Two-proton emission from proton drip-line nuclei

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Abstract

In the first part, new results on two proton emission from excited states in ^{17}Ne are presented. In these complete kinematics measurements performed at the SPEG facility of GANIL, the angle between the two protons has been measured evidencing a ^{2}He emission pattern. In a second part, recent results on the two-proton radioactivity of ^{45}Fe from GANIL and GSI are presented, which show the first evidence of this new radioactivity. Beyond the present results, future studies are discussed.

1 Introduction

Two-proton radioactivity was proposed 40 years ago as a possible decay route for even-Z nuclei beyond the proton drip line [1]. In cases, where the sequential decay is energetically forbidden due to the pairing energy, a simultaneous two-proton emission is the only possible decay branch.

Despite many experimental efforts over the last two decades, no such case could be found. Cases of observed two-proton (2p) emission included β-delayed 2p emission from highly-excited states (see e.g. [2]), from states excited by Coulomb excitation [3] or by other means [4, 5], or from ground states of very light nuclei [6, 7]. In all cases, where a consistent picture resulted, the decay pattern was consistent with a sequential decay.

In cases, where intermediate levels are accessible for a sequential decay, a simultaneous correlated decay may only be expected, if nuclear structure, i.e. very small overlapp between the initial and the final wavefunctions, prevents the one-proton decay to the intermediate nucleus to take place. In these rare cases, a ^{2}He emission pattern may be observed, which should be observable by means of an angular correlation between the two protons peaking at forward angles.

Much better cases for such a correlated emission to take place are expected in the medium-mass region (A=40-60), where the Coulomb barrier of the nuclei is strong enough to ensure longer half-lives (microseconds to milliseconds) and narrow levels. Such a situation arises for nuclei like ^{39}Ti, ^{42}Cr, ^{45}Fe, ^{48,49}Ni, and ^{54}Zn. Due to mass and Q-value estimates [8, 9, 10], these nuclei turned out to be promissing candidates for 2p radioactivity with the sequential decay energetically forbidden. Most of these nuclei have been observed in recent projectile-fragmentation experiments at GANIL and at GSI (see e.g. [11, 12]), with the only exception being ^{54}Zn which was not yet seen experimentally.

As the sequential decay is not an open channel in these cases, generally two different decay modes for simultaneous emission are discussed: i) the three-body breakup where only phase space governs the decay and ii) ^{2}He emission where a correlated proton pair is emitted which then breaks up into two protons. Both pictures should be considered as extremes of a more realistic description of the emission process.

In the past, theoretical approaches used the di-proton picture to calculate decay widths and half-lives via a barrier-penetration picture [8, 9, 10]. Recently, more realistic model were developped. One of them is the three-body model of Grigorenko et al. [13] which explicitly treats the proton-proton and the proton-core interaction. Another model is the R-matrix model of Barker [14, 15] which can be used for sequential decay or in the case of ^{2}He emission.

In recent experiments at GANIL and GSI, we studied the decay of ^{45}Fe, one of the most promissing cases of 2p radioactivity. In another experiment at GANIL, 2p emission was observed from excited states in ^{17}Ne in a complete-kinematics experiment. Both results will be presented and discussed in the following.

2 Two-proton emission from excited states in ^{17}Ne

In an experiment on SPEG at GANIL [16], the decay of excited states in ^{17}Ne has been studied by reconstructing the invariant mass from a complete-kinematics measurement. A ^{24}Mg primary beam at 95 MeV/nucleon was fragmented in a carbon target in the SISSI device. By means of an achromatic degrader in the Alpha spectrometer, a secondary cocktail beam containing ^{17}F, ^{18}Ne and ^{20}Mg was selected. These isotopes interacted again in a beryllium target at the entrance of the SPEG spectrometer to produce short-lived proton-rich products by e.g. one-neutron stripping reactions.

The decay of these unstable nuclei was observed by means of the MUST array [17], which detected protons from decays in the target, and the SPEG spectrometer, which was used to select the reaction channel and to determine the momentum vector of the heavy recoil. In this way, the momentum vectors of all decay products were measured which allowed us to determine the invariant mass of the decaying nucleus as well as, in the case of 2p emission, the proton-proton emission angle.

To study the decay of excited states in ^{17}Ne, one-neutron stripping reactions of ^{18}Ne nuclei incident on the seconday target were used. Figure 1 shows the invariant mass spectrum as determined from ^{15}O + 2p events. The peak at a mass excess of 18.5 MeV is due to the decay of the second and third excited states in ^{17}Ne which are not resolved in our experiment (we estimate our experimental resolution to be about 250 keV). Above 20 MeV events from higher-lying states are visible.

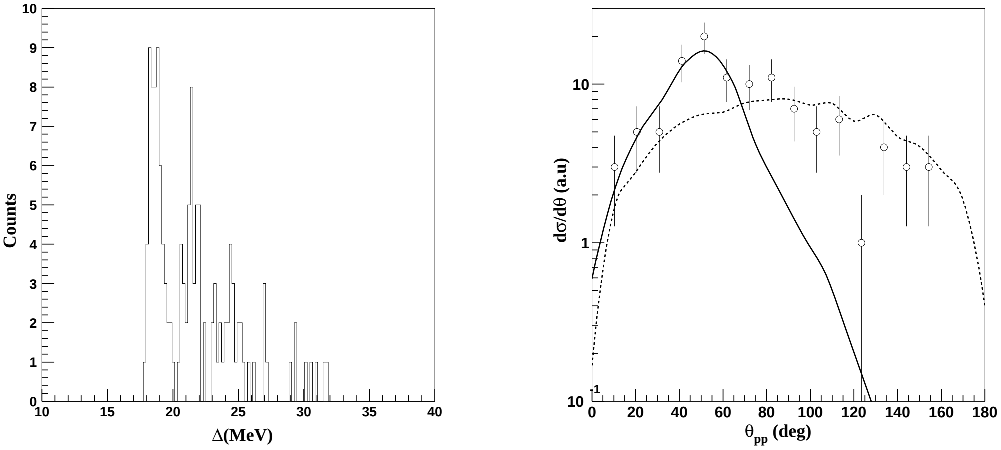

Figure 1: Left: Invariant mass spectrum for ^{15}O + 2p events. The peak at 18.5 MeV is interpreted as the decay of the second and third excited states ($E^* = 1.76$ MeV and 1.91 MeV) in ^{17}Ne by two-proton emission, whereas the activity above 20 MeV arises from the decay of higher lying states. Right: Angular distribution in the center of mass for all 2p events correlated with the observation of a ^{15}O recoil. The solid curve is a simulation of a correlated two-proton emission via a ^{2}He resonance, whereas the dashed line corresponds to a sequential emission pattern via the ground state of ^{16}F.

The angle between the two protons in the center of mass of ^{17}Ne is shown in figure 1. A more or less continuous spectrum is observed, however, with an excess of counts at about 50^o. Monte Carlo simulations, which include experimental acceptances, straggling effects, energy-loss etc., show that neither a sequential picture nor a pure ^{2}He emission pattern can reproduce the experimental data. The best fit is obtained by assuming a 40% ^{2}He branch and 60% of sequential decay. Details concerning the physics used in the simulations can be found in [7].

A more detail analysis is possible by performing energy cuts. Figure 2a shows the same angular distribution for decays from the second and third excited states. This angular distribution is in agreement with the expected seqential emission pattern. A similar results was recently obtained by Chromik et al. [3] at MSU where only states up to 2 MeV excitation energy were produced due to the use of Coulomb excitation.

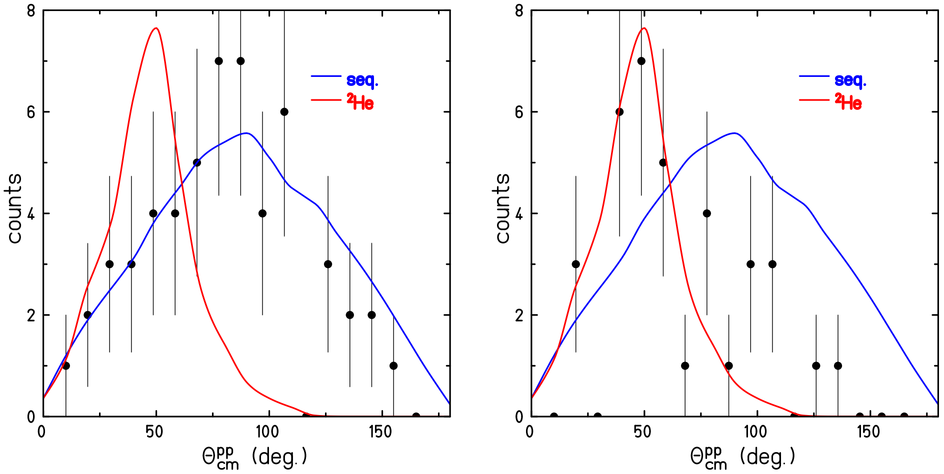

Figure 2: Angular distribution for 2p events with a ^{15}O recoil yielding a mass excess of less than 20 MeV (a) and above 20 MeV (b). The solid and the dashed curves are again simulation of a correlated two-proton emission via a ^{2}He resonance and a sequential emission pattern, respectively.

However, for the events from states with a mass excess above 20 MeV, a significantly different angular distribution is obtained. Although the statistics is low, an enhancement of events around 50^o is observed. Again the distribution is in agreement neither with a simulation for a sequential decay nor with a ^{2}He picture alone. However, in these events the ^{2}He portion has to be raised to 50% to get agreement with the experimental data. This seems to indicate that one or several high-lying states could decay by a correlated 2p emission, despite the fact that the sequential branch is widely open.

Much higher statistics data are clearly needed to confirm or infirm the present finding. New experimental studies can take profit from the high-intensity radioactive neon beams now available at the SPIRAL facility of GANIL. In addition, theoretical calculations which try to locate states in ^{17}Ne, where the wavefunction has very little overlap with states in the 1p daughter ^{16}F, but large overlap with the ground state in ^{15}O, the 2p daughter, are most wellcome.

3 Two-proton radioactivity of ^{45}Fe

In experiments at the GANIL LISE3 facility and at the FRS of GSI, ^{45}Fe was produced by projectile fragmentation of a primary ^{58}Ni beam. After selection of exotic species with the respective fragment separators, the isotopes of interest were identified on an event-by-event basis by means of time-of-flight and energy-loss measurements and implanted in a silicon stack. Implantation events of a ^{45}Fe isotope were correlated with decay events. In the GANIL experiment, a 16×16 silicon strip detector served as the implantation device, whereas at GSI a stack of seven large-area silicon detectors were used. This correlation technique allowed for basically background-free spectra to be generated for the decay of ^{45}Fe.

In the GSI experiment, 6 ^{45}Fe implantatins were observed in a six-day experiment. 22 ^{45}Fe isotopes could be implanted in the detection setup in a 36h run at GANIL. The decay events were observed after ^{45}Fe implantation. Figure 3 shows the decay energy spectra from the two experiments. From the GSI data, we deduce a total decay energy of (1.1±0.1) MeV. The GANIL data yield an energy of (1.14±0.06) MeV, in nice agreement with the GSI result. This energy is very close to theoretical prediction from Brown [8] of 1.15(9) MeV, from Ormand [9] of 1.28(18) MeV, and from Cole [10] of 1.22(5) MeV and is a first indication for a 2p decay of ^{45}Fe.

Both experiments were equipped with detectors to detect β particles emitted in a possible β^+ decay of ^{45}Fe. In the GSI experiment, a NaI barrel surrounded the silicon telescope and was meant to detect the 511 keV annihilation quanta from the positrons. At GANIL, we used a 6 mm thick Si(Li) detector to search directly for the positrons. This detector was installed behind the silicon strip detector and had an efficiency of 30% to observe β particles emitted in the implantation device. No β particle nor its annihilation was observed in either experiment. From both experiments, we determine a probability far below 1% to miss all β particles.

The half-life of the ^{45}Fe decay was determined to be $(3.2^{+2.6}_{-1.0})$ms (GSI) and $(4.7^{+3.4}_{-1.4})$ms (GANIL), which yields an average value of $(3.8^{+2.0}_{-0.8})$ms. This half-life is not far from a typical β-decay half-life as predicted for this isotope region. Therefore it might be expected that ^{45}Fe decays in part by β-delayed decays. Indeed counts observed above 6 MeV in both experiments in coincidence with

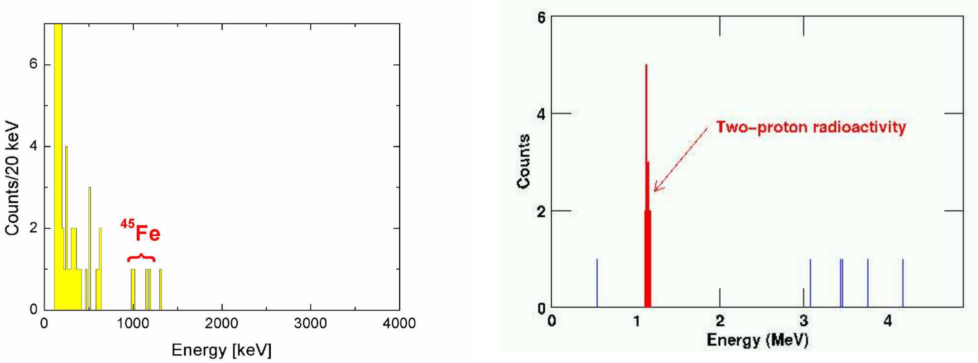

Figure 3: Decay-energy spectra from the GSI (left-hand side) and the GANIL (right-hand side) experiments. These data yield decay energies of (1.1±0.1) MeV and (1.14±0.06) MeV, respectively.

^{45}Fe implants (not shown in figure 3) are indications of such decays. We estimate that the branching ratio for 2p decay is of the order of 80%.

Due to higher statistics, the width of the decay-energy peak in the GANIL experiment could be further analysed. It turned out that its width is about 30% smaller than similar peaks originating from β-delayed 1p emission in e.g. ^{52}Ni. In addition, the known decay characteristics of the ^{45}Fe 2p daughter, ^{43}Cr, are in agreement with the observation of events with a decay energy between 3 MeV and 5 MeV and a half-life of about 15 ms.

These different observations can be consistently explained by a ground-state two-proton decay of ^{45}Fe. All other explanations such as β-delayed decay modes can be excluded with a rather high probability. As, due to mass predictions, it seems to be very unlikely that the sequential decay via the ground state of ^{44}Mn is energetically possible and contributes significantly, only a simultaneous emission pattern has to be considered. However, as only total decay energies and half-lives have been measured, no experimental information is available on the energies of the individual protons and on their relative emission angle. This information has to await further experimenal studies designed for this purpose.

Recent theoretical studies of the decay of ^{45}Fe were performed by Grigorenko and co-worker [18] and by Brown and Barker [19]. Brown and Barker used an R-matrix model which explicitly includes the decay of ^{45}Fe via the ^{2}He resonance. Their calculations yield half-lives for 2p decay of 4 - 41 ms, depending on the decay energy they use (the experimental uncertainty enters exponentially) and correction factor for the shell-model calculations they determined from mirror nuclei. These results therefore indicate that the decay could indeed proceed via the ^{2}He resonance.

Grigorenko et al. [13] use their three-body model to determine the 2p decay half-life as a function of the Q value. As shown in figure 4 their theoretical results are in agreement with the experimental data, if they assume that the protons are emitted from a $p_{1/2}$ state rather than from a $f_{7/2}$ state as expected from the mirror nucleus. However, a small low-ℓ contribution in the wavefunction might be sufficient to dominate the decay.

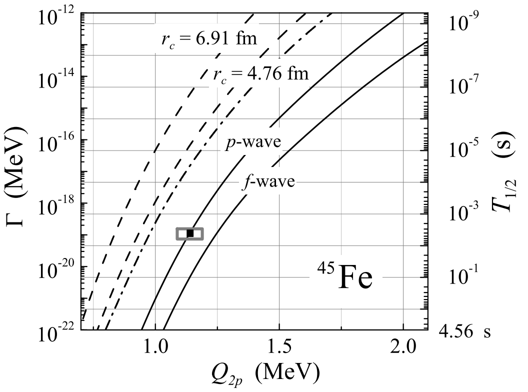

Figure 4: Widths and decay half-lives as calculated in different models. The dashed lines correspond to the di-proton model with channel radii of 6.91 fm and 4.76 fm. The dashed-dotted line originates from an R-matrix calculation assuming simultanuous, but independent emission of two s-wave protons. The solid lines correspond to results from the 3-body model using p-wave or f-wave protons [18]. The experimental point and its error bar is also shown.

Clearly further theoretical work is still needed to get a consistent description of 2p emission. On the experimental side, higher-statistics data on ^{45}Fe and search for 2p emission from the other top candidates ^{48}Ni and ^{54}Zn are the next steps. A study of the decay mechanism should be possible by measuring the individual decay energies of the protons emitted and their relative angle as already done in the complete-kinematics measurements described above. However, for long-lived 2p emitters like ^{45}Fe new techniques, such a time-projection chambers, have to be developped to get a three-dimensional view of the decay.

4 Conclusions

We have performed experiments to search for and study 2p emission from ground and excited states. The experiments on the decay of ^{45}Fe represent the first case of two-proton radioactivity with a measurable half-life. In the case of 2p emission from excited states in ^{17}Ne, first indications of a correlated two-proton emission yielding an angular correlation between the protons were observed.

Acknowledgement

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