# Emission of $\beta^+$-delayed pairs of protons and doubly $\beta^+$-delayed protons and $\alpha$ particles

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In addition to the two types of radioactive decay with the emission of nucleon pairs that were predicted in 1960—two-proton radioactivity so far not observed experimentally and the $\beta^-$-delayed neutron pairs first observed in 1979—an emission of $\beta^+$-delayed proton pairs is possible. A list of probable examples is presented. The emission of doubly $\beta^+$-delayed protons and $\alpha$ particles, in particular, the doubly $\beta^+$-delayed, proton-radioactive decays from an excited nuclear state, should be observed after a chain of two $\beta^+$-decay events.

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The existence of two types of radioactive decay with the emission of nucleon pairs–two-proton radioactivity and the emission of $\beta^-$-delayed neutron pairs–was predicted in 1960.[1,2]

Two-proton radioactivity, whose predicted properties have been analyzed in detail in several papers (see review article[3]), so far has not been observed experimentally, since a nucleus with the required, very large neutron deficit could not be successfully synthesized until now. However, the emission of $\beta^-$-delayed neutron pairs was recently observed for the first time in $^{11}$Li (Ref. 4) and subsequently in 30, 31, 32 Na.[5]

The possibility of observing its mirror process–the emission of $\beta^+$-delayed proton pairs–is of interest. The prospects of observing this process may prove to be better than those of "pure" 2*p* radioactivity, because it must be realized for lower neutron deficit when the binding energy of a proton pair is positive. If, moreover, the escape of delayed proton pairs requires tunneling through the potential barrier, then the observation of the energy and angular correlation of two delayed protons can give–just as for the "pure", two-proton, radioactive decay–information on the interaction between these protons in the subbarrier region in which the attraction due to nuclear forces is gradually replaced by Coulomb repulsion.

The existence of a rather large number of $\beta^+$ emitters of the delayed proton pairs, in which the proton-pair, the single-proton, the $\alpha$-particle, and the $\gamma$-ray emission processes that compete with each other can occur after a $\beta^+$ decay that determines the observed delay time, can be deduced from the experimental values and predictions of the masses of atomic nuclei and the energies of their different decay paths.[6]

Using the known masses of the isotopes with $A = 4K - 2$ in the range of $^{18}$Ne to $^{38}$Ca (Ref. 7) and the predicted properties of neutron-deficient nuclei,[8] we can see that the emitters of $\beta^+$-delayed proton pairs must be the nuclei with $Z = 2K + 1$ and $A = 2Z - 4$ (for $K = 5$–$15$), $A = 2Z - 2$ (for $K = 16$–$19$), and $A = 2Z$ (for $K = 20$–$25$).

It is clear from the data for the excitation energies of the states with higher isotropic spins than the ground state[9] that, beginning with $^{50}$Co, the emission of $\beta^+$-delayed proton pairs is energetically possible even after a superallowed $\beta^+$ decay ($\Delta T = 0$) with the formation of the excited state of the daughter nucleus–a $2p$ emitter, which is analogous to the original nucleus. The half lives of such superallowed transitions decrease from $\sim 120$ msec to $\sim 10$ msec in the series ranging from $^{58}$Co to $^{102}$Sb.

The sequential and one-stage emission of two protons as a result of decay from the excited level of a nucleus $A^Z$, whose energy ($E^*$) exceeds the binding energy of the two protons ($S_{2p}$),

$$^{A}Z^* \longrightarrow p + {}^{A-1}(Z-1)^* \to p + {}^{A-2}(Z-2)$$

$$^{A}Z^* \longrightarrow 2p + {}^{A-2}(Z-2)$$

can be easily distinguished in an experiment even if it is impossible to resolve them directly with respect to time.

In fact, in the recording of proton pairs by means of coincidence schemes the sequential emission of two single protons corresponds to different lines in their energy spectra–$E_1$ and $E_2$, where $E_1 + E_2 = E^* - S_{2p}$ (the recoil energy of nuclei is disregarded here), whereas a Gaussian region of the continuous spectrum appears in the one-stage, two-proton decay in the proton energy spectrum whose center is at $\frac{1}{2}(E^* - S_{2p})$ and whose characteristic width is determined by the energy correlation of the two emitted protons.[1-3] In the simplest case this width is $\Delta E \sim \sqrt{[\epsilon_0(E^* - S_{2p})]}$, where $\epsilon_0 \approx 70$ keV is the energy of the virtual $^1S_0$ level of a two-nucleon system. Such protons also have a certain angular correlation in a region of the order of $\Delta\theta \sim \sqrt{[\epsilon_0/(E^* - S_{2p})]}$, whereas the sequential emission of two protons must be almost isotopic.

The competition among the three types of emission of $\beta^+$-delayed, charged particles–($\beta^+ 2p$), ($\beta^+ p$), and ($\beta^+\alpha$)–can be easily estimated quantitatively, especially when these emissions can also be obtained from an isotopically analogous state of the daughter nucleus. The emission of $\beta^+$-delayed, charged particles can occur if the escape of these particles is not delayed by Coulomb and centrifugal potential barriers to such an extent that the main channel for removal of the excitation of the daughter nucleus becomes the emission of $\gamma$ quanta, after which the emission of protons and $\alpha$ particles becomes energetically impossible.

It is important, however, that new types of radioactive decay of neutron-deficient nuclei, specifically, the emission of doubly $\beta^+$-delayed protons and $\alpha$ particles, can be observed in this case. Beginning with $^{38}Ca$, the isotopes listed above, which probably are $2p$ emitters from the excited states, become $\beta^+p$ emitters of the delayed protons in the ground state (see review articles[10,11]) and, beginning with $^{58}Zn$, they also become $\beta^+$ emitters of the delayed $\alpha$ particles. The emission of protons and $\alpha$ particles after a chain of two, sequential, $\beta^+$-decay events can also occur in much heavier isotopes than those mentioned above. We give, for example the decay chains

$$^{109}Sb \xrightarrow{\beta^+} {}^{109}Sn^* \xrightarrow{\gamma} {}^{109}Sn \xrightarrow{\beta^+} {}^{109}In \quad \text{or}$$

$$^{107}Sb \xrightarrow{\beta^+} {}^{107}Sn^* \xrightarrow{\gamma} {}^{107}Sn \xrightarrow{\beta^+} {}^{107}In \, .$$

We can expect in cases such as $^{107}In$ the proton and $\alpha$ radioactive decays of the excited nuclei produced because of the two, preceding, $\beta^+$-decay events, which proceed at rather small, measurable rates. We know that until now only one case of proton radioactivity of excited nuclei–the decay of the $^{53}Co$ isomer[12,13]–has been observed. The discussed mechanism considerably broadens the range of such possibilities.


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