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Abstract

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ON THE MECHANISM OF RADIOACTIVE DECAY WITH EMISSION OF PROTONS

For neutron-deficient isotopes of many elements, three principal variants of radioactive decay with the emission of protons are characteristic: proton radioactivity (^{1}), two-proton radioactivity (^{2}), and the emission of delayed protons.

The first variants are two new types of elementary acts of radioactive transformations, of which until now only three have been known: α-decay, β-decay, and spontaneous fission. The delay in the emission of single protons or pairs of protons is here caused by the potential barrier surrounding the nucleus. Of course, not every subbarrier transition is defined as radioactive—it is enough to recall, for example, the emission of subbarrier protons in nuclear reactions; by radioactivity is meant only such a spontaneous change of composition whose duration substantially exceeds the lifetime of compound nuclei. Forgetting this condition, we would have to regard both proton and two-proton radioactivity as having long ago been discovered, at least in the examples of B^9 (^{3}) and Be^6 (^{4}), respectively.

In fact, the decay $B^9 \to p + Be^8$ occurs from the ground state of the B^9 nucleus and is deeply subbarrier—the ratio of the decay energy to the height of the Coulomb potential barrier is $X = 0.14$. However, the duration of this decay is so small ($\tau \approx 10^{-18}$ sec) that the B^9 nucleus (like Be^6) is not considered radioactive. As is well known, Be^8 is also not considered an α-radioactive nucleus, although its decay is characterized by still deeper subbarrier behavior: $X = 0.075$, $\tau \approx 10^{-15}$ sec. Below we shall conventionally call such rapid decays instantaneous.

The emission of delayed protons is another complex two-stage process in β-decay, analogous to the previously known emission of delayed neutrons and the emission by light nuclei of delayed (long-range) α-particles. Above-barrier or subbarrier protons are here emitted instantaneously by excited products of β^+-decay. It is of interest to determine which of the variants of radioactive decay with proton emission was discovered in 1962-1963 by V. A. Karnaukhov and coworkers ($^{5-7}$). The most detailed account of the results of these authors is given in a recent review article (^{8}). Two proton emitters were found—a "light" one with half-life $T_{1/2} = 0.085 \pm 0.015$ sec and proton energy $E_p \approx 5 \pm 0.2$ MeV, and a "heavy" one with $T_{1/2} = 23 \pm 4$ sec and $E_p = 2.5 \pm 0.2$ MeV. Even a comparison of the values of $T_{1/2}$ and E_p in both cases speaks in favor of explaining the delay in proton emission not by the Coulomb barrier, but by a preceding β^+-decay. Even for the heavy emitter $X = 0.35$ (2.5 times greater than for B^9), which would correspond to a lifetime $\tau \approx 10^{-19}$ sec.

Analysis of the properties of the "light" emitter, obtained in a nucleon-transfer reaction and therefore close to neon, should help in choosing among three possible variants (in accordance with ($^{8-10}$)) for its identification: Ne^{17}, Mg^{20}, Mg^{21}. Data on the decay of N^{17} (^{11}), together with estimates of the properties of Ne^{17} (^{12}), make it possible to obtain the characteristics of the β^+-decay of Ne^{17}: $T_{1/2} \approx 0.25$ sec; energy of the delayed protons $E_p = 5.3$ ($\sim 30\%$); 4.8 ($\sim 60\%$), and 4 ($\sim 10\%$) MeV.

Judging from the estimates (^{12}) and the data on the decay of mirror neutron-excess···

nuclei ($^{13-15}$), the half-life of the Mg^{21} nucleus is $T_{1/2} \approx 0.2$ sec, while its decay into the ground state of Na^{21} predominates, and the probability of emission of 5-MeV delayed protons (w_p) is about 0.01.

For Mg^{20}, the decay $Mg^{20} \xrightarrow{\beta^+} Na^{20}$ ($1^+, \sim 1$ MeV), with $T_{1/2} \approx 1$ sec, should dominate. In this case $w_p \approx 0.01$–0.03.

Taking into account, in addition, the very approximate nature (to within a factor of 2-3) of the estimates of $T_{1/2}$ given above, it may be assumed that the Dubna "light" proton emitter is the isotope Ne^{17} or Mg^{21}, but not the Mg^{20} mentioned in (^{8}) (it is possible that Mg^{20} was responsible for the half-life of 0.5-1 sec mentioned in (^{6})). We note that delayed protons with energies close to 5 MeV were observed in the decay of Ne^{17} also in later foreign work—Canadian (^{16}) ($E_p \approx 4.5$–4.7 and ≈ 3.7 MeV) and American (^{17}) ($E_p \approx 4.85$–5.15 MeV at $T_{1/2} = 0.1$–5 sec).

In the Canadian work (^{16}), the emission of delayed protons by O^{13} nuclei was also noted ($E_p = 4$ and 3.5 MeV) and by Mg^{21} ($E_p = 4.5$–4.7 and 3.7–4 MeV), and the formation and decay of one more delayed-proton emitter, Si^{25}, was studied in more detail ($E_p = 4.65$; 4.1 and 3.4 MeV; $T_{1/2} = 0.3$ sec). The half-life of Si^{25} proved to be in good agreement with the value 0.4 sec predicted in (^{12}). For O^{13}, estimates based on (^{12}) and on data on the β^+-decay of B^{13} lead to the value $T_{1/2} \approx 0.02$ sec. The probability of β^+-decay with emission of the groups of delayed protons observed in (^{16}) may be estimated as $w_p \lesssim 0.05$ for Si^{25} and $w_p \lesssim 10^{-4}$ for O^{13}. Accordingly, the formation cross section of delayed-proton emitters in experiments with O^{13} turned out to be two orders of magnitude smaller than in the cases of Si^{25}, Mg^{21}, and Ne^{17}.

We now turn to the "heavy" proton emitter discovered in (^{5}) ($T_{1/2} = 23 \pm$

4 sec; $E_p = 2.5 \pm 0.2$ MeV). This emitter was obtained by bombarding nickel with Ne^{20} ions and with oxygen O^{16} ions—in reactions proceeding through the intermediate stage of compound-nucleus formation.

As stated in (^{8}), the "heavy" emitter is presumably an isotope of bromine or krypton with mass number 70-72. Below we shall see that the available data permit more definite conclusions.

The threshold position in the reaction of nickel with neon ($E_{Ne^{20}} \lesssim 90$ MeV), taking into account the data of (^{18}), at once compels us to reject the possibility of forming such nuclei as $Kr^{\leq 69}$, $Br^{\leq 68}$, i.e., it completely excludes an explanation of the observed proton emission by the formation of p- or 2p-radioactive nuclei in their ground states.

The nuclei $Br^{69,70}$ and Kr^{71} would undergo primarily very fast "superallowed" β^+-decays ($T_{1/2} \approx 0.04$ sec) without subsequent proton emission. Still heavier Br and Kr nuclei would not yield 2.5-MeV delayed protons under any variants of β^+-decay from their ground states. Therefore the "heavy" proton emitter cannot be identified as an isotope of bromine, and only one possibility remains—Kr^{70}, which corresponds to the reactions $Ni^{58}(Ne^{20}; \alpha, 4n)Kr^{70}$ with a threshold of ~ 83 MeV and $Ni^{58}(O^{16}; 4n)Kr^{70}$ with a threshold of ~ 73 MeV. The β^+-decay energy of Kr^{70} is insufficient to ensure a superallowed transition; at the same time it considerably exceeds the proton binding energy in the daughter product of β^+-decay—Br^{70} (~ 1.1 MeV).

The maximum positron energy for the decay of Kr^{70} into the ground state of Br^{70} is 7.5 MeV; to the value $T_{1/2} = 25$ sec there corresponds $\log ft \approx 6$. Similar values of $\log ft$, incidentally, are also observed in other cases of β^+-transitions between even-even nuclei and such odd-odd nuclei in which the "odd" proton and neutron are in identical shells. Thus, for the β^+-decay of Nb^{90}, Mo^{90}, Tc^{92}, $\log ft$ is estimated, respectively, as ~ 6.1, ~ 5.6, and ~ 5.7 (^{15}). What exactly the most probable decay path of Kr^{70} is—whether it goes to the ground state or, more likely, to states of Br^{70} excited up to ~ 1 MeV—is immaterial for the further conclusions.

Let us now turn to the scheme of formation of proton radiation. In the reaction $Ni^{58}(Ne^{20}; \alpha, 4n)Kr^{70}$, the maximum ratio of formation cross sections of the emit—

of 2.5 MeV protons (σ_p) and of compound nuclei (σ_c—see (^{19})) is very small and amounts to only 10^{-6}. For the similar reaction $\mathrm{Pr}^{141}(\mathrm{C}^{12}, 4n)\mathrm{Tb}^{149}$ the analogous ratio $(\sigma/\sigma_c)_{\max} \approx 4.5 \cdot 10^{-2}$ (^{20}), while the transition from carbon "projectiles" to neon ones, judging from (^{21}), can hardly reduce this ratio by more than to $2 \cdot 10^{-3}$ (the maximum cross sections of the reactions (ion; $4n$) and (ion; $\alpha, 4n$) are, as a rule, close). Thus, the probability of decay of Kr^{70} with subsequent emission of 2.5 MeV protons is close to $10^{-6}/2 \cdot 10^{-3} = 5 \cdot 10^{-4}$, i.e., for this channel $T_{1/2} \approx 5 \cdot 10^4$ sec, and hence for β^+-decay of Kr^{70} into the 3.6 MeV excited state of Br^{70} ("instantaneously" decaying with emission of 2.5

Fig. 1

Figure 1: Fig. 1

MeV protons) $\log ft \approx 8$.

A β^+-decay of Kr^{70} with $\log ft \approx 6$ to the ~ 6 MeV level of Br^{70}, followed by instantaneous emission of 2.5 MeV protons and formation of the Se^{69} nucleus excited by 2.5 MeV, is also possible. Such a variant would be analogous to that proposed in (^{16}) for the decay of Si^{25}.

The scheme of the β^+-decay of Kr^{70} and of the subsequent emission of delayed protons, consistent with the totality of the experimental data (^{7}), is presented in Fig. 1.

Fig. 1

Thus, the behavior of the "heavy" proton emitter also finds a simple explanation as the emission of delayed protons, analogous to the emission of delayed α-particles by light nuclei (but not of the "long-range" α-particles of Po^{212} and Po^{214}, since for them the partial α-decay time reaches radioactive scales: $\tau \approx 10^{-11}$ sec).

In conclusion we note that the occurrence in reactions between complex nuclei of compound states with very large angular momenta opens wide scope for conjectures such as that the "heavy" proton emitter is a proton-active isomer of the type of the α-active isomer Po^{212m} (see, for example, (^{22})) or of the spontaneously fissioning isomer Am^{242m} (^{23}).

Such assumptions, however, have no particularly serious grounds. The angular momentum of the configuration isomer Po^{212m} (18^+) arises through the breaking of two $h_{9/2}$ protons and two $i_{11/2}$ neutrons. The large change of angular momentum in the α-decay of Po^{212m} ($\Delta I = 18$) is due to the simultaneous removal of all four nucleons forming the group with angular momentum 18^+ above the doubly magic structure ${}_{82}Pb^{208}_{126}$.

Judging from all data on the angular momenta of nuclei with Z or $N = 31, 33, 35, 37, 39$, the protons and neutrons in ${}_{36}Kr^{70}_{34}$ are in the states $p_{3/2}$, $p_{1/2}$, or (less probably) $f_{5/2}$.

The maximum angular momentum of a configuration isomer is then $I_{\max} = 8$, and the maximum change of angular momentum in a one-nucleon transition associated with the emission of a proton is $\Delta I = 3$. Only if two unpaired protons and two unpaired neutrons appear in the $g_{9/2}$ state (transitions for which there would scarcely even be enough excitation energy of the hypothetical isomer) does one obtain here $I_{\max} = 16$, but even in this case the maximum change of angular momentum in a one-nucleon transition ($\Delta I = 5$) is far from sufficient to explain the observed lifetime of the "heavy" proton emitter: a half-life of 25 sec corresponds to emission from the nucleus of a proton with $l = 15$, while for $l < 8$, $T_{1/2} < 10^{-12}$ sec. One may confidently consider that V. A. Karnaukhov and coworkers have discovered ([5–7]), in two examples, precisely the emission of delayed protons—a phenomenon very interesting, but still to a lesser degree than the long-known decay of B^9 (occurring with bo-

with a deeper subbarrier character and, moreover, from the ground state), resembles proton radioactivity.

The much more difficult and as yet unsolved problem of discovering and studying proton and two-proton radioactivity requires obtaining nuclei with a deeper neutron deficiency and recording the emission of protons or proton pairs of considerably lower energies and at incomparably shorter delay times.

Note added in proof. In a preprint received by us after the writing of the present article ([24]), it is reported that the half-life of Ne^{17} is 0.69 ± 0.03 sec, and the spectrum of delayed protons from the decay of Ne^{17} is given (from 5.1 to 2.3 MeV). In light of these data it remains to conclude that the "light" proton emitter detected at Dubna is the isotope Mg^{21}, while the half-life of 0.5-1 sec mentioned in ([6]) was associated with Ni^{17} or Mg^{20}.

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