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TWO-PROTON RADIOACTIVITY: TRACKING ^2He EMISSION

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Two proton radioactivity has been observed experimentally in the decay of ^{45}Fe and ^{54}Zn, and possibly of ^{48}Ni. These first experiments only allowed for a limited comparison with theory: $T_{1/2}$ and Q_{2P} values. Experimental efforts have been achieved to measure dynamical observables in order to perform a more detailed study of the decay mechanism. Time projection chambers have been developped by groups of Bordeaux and Warsaw, and were successfully used at GANIL and MSU: those devices allowed for a first direct observation of the individual protons in the 2-proton radioactivity of ^{45}Fe, and a first estimate of correlations of these protons.

1. Introduction

For nuclei at the proton drip-line, Goldanskii predicted two new decay modes in the early 60's [1]: one-proton radioactivity for odd-Z nuclei, and two-proton radioactivity for even-Z nuclei. For this latter decay mode, the emission of one single proton is forbidden, and the two protons have to be emitted simultaneously. The pairing correlation of the last protons makes such a decay process possible, and the emitted particles may keep a trace of this correlation.

Experimentally, two-proton radioactivity was observed recently in the decay of ^{45}Fe at GANIL[2] and GSI[3], and in the decay of ^{54}Zn and also possibly of ^{48}Ni at GANIL [4,5]. In all these experiments, performed at projectile fragmentation facilities, the emitted protons were not observed directly.

Beside the observation of the 2-proton ground state emission, no information about the decay mechanism could be extracted. Despite the sequential decay option is excluded, the emission could be either a 3-body break-up, or a correlated emission. In such a case, the 2 protons can emitted as a ^2He resonance, comparable to a cluster radioactivity.

In order to go further in the understanding of this new decay mode, throught a deeper comparison with theoretical calculations, a new type of experiments arised, that allows the observation of individual protons. Those experiments use tracking devices, in order to perform energy and angular correlations of the emitted particles. The first results of this new generation of experiments are discussed in this paper.

2. Discovery of 2-proton radioactivity

In an experiment[2] performed at GANIL/LISE3 facility, ^{45}Fe ions were produced in the SISSI device by fragmentation of a ^{58}Ni at 75 MeV/A in a natural nickel target. The fragments were selected by mean of the alpha spectrometer and the LISE3 separator, and implanted in a silicon telescope. The ions were identified by a standard energy loss and identification technique.

After implantation, the ions decay inside the implantation silicon detector. The energy deposit of the charged particles in the detector, and the time difference between implantation and decay, are measured. For the decay events after ^{45}Fe implantations, a peak at 1.14 MeV was clearly observed, with 12 counts. It has been attributed to the 2-proton decay for the following reasons:

(i) protons up to few MeV are stopped in the implantation detector, and β escape it, but no β were observed, which would correspond to a probability less than 1 % if the peak is from β-particle (β-p, β-2p, β-α,...) decay;
(ii) in case of a β-particle decay, the peak would be broader, due to the pile-up of the particle (proton(s) or α) energy and the energy loss of the β, and this broadening is not observed;
(iii) the decay half-life measured for the daughter nucleus is only compatible with ^{43}Cr, which is the daughter of ^{45}Fe after 2-proton emission (fig. 1).

The 2-proton branching-ratio was estimated to 70 to 80 %, indicating a competition between β and 2-proton decay modes. The half-life of ^{45}Fe measured during this experiment was $4.7^{+3.4}_{-1.4}$ ms.

^{45}Fe decay has been observed also in another experiment[3], performed at GSI on the FRS separator. The fragments of interest, identified with standard FRS techniques, where also implanted in a silicon telescope. This device was surrounded by a high efficiency NaI barrel detector, in order to observe the 511 keV γ rays of the positron annihilation in case of a β^+ decay. Four decay events out of six were observed at an average energy of 1.1 MeV, and no γ was observed in coincidence, indicating that there was no β^+ decay. A decay half-life of $3.4^{+2.4}_{-1.1}$ ms was measured for ^{45}Fe. Thus, the GSI experiment is in nice agreement with the GANIL one for the 2-proton branching ratio, the energy Q_{2P} of the transition and the ^{45}Fe half-life $T_{1/2}$.

This result concerning the decay of ^{45}Fe has been confirmed by another experiment at GANIL, using the same technique than the previous one[5]. During this experiment, ^{54}Zn has been observed for the first time and its decay could be measured[4]: it was concluded that it decays by 2-proton radioactivity, with the same arguments than for ^{45}Fe. In addition, the doubly-magic nucleus ^{48}Ni was also produced (4 identified ions), and 3 decay events were observed[5]. One of those decay events is compatible with a 2-proton decay, but more statistics is required to conclude.

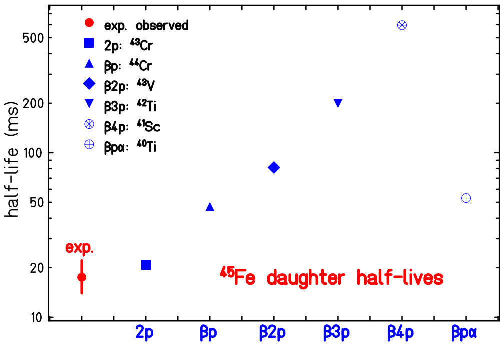

Fig. 1. Measured half-life of the daughter nucleus of ^{45}Fe compared with the expected value for different decay modes: the observation is only in agreement in the case of a 2-proton decay.

The results from this first series of experiments can be compared with theoretical approaches. The experimental Q_{2P} value is used as an input of the calculations of the theoretical half-life $T_{1/2}$. The calculations are in fairly good agreement with the experiments for the different models (fig. 2-left): models with an emphasis on nuclear structure like R-matrix formalism including a proton-proton resonance[6] and shell-model embedded in the continuum[7] ($SMEC$) or with an emphasis on the decay dynamics like the 3-body model from L.V. Grigorenko[8].

The experimental results for Q_{2P} and $T_{1/2}$ only allow for a limited comparison with theory. In order to learn more about the 2-proton radioactivity process, and to determine the mechanism of the decay, more detailed observations are required, like energy and angular correlations of the emitted protons, as shown on right part of figure 2. For this purpose, new detection tools had to be developped, leading to a new type of experiments.

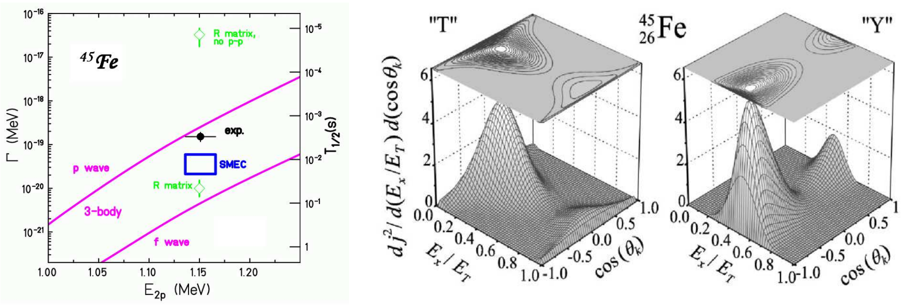

Fig. 2. Left: comparison of the experimental half-life with theoretical calculations from R-matrix formalism with or without a proton-proton resonance[6], from the shell-model embedded in the continuum[7] and from a 3-body model[8]; the uncertainties on theoretical values are due to the experimental uncertainty on Q_{2P}. Right: angular versus energy distribution for the proton-proton and core (T) or core-proton and proton (Y) subsystems in the 3-body model from Grigorenko[8].

3. Tracking experiments

Two experiments have been performed with *time projection chambers* (TPC), at GANIL in 2006[9] and MSU in 2007[10]. The purpose of such devices is to reconstruct the trajectories of each proton in the decay of ^{45}Fe, in order to measure their individual energy and their relative angle. In both cases, the ions were produced by fragmentation reaction of a ^{58}Ni beam.

The principle of the TPC used at GANIL is illustrated in figure 3. The ions are implanted in a 15×15×6 cm^3 gaz cell filled with $P10$ (90% Argon, 10% Methane) at a pressure of 500 $mbar$. After the implantation, the decay occurs from where the ions where stopped. Charged particles (the ion for an implantation event or the two protons for a decay event) produce ionization electrons. Due to an electric field in the chamber, the ionisation electrons drift towards a X-Y strip detector that measures a 2D projection of the signal. For each strip, the drift time of the electrons is measured, thus providing the $3^{\rm rd}$ dimension.

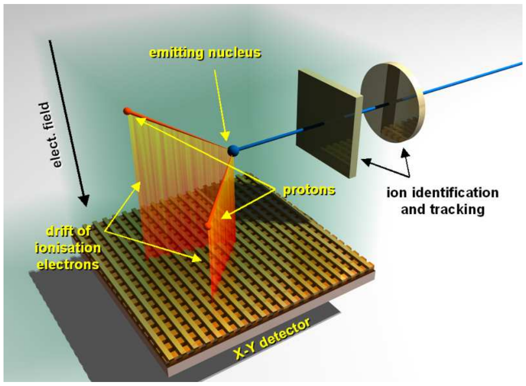

Fig. 3. Principle of the TPC used at GANIL: the ionisation electrons drift towards a 2D detector, and the third dimension is measured by means of the drift time of electrons on top of each strip of the 2D detector. Silicon detectors are located at the chamber entry, to identify implanted ions.

The 2D detector is made of two perpendicular sets (X and Y) of 384 strips. The energy and time signal on each strip is read by an integrated electronics based on ASIC (*Application Specific Integrated Circuits*) technology. In addition, *Gas Electron Multipliers* (GEM) are located above the strips detector, in order to amplify the signal from drift electrons.

A typical exemple of the energy signals observed on the strips for a ^{45}Fe implantation and its 2-proton decay is presented on figure 4-left, which clearly shows the individual contributions of each proton. Figure 4-right presents other cases of 2-proton decay events.

The results from this experiment are in agreement with known values of $T_{1/2}$

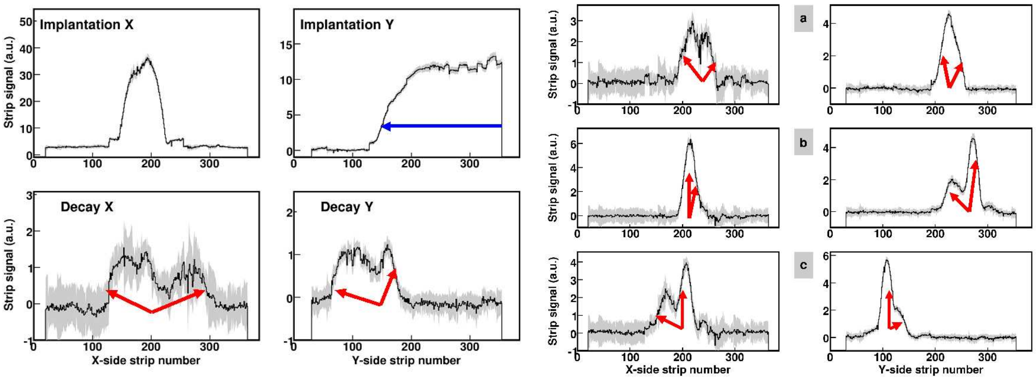

Fig. 4. Left: the upper part shows the energy signal for X and Y strips for a ^{45}Fe implantation event; the lower part shows the energy signals for the subsequent 2-proton decay: the arrows represent the particles movement in X and Y directions, and the protons are emitted from the place where the ion was stopped. Right: other exemples of energy signals for 2-proton decay events after ^{45}Fe implantations (not shown here).

and Q_{2P} (despite a bad total energy resolution). This experiment is also the first successful attempt to observe separately the two particles emitted in the 2-proton radioactivity. Nevertheless, the time analysis is not completed yet, and the poor statistics (about 15 events, 10 times less than expected), did not allow for any reasonable angular correlation measurement.

The experiment performed at MSU used an optical time projection chamber[10] (OTPC). The principle is the same, but the X-Y strip detector is replaced by an optical device: the drift electrons are converted to light. The cumulated light from the implantion of ^{45}Fe and from the emitted protons is measured with a CCD camera (fig. 5-left). This light is also measured with a photomultiplier tube connected to a sampling ADC, in order to get the time distribution of the total signal. For a 2-proton decay event, the drift time of ionisation electrons gives the Z-components of the two trajectories.

With about 80 decay events, first energy and angular distributions could be determined (fig. 5-right). The comparison with the 3-body model from Grigorenko[8] is remarquable.

Despite they are based on the same principle, the two devices presented here have conceptual differences. The 2D projection is obvious in the case of the OTPC, while it has to be extracted from two 1D projection (X and Y strips) in the X-Y TPC. Concerning the third dimension, the X-Y TPC has a time information for each strip, while the time information of the OTPC is not related to the X and Y position. In the first case, the Z information for the 2 protons is overlapping if both are emitted in the same X and Y directions, while in the second case, the overlap occurs if the protons are emitted in the same Z direction. In any case, this limits the reconstruction efficiency and has to be taken into account in order not to bias the angular distribution.

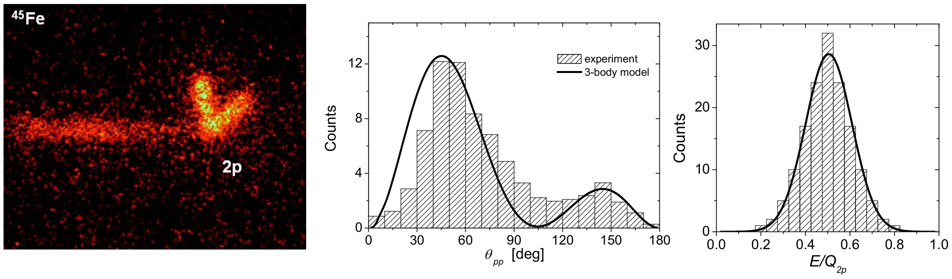

Fig. 5. Left: exemple of light collection for a 2-proton decay event with the OTPC, showing the implantation trace and the trajectories of the protons. Right: first angular and energy correlation from the observed 2-proton decay events withe the OTPC, compared with the 3-body model from grigorenko.

4. Concluding remarks

After the recent discovery of the 2-proton radioactivity, new tracking devices, based on the principle of time projection chambers, have been successfully used in experiments at GANIL and MSU, that allowed for the first direct observation of individual protons, and a first angular distribution of the emitted particles.

The statistics is still low and the results need to be confirmed, but these experiments have already shown that the detection devices based on the TPC principle were very promising tools for this kind of measurements. Some improvements are already considered for the devices, especially for a careful time projection analysis.

Other experiments will be performed, in order to check if the correlation pattern observed for the decay of ^{45}Fe is reproduced for other 2-proton emitters, and also to search for new precursors ($^{59,58}Ge$, $^{63,62}Se$, ^{67}Kr,$\ldots$). In any case, the interpretation of experimental results requires the comparison with theoretical approaches. This would require a model taking into account realistic descriptions of both the structure of the nuclei and the decay dynamics.

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