nuclear structure information can only be extracted by a comparison to theoretical models. Therefore, a development in parallel of powerful 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 $\mu$A was fragmented in a $^{nat}$Ni target (200µm) in the SISSI device. The fragments of interest were selected by a magnetic-rigidity, an energy-loss, and a velocity analysis by means of the ALPHA spectrometer and the LISE3 separator including an energy degrader (500µm 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 for an event-by-event identification of individual fragments. Details of the identification procedure can be found in reference \[19\].

![Diagram](image)

FIG. 1: 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 150µm and a second position-sensitive detector (150µm) 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 gas electron multipliers (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 200µm) allow for 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.

Fragments transmitted to the LISE3 final focal plane were finally implanted in the center of newly developed time-projection chamber (TPC) \[20\], which allows for a visualisation in three dimensions of implantation and decay events (see figure 1). For this purpose, the charges created by the primary ionising 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 (GEMs) \[21\], where the charges are multiplied, and are finally detected by two orthogonal sets of 768 strips with a pitch of 200µm. The front-end electronics, based on ASIC technology, allows for the measurement of the charge deposited on each strip and of the arrival time of the charge on this strip with respect to a start triggered by the first strip that fires. The ASICs were readout by VME multiplexed ADCs. This readout mode yielded a dead time per event of about 1.3 ms.

The signals from different strips were gain-matched first by injecting a pulser signal into the last 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 off-line with a sources and on-line with different beams, which consituted a proof of the working principle of the chamber. Details of this new instrument will be published elsewhere \[20\].

After a setting on $^{52}$Ni, a well known $\beta$-delayed proton emitter with decay energies around 1.2 MeV (see e.g. \[19\]), the main setting of the SISSI-ALPHA-LISE3 facility was optimised 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 $\beta$-delayed two-proton ($\beta 2p$) emitter, for which, however, the two protons were never directly observed \[19, 22, 23\].

In the present paper, we will present only the results obtained from the energy signals of the strips, which allows for 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 is beyond the scope of the present paper. 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 figure 2). There, the decay 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 de-
Implantation X decay Y evidence, even if equally conclusive, was indirect. Almost two-proton emitter. As mentioned above, all previous two protons in the ground-state decay of a long-lived pattern.

There is no other explanation possible for such a decay presence of two charged particles in the decay of these strips. Therefore, this figure clearly evidences the where 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 narrow one. The first indicates that one proton flies more or less perpendicular to the Y strips, whereas the second proton has a trajectory parallel to these strips. Therefore, this figure clearly evidences the presence of two charged particles in the decay of $^{45}\text{Fe}$. 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, even if equally conclusive, was indirect. Although the third coordinate $Z$ is not yet determined - it will follow from the drift-time analysis, one can already state at this stage 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 pre-amplifier and a shaper. In figure 3a, we plot this charge signal from the last GEM. A rough energy calibration was achieved by means of a triple $\alpha$ source. The decay energy thus determined corresponds roughly to the expected decay $Q$ value of 1.15 MeV [12].

The time difference between an implantation event and its subsequent decay event allows for a determination of the half-life of $^{45}\text{Fe}$. This spectrum is shown in figure 4b.

A fit with an exponential, excluding the first 2 ms which are affected by the data acquisition dead time, yields a half-life value of $(2.5\pm1.0)$ ms. This value is in agreement with the average value from previous experiments of $1.75^{+0.28}_{-0.49}$ ms [12].

As mentioned above, the setting of LISE3 on $^{45}\text{Fe}$ allowed us also to study the decay of $^{43}\text{Cr}$, a known $\beta$-delayed two-proton emitter, for which the $\beta^2p$ decay was only identified by means of the total decay energy [18, 22, 23]. The present experiment with the TPC enabled us for the first time also to visualise the emission of two protons from this nucleus. Although the active volume of the present version of the TPC is too small

![FIG. 2: Upper part: The figure shows a typical implantation event for $^{45}\text{Fe}$. The ion enters parallel to the X strips (left figure) and stops at a certain depth in Y direction (right figure). This plot allows to determine the stopping position of the ion, where then the decay has to occur. Lower part: The decay of $^{45}\text{Fe}$ 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.](image-url)

![FIG. 3: The figure shows three of the ten decay events observed after implantation of $^{45}\text{Fe}$. We have chosen here events, where the two protons can be nicely identified. For two of the ten events, the two protons can not be separated, as they fire the same strips.](image-url)
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 figure 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 $^{45}\text{Fe}$ 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 try to 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 allow for a more detailed access to the decay kinematics. This will enable us to determine the proton-proton angle which then can be compared to model predictions for the decay pattern of two-proton radioactivity. 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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