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β-delayed Multi-particle Emission From ^{31}Ar

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Abstract: The β^+ decay of ^{31}Ar was investigated in an experiment at the GSI-FRS spectrometer. The ions of interest have been produced in the fragmentation of a ^{36}Ar beam at 880 MeV/nucleon and implanted in a time projection chamber with optical readout. In addition to β-delayed one and two proton emission, for the first time the emission of β-delayed 3 protons has been observed. The branching ratio for this decay mode is found to be (0.07 ± 0.02)%.

Key words: ^{31}Ar; beta-delayed protons; OTPC

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1 Introduction

Proton drip-line nuclides are characterised by the fact that, due to the large $Q_{\beta+}$ values, highly excited and particle-unbound states in the daughter nuclei can be populated in beta decay. This can lead to β-delayed one, two or even three proton emission (βp, β2p and β3p, respectively). The latter decay mode has been observed so far only in three nuclides: ^{45}Fe[1], ^{43}Cr[2] and ^{31}Ar[3]. Among these, ^{31}Ar was the first candidate for the observation of β3p emission, with its $Q_{\rm EC} = 18.3(2)$ MeV[4] and $T_{1/2} = 15.1(3)$ ms[5], even though it was

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the last to be observed experimentally. Historically, the observation of this decay mode was first announced in 1992 following work performed in GANIL, with a branching ratio $b_{\beta 3\mathrm{p}} = 2.1(10)\%$[6]. Later measurements at CERN-ISOLDE could not confirm the observation and an upper limit on the branching ratio for this decay mode was inferred $b_{\beta 3\mathrm{p}} < 0.11\%$[7].

Following the successful studies on β-delayed multi particle emission with the optical time projection chamber (OTPC)[1–2], the β-decay of ^{31}Ar was reinvestigated and its β3p decay channel observed unambiguously[3, 8]. Shortly after the announcement of this result[8], the reanalysis of data collected previously at the CERN-ISOLDE fully supported this observation[5, 9]. Here we present further details on the data analysis of our experiment with respect to Ref. [3].

2 Experimental technique

The ions of interest, namely ^{31}Ar, were produced at the GSI Fragment Separator (FRS) in Darmstadt, Germany[10] in the fragmentation of a primary ^{36}Ar beam at 880 AMeV on a 8 g/cm^2 Be target. Event-by-event identification of the separated fragments was achieved by standard energy loss (ΔE) and time-of-flight (TOF) technique. Details on the experiment are given in Ref. [3]. In brief, the ^{31}Ar ions were then implanted into the detection set-up (Optical Time-projection Chamber-OTPC) positioned at the final focal plane of the spectrometer. The OTPC, developed at the University of Warsaw to study 2p radioactivity[11–12], is a unique tool for identifying rare decay modes. It consists of a drift chamber, where an ion is implanted and later decays, and an amplification stage, where the secondary ionisation generates light emission. The light is recorded by a CCD camera and a photomultiplier tube (PMT). The CCD images show the projection of the tracks generated by charged particles (protons or heavier) in the xy plane, while the PMT signal gives the total light intensity as a function of time. This is used for the reconstruction of z coordinate, given the drift velocity of electrons in the gas used. For this experiment the gas mixture in the active volume was 98% Ar+2% N_2 at atmospheric pressure. Such thick gas allowed to maximise the implantation efficiency for the ^{31}Ar ions and to observe the emitted βp.

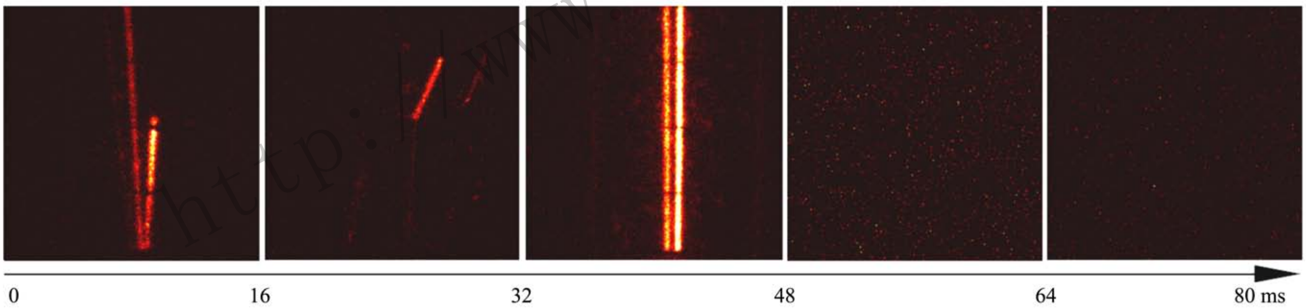

Fig. 1 (color online) Five consecutive frames collected by the CCD camera after the trigger generated by one ^{31}Ar ion. On the first frame the ion of interest is stopped in the active volume of the detector. In the second frame the ion decays and a β-delayed proton is emitted.

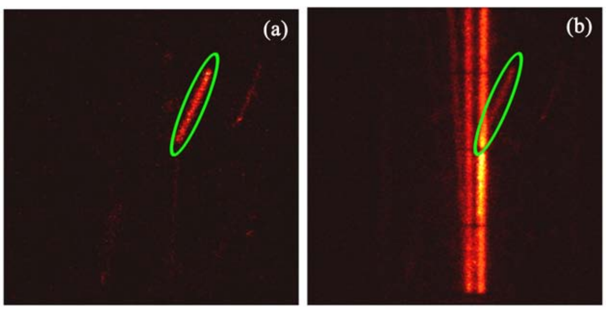

Fig. 2 (color online) (a) Second frame collected for the event shown in Fig. 1. The proton trajectory is visible and marked with a green elipse. (b) Sum of the light from all the frames in the event shown in Fig. 1. Such an image would be recorded if only one frame with 80 ms-long exposition would be acquired. The proton trajectory (marked with a green elipse) is much less distinguishable than in (a).

A trigger for the data acquisition was generated on the basis of the TOF and ΔE of ^{31}Ar ions, thus reducing the amount of data recorded. As the beam could not be stopped after each trigger while waiting for the decay to happen, the exposition time of the camera was subdivided into five consecutive time sections (frames), each 16 ms long, forming a short "movie" (see Fig. 1). In this way, when other ions entered the detector during the data collection period, tracks of the ion and protons could be easily distinguished (see Fig. 2).

3 Identification of βp, β2p and β3p events

Each event of ^{31}Ar which was implanted into the detector was inspected individually. It was categorised according to number of clearly visible proton tracks. Events displaying the emission of βp, as well as cases of β2p and β3p have been observed. Example events of these three categories are shown in Fig. 3.

Given the very small branching ratio expected for

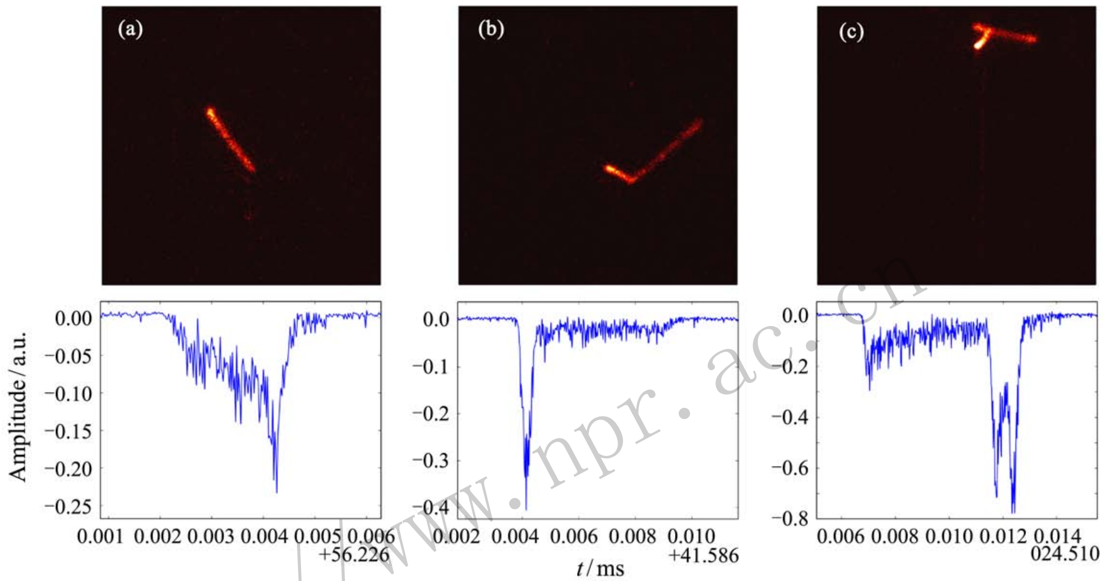

Fig. 3 (color online) Example events of β-delayed (a) one, (b) two and (c) three protons emission from ^{31}Ar. The upper panels show the CCD images, while the lower ones the respective PMT signals.

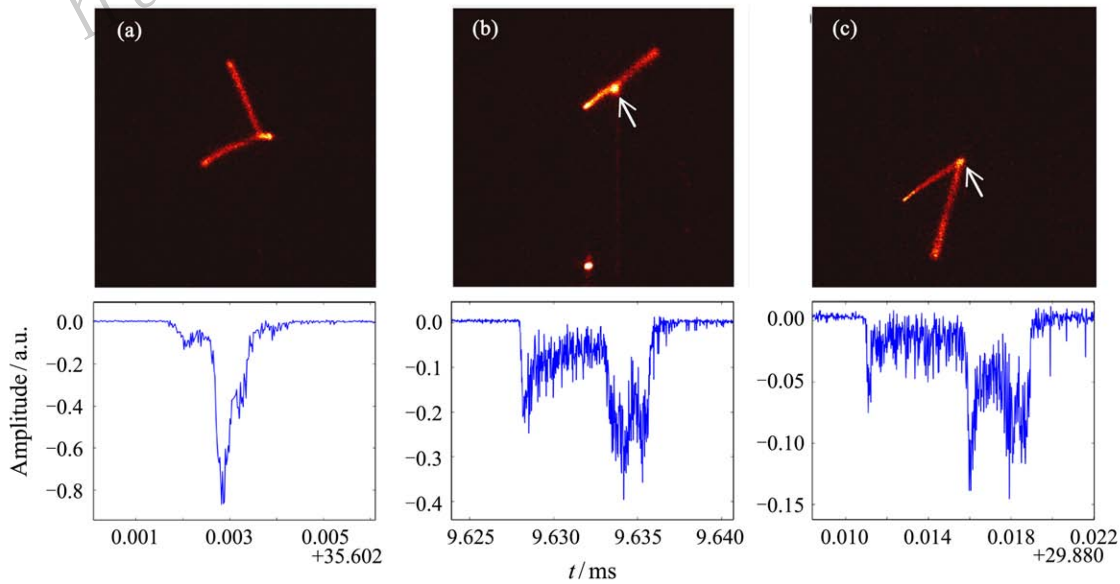

Fig. 4 (color online) Example events of ^{31}Ar β3p emission. (a) Example event in which the three trajectories are clearly visible in the CCD image, with the respective PMT signal. (b) and (c) Two examples in which one of the three proton tracks (marked by a white arrow) appears as a bright spot in the image. This is due to its trajectory being almost perpendicular to the CCD plane. The three time-distributions of the drifting electrons generated by the three protons can be clearly seen in the PMT signal.

β3p emission ($b_{\beta 3\mathrm{p}} < 0.11\%$[7]), the correct identification of each such event was mandatory. In most cases the three trajectories of the emitted protons were easily identified in the CCD image, see for example Fig. 3(c) and Fig. 4(a), and the inspection of the PMT signal merely confirmed it. Such cases correspond to events in which all the three protons followed trajectories with a large angle with respect to the electric field lines in the chamber. In some cases, the CCD image was not as unambiguous. These were events in which one of the protons appeared as a bright spot at the implantation point, see Fig. 4(b) and (c). Such topology can be due to low energy of the emitted proton (<0.5 MeV) or to emission of the proton along the z axis. In these cases unambiguous assignment of the events to the β3p decay mode was achieved by careful investigation of the PMT signal associated to them. The drifting electrons generated by a proton emitted in the z direction will give a signal of low amplitude and longer duration with respect to the one generated by a proton emitted in another direction, which in general has higher maximum intensity and shorter duration. Such events are shown in Fig. 4(b) and (c).

About 23 000 ions of ^{31}Ar were implanted in the active volume of the detector. Among their decays, 13 events of β3p emission were found. This leads to a branching ratio $b_{\beta 3\mathrm{p}} = 0.07(2)\%$, result which is in good agreement with literature[5].

4 Summary

We have reinvestigated the beta decay of ^{31}Ar at the GSI-FRS with an optical-readout time-projection chamber. The first evidence of its β3p decay branch was obtained and a branching ratio of $7(2)\times10^{-4}$ for this decay mode was determined.

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