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First observation of ^{54}Zn and its decay by two-proton emission

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Abstract. In an experiment performed at the LISE3 facility of GANIL, the isotope ^{54}Zn and its decay via two-proton emission were observed for the first time. In addition, preliminary results indicate that three implantation events of ^{48}Ni were observed. One of the associated decay events is compatible with a two-proton emission. New data on the decay of ^{45}Fe and its two-proton branch were recorded at the same time. The results for ^{54}Zn are compared to theory.

PACS. 23.50.+z Decay by proton emission – 23.90.+w Other topics in radioactive decay and in-beam spectroscopy – 27.40.+z $39 \leq A \leq 58$

1 Introduction

Nuclear structure experiments near the proton drip line represent an important tool to investigate the properties of the atomic nucleus. The mapping of the proton drip line provides a first stringent test for mass models. The information is refined by the observation of the radioactive decay of isotopes at the proton drip line via *e.g.* β-delayed protons and by half-life measurements. One of the most exciting phenomena at the proton drip line is probably the occurrence of the ground-state two-proton (2p) decay which has been predicted about 40 years ago [1]. Although considerable efforts have been made in order to observe this radioactivity, it was observed only recently in the decay of ^{45}Fe [2,3]. Other possible candidates according to theoretical predictions [4,5,6] are ^{48}Ni, ^{54}Zn, and ^{59}Ge with predicted half lives in the $1\,\mu$s–10 ms range.

The study of 2p radioactivity may be a tool to test mass predictions very far away from stability, may allow to determine single-particle level sequences, and in particular to study pairing in nuclei. However, up to now, only very rough information can be obtained about this decay process. Therefore, research in this domain goes mainly in two directions: i) obtaining more refined information about 2p radioactivity such as the energy sharing between the two protons and their angular correlation and ii) searching for new 2p emitters.

The paper presents very recently obtained results for the observation and the decay of ^{54}Zn as well as for the decay of ^{48}Ni. In addition, new results on the decay of ^{45}Fe are discussed, which nicely agree with the published data and allow therefore to decrease the overall errors on its half-life, its 2p decay energy and on the branching ratios.

2 Experimental details

In two experiments performed in April/May 2004 at the SISSI-LISE3 facility of GANIL, we used the projectile fragmentation of a ^{58}Ni primary beam at 75 MeV/nucleon to produce proton-rich nuclei in the range $Z = 20$–30. After production in a $^{\mathrm{nat}}$Ni target in the SISSI device, the fragments of interest were selected by the Alpha/LISE3 [7] separator equipped with an intermediate beryllium degrader.

At the focus of the LISE3 separator, a set-up was mounted to identify and stop the fragments of interest as well as to study their radioactive decays. This set-up consisted in two channel-plate detection systems for timing

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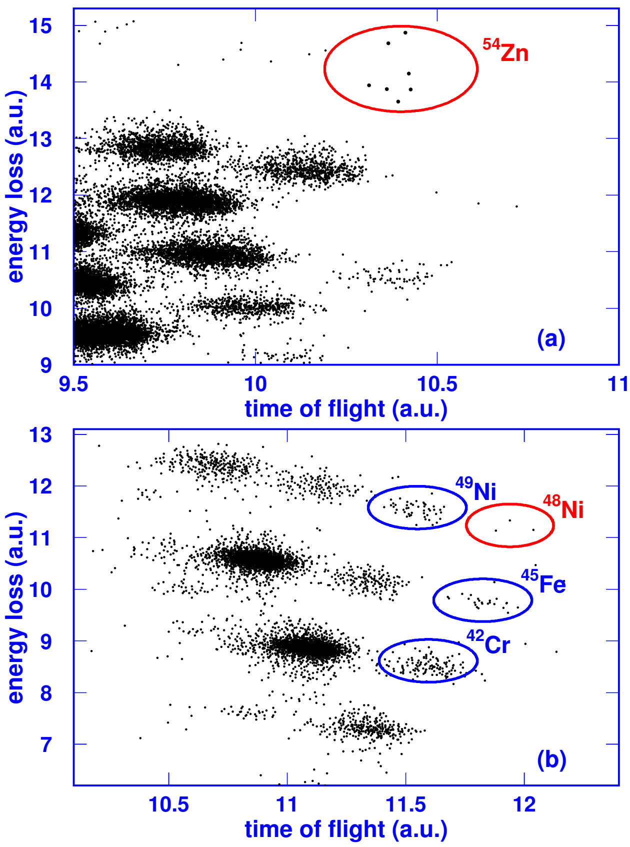

Fig. 1. Isotope identification spectra with the energy loss in the first silicon detector as a function of the ToF of the isotopes. (a) Setting optimized for ^{54}Zn which allows to observe 7 events for this isotope. In this plot, the statistics comes only from runs where we detected a ^{54}Zn isotope. Therefore, the relative intensities are biased. (b) Setting optimized on ^{48}Ni with 3 events observed for this nucleus.

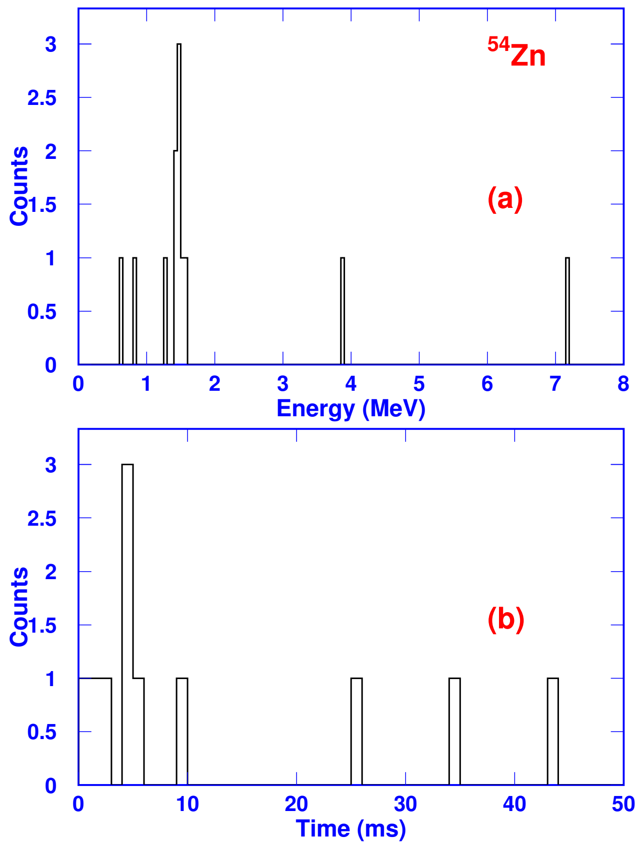

Fig. 2. Energy (a) and time (b) spectra for decay events correlated with the implantation of ^{54}Zn. A peak at 1.47(5) MeV is observed yielding a half-life of $3.6^{+2.5}_{-1.0}$ ms.

purposes mounted at the first LISE focal point and a silicon detector stack with a silicon-strip detector being the implantation device. Two silicon detectors adjacent to the strip detector served also to observe β-particles emitted in radioactive decays. For more details about the detection setup, see ref. [2]. We obtained an average production rate of about two ^{54}Zn per day for a setting optimized on this nucleus and rates of one ^{48}Ni per day in a setting optimized for ^{48}Ni.

3 Experimental results

The fragment identification was performed by means of the standard ΔE–time-of-flight (ToF) technique using the first silicon detector and one of the channel-plate detectors. Additional energy-loss information from the other detectors and the other ToF information was used to clean the spectra. Figure 1 shows the preliminary identification spectra for the two settings. Seven ^{54}Zn events are observed for the first time (fig. 1a). ^{54}Zn is therefore the most neutron-deficient zinc isotope. Basically all modern mass predictions agree on its particle instability, however, with much varying decay energies. This spread in decay energy is so large that some predictions see it rather β-decay, whereas from others one can deduce a half-life which would make it unobservable in the present type of experiments.

In the experiment optimized for the identification and spectroscopy of ^{48}Ni, three ^{48}Ni nuclei have been identified together with 14 events for ^{45}Fe (fig. 1b). The observation of the three ^{48}Ni events confirms for the first time our 1999 results where this doubly-magic nucleus was identified for the first time [8].

The decay of these three nuclei (^{45}Fe, ^{48}Ni, ^{54}Zn) was then studied by correlating these implantations in time with subsequent decays in the same pixel of the silicon strip detector. In this way, basically pure decay spectra, "contaminated" only by the daughter decays, can be generated.

The resulting decay spectra for ^{54}Zn, still preliminary at this stage, are presented in fig. 2. A peak of six events at an energy of 1.36(5) MeV is observed (fig. 2a). Corrected for the β pile-up for the nuclei used to calibrate the spectrum, the 2p energy is 1.47(5) MeV. The other events come from daughter decays as well as from the β-decay of one ^{54}Zn. Two events in the vicinity of the

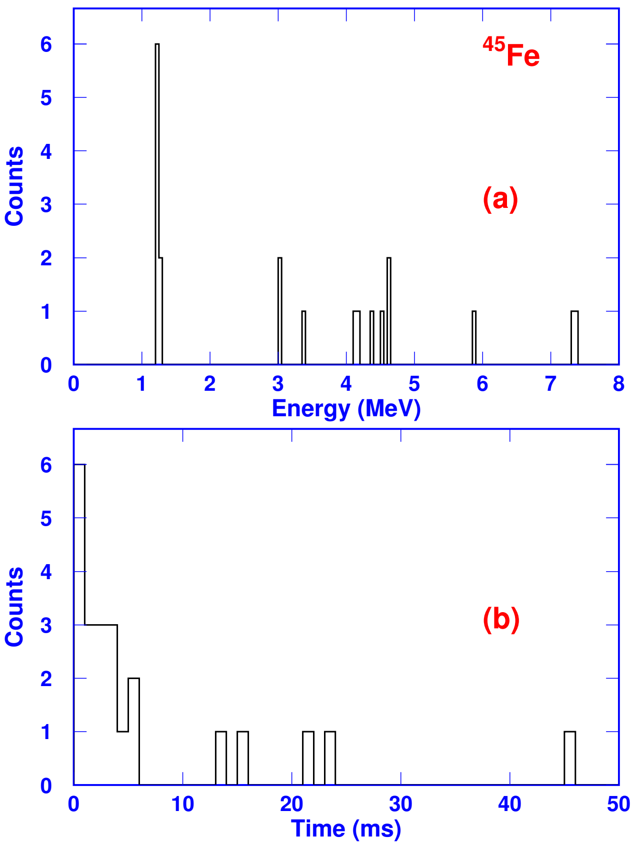

Fig. 3. Energy (a) and time (b) spectra for decay events correlated with the implantation of ^{45}Fe. A peak at 1.14(4) MeV is observed yielding a half-life of $1.6^{+0.9}_{-0.4}$ ms.

1.36 MeV peak are due to the decay of ^{52}Ni, the 2p daughter of ^{54}Zn, which decays with a branching ratio of about 15% by emission of protons with energies of 1.06 MeV and 1.34 MeV [9]. These decays follow a first decay event attributed to ^{54}Zn and occur 25 ms and 35 ms, respectively, after the implantation of ^{54}Zn, in nice agreement with the half-life of ^{52}Ni ($T_{1/2} = 40.1(7)$ ms). One of them is in coincidence with a β-particle in the adjacent detector. The decay-time distribution of all these events is also shown (fig. 2b) and yields a preliminary half-life of $3.6^{+2.5}_{-1.0}$ ms for ^{54}Zn.

The data shown in fig. 3 confirm the results already published for ^{45}Fe [2,3]. Preliminary values are $E_{2p} = 1.14(4)$ MeV and $T_{1/2} = 1.6^{+0.9}_{-0.4}$ ms. In both cases, ^{45}Fe and ^{54}Zn, the half-life of the daughter activity is in agreement with previously measured values [9]. In addition, for none of the events in either of the two peaks, a β-particle could be observed in coincidence in the adjacent silicon detectors. Although the β efficiency of our set-up is not yet determined, the absence of any β-particle strongly supports the identified peaks to be of 2p origin.

In the case of ^{48}Ni, the conclusions are more elusive. Two of the three implantation events seem to be followed by decays the characteristics of which are in contradiction with a 2p emission pattern: Either we missed the first ra-

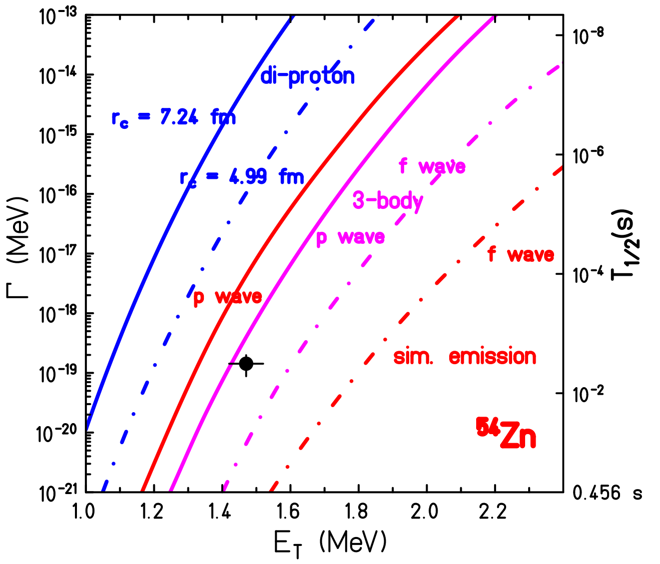

Fig. 4. Comparison of our preliminary experimental results for ^{54}Zn with the di-proton model and the three-body model of Grigorenko *et al.* [12,13]. Best agreement is obtained with the three-body model assuming a pure *p*-wave emission of the two protons.

dioactive decay after implantation due to dead time which we think is unlikely (we still have to determine the exact dead time) or the disintegration proceeds via β-decay. This is still under study. The third event, however, has all characteristics of a 2p emission: No coincident β-decay, a decay energy of about 1.4 MeV roughly 1.7 ms after the implantation. This event could be a first indication of a 2p decay of ^{48}Ni. However, higher-statistics data are needed to confirm this hypothesis.

4 Comparison to theory

The two-proton decay Q value of $Q_{2p} = 1.47(5)$ MeV for ^{54}Zn can be compared to different model predictions for this Q value. Brown *et al.* [10] predicts a value of 1.33(14) MeV in agreement with our result. Ormand [11] calculated a value of 1.87(24) MeV. Finally, Cole [6] proposes a Q value of 1.79(12) MeV. The latter two values are slightly higher than our experimental value.

In fig. 4, we compare our results on the 2p decay of ^{54}Zn to two different theoretical approaches: i) the di-proton model and ii) the three-body model of Grigorenko *et al.* [12,13]. In the di-proton model, the two protons are considered to be a structureless ^{2}He particle which is preformed in the nucleus and to be emitted together, *i.e.* no internal degrees of freedom for ^{2}He are considered and the total angular momentum of ^{2}He is zero. The emission then depends only on the channel radius in the R-matrix sense. The three-body model treats the core-proton as well as the proton-proton interaction realistically and adds thus dynamics to the decay. The best agreement is indeed obtained with the more realistic three-body model assuming a pure p-wave emission (see fig. 4) which is in agreement with the protons being in the $p_{3/2}$ orbital as predicted by the shell model.

However, a much more refined analysis is still required. For example, it is not yet clear how non-zero spectroscopic factor for other orbitals modify the picture. In a similar way, our data should be compared to the Brown-Barker model [14] which is based on the R-matrix model.

5 Conclusion and outlook

With the observation of 2p radioactivity for ^{54}Zn, a second 2p emitter could be clearly identified. Combined with additional data for ^{45}Fe, different theories of 2p radioactivity can now be confronted to our data. Future studies will concentrate on higher statistics for already observed 2p emitters, which will allow for a detailed comparison to theory in particular concerning the 2p branching ratios, the half-lives and the decay energies, as well as on more refined data such as the energy of the individual protons and their angular correlation. For this last topic, we have developed a time-projection chamber which will allow for the visualisation in 3D of the trajectories of the decay protons.

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