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TWO-PROTON RADIOACTIVITY AS A TOOL OF NUCLEAR STRUCTURE STUDIES*

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New results on two-proton radioactivity, predicted 50 years ago and observed for the first time in 2002, are presented. These results have been obtained with a time projection chamber at the LISE3 facility of GANIL. After ^{45}Fe, the direct observation of the two protons for ^{54}Zn is only the second such case from a long lived ground-state two-proton emitter. The new results are discussed and future perspectives highlighted.

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1. Introduction

With his prediction of new radioactivities at the proton drip line, notably of two-proton (2*p*) radioactivity, Goldansky [1] opened the chase of this new radioactivity. Unlike one-proton radioactivity discovered beginning of the 1980s at the GSI laboratory [2, 3], two-proton radioactivity was discovered

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only in 2002 when experiments at GANIL [4] and GSI [5] evidenced this new decay type for the first time in the decay of ^{45}Fe. By means of silicon detectors, the decay energy, the decay time and the branching ratio could be determined. In addition, the absence of positrons from β decay could be demonstrated with high probability. These experimental data allowed a detailed comparison with existing theoretical models [6,7,8] to be performed and convincing agreement was achieved.

The next step in the discovery and study of two-proton radioactivity was the observation of this decay mode for ^{54}Zn. This experiment was performed at GANIL using the same set-up as in the first GANIL experiment on ^{45}Fe. Again only the decay energy, the half-life, and the branching ratio could be determined and the absence of β radiation could be shown.

Both cases, ^{45}Fe and ^{54}Zn, have a rather high $2p$ branch reaching 70–90 %. The third case studied, ^{48}Ni, seemingly has a much lower branching ratio. In an additional measurement performed at the LISE3 separator of GANIL, only one out of four observed ^{48}Ni decayed most likely by $2p$ radioactivity, which is, of course, too little of evidence to claim definitively the observation of $2p$ radioactivity also for this nucleus, although all parameters observed for this decay are in agreement with the expectation for $2p$ radioactivity and ^{48}Ni has most likely a weak $2p$ branch.

In this and the previous experiment, it could also been shown that the daughter decay in the cases of ^{45}Fe and ^{54}Zn is in nice agreement with the known decay characteristics of ^{43}Cr and ^{52}Ni, the $2p$ daughters of ^{45}Fe and ^{54}Zn, respectively (see Fig. 1). From these observations, it is evident that two-proton radioactivity was indeed observed. However, none of these

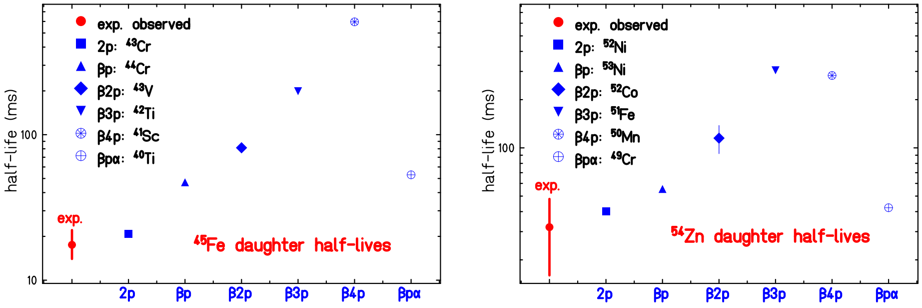

Fig. 1. The daughter decay half-life determined for the second decay after ^{45}Fe (left) and ^{54}Zn (right) implantation is compared with the known half-lives of all possible daughter nuclei. For this purpose, a gate on the $2p$ energy peak is used. In the case of ^{45}Fe, only the half-life of ^{43}Cr is in agreement with the observed half-life demonstrating unambiguously the observation of $2p$ radioactivity. Although in the case of ^{54}Zn the conclusions are less strict, the measured half-life is in agreement with expectations.

experiments could observe the two protons directly. The use of thick silicon detectors prevent the protons to escape from these detectors and only their sum effect could be observed.

The direct detection of the two protons needed to turn the attention to another type of detector hardly ever used in nuclear physics: a time projection chamber (see Fig. 2). In such a system, the thick and dense silicon detector is replaced by a gas volume in which the ions of interested are stopped and emit afterwards their decay products. The gas ionisation from the charged particles, be it the heavy ions implanted in the chamber or the protons from the decay, can be detected with an electronic or an optical readout. At CEN Bordeaux–Gradignan, we realised such a system based on charge amplification in the gas by means of four gas electron multipliers (GEMs). The amplified signal was then detected by a set of orthogonal strips yielding the particle direction and its energy loss in two dimensions [9]. A TPC based on an optical readout was produced at Warsaw University [10].

In the following, we describe the results obtained for ^{45}Fe and ^{54}Zn at GANIL in experiments at the LISE3 separator.

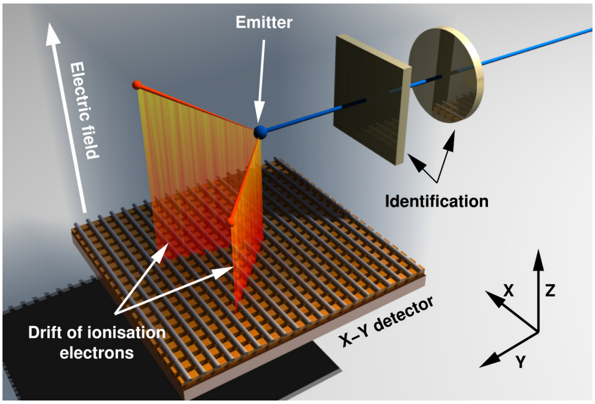

Fig. 2. Schematic representation of the TPC built at the CENBG. The isotopes of interested are implanted in the centre of the device where they decay. After amplification of their signals with GEMs (not shown), implantation and decay events are observed by a two-dimensional detector.

2. Direct observation of two-proton radioactivity of ^{45}Fe

^{45}Fe isotopes were produced by means of projectile fragmentation of a ^{58}Ni beam at 75 MeV/nucleon. The beam impinged on a $^{\mathrm{nat}}$Ni and the projectile fragments of interest were selected by the LISE3 separator and directed to the TPC installed at the exit of the LISE3 beam line. At the entrance of the

TPC, silicon detectors allowed the fragments to be identified on an event-by-event basis by means of their energy loss and their time-of-flight from the production target to the detector. Finally, the isotopes of interest were stopped in the centre of the TPC and their decay could be studied.

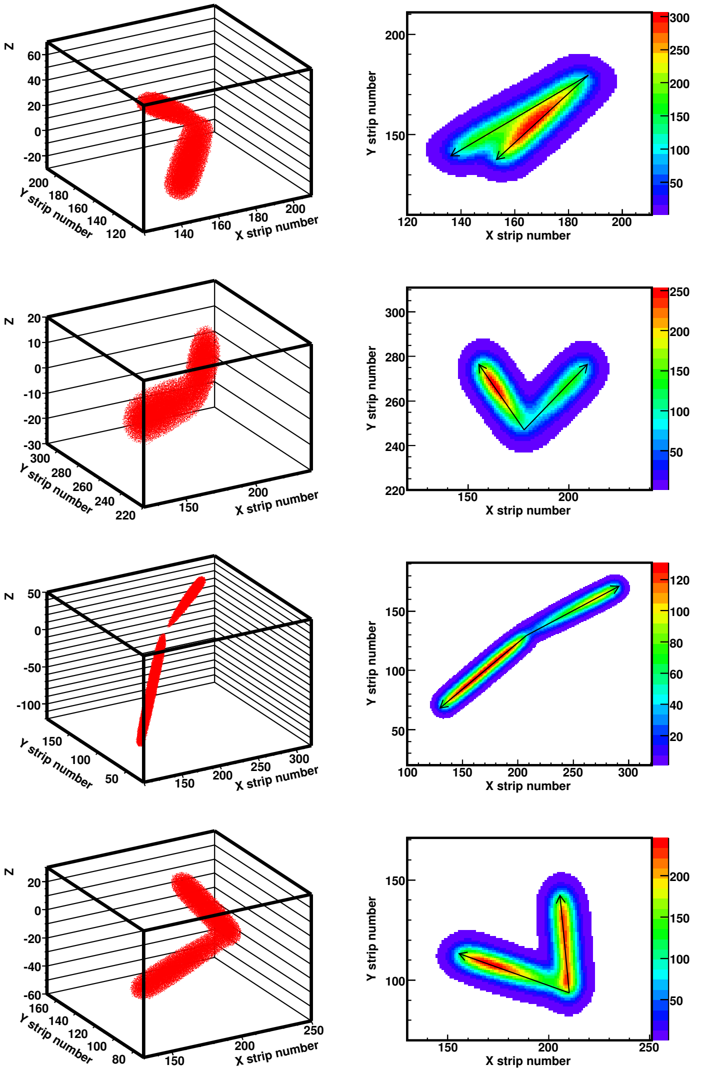

Fig. 3. Four ^{45}Fe decay events are presented in two (right) and three (left) dimensions as reconstructed from the energy signals of the strips alone and from the energy and time signals, respectively.

Fig. 3 shows decay events correlated to a ^{45}Fe implantation as reconstructed from the signals in energy and time registered by the different strips. Only seven of the ten ^{45}Fe decay events could be completely reconstructed. For three events, the event configuration or a faulty electronics did not allow to access the time signals. The seven events allowed the three-dimensional proton–proton angle to be determined. In Fig. 4, we use two different presentations of these results: *(i)* each event is represented at the angle determined by the analysis and *(ii)* each event is distributed in angle according to the precision obtained for the angle, *i.e.* the larger the error on the angle the larger the Gaussian over which the event is distributed. The experimental data are compared to the angular distribution as predicted from the three-body model of Grigorenko and co-workers [7]. Although our statistics is not enough to formulate definitive statements, it is evident that our angular distribution is in agreement with the theoretical predictions.

The energy signals of the different strips allow also to calculate the energy sharing between the two protons. For a simultaneous emission it is expected that the two protons share their energy equally. This is exactly what can be seen in Fig. 4 where experimental and theoretical data are shown together.

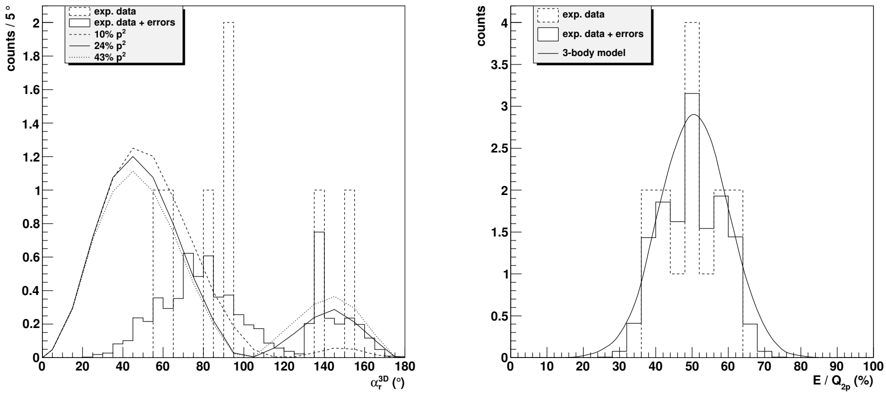

Fig. 4. The left-hand side shows the experimental angular distribution compared to the theoretical prediction from the three-body model [7]. The experimental distribution is shown in two different ways: *(i)* one count for each event at the position of the angle determined from the experimental data (dotted histogram) and *(ii)* each event is distributed according to a Gaussian where the width of the Gaussian is determined by the precision of the angle determined (full histogram). Thus, an angle obtained with less precision gives rise to an event distributed over a larger angular range. The right-hand side presents the energy sharing between the two protons as determined from the energy signal of the different strips.

These results show that the device developed for $2p$ radioactivity studies is indeed able to perform such research. The results obtained are in good agreement with theoretical expectations.

Part of the present results was published [11], before a high-statistics experiment performed at Michigan State University [12,13] could demonstrate beautiful agreement between the data and theoretical predictions, as also evidenced by our full analysis presented here.

3. Direct observation of ^{54}Zn $2p$ radioactivity

To overcome a few shortcomings of the first version of our TPC, several modifications were made to optimise the device for a new experiment dedicated to study the $2p$ decay of ^{54}Zn (see Fig. 5). First of all, the entrance of the heavy-ion beam was changed from being parallel to one strip set to a 45° angle with respect to both strip directions. This has two advantages: First, the detector is longer and more isotopes of interest are stopped in the chamber and second, the strips which were parallel to the beam direction were saturated by the implantation signals of the heavy ions. With the 45° entrance this is no longer the case. The new configuration renders also the gain matching by means of a traversing beam simpler. In addition, the height of the active volume of the TPC was increased (from 6 to 12 cm) and the pressure was raised from 500 mb to 750 mb.

The ^{54}Zn beam was produced in the same manner as ^{45}Fe, however with a production rate of only 2 per day. This permitted to observe eighteen ^{54}Zn implantation events. Five decay events were lost due to the data acquisition dead time and the short half-life of ^{54}Zn. Thus, only thirteen implantations could be correlated in time and space with decays. Observables already

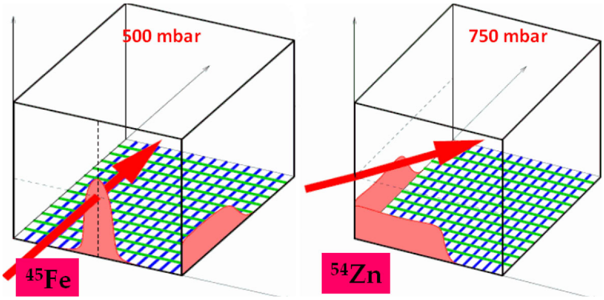

Fig. 5. The left-hand side shows the TPC configuration of the first experiment, whereas the right-hand side gives the configuration after modification for the ^{54}Zn experiment (see text for details). The arrow shows the trajectory of a heavy ion entering the chamber. The signals shown schematically give the energy deposition on the two strip sets.

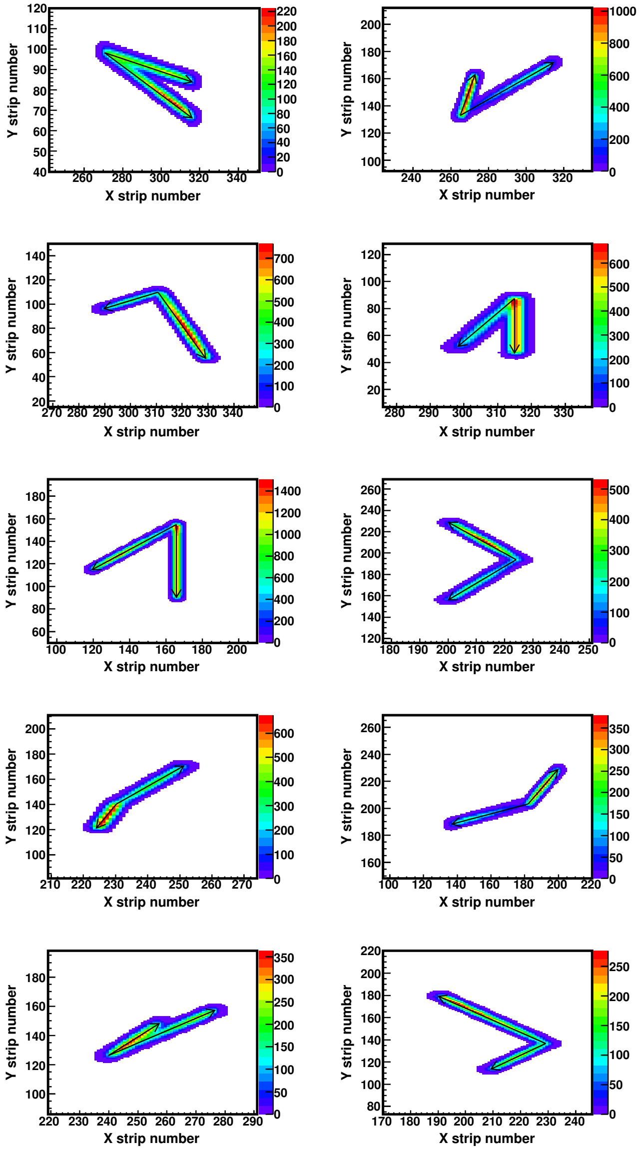

Fig. 6. Ten ^{54}Zn decay events are presented in two dimensions as reconstructed from the energy signals of the strips.

measured in the previous experiment [14] like the decay energy Q_{2p} and the half-life $T_{1/2}$ could be reproduced. For ten events, all information necessary to reconstruct events in two dimensions could be used. The 3D analysis is still under way.

Figure 6 shows the ten events reconstructed in 2D. These events can be used to determine the energy sharing between the two protons. As in the case of ^{45}Fe, an equal energy sharing is observed for the two protons (Fig. 7).

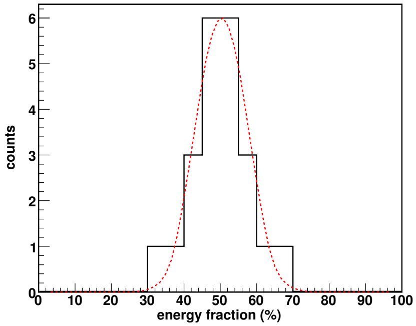

Fig. 7. The figure presents the energy sharing between the two protons in the decay of ^{54}Zn as determined from the energy signal of the different strips.

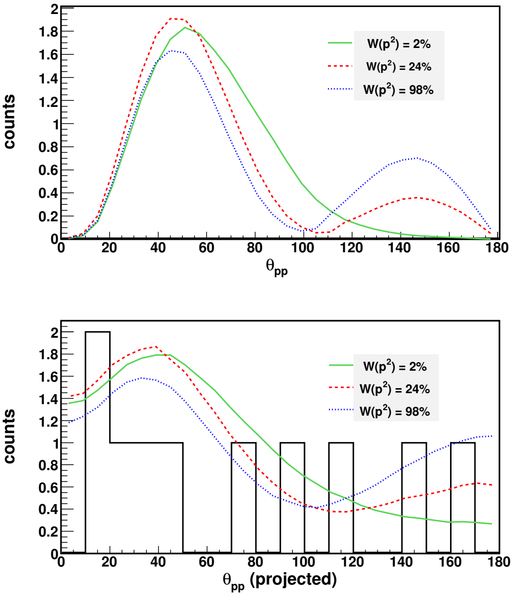

Fig. 8. The theoretical 3D angular distribution (upper part) is projected onto two dimensions and compared to the experimental distribution (lower part). The different curves correspond to different contributions of the p^2 proton configuration to the (dominant) f^2 configuration.

The 2D analysis of the data allows also to determine the projected angular distribution of the protons. This quantity can be compared to the model prediction of the three-body model (Fig. 8). Despite the low statistics, reasonable agreement between experiment and theory is obtained.

4. Conclusion

The experiments performed with the CENBG TPC to study the decay of ^{45}Fe and ^{54}Zn yielded original data on the decay by two-proton emission of these nuclei. Future high-statistics studies also for nuclei other than ^{45}Fe should allow to use two-proton radioactivity as a powerful tool of nuclear structure. Future candidates to study are ^{59}Ge, ^{63}Se, and ^{67}Kr. For this purpose, production rates of 1 to 2 nuclei per days is a minimum requirement.

REFERENCES

[1] V.I. Goldansky, *Nucl. Phys.* **19**, 482 (1960).
[2] S. Hofmann *et al.*, *Z. Phys.* **A305**, 111 (1982).
[3] O. Klepper *et al.*, *Z. Phys.* **A305**, 125 (1982).
[4] J. Giovinazzo *et al.*, *Phys. Rev. Lett.* **89**, 102501 (2002).
[5] M. Pfützner *et al.*, *Eur. Phys. J.* **A14**, 279 (2002).
[6] F.C. Barker, *Phys. Rev.* **C63**, 047303 (2001).
[7] L.V. Grigorenko *et al.*, *Phys. Rev.* **C60**, 044312 (1999).
[8] J. Rotureau, J. Okolowicz, M. Ploszajczak, *Nucl. Phys.* **A767**, 13 (2006).
[9] B. Blank *et al.*, *Nucl. Instrum. Methods* **B266**, 4606 (2008).
[10] K. Miernik *et al.*, *Nucl. Instrum. Methods* **A581**, 194 (2007).
[11] J. Giovinazzo *et al.*, *Phys. Rev. Lett.* **99**, 102501 (2007).
[12] K. Miernik *et al.*, *Phys. Rev. Lett.* **99**, 192501 (2007).
[13] K. Miernik *et al.*, *Eur. Phys. J.* **A42**, 431 (2009).
[14] B. Blank *et al.*, *Phys. Rev. Lett.* **94**, 232501 (2005).