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THE CURRENT STATUS OF $2p$ EMISSION STUDIES*
(*A Special Lecture of the Winner of the Zdzisław Szymański Prize***)

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A review of recent achievements obtained in the field of the $2p$ emission is given. The results obtained for excited states of ^{17}Ne and ^{18}Ne as well as for the ground state of ^{45}Fe are discussed. Other candidates for $2p$ radioactivity are mentioned. A design of a new type of time projection chamber with optical readout, for studies of pp correlations in the decay of ^{45}Fe, is briefly presented.

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1. Introduction

Two-proton ($2p$) emission from nuclear states was observed for the first time in 1983 for excited states populated in the β decay of ^{22}Al and ^{26}P [1,2]. Presently, numerous excited states, populated both in the β decay and by nuclear reactions, are known to emit two protons [3, 4]. Decays in all these cases, however, are found to be sequential 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 in ^{11}N [5,6]. There is an intriguing possibility, suggested by Goldansky in 1960 [7], that the diproton (^{2}He) correlation may play an important role in the mechanism of the $2p$ emission. This question, being still open, continues to motivate studies in this field.

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The present paper reviews shortly achievements in the field of $2p$ emission studies realized in the last few years. In the first section, recent results obtained for the emission from the excited states will be presented. In the second section, the discovery of the ground-state $2p$ radioactivity of ^{45}Fe will be recalled and a survey of other candidates for such a decay mode will be presented. Finally, an approach to study the pp correlations in the decay of ^{45}Fe will be described. An important element of the latter project is the development of a new type of time projection chamber with optical readout.

2. Two-proton emission from excited states

One of the interesting results achieved recently was the observation of the $2p$ emission from the 1^- resonance at 6.15 MeV in ^{18}Ne [8]. This resonance was produced in a reaction of radioactive beam of ^{17}F on a hydrogen target, performed at the HRIBF facility (ORNL). Since no states in the intermediate nucleus (^{17}F) are known through which sequential emission could proceed, it was hoped that the evidence for the direct 3-body $2p$ decay could be obtained. 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 data points, having large statistical uncertainties, were found to be located just between the two theoretical curves. Thus, no firm conclusion on the decay mechanism could be drawn. Additionally, since the coverage of the solid angle in the experiment was limited, 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 I.

TABLE I

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

The ^{18}Ne became a testing case for the theoretical models. One approach, initiated particularly to describe the expected diproton emission, is based on the R-matrix formalism. Recently, an improved version of this model, taking into account the s-wave pp resonance in the final state, was given by Brown and Barker [9]. A completely new model was developed on the basis of the Shell Model Embedded in Continuum (SMEC) by Rotureau and others [10]. The predictions for the ^{18}Ne case represent the very first application of this model. Apart from the diproton mechanism, both models consider a different possibility for the decay: the sequential transition via a ghost (resonant halo) of the $1/2^+$ state in ^{17}F. It can be seen from Table I, where all results are collected, that according to both models the latter mechanism seems to be the dominant decay mode. The predicted widths, however, happen to be smaller then experimental estimates by a factor 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 status of the $2p$ emission from ^{18}Ne* is not yet clear, and further experimental studies are needed in this case.

Very interesting situation is found in a more neutron-deficient neon 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.*, at the NSCL/MSU facility [12]. Coulomb excitation of the 59 A MeV ^{17}Ne beam on a gold target was followed by the kinematically complete detection of reaction products. No evidence for the simultaneous $2p$ emission from the first excited state was obtained — an electromagnetic transition to the ground state dominates its width. On the other hand, the second excited state ($5/2^-$ at 1764 keV) was observed to decay by the sequential emission to ^{15}O. In a different experiment, performed at GANIL, the states in ^{17}Ne were populated by the $1n$ stripping from the 36 A MeV ^{18}Ne beam [13]. Light particles (protons) were detected by the MUST array and heavy fragments were identified in the SPEG spectrometer allowing the full kinematical reconstruction of the process. The $2p$ emission from ^{17}Ne* states was observed and the proton–proton angular correlations were recorded. For the first two proton-emitting states ($5/2^-$ and $1/2^+$) the isotropic distribution was found, supporting the observations of Chromik *et al.* In contrast, the angular distribution of protons emitted from higher lying states ($E^* > 2$ MeV) showed a distinct feature: a clear maximum for the emission angles around 50°. This observation was interpreted as the first experimental evidence for the occurrence of the diproton correlations. A comparison with theoretical predictions, based on the

R-matrix model, suggested that up to 70 % of decays may proceed through this channel. On the other hand, the distribution of energy difference between protons was found to be at variance with such a hypothesis. Thus, the question whether the diproton correlation indeed contributes to the $2p$ emission in this case remains open. Evidently, more detailed measurements are needed. Independently, the interpretation of data may require the application of a rigorous 3-body model, like the one developed by Grigorenko and others [14, 15].

3. Ground state $2p$ radioactivity

The phenomenon of the $2p$ radioactivity was 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. The precise theoretical predictions of masses of very proton-rich nuclei identified a few possible candidates: ^{45}Fe, ^{48}Ni, and ^{54}Zn [16–19]. Experimental attempts progressing in parallel [20–23] succeeded finally in 2002 by finding the evidence for the $2p$ radioactivity of ^{45}Fe [24,25]. This breakthrough, opening a new field in nuclear spectroscopy, was already presented in various publications [24–30]. Here, we give only a brief recollection of the main points.

The success was possible mainly because of extreme sensitivity of projectile fragmentation technique allowing an efficient separation and identification of single ions. The decay of ^{45}Fe was detected in two experiments: one performed at the FRS separator at GSI [24], the other at the LISE facility at GANIL [25]. In both of them, ions of interest were produced by the fragmentation of ^{58}Ni beam. At GSI the primary beam at 650 A MeV and having an average intensity of $\approx 5 \times 10^8$ ions/s impinged on a 4 g/cm^2 thick beryllium target, while at GANIL the beam energy was 75 A MeV, its average intensity was ≈ 4 μA, and a natural nickel target of 240 μm thickness was bombarded. In both experiments the selected ions were implanted into a stack of Si detectors mounted at the final focus of the separator. As the result, 22 ions of ^{45}Fe were detected at the LISE, while 6 ions were identified at the FRS.

In the GSI experiment a special data acquisition system based on the digital electronics modules was applied [26], allowing a practically deadtime free collection of signals from all detectors following the implantation of an ion. Thus, the implantation-decay correlations could be established with a high degree of statistical significance. Additionally, the Si telescope mounted at the final FRS focus was surrounded by a set of large volume NaI detectors providing large efficiency (93 %) for detection of γ-rays following β-delayed proton emission (βp). Information from these detectors was crucial in discrimination against the β decay events. Similarly, 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 errors. 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 in fact such 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 [16], (1.279 ± 0.181) MeV [17], and (1.218 ± 0.049) MeV [18]. Additionally, the measured half-life is consistent with predictions of a rigorous 3-body model developed by Grigorenko *et al.* [15], as well as with the model of Brown and Barker based on the R-matrix approach [9].

TABLE II

Other candidates for the $2p$ radioactivity with the theoretical predictions for the decay energy Q_{2p} and the partial half-life $T^{2p}_{1/2}$

Nucleus	Q_{2p} [MeV]	$T^{2p}_{1/2}$
^{19}Mg	0.55–0.85 [15]	0.2–700 ps [15]
^{30}Ar	1.43(34) [31]	10 fs–10 ns [15]
^{34}Ca	>1.1 [15]	< 35 ns [15]
^{48}Ni	1.36(13) [16]	0.4–260 ms [9]
^{54}Zn	1.33(14) [32]	~ 500 ms [35]
	1.79(12) [18]	1–300 μs [35]
^{62}Se	2.76(14) [32]	1.4–55 ns [35]
	2.89(30) [33]	0.4–16 ns [35]
^{66}Kr	2.83(30) [33]	6–400 ns [35]
^{67}Kr	1.76(14) [32]	260 ms [9]
	1.54(26) [33]	
^{71}Sr	2.06(14) [32]	12 ms [9]

In one decay event observed at GSI a release of 10 MeV energy was observed and a γ-ray was found in coincidence. Such observation is consistent with the β decay of ^{45}Fe followed by a proton emission, suggesting that this decay mode cannot be neglected. It is clear that further studies of ^{45}Fe, with much larger statistics, are needed to achieve a detailed picture of its decay properties. The discovery of the $2p$ radioactivity in ^{45}Fe will be followed by the search for other cases of such a decay mode. First nuclei to test will be, as already mentioned, ^{48}Ni and ^{54}Zn. Their predicted half-life is within a range appropriate for the implantation technique. Recently, also other nuclei are taken into consideration as possible candidates for the $2p$ radioactivity [9, 14, 15, 35]. Some cases discussed in the literature are compiled in Table II. Among these candidates only ^{48}Ni was observed [22]. The experimental production cross section of 0.05 pb was found to be in a good agreement with the Experimental Parameterization (EPAX) model [37]. According to this model, all other nuclei collected in Table II can be produced with the larger cross sections than ^{48}Ni which suggests that they should be accessible by the fragmentation reaction.

An interesting case is ^{19}Mg which is predicted to decay in a picosecond time range [15, 34]. In an experiment, currently under preparation at GSI, ions of ^{19}Mg will be produced by $1n$ knock-out from the ^{20}Mg beam in a thin secondary target located in the middle focal plane of the FRS [36]. The decay will occur in-flight within centimeters after leaving the target and tracking of the products ($^{17}\mathrm{Ne} + p + p$) will allow the full kinematical reconstruction of the process. This method, if successful, will simultaneously provide the decay energy, the lifetime and the information on proton–proton correlations. It is expected that such an in-flight decay technique may also be applicable to other proposed short-lived candidates, like ^{30}Ar, ^{34}Ca, ^{62}Se, and ^{66}Kr [35].

4. Approach to *pp* correlations in ^{45}Fe

The implantation technique has a serious disadvantage that only the total decay energy is registered and no information on *pp* correlations is obtained. Detection of the two emitted protons separately and the measurement of their momenta is, therefore, the next necessary step in the study of the $2p$ decay of ^{45}Fe. Besides of providing a direct experimental proof for the $2p$ emission, it will shed light on the decay mechanism. To achieve this goal, special detectors are currently being developed at CEN Bordeaux [38] and independently at Warsaw University. In the following, the latter project will be briefly presented.

The apparatus, called Optical Time Projection Chamber (OTPC), will consists of several parallel wire-mesh electrodes inside a gaseous medium which form the conversion region and the multistage charge amplification structure. Selected gas mixture of Ar and He with a small addition of N_2 or triethylamine (TEA) will provide strong emission of UV photons during avalanche process. These photons will be converted into visible light by means of a wavelength shifter (WLS) foil. A CCD camera located outside the detection volume will record a 2-D image of the decay process. 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 [39].

In the first step 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). The results for selected mixtures are shown in Fig. 1. The mixtures containing equal amounts of Ar and He with the small addition of TEA and/or N_2 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 the drift velocity of 1.5 cm/μs and 100 MHz sampling rate, the position measurement in such mixtures will be possible with the accuracy of 150 μm.

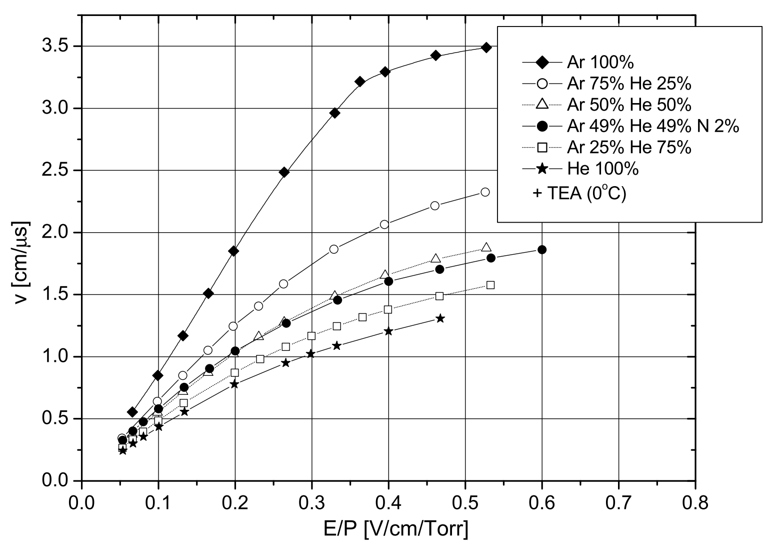

Fig. 1. The electron drift velocity as a function of the reduced electric field measured for selected gas mixtures.

The correlation between charge gain and light yield was measured in a test chamber housing three electrodes of 10 cm × 10 cm area and forming the drift region of 4 cm thickness and the amplification gap of 3.5 cm thickness. Collimated alpha particles from ^{241}Am source entered the drift volume through a thin hole in the cathode. The middle electrode, at ground potential, served to pick-up the avalanche charge. The UV photons emitted during electron multiplication were converted with help of a WLS foil and detected by a photomultiplier mounted behind a thin quartz window. The results obtained for three mixtures containing equal concentrations of Ar and He with a small admixtures of N_2 and/or TEA vapour are combined in Fig. 2. It can be seen that the mixture of 49.5% Ar + 49.5% He + 1% N_2 (full circles) appears as the most promising one providing more light from electron avalanches for a given charge gain than the corresponding mixture with TEA vapour only (open circles). However, the comparison of mixtures having nitrogen concentration of 2% and 1% (full squares and full circles, respectively) may suggest that an optimal concentration of N_2 could be even below 1%.

Presently, the imaging capabilities are being tested with selected CCD devices. More details on the construction of the OTPC detector and on results of the test studies will be given in Ref. [40].

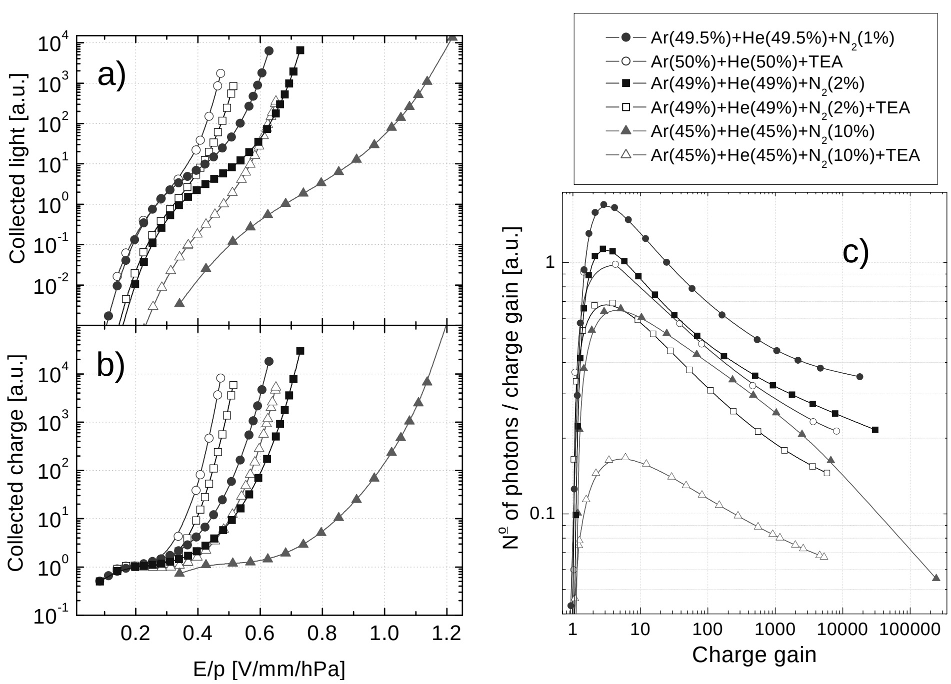

Fig. 2. Properties of selected gas mixtures measured in a test chamber with a 3.5 cm thick amplification gap: (a) the light yield from electron avalanches as a function of the reduced electric field in the gap, (b) the electron charge gain as a function of the reduced electric field, (c) the number of photons per single electron as a function of the charge gain.

5. Summary

The paper summarizes the main achievements obtained in the field of the $2p$ emission studies in last years. The correlations between protons emitted from excited states in ^{18}Ne and in ^{17}Ne were measured. 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 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, with the excitation energy above 2 MeV, suggest a strong correlation between protons, consistent with a substantial contribution from the diproton mechanism. Also in this case the further measurements are necessary to resolve doubts and uncertainties. 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 at 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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