V. I. Gol'danskiĭ. *On two-proton radioactivity.* At the present time we know of four basic forms of radioactive decay of nuclei: α decay, β decay (in three forms: β^-, β^+, and electron capture), spontaneous fission, and proton radioactivity. In 1960 the author predicted existence of a fifth basic form of radioactive decay: two-proton radioactivity[1,2] and subsequently described in detail its main properties (see the review in Ref. 3). In a series of specific examples there was special discussion of the possibility of two-proton decay of nuclei from a long-lived multiparticle isomeric state[4] and β emission accompanied by delayed proton pairs.[5]

In this report we describe the main distinguishing features of two-proton radioactivity, which make it a very promising source of information which is completely absent so far on the nucleon-nucleon interaction at large distances (up to several tens of fermis), and we report the results of the first experimental observations of the emission of delayed pairs at the end of 1982 in the USA.[6–8]

The possibility (and certainty) of the existence of two-proton radioactivity first became obvious as the result of analysis and systematization of the binding energy of protons in the still unknown neutron-deficient isotopes of the light elements by means of the simple formula derived in Refs. 1 and 2 on the basis of the principles of isotopic invariance:

$$B_p\left({}^{A}_{Z}\mathrm{M}_N\right)=B_n\left({}^{A}_{N}\mathrm{M}_Z\right)-\left[B_n\left({}^{2Z}_{Z}\mathrm{M}_Z\right)-B_p\left({}^{2Z}_{Z}\mathrm{M}_Z\right)\right], \qquad (1)$$

which was the first prototype of the future well known Garvey-Kelson formula (Refs. 9 and 10).[1)]

[1)] Here B is the binding energy of the proton (B_p) or neutron (B_n), M is the symbol of the chemical element, and the subscripts and superscripts on M denote the mass number (above), the proton number (lower left), and the neutron number (lower right).

Two-proton radioactivity is a direct consequence of pairing of fermions with opposite spins, in the present case two protons inside the nucleus, as a result of which for nuclei with a strong deficiency of the number of neutrons (when the binding energy of the $(2m+1)$-th excess proton $(B_p)_{2m+1}$ is already negative) it turns out to be easier to eject immediately a pair of protons than to remove the even $(2m+2)$-th proton from the odd $(2m+1)$-th proton. The situation also arises in which the binding energy of the $(2m+2)$-th proton $(B_p)_{2m+2}=(B_p)_{2m+1}+E_{\text{pairing}}$ is still positive, whereas the *binding energy of two protons taken together is already negative*: $B_{2p}=2(B_p)_{2m+1}+E_{\text{pairing}}<0$ (numerically $E_{\text{pairing}}\approx 1$–$2$ MeV). This is also the "purest" case of two-proton radioactivity of nuclei in the ground state, which should be observed for several tens of neutron-deficient isotopes of even elements from $Z=12$–14 to $Z=70$–80. It is also possible to have competition of the simultaneous and successive emission of two protons, when the two quantities $(B_p)_{2m+2}$ and $(B_p)_{2m+1}$ are both negative.

The exponential factor of the rate of 2p decay was obtained in Refs. 1 and 2 on the basis of a very simple formula of the Gamow type for emission of a doubly charged particle—the diproton ${}^2\mathrm{He}({}^1S_0)$, and the pre-exponential factor was taken as $K\sim10^{22}$ sec^{-1}. Subsequent rigorous calculations[11] on the basis of the superfluid theory of nuclear matter have quantitatively confirmed the initial estimates.

Two-proton radioactivity is characterized by the energy and angular correlations of the emitted protons.[1–3] The probability of such decay in which one of the protons carries away an energy

$$E_{p_1}=\frac{Q}{2}(1+\varkappa),$$

and the other an energy

$$E = \frac{Q}{2}(1-\varkappa),$$

where Q is the total decay energy (neglecting nuclear recoil $Q = B_{2p}$), is given by the Gaussian distribution

$$W(\varkappa) = W(0)\, e^{-\alpha\varkappa^2} = W(0) \exp\left(-\frac{3\pi Ze^2 \sqrt{m}}{2\hbar \sqrt{Q}} \varkappa^2\right), \quad (2)$$

where m is the proton mass and Z is the charge of the daughter nucleus.

The angular distribution between the directions of emission of the two protons (the angle ϑ) can be written to a rather good approximation in a form characteristic of neutron pairs[12]:

$$\Phi(\vartheta) \approx \left[\frac{\varepsilon_0}{Q} + \left(\frac{\vartheta}{2}\right)^2\right]^{-1/2}, \quad (3)$$

where $\varepsilon_0 \approx 7$ keV is the energy of the virtual $^1S_0$ level of the nucleon-nucleon system (with some broadening as a result of the Coulomb repulsion of the protons).

The coefficient α in the argument of the Gaussian distribution is written out in Eq. (2) for the case of a square nuclear potential well and a pure Coulomb barrier, and the deviations of α from this value should serve as a source of information on the shape of the potential at the edge of the nucleus and on the sub-barrier nuclear interaction of the emitted protons.

This interaction can lead to an increase of the barrier transmission for a dinucleon in comparison with the emission of two independent nucleons (the nuclear Josephson effect, which was predicted in Refs. 3, 13, and 14 and which has subsequently been observed experimentally[15]), and to confinement of the pair of nucleons in the sub-barrier region at rather large distances. For a purely centrifugal barrier the effective coordinate of the "unpairing" of a singlet $^1S_0$ dinucleon is $r_0 = \hbar[l(l+1)/m\varepsilon_0]^{1/2}$, where l is the orbital angular momentum of the shell from which the nucleons are emitted. Estimates for the expected 2p-radioactive isotope ^{58}Ge ($l = 3$, $Q \approx 1.1$ MeV) give $r_0 \approx 8\cdot 10^{-12}$ cm, i.e., the diproton should traverse as a single entity a distance approximately 12 times the radius of the emitting nucleus!

In Refs. 1 and 2 we predicted also the phenomenon of β decay accompanied by emission of a delayed pair of neutrons, which actually was observed in 1979–1980 (see Refs. 16 and 17) in the cases ^{11}Li, ^{30,31,32}Na, and the fission fragment ^{98}Rb.

β^+ decay with a delayed proton pair was predicted in Ref. 5 to be most probable (since it should be observed even after superallowed β^+ decay without change of isotopic spin: $\Delta T = 0$) for isotopes with $T_Z = -2$ from ^{22}Al to ^{58}Ga.

At the end of 1982 this type of emission was observed experimentally[6–8] for ^{22}Al and ^{26}P. These new neutron-deficient isotopes were obtained in the reaction (^{3}He, p4n) in bombardment of ^{24}Mg and ^{28}Si, respectively, by 110-MeV ^{3}He ions (the cross sections are $\sigma \sim 10^{-33}$ cm^2). Two counter telescopes in combination with a coincidence circuit (with angles between the two telescopes from 0 to 70°) were used for detection both of the spectrum of single protons and of their combined energy in pp coincidences. In this way it was possible to separate distinctly the lines of this total energy corresponding to 2p decay with $T = 2$ of levels of ^{22}Mg and ^{26}Si to the ground state and the excited states of the daughter nuclei (1.634 MeV for ^{20}Ne and 1.369 MeV for ^{24}Mg).

The spin and parity selection rules forbid emission of a diproton, as an entity, in the decay $^{26}\text{Si} \to {}^2\text{He} + {}^{24}\text{Mg}$ from the 13.080-MeV level of ^{26}Si (3^+, $T = 2$), but permit the similar decay for the 14.044-MeV level of ^{22}Mg (4^+, $T = 2$). Accordingly the observation of energy correlations in pp coincidences in decay of ^{26}P led to the conclusion that there is consecutive emission of two delayed protons, while in the decay of ^{22}Al with formation of the 1.634-MeV level of ^{20}Ne data were obtained which indicate emission of the diproton ^{2}He as a single entity.

Among the isotopes for which observation and study of two-proton radioactivity must be considered most promising we must include ^{30}Cl and ^{34}K ($\Delta A = 1$) for β^+2p decay, ^{47}Fe ($\Delta A = 2$), ^{96}Cd ($\Delta A = 1$), and ^{106,108}Te ($\Delta A = 0$) for the 2p decay of isomers, and ^{19}Mg ($\Delta A = 1$, $Q \approx 1$ MeV), ^{39}Ti ($\Delta A = 2$, $Q \approx 0.7$–1 MeV), ^{55}Zn, ^{59}Ge, and ^{108}Xe ($\Delta A = 2$) for 2p decay from the ground state of nuclei (here ΔA denotes the decrease of the mass number in comparison with the lightest elements of the given element which have already been obtained).

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