TWO PROTON RADIOACTIVITY STUDIES WITH A TIME PROJECTION CHAMBER*

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In the framework of the two proton radioactivity studies, a Time Projection Chamber was recently developed at CENBG, in order to study the correlations between the two protons emitted. In fragmentation experiments performed at LISE3/GANIL, the $2p$ radioactivity of ^{45}Fe and ^{54}Zn was directly observed with the TPC. Results on correlations between the two protons are presented and compared to a recent theoretical model.

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1. Introduction

The emission of two protons from the ground state of a radioactive nucleus was predicted in the 1960s by Goldansky [1]. This exotic decay concerns even-Z nuclei beyond the proton drip line. Due to the pairing interaction, the $Z-1$ nucleus is unbound and one proton emission is energetically forbidden. It has been observed first in the decay of ^{45}Fe in two independent experiments [2,3] and later also in ^{54}Zn [4] and possibly in ^{48}Ni [5]. In these experiments, the ions of interest were deeply implanted in silicon detectors in which the decay was observed. Therefore, only the total decay energy, the half-life, and the absence of β particles from the competing decay by β-delayed-particle emission could be clearly established. In addition, the observation of the daughter decay helped to unambiguously assign the observed decay to $2p$ radioactivity. These experimental results were found in reasonable agreement with predictions from different theoretical models [6], like the R-matrix theory [7], the Shell Model Embedded in the Continuum (SMEC) [8] or the three-body model [9, 10].

However, in none of these experiments, the two protons were identified separately, while the main physics question in the context of $2p$ radioactivity is how the two protons emitted are correlated in energy and in angle. An answer to that would enable to investigate the decay dynamics of $2p$ radioactivity and thus reveal details of nuclear structure at the limits of stability [11].

This paper describes two different experiments performed at GANIL, where emission of two protons in the decay of ^{45}Fe [12,13] and ^{54}Zn [14] was observed in a Time Projection Chamber. Angular and energy correlations have been determined. These results allowed a comparison with theoretical predictions of the three-body model.

2. Experiments

In both experiments, the nuclei of interest were produced by quasi-fragmentation of the projectile at GANIL. A primary ^{58}Ni^{26+} beam with an energy of 74.5 MeV/nucleon and an average intensity of 3.5 μA was fragmented in a $^{\text{nat}}$Ni target (200 μm). The fragments were selected by a magnetic-rigidity, energy-loss, and velocity analysis by means of the LISE3 separator. Two silicon detectors located at the end of the spectrometer allowed to identify individually the fragments by means of an energy-loss and time-of-flight analysis. The fragments were finally implanted in the TPC (*cf.* Fig. 1).

The TPC is a gas detector (argon 90% — methane 10%), where the heavy ions are stopped and their decay observed. The electrons, produced by the slowing down of either the incoming ions or the decay products, drift in the electric field of the TPC towards a set of four gas electron multipliers (GEM) where they are multiplied and finally detected in a two dimensional strip detector. The analysis of energy signals allows to reconstruct the tracks of the particles in two dimensions; the drift time analysis gives the third one. Details can be found in [15].

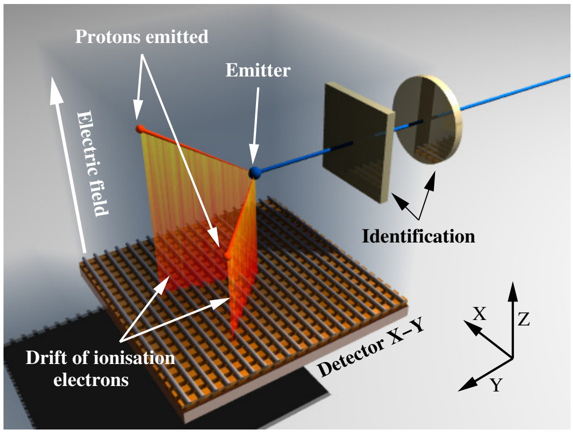

Fig. 1. Schematic view of the TPC developed at CENBG. The ions of interest selected by the LISE3 separator go through a set of two silicon detectors used for the identification of the ions and are implanted in the center of the chamber, where the decay takes place. The electrons produced by the slowing down of the charged particles in the gas are detected on a X–Y detector.

3. Analysis

During these experiments, ten $2p$ decay events could be correlated with implantations of ^{45}Fe whereas eleven $2p$ decay events have been obtained for the ^{54}Zn case. Figure 2 shows an example of a $2p$ event from the decay of ^{54}Zn. The energy spectra correspond to the energy loss of the protons on each dimension: we can clearly see the tracks of the two protons. These spectra are analysed by fitting a function which is a good approximation of the Bragg curve (more details in [14]). This analysis allows to get the starting and the stopping points of each proton track, and thus to determine the projection of the proton tracks on the detection plane (*cf*. Fig. 2).

In a final step, the analysis of the corresponding time spectra allows to determine the third component Δz of each track. Finally, seven events could be reconstructed in three dimensions for each experiment. The right part of Fig. 2 shows an example of a decay event reconstructed in three dimensions.

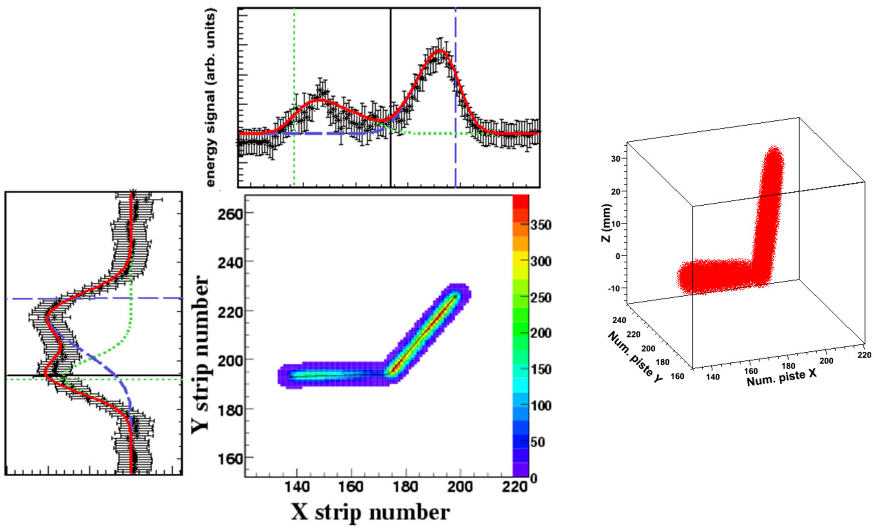

Fig. 2. Left: Reconstruction in two dimensions of a $2p$ event from the decay of ^{54}Zn. On the top and on the left, energy spectra are represented, corresponding to the energy deposited along the strip on the X (top) and Y direction (left). Right: Representation of the same decay event reconstructed in the three dimensional space.

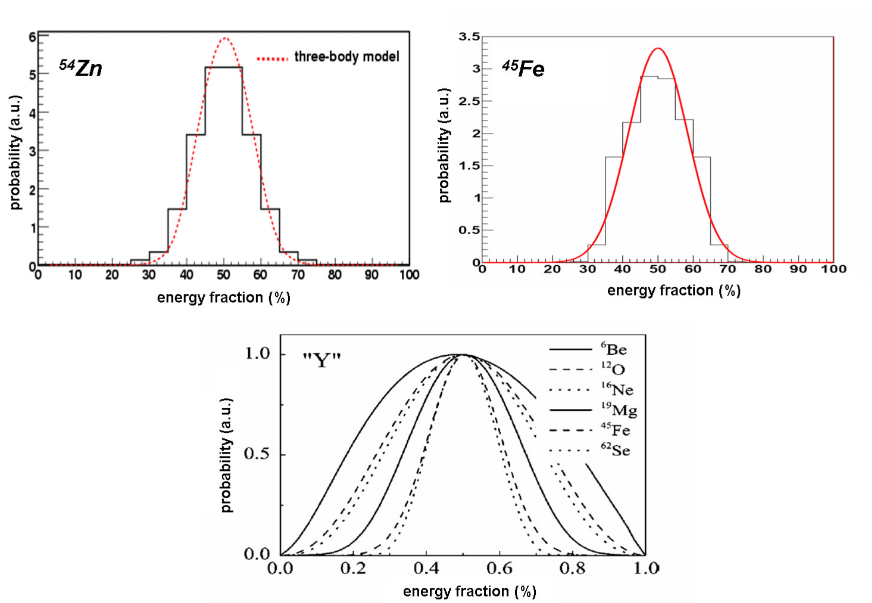

Fig. 3. Top: Energy sharing between the two protons emitted in the decay of ^{54}Zn (left) and ^{45}Fe (right). Each event in the histograms is convoluted with a Gaussian in order to reflect the error on the determined fraction. The lines are the distributions predicted by the three-body model. Bottom: Predictions from the three-body model of the energy correlations for different nuclei.

4. Results

The energy fraction distribution of the individual protons as determined from the energy signals is plotted in Fig. 3. As expected in a simultaneous emission, the two protons share the decay energy equally in order to favor the barrier penetration. Concerning the width of the distribution which depends strongly of the different nuclei (see bottom part of Fig. 3), the experimental ones are in a very good agreement with predictions of the three-body model [9, 10].

The complete analysis of the decay events allowed to provide angular correlations between the protons. Figure 4 shows the experimental angular distributions determined for the ^{45}Fe and ^{54}Zn decays. The bottom part of Fig. 4 shows the predictions of the three-body model for the decay of ^{54}Zn for different configurations of the two protons in the initial nucleus. $W(p^2)$ corresponds to the weight of a p^2 configuration compared to the f^2 configuration. A quantitative comparison has been done between the experimental and theoretical distributions for ^{54}Zn, yielding $W(p^2)= 30^{+46}_{-22}\%$. The standard shell model predicts a $W(p^2)$ of 80% but considering the very large

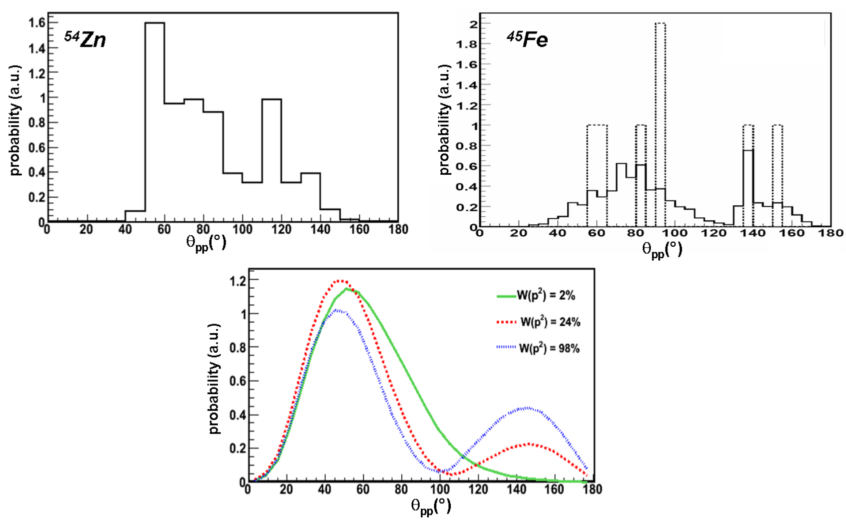

Fig. 4. Top: Experimental angular distributions between the two protons in the decay of ^{54}Zn (left) and ^{45}Fe (right). Each event is convoluted with a Gaussian in order to reflect the error on the determined angle. For the ^{45}Fe case, the dashed histogram corresponds to the angles without this convolution. Bottom: Predictions from the three-body model of the angular correlations for different weights of a p^2 configuration (for the ^{54}Zn case).

error bars coming from the poor statistics, the interpretation of the result is extremely limited. Concerning the ^{45}Fe data, no quantitative comparison has been done yet but this was done with other results coming from an experiment performed with an optical TPC at MSU [11].

5. Conclusion

In summary, the two protons emitted in the decay of ^{45}Fe and ^{54}Zn were observed for the first time in a TPC. Energy and angular distributions could be obtained and allowed a comparison with theoretical models giving information about nuclear structure. However, to establish a detailed picture of the decay process, higher statistics of implantation-decay events are needed, which can be obtained in future experiments. In parallel, improvements of theoretical model predictions are essential to elucidate the decay mechanism which governs two-proton radioactivity.

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