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Two-proton emission

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Abstract. A review of experimental and theoretical achievements obtained in the field of the direct two-proton emission in the the last three years is given. The topics discussed include emission from excited states of ^{17}Ne and ^{18}Ne as well as from the ground state of ^{45}Fe. A search for other candidates of two-proton radioactivity is mentioned. A design of a new type of time projection chamber with optical readout, suitable for studies of proton-proton correlations in the decay of ^{45}Fe, is presented.

PACS. 23.50.+z Decay by proton emission – 27.20.+n Properties of specific nuclei listed by mass ranges: $6 \leq A \leq 19$ – 27.40.+z Properties of specific nuclei listed by mass ranges: $39 \leq A \leq 58$ – 29.40.Cs Gas-filled counters: ionization chambers, proportional, and avalanche counters

1 Introduction

Two-proton (*2p*) emission from nuclear states is a process known since 1983 when it was observed to proceed from excited states populated in the β decay of ^{22}Al and ^{26}P [1,2]. Later, several other excited states were found to emit two protons, following both the β decay and nuclear reactions [3,4]. Decays in all these cases, however, were found to be consistent with a sequence of two one-proton emissions proceeding through states in the intermediate nucleus. Similarly, the ground state of ^{12}O, being a broad resonance, was found to emit two protons sequentially via very broad intermediate states [5,6]. There is an intriguing possibility, predicted by Goldansky already in 1960 [7], that the diproton (^{2}He) correlation may play an important role in the mechanism of the *2p* emission. This possibility continues to inspire and motivate studies in this field. Recently, a few experimental achievements renewed this interest and brought hopes for substantial progress.

The purpose of the present paper is to review experimental as well as theoretical results obtained in the field of *2p* emission studies since 2001. Firstly, the emission from excited states will be discussed. Secondly, the discovery of the ground-state *2p* radioactivity of ^{45}Fe will be recapitulated and searches for other cases exhibiting such a decay mode will be mentioned. Finally, an approach to study the proton-proton (*pp*) correlations in the decay of ^{45}Fe will be presented. An important element of the latter project is the development of a new type of time projection chamber with optical readout.

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Table 1. Partial width (in eV) for the *2p* emission from the 1^- resonance at 6.15 MeV in ^{18}Ne. Experimental results, as well as predictions of two models, are given for two scenarios of the decay mechanism.

	Diproton	Alternative
Exp. [8]	21 ± 3	57 ± 6 (a)
R-matrix [9]	3–10	9–19 (b)
SMEC [10]	0.8–2	15–24 (b)

(a) Simultaneous, independent emission.
(b) Sequential transition through the ghost of the $1/2^+$ state in ^{17}F.

2 Two-proton emission from excited states

In an experiment performed at the HRIBF facility (ORNL) the reaction of a radioactive beam of ^{17}F on hydrogen was used to populate excited states of ^{18}Ne [8]. The observation of *2p* emission from the 1^- resonance at 6.15 MeV yielded hopes that the evidence for the direct 3-body *2p* decay was obtained. This suggestion was based on the fact that no states in the intermediate nucleus (^{17}F) are known through which sequential emission could proceed. The measured distribution of the opening angle between two protons was compared with the theoretical predictions for two extreme assumptions: the independent, uncorrelated emission of both protons, and the emission of a diproton particle. The experimental points, with large uncertainties due to limited statistics, were found to be located just between the two theoretical curves. Thus, no firm conclusion on the decay mechanism could be drawn. Since the coverage of the solid angle was limited in the experiment, the partial width determined for the *2p* branch depends on the decay mechanism. The values deduced for the two assumed scenarios are given in table 1.

Recently, new theoretical models of the *2p* emission were developed, one based on the improved *R*-matrix approach [9], and another one formulated within the Shell Model Embedded in Continuum (SMEC) [10]. They consider, apart from the diproton mechanism, yet a different possibility for the decay in the ^{18}Ne* case: the sequential transition via a ghost (resonant halo) of the $1/2^+$ state in ^{17}F. The latter mechanism is in fact, according to both models, the dominant decay mode, see table 1. The predicted widths, however, fall short of the experimental result by a factor of 3–4. On the other hand, Grigorenko *et al.* [11] pointed out that other processes, like independent simultaneous emission from the 2^- state at 6.35 MeV in ^{18}Ne, and/or direct breakup of ^{17}F projectile on target protons, can possibly contribute to the observed *2p* width. Thus, the experimental data for ^{18}Ne* and their interpretation are far from being unambiguous, and further studies are evidently needed in this case.

An even more interesting situation is found in the neighbouring, more neutron-deficient isotope: ^{17}Ne. The first excited state of this nucleus ($3/2^-$ at 1.288 MeV) is bound by about 200 keV with respect to the emission of one proton but unbound relative to the direct *2p* emission to the ^{15}O ground state. Decays of ^{17}Ne* states were studied first by Chromik *et al.* [12] who used Coulomb excitation of the 59 $A\cdot$MeV ^{17}Ne beam on a gold target, followed by the kinematically complete detection of reaction products at the NSCL/MSU facility. Unfortunately, no evidence for the simultaneous *2p* emission from the first excited state was obtained which apparently decays by an electromagnetic transition to the ground state instead. In turn, the second excited state ($5/2^-$ at 1.764 MeV) was found to decay by the sequential emission of two protons to ^{15}O, in agreement with expectations. In another experiment performed at GANIL, Zerguerras *et al.* [13] populated ^{17}Ne* states by the one-neutron stripping from the 36 $A\cdot$MeV ^{18}Ne beam in a beryllium target. Decay products were detected by the MUST array (light particles) and the SPEG spectrometer (heavy fragment) allowing the full kinematical reconstruction of the process. Indeed, *2p* emission from ^{17}Ne* states was observed and the proton-proton angular correlations established. For the first two proton-emitting states ($5/2^-$ and $1/2^+$) the isotropic distribution was found, consistent with the result of Chromik *et al.* However, the angular distribution of protons from higher lying states ($E^* > 2$ MeV) showed a correlation pattern characterized by a clear maximum for emission angles around 50°. Such a pattern is expected in case of the diproton emission. A quantitative analysis suggested that up to 70% of decays may proceed through this channel. Such a scenario, however, is not supported by the distribution of energy difference between protons. Instead of equal energy sharing, as expected for diproton emission, the energy difference of about 2 MeV and more was found for most of events. Thus, the question whether the diproton correlation indeed contributes to the *2p* emission in this case remains open. It is possible that other mechanism, like final-state interactions, are responsible for the peculiar angular distribution observed. Clearly, more detailed measurements are needed, as well as an application of a rigorous 3-body model to the analysis of proton-proton correlations in this case.

It is interesting to note that the next lighter neon isotope, ^{16}Ne, most probably belongs to the class of "democratic" *2p* emitters [14], like ^{6}Be and ^{12}O. In the latter two cases the width of the decaying state is comparable with the energy taken by the first proton [15]. Experimentally, only the width of the ground state of ^{16}Ne was estimated to be $\Gamma = 110(40)$ keV [16] so far. Detection of protons emitted by ^{16}Ne and the measurement of their correlations remains to be an important goal for future studies.

3 Ground-state 2p radioactivity

The phenomenon of the *2p* radioactivity, as noticed by Goldansky [7], is expected to occur in medium mass, extremely neutron-deficient even-Z nuclei in which the emission of a single proton is energetically forbidden and where due to Coulomb barrier the relevant states are narrow. Over years of theoretical efforts to calculate masses of very proton-rich nuclei as precise as possible, a choice of best candidates was narrowed down to three cases: ^{45}Fe, ^{48}Ni, and ^{54}Zn [17,18,19,20]. Experimental attempts progressing in parallel [21,22,23,24] were crowned in 2002 by finding the first evidence for the *2p* radioactivity of ^{45}Fe [25,26].

This breakthrough profited mainly from the development of extremely sensitive experimental methods utilizing projectile fragmentation of heavy ions, in-flight separation of reaction products, and identification of single ions. Indeed, the decay of ^{45}Fe was detected in two experiments employing the fragmentation technique: one performed at the FRS separator at GSI [25], the other at the LISE facility at GANIL [26]. In both of them, ions of interest were produced by the fragmentation of ^{58}Ni beam. At GSI the primary beam at 650 $A\cdot$MeV and having an average intensity of $\approx 5\cdot 10^8$ ions/s impinged on a 4 g/cm^2 thick beryllium target, while at GANIL the beam energy was 75 $A\cdot$MeV, its average intensity was $\approx 9\cdot 10^{11}$ ions/s, and a natural nickel target of 213 mg/cm^2 thickness was used. In both experiments the selected ions were implanted into a silicon detector telescope mounted at the final focus of the separator. Finally, 22 ions of ^{45}Fe were detected at the LISE, while 6 ions were identified at the FRS. The smaller statistics recorded at GSI was partly compensated by using a dead-time free data acquisition system, based on the digital electronics modules [27]. This system allowed, in contrast to the standard system used at GANIL, to record all signals from each detector in the period of 10 ms after implantation of the ^{45}Fe ion. Thus, the implantation-decay correlations and discrimination against background could be established with a high degree of statistical significance. Moreover, the telescope mounted at the final FRS focus was surrounded by a set of large volume NaI detectors providing a large efficiency (93%) for detection of γ-rays following β-delayed proton emission (βp), and thus allowing a sensitive discrimination against β decay events. For similar reason, the set-up mounted at GANIL included a thick Si(Li) detector to register positrons emitted by β^+-decaying nuclei stopped in the telescope.

The careful analysis of data collected in both experiments yielded results consistent within experimental uncertainties. Taken together they led to the conclusion that the half-life of ^{45}Fe is $3.8^{+2.0}_{-0.8}$ ms and that it decays predominantly by emission of particle(s) with the total energy of 1.14 ± 0.05 MeV with no γ-rays or β-particles in coincidence. Such pattern is characteristic for the *2p* radioactivity and such an interpretation is the only one fitting the data. The measured decay energy is in excellent agreement with predictions for the *2p* decay of ^{45}Fe which are (1.154 ± 0.094) MeV [17], (1.279 ± 0.181) MeV [18], and (1.218 ± 0.049) MeV [19]. Additionally, the measured half-life is consistent with predictions of a rigorous three-body model developed by Grigorenko *et al.* [11,14], as well as with the model of Brown and Barker based on the *R*-matrix approach [9].

However, one decay event observed at GSI is consistent with the β decay (release of 10 MeV energy plus occurrence of a γ-ray in coincidence) suggesting that this decay mode may occur for ^{45}Fe with the branching ratio of roughly 20%. It is evident that more accurate measurements on decay properties of ^{45}Fe, with much larger statistics, are needed to make the comparison with different versions of theoretical models conclusive.

Independently, the search for the *2p* ground-state decay in other nuclei is of great importance, as it may offer new insights into the structure of nuclei at and beyond the proton-drip line. Very recently, the evidence for the *2p* emission from ^{54}Zn was reported from GANIL [28]. In the same experiment, the first decay data for ^{48}Ni were obtained but no firm conclusion could be drawn. Additionally, other candidates are being proposed by theoretical predictions and considered by experimentalists. The implantation technique may possibly be applied to study decays of ^{67}Kr and ^{71}Sr [9]. An interesting case is ^{19}Mg which is predicted to decay in a picosecond time range [29,30]. In an experiment, currently under preparation at GSI, ions of ^{19}Mg will be produced by one-neutron knock-out from a ^{20}Mg beam in a thin secondary target located in the middle focal plane of the FRS [31]. The decay will occur in-flight within centimeters after leaving the target. Thus tracking of the products ($^{17}\mathrm{Ne} + p + p$) will allow the full kinematical reconstruction of the process. It is expected that such an in-flight decay method may also be applicable to other proposed short-lived candidates, like ^{30}Ar, ^{34}Ca, ^{62}Se, and ^{66}Kr [32].

4 Approach to pp correlations in ^{45}Fe

A serious disadvantage of the implantation technique is that only the total decay energy is registered and no information on *pp* correlations can be deduced. Thus, the detection of the two emitted protons separately and the measurement of their momenta represent the crucial next step in the study of the *2p* radioactivity of ^{45}Fe. It will constitute a direct experimental proof for the *2p* emission and hence may shed light on the decay mechanism, in particular on questions concerning the role of the diproton correlations. To achieve this ambitious goal, special time projection chambers are currently being developed at CEN Bordeaux [33] and independently at Warsaw University. In the following, the latter project will be briefly presented.

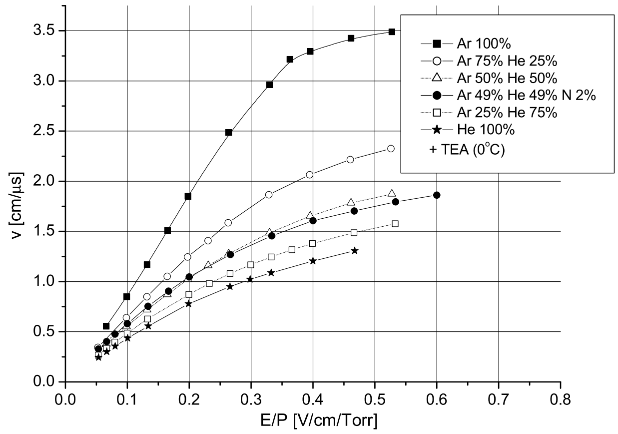

Fig. 1. The electron drift velocity as a function of the reduced electric field measured for selected gas mixtures.

The apparatus, called Optical Time Projection Chamber (OTPC), will consist of several parallel wire-mesh electrodes inside a gaseous medium which form the conversion region and the multi-stage charge amplification structure. A selected gas mixture of argon and helium with a small addition of nitrogen or triethylamine (TEA) will provide strong emission of UV photons during the avalanche process. These photons will be converted into visible light by means of a wavelength shifter foil. A CCD camera located outside the detection volume will record a 2-D image of the decay process. The drift time of primary ionization charge towards the amplification stage will provide the third coordinate. Correlation of the 2-D image with the drift-time structure will allow 3-D reconstruction of the decay topology. The underlying idea of optical detection of particle tracks has been demonstrated by Charpak *et al.* for gas mixtures containing TEA vapour [34]. A similar technique using pure TEA vapour at low pressure has been used by Titt *et al.* [35].

In the course of design studies the electron drift velocity has been measured for various gas mixtures containing TEA vapour. All measurements were performed under atmospheric pressure and at room temperature (24 °C). Pure noble gases (or their mixtures) were bubbled through liquid TEA at 0 °C. The results for selected mixtures are shown in fig. 1. The mixtures containing equal amounts of argon and helium with the small addition of TEA and/or nitrogen are expected to represent a good compromise between providing enough stopping power for heavy ions like ^{45}Fe and yielding long enough tracks for low-energy protons. Assuming a drift velocity of 1.5 cm/μs and 100 MHz sampling rate, the position measurement in such mixtures will be possible with an accuracy of 150 μm.

Fig. 2. Image of a few α-particle tracks recorded with a low-noise CCD device. The exposure time is 0.1 s.

First tests of imaging capabilities were performed with a small prototype chamber having 20 cm × 20 cm active area and 20 mm thick drift volume followed by a double amplification structure. The detector was filled with 49.5% Ar + 49.5% He + 1% N_2 gas mixture under atmospheric pressure. A low-intensity ^{241}Am source was mounted inside the active volume in such a way that α-particles, having 4.5 MeV effective energy due to internal absorption, were emitted perpendicularly to the drift direction. Images were taken with help of a low-noise, Peltier cooled, 15-bit CCD camera. A few α tracks are visible on an example shown in fig. 2. It should be stressed that no image intensifier was used, yet single tracks can be clearly distinguished from the background. More details on the construction of the OTPC detector and on results of the test studies are given in ref. [36].

5 Summary

In this review the main achievements obtained in the *2p* emission studies since 2001 are summarized. The correlations between protons emitted from excited states in ^{18}Ne and in ^{17}Ne were accomplished. Although the data obtained for the 1^- resonance at 6.15 MeV in ^{18}Ne are not yet conclusive, mainly because of low statistics, the theoretical predictions, based on the modern version of the *R*-matrix approach as well as on the newly developed Shell Model Embedded in Continuum, suggest that sequential transitions through ghost states in the intermediate ^{17}F nucleus dominate in this case. The results for the states in ^{17}Ne, especially those with excitation energies above 2 MeV, seem to provide evidence for the strong correlation between protons, consistent with a substantial contribution from the diproton mechanism. Also in this case, the further measurements are necessary. In the decay of ^{45}Fe the first case of *2p* ground-state radioactivity was established. Since only the total decay energy and the lifetime were determined, no information on the emission mechanism could be deduced. To settle this problem, special TPC detectors are being developed at Bordeaux and Warsaw with the aim to study the *pp* correlations in case of ^{45}Fe. Other cases of *2p* radioactivity are sought for. The most promising candidates considered are ^{54}Zn, ^{48}Ni, and ^{19}Mg.

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