Two-Proton Correlations in the Decay of ^{45}Fe

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The decay of extremely neutron-deficient ^{45}Fe has been studied in detail by means of a novel type of a gaseous detector employing digital imaging to record tracks of charged particles. The two-proton radioactivity channel was clearly identified. For the first time, the angular and energy correlations between two protons emitted from the nuclear ground state were determined, indicating the genuine three-body character of this decay. The half-life of ^{45}Fe was found to be 2.6 ± 0.2 ms and the observed $2p$ decay branching ratio is $70 \pm 4\%$.

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For over 100 years now radioactive decay has been an important probe used to study properties of atomic nuclei. Ground-state proton radioactivity, first predicted by Goldansky [1], plays a significant role in the studies of very neutron-deficient nuclei. It occurs for nuclei beyond the dripline, where proton separation energy becomes negative, and thus the emission of a constituent proton is feasible. The first ground-state proton emitter, ^{151}Lu, was reported in 1982 [2]. Since that time, proton emission studies have brought a wealth of data proving to be an extremely sensitive tool to explore the structure of nuclei at the neutron-deficient limit of existence [3,4].

While ground-state proton radioactivity is observed for nuclei with an odd number of protons (Z), one of the new phenomena predicted for extremely neutron-deficient even-Z nuclei is ground-state two-proton ($2p$) radioactivity. Early considerations of Goldansky [1] led him to predict this process for nuclei in the vicinity of the proton dripline for which, due to pairing interactions, emission of a single proton would be energetically forbidden. His prediction, later supported by more refined calculations [5–7] focused on nuclei in the mass $A \approx 50$ region, with ^{45}Fe being the optimum candidate for two-proton radioactivity.

The first observation of this isotope occurred in 1996 when three ions of ^{45}Fe were identified among fragmentation products synthesized by bombarding a beryllium target with a 600 MeV/nucleon ^{58}Ni beam [8]. The key feature of this success, and of all subsequent studies of this and neighboring nuclei, is the extremely high sensitivity provided by the magnetic separation and in-flight identification of single ions. The first information on the decay of ^{45}Fe was obtained at GSI Darmstadt with 5 events [9] and at GANIL Caen with about 20 events [10]. In both experiments, the identified ions were implanted into a thick silicon detector where only the total energy released in a decay and the decay time were recorded. A further experiment performed subsequently at GANIL, using the same techniques as previously, yielded additional 30 events [11]. The average over the three results on ^{45}Fe yielded a half-life value of $1.75^{+0.49}_{-0.28}$ ms and a $2p$ decay energy of 1.151(15) MeV [11]. Satisfactory agreement of these observables with the predictions of two models, one based on the R-matrix theory [12] and another, invoking explicitly 3-body dynamics [13,14], was used as the argument in favor of the $2p$-decay interpretation of the data. Such a conclusion, however, could not be reached from the experimental results alone. Very recently, Giovinazzo *et al.* [15] succeeded to record a few events of the $2p$ decay of ^{45}Fe by observing directly individual protons in a time projection chamber; however, no information on the decay mechanism could be deduced.

The main physics question faced in the context of $2p$ emission is what are the angular and energy correlations between ejected protons? Does a strong diproton (^{2}He) correlation, as was speculated already by Goldansky [16], play a role? Furthermore, correlations may reveal details of the nuclear wave function and shed light on nucleon interactions inside the nucleus and thus provide sensitive tools to study their structure.

In this Letter we present the results of recording tracks of both protons emitted in the decay of ^{45}Fe which, for the first time, has allowed investigation of angular correlations between these protons. To meet this challenge, we developed a new type of a gaseous detector—the Optical Time Projection Chamber (OTPC) [17] in which images of ionizing particle trajectories are recorded optically. 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, towards 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 signals from the PMT are digitized with a 50 MHz sampling frequency providing information on the drift-time which is related to the position along 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 pioneering research on gaseous detectors with position sensitive optical readout was performed by Charpak *et al.* [18]. To the best of our knowledge the detector described here represents the first application of this idea to nuclear physics studies.

The experiment was performed at the National Superconducting Cyclotron Laboratory at Michigan State University, East Lansing, USA. Ions of ^{45}Fe were produced in the 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 [19] 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 aluminum foil and stopped inside the OTPC. 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 about 75 ms to prevent other ions from entering the detector while waiting for the decay of the stopped ion.

An example of a recorded radioactive decay event of ^{45}Fe is presented in Fig. 1. A track of ^{45}Fe ion entering the chamber from left can be seen on the CCD image (top). After 535 μs, two short and bright tracks occurred which originated from the end of the ^{45}Fe track. Their length, inferred from the image and from the time distribution of the total light intensity measured by the PMT (bottom), agrees with the value of 2.3 cm expected for protons of about 0.6 MeV in the counting gas of the OTPC. The CCD image shown in Fig. 1, supported by the PMT time profile, represents direct and clear proof of the occurrence of the $2p$ radioactivity in ^{45}Fe.

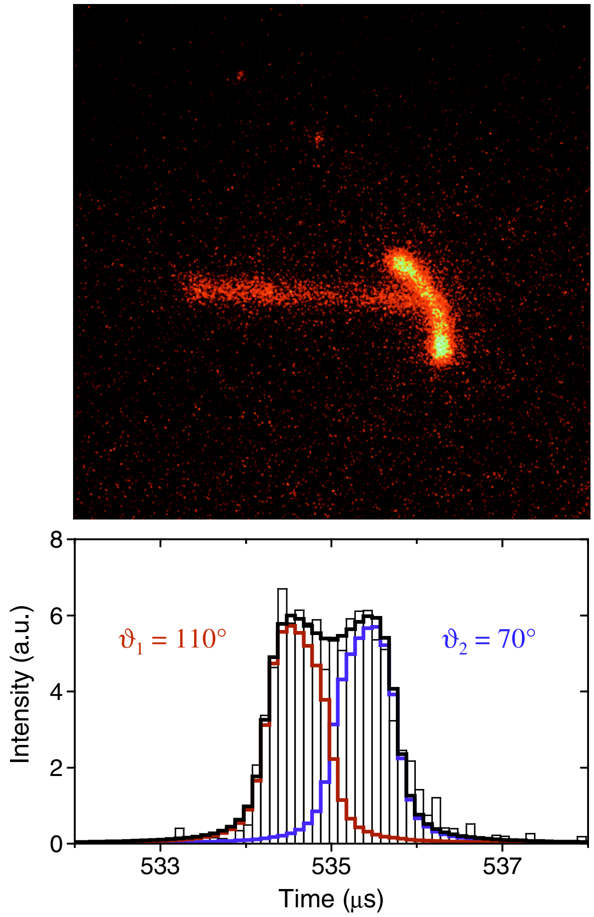

FIG. 1 (color online). An example of a registered two-proton decay event of ^{45}Fe. Top: an image recorded by the CCD camera in a 25 ms exposure. A track of a ^{45}Fe ion entering the chamber from left is seen. The two bright, short tracks are protons of approximately 0.6 MeV, emitted 535 μs after the implantation. Bottom: a part of the time profile of the total light intensity measured by the PMT (histogram) showing in detail the $2p$ emission. Lines show results of the reconstruction procedure yielding the emission angles ϑ with respect to the axis normal to the image.

Apart from the $2p$ decay leading to ^{43}Cr, the nucleus ^{45}Fe can also decay by β^+ transitions to excited states of ^{45}Mn. The decay energy for this disintegration mode is predicted to be about 18.7 MeV [6] and in consequence many decay channels involving β-delayed particle emission are possible. In fact, it is expected that 100% of the β^+ decays of ^{45}Fe are followed by charged particle emission and that these particles have energies large enough to escape the active volume of the OTPC in most cases [6]. Such decay channels, including β-delayed $2p$ and β-delayed $3p$ emission, have also been observed and will be published separately [20].

In the course of the 9-day 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.

This yields the branching ratio for the $2p$ decay of 0.70(4). Using the maximum likelihood method, the decay half-life of ^{45}Fe was determined as 2.6(2) ms. The partial $2p$ decay half-life of ^{45}Fe is then $T_{1/2}(2p) = 3.7(4)$ ms and the corresponding $2p$ decay width $\Gamma_{2p} = 1.23^{+0.15}_{-0.12} \times 10^{-19}$ MeV.

The deduced partial $2p$ decay width of ^{45}Fe is presented in Fig. 2 showing the dependence of the $2p$ half-life on the decay energy as predicted by the 3-body model of Grigorenko and Zhukov [13,21]. The experimental decay energy is taken from Ref. [11] as it is the most precise value to date. The various theoretical lines correspond to different configurations of the two valence protons in the initial nucleus. The location of the experimental point suggests that the initial state is characterized by the ratio of the dominant p^2 and f^2 configurations equal to about 30/70. This finding is consistent with the realistic shell-model calculation for ^{45}Fe predicting the dominant role of the f orbitals with a significant contribution of the p states [12].

The information contained in the image and in the time profile allows the reconstruction of the decay event in three dimensions. By using a fitting procedure that takes into account the ionization density distribution along a proton track in the OTPC gas and includes corrections for the detector response, the angles ϑ of both proton tracks with respect to the axis normal to the image plane can be determined. This procedure, applied to the event shown in Fig. 1, resulted in values $\vartheta_1 = 110° \pm 3°$ and $\vartheta_2 = 70° \pm 2°$. The combination of these angles with the angle ϕ between tracks measured on the image plane allows the calculation of the angle θ_{pp} between the momenta of the two protons. For the event of Fig. 1, $\phi = 140° \pm 3°$ and $\theta_{pp} = 143° \pm 5°$.

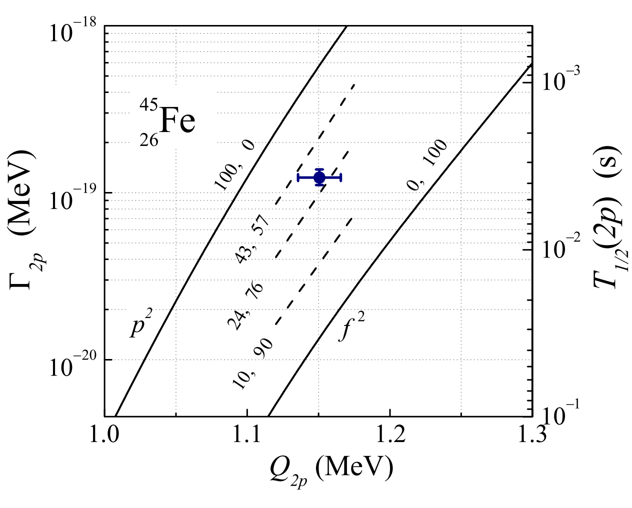

FIG. 2 (color online). The partial $2p$ half-life of ^{45}Fe as a function of the $2p$ decay energy. The experimental result is shown superimposed on predictions of the 3-body model [13,21]. The decay width is taken from this work; the energy is taken from Ref. [11]. The numerical labels indicate the relative weights of the p^2 and f^2 configurations, respectively.

This procedure was applied to all recorded $2p$ decay events, and for 75 of them it yielded reliable and unambiguous results. The distribution of the opening angle has been constructed in the following way. Each event was represented by a Gaussian distribution centered at the determined value of θ_{pp}, with the area and the variance equal to one and to the estimated error, respectively. The sum of all such contributions is shown as a histogram in Fig. 3. A two-bumped structure is evident—one broad peak is centered around 50° and a second smaller one is present at about 145°. In the case of the pure diproton scenario, the distribution was expected to contain one narrow peak centered at about 30° [22] while in the case of fully uncorrelated emission, the distribution would be proportional to $\sin\theta_{pp}$. Evidently, measured distribution does not follow these scenarios. It agrees, however, with the prediction of the 3-body model for the f-p shell nuclei. The calculated distributions for three mixtures of p^2 and f^2 configurations, normalized to the same integral as the experimental spectrum, are shown in Fig. 3 by smooth lines. Using a quadratic interpolation we estimate that the experimental data are best described by the model when the contribution of the p^2 configuration is equal to $(30 \pm 10)\%$.

We would like to stress the following points. (i) There is remarkable consistency between observables shown in Figs. 2 and 3 and theoretical predictions [21]. Both the $2p$ decay width as a function of the decay energy and the opening angle distribution are best described by the same composition of the initial $2p$ wave function. (ii) In two-body decays, like proton radioactivity, the structure information (spectroscopic factor) is extracted only by the comparison of the measured width with the theoretically calculated value (namely, the Wigner limit). In this experiment we show for the first time that in a three-body decay the structure information can be extracted both from the

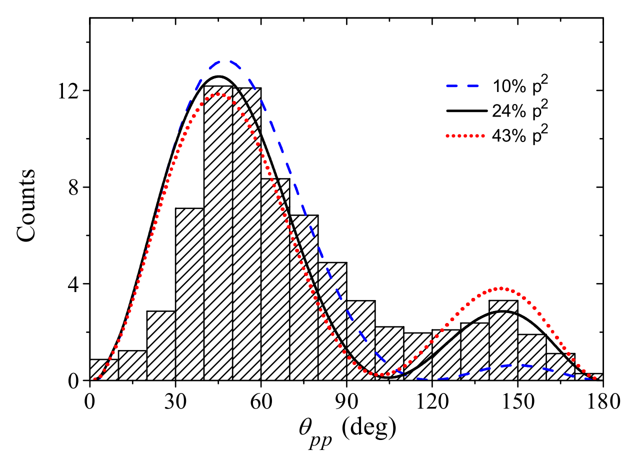

FIG. 3 (color online). The measured distribution of the opening angle between two protons emitted in the decay of ^{45}Fe (histogram). Lines show the predictions of the 3-body model for the same mixtures of p^2 and f^2 configurations as shown in Fig. 2 with the dashed lines.

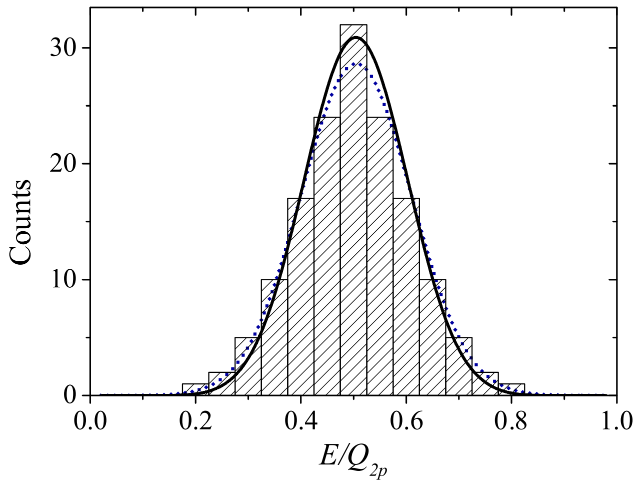

FIG. 4 (color online). The energy distribution of individual protons emitted in the $2p$ decay of ^{45}Fe (histogram). The energy is given in units of the total decay energy $Q_{2p} = 1.15$ MeV. The solid line indicates the prediction of the 3-body model [13] while the dotted line shows this theoretical prediction folded with a Gaussian function representing the detector energy resolution of 20%.

width and from the correlation pattern in an independent way, providing an important cross-check, never available before. (iii) The theoretical model of Ref. [21] is rather simple when nuclear structure is concerned, as it deals only with single-particle motion of the valence protons. Further careful studies of other aspects of nuclear dynamics which may influence the correlations are warranted. However, the consistency of different observables with the present theoretical model may be regarded as encouraging. (iv) Strong sensitivity of angular correlations to details of nuclear structure is predicted to be a general feature of the $2p$ decays of the f-p shell nuclei [21]. This opens interesting prospects for further studies of other cases of the $2p$ radioactivity in similar experiments.

The event reconstruction procedure used to determine angles yields also the energies of emitted protons, although the energy resolution of the OTPC detector is rather poor and estimated to be about 20% (FWHM) for protons of 0.5 MeV. The resulting individual proton energy distribution, obtained with a constraint that the sum of both proton's energies equals 1.15 MeV, is presented in Fig. 4. The prediction of the 3-body model [13], normalized to the same number of events, is also plotted in Fig. 4 showing a good agreement with the data.

In summary, we have applied a new type of ionization chamber, utilizing an optical imaging technique, to the decay study of ^{45}Fe. We have proved in a direct and clear way that this extremely neutron-deficient nucleus disintegrates by the simultaneous emission of two protons. The reconstruction of $2p$ decay events in three dimensions allowed the first observation of the angular and energy correlations between protons emitted in ground-state $2p$ radioactivity. The measured distribution rules out a simple diproton scenario. It agrees, however, with a model which includes explicitly the 3-body dynamics of the process. Both the new value of the half-life and the angular distribution are reproduced consistently by the assumption that the protons are ejected from the ^{45}Fe ground state characterized by a significant mixture of p^2 and f^2 configurations. Also, the energy distribution of emitted protons shows a good agreement with the prediction of the 3-body model.

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