

Two-proton radioactivity: 10 years of experimental progresses

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Abstract. The two-proton radioactivity has been observed experimentally in 2002, at projectile fragmentation facilities, more than 40 years after the first theoretical prediction of this process. First observations were indirect measurements, using standard silicon detector devices. Since then, a new generation of experiments allowed for a direct observation, and opened the field of more detailed studies, using tracking devices for the detection of the emitted protons.

1. Introduction

In the early 60s, Goldanskii proposed a first description of two decay processes at the proton drip-line: the 1-proton and the 2-proton radioactive decays [1], for odd- and even- Z nuclei respectively. These decay modes may occur for very proton-rich isotopes, where the nuclear strong interaction should not bind the last protons anymore. The existence of such isotopes is due to the Coulomb barrier, and in the case of the 2-proton decay, to the extra binding energy provided by the pairing of the last protons.

A first description of the emission process was proposed, based on the tunnelling of the 2-proton sub-system, that breaks-up into 2 individual protons in the final state since the diproton system is unbound. In addition to this unique quantum mechanics process, the 2-proton radioactivity studies allow for the characterisation of the masses and the structure of isotopes beyond the proton drip-line. The best candidates for this new decay mode were predicted in $A=50$ mass region, which was confirmed by the mass models in the 90's [2].

Experimentally, the 2-proton radioactivity has been evidenced in the decay of ^{45}Fe in two independent experiments in 2002, and in the decay of ^{54}Zn in 2005, using standard implantation-decay technique in silicon detectors. After these experiments, an effort has been made in order to

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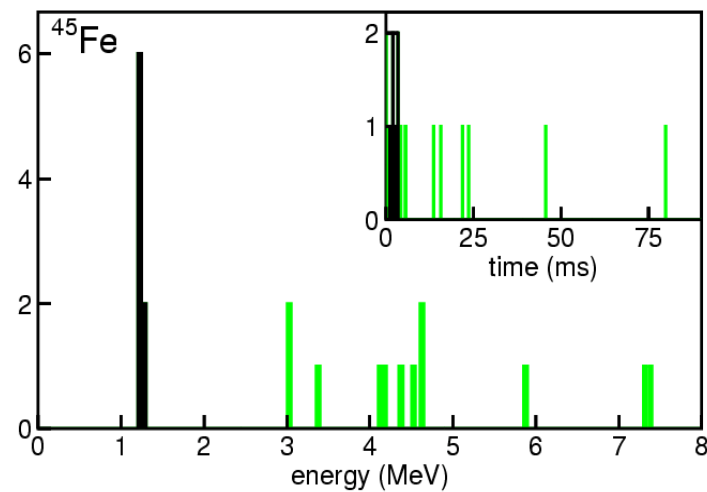


Figure 1. Energy and time distribution of decay events in the implantation silicon detector after implantation and identification of a ^{45}Fe (left) and ^{54}Zn (right) implantation. The events represented in black correspond to the 2-proton decay peak, while the grey ones are beta-decay events (most of them being the second decay after implantation, i.e. the daughter decay).

develop detection tools that allows to observe and characterise individually the emitted protons, in order to study in more details the decay process.

2. The standard silicon experiments

The first evidence of the 2-proton radioactivity could be obtained from indirect measurements, in the decay of ^{45}Fe , in projectile fragmentation experiments at GANIL [3] and GSI [4]. The ^{45}Fe nuclei, identified by standard energy loss and time-of-flight technique, were implanted in a silicon detector. The decay occur from the implantation position. From estimated masses, there are 2 possibilities for the decay: either the 2-proton decay, either beta delayed proton(s) emission. Protons up to few MeV are stopped in the detector, leaving their full energy, while beta particles (positrons) may escape it and only deposit a variable fraction of their energy.

In the GANIL experiment, the 2-proton radioactivity could be concluded from several observations. A narrow peak around 1.1 MeV was observed in the silicon detector energy distribution of the decay events after ^{45}Fe implantation. The implantation detector was surrounded in a close geometry by other silicon detectors, where no beta was observed in coincidence with the peak. The second decay events (after the events from the peak), are only compatible with ^{43}Cr decay, which is the ^{45}Fe daughter for 2-proton emission. This decay process was thus the only decay mode consistent with the observations. The GSI experiment leaded to the same conclusion, from the absence of positron annihilation gamma-rays that should have been observed in case of beta decay.

Using the same type of measurement, another experiment has been performed at GANIL, were the 2-proton decay of ^{54}Zn could be observed [5] and the previous results for ^{45}Fe could be confirmed [6]. The time and energy distribution of the corresponding decay events are shown in Figure 1. In addition, a first indication that ^{48}Ni could be a 2-proton emitter was proposed.

Those first experiments allowed to measure the global characteristics of the decay process: the transition energy Q_{2p} , the half-life $T_{1/2}$ and the branching ratio of the 2-proton decay (in competition with beta decay). The results could be compared with available theoretical descriptions from R-matrix formalism [7], from shell model embedded in the continuum (SMEC)

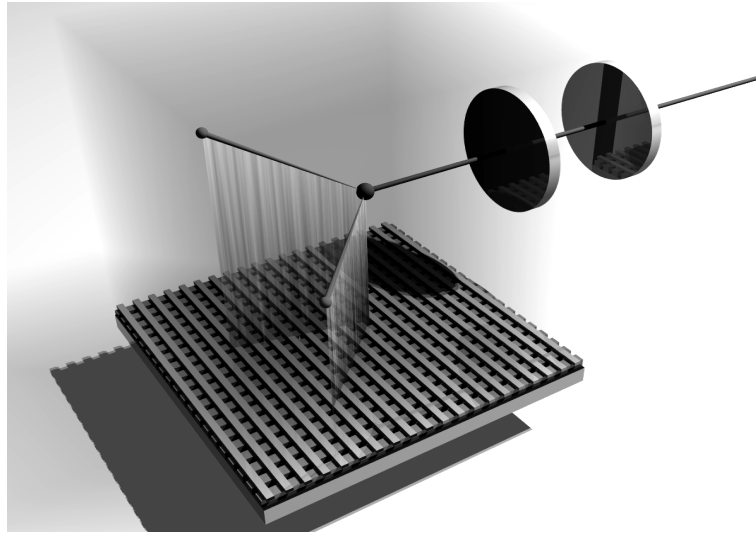


Figure 2. Schematic view of the TPC: the ions produced by projectile fragmentation and identified with silicon detectors, are implanted in a gas volume, where the decay occurs. When the protons are emitted, they ionise the gas, and due to a vertical electric field in the chamber, the ionisation electrons drift towards a double stripped X-Y detection plane. The energy signal on each strip is collected to provide the X and Y projections of the energy distributions. The time that charges arrive on strips gives the Z position where ionisation occurred.

[8], or from a 3-body model [9].

3. The tracking experiments

In order to get a more detailed description of the decay mechanism, in particular with comparison with the 3-body model that predicts angular and energy distributions for the emitted protons, the second generation of experiments was designed to measure the energy and the emission direction of both protons individually. Since the 2-proton ground-state emitters have half-lives in the order of few milliseconds, they can only be produced and studied in fragmentation experiments. To detect individually each emitted proton, an experimental option is to use an active implantation material.

For this purpose, a new detection device was developed, on the principle of a time-projection chamber (TPC) [10], as described in Figure 2. The purpose of this device is to reconstruct the tracks of the 2 protons, that are emitted from nuclei implanted in a gas chamber. The 2-dimension X-Y is composed of 2 sets of orthogonal strips, which collects the ionization signal from the protons along their track in the gas volume. The amplitude of the collected signal is used for the reconstruction of the energy loss distributions of the protons along the X and Y directions. The collection time on each strip is related to the drift time of the ionization electrons, and thus allows to reconstruct the vertical information associated to the previous distributions.

This TPC has been successfully used for 2 experiments performed at GANIL, the first one for the 2-proton radioactivity of ^{45}Fe [11], and the second one for ^{54}Zn [12]. An example of the tracks reconstruction of the emitted protons is presented in Figure 3, in the case of ^{45}Fe decay. The result from this experiment is the first direct observation of the 2-proton radioactivity, and confirms the previous conclusions from indirect measurements. Nevertheless, only few events have been observed and fully reconstructed in these experiments: 7 events in both cases, which considerably limits the comparison with theory.

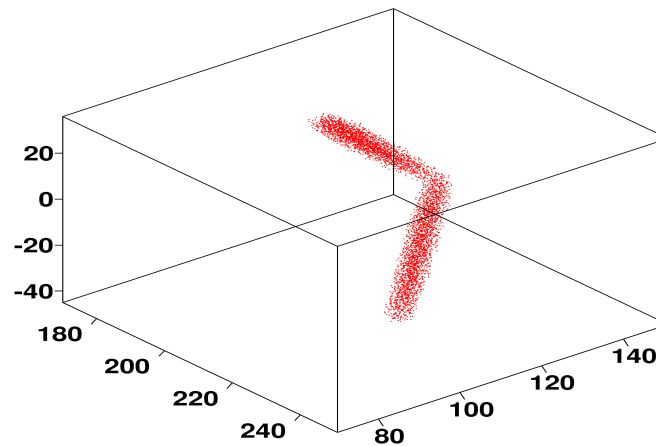


Figure 3. Example of the tracks reconstruction in 3 dimensions, for the protons emitted in the decay of ^{45}Fe . The X and Y coordinates are the strip numbers (the strips pitch is 0.4 mm), and the Z axis is expressed in the same units. The full reconstruction is used for proton-proton angle estimates.

Another TPC device, based on the same principle but with a different 2D detection technique has been developed by a Warsaw group [13]. It has been used in an experiment at MSU, where a first angular distribution of the emitted protons could be obtained for the decay of ^{45}Fe [14]. This result opens new structure studies at the drip-line, since the angular distribution is sensitive to the wave function of the parent nucleus, according to the 3-body model. In another experiment, the 2-proton radioactivity of ^{48}Ni could be established [15].

4. Experimental and instrumental perspectives

Up to now, three isotopes have been identified as ground-state 2-proton emitters: ^{45}Fe (the most studied one), ^{54}Zn and ^{48}Ni . To test our understanding of this new decay process, with comparison with theoretical descriptions, the known decays must still be characterised more precisely. In addition, we also need to extend the observation to other emitters, in order to compare experiment and theory on a wider range of nuclear configurations.

Any isotopes at the drip-line, with an even proton number, is a potential candidate for the 2-proton radioactivity. According to mass models [2], new candidates could be found for higher proton numbers, with Q_{2p} values between 1 and 2 MeV, and for which the Coulomb barrier could be responsible for a half-life in an observable range. The next isotopes that should be studied are ^{59}Ge , ^{63}Se and ^{67}Kr . An experiment has been proposed [16] to determine whether these isotopes are bound, and in such case, to search for a 2-proton radioactivity branch in their decay. This study will first be performed with standard experimental techniques (with silicon detectors).

Another perspective for the 2-proton radioactivity studies is the development of the detection tools for energy and angular correlation measurements. The TPC used for the tracking experiments suffer from various instrumental limitations, that limit the tracks reconstructions, and for some cases, even make it impossible. For the TPC used in GANIL experiments, some limitations comes from the 2D detection plane: the 2 sets of strips provide X and Y one-dimension distributions for energy and time. The 3D reconstruction has to be performed from the combination of the 1D distributions. If protons are emitted in the same X or Y directions,

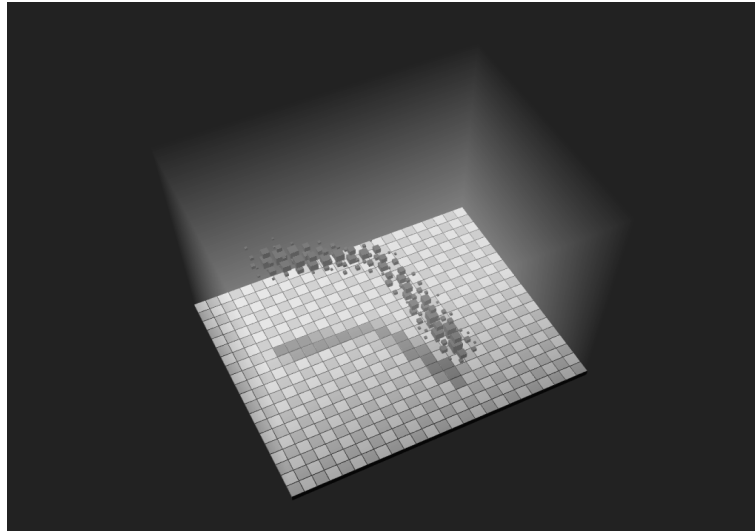


Figure 4. Schematic view of the ACTAR-TPC device: as the previous detectors, it works on the principle of a TPC. In this case, the X-Y detector for charges collection is a pad plane, which measures a digitised 2D projection of charged particles tracks. Since the signal on each pad is sampled in time, this sampling corresponds to a Z digitisation of the charges created (by ionisation) along the vertical axis above the pads. As a result, the detector should provide a 3D digitisation of the ionisation along the particles tracks. In this picture, the size of the boxes represents the amplitude of the signal in the 3D cells.

the signals from the 2 protons are mixed, and the unfolding of the contribution of each is difficult.

We started to design a new generation of TPC, which purpose is to be able to obtain a real 3D image of the ionisation of charged particles along their tracks. The 2D plane for ionisation charges collection is a pad detector (for a real 2D projection), with time sampling of the signal on each pad, to get a digitisation of the signal along the vertical axis above the pad (since the drift time is related to the vertical position where charges are created). The principle of this new detector is shown in Figure 4.

The final detector will have 16384 pads, each pad been 2x2mm², with a micromegas [17] for amplification of the ionisation signal. A small size demonstrator is currently under construction in the context of the ACTAR-TPC collaboration [18], to test the feasibility of the detector.

The readout electronics is developed by the GET collaboration [19]. The input signal from collected charges is shaped and stored into analog memories, and when the system is triggered, the samples are digitised and the full event is build. The trigger has several levels, based on the multiplicity of pads hits. The amount of data to process is huge for an event, which will result in important dead-time, limiting the running capabilities around 1000 events per second. For the case of 2-proton radioactivity, where the decay event occurs few milliseconds after the implantation event, a special mode is requested: the implantation signal is stored in half the memory, and the system waits for the decay signals (stored in the 2nd half of the memory) before the full data is processed.

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