Neutron-rich nuclei and two-proton radioactivity

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New experimental data on nuclei with a pronounced neutron excess have been obtained. They are combined with an equation (proposed earlier) which relates the neutron binding energy in neutron-rich nuclei and the proton binding energy in the neutron-deficient mirror nuclei to generate some fairly reliable predictions of the properties of four isotopes for which it would be worthwhile to search for two-proton radioactivity: ^{22}Si, ^{31}Ar, ^{39}Ti, and ^{42}Cr.

It has been twenty-eight years since two-proton radioactivity—a fifth basic type of radioactive decay of nuclei—was predicted, and its expected properties described.[1–3] However, the two-proton decay of nuclei from their ground state has yet to be observed. All that has been detected so far has been a beta-delayed sequential emission of two protons.[4–7]

In this situation it is definitely worthwhile to refine the region in which we should search for the proposed $2p$-radioactive nuclei now that there is a large body of experimental data[8] on the binding energies of neutron pairs (S_{2n}) in nuclei of light elements from beryllium to scandium which have a pronounced neutron excess (Fig. 1).

According to an expression proposed in Refs. 1 and 2, which is based on the isotopic invariance of nuclear forces, the binding energy (S_{2p}) of a pair of protons in a nucleus (A, Z) containing Z protons and A-Z neutrons is related to the binding energy (S_{2n}) of a pair of neutrons in the mirror nucleus $(A, A$-$Z)$ by the extremely simple relation

$$S_{2n}(A, A-Z) - S_{2p}(A, Z) = \Delta B_{2n,\,2p}$$

$$= \Delta B_0 + \Delta B'_0 \doteq S_n(2Z, Z) - S_p(2Z, Z) + S_n(2Z-2, Z-1) - S_p(2Z-2, Z-1), \tag{1}$$

where ΔB_0 and $\Delta B'_0$ are the differences between the neutron and proton binding energies in the isotopically self-conjugate nuclei which contain equal numbers (in terms of Z or Z–1) of protons and neutrons.

A comparative analysis[9] of various predictions of nuclear masses shows that expressions like (1) predict masses and decay energies of neutron-deficient nuclei which are more reliable than those predicted by the Garvey–Kelson expression.[10] The error of predictions based on (1) is usually no worse than 100 keV.

Figure 1 shows a set of data[8] on the binding energies of neutron pairs, S_{2n}, in neutron-deficient isotopes of 18 elements, from beryllium to scandium. From the lower left to the upper right, the figure is crossed by a curve of values of $\Delta B_{2n,2p}$, plotted primarily on the basis of the experimental data in the nuclear-mass tables of Ref. 11.

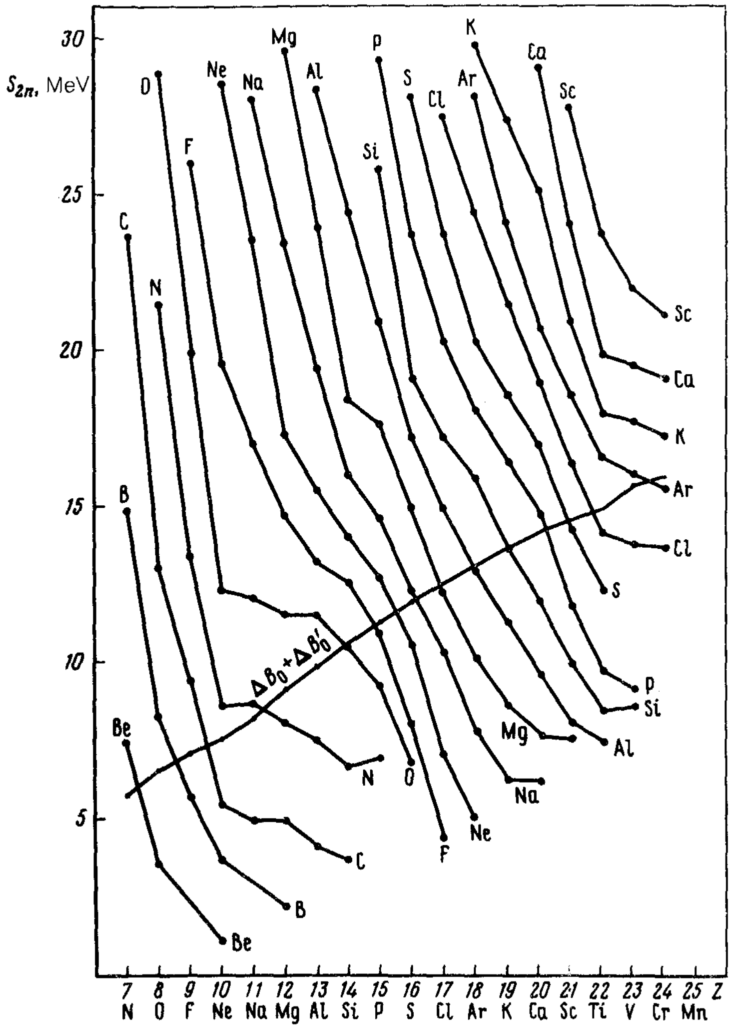

FIG. 1. Data on the binding energies of neutron pairs (S_{2n}) in neutron-rich isotopes and proton pairs (S_{2p}) in the mirror neutron-deficient isotopes. The values of S_{2n} (according to Ref. 8) are shown on the 18 broken lines for the elements from beryllium to scandium. The $\Delta B_0 + \Delta B'_0$ curve (which runs from the lower left corner upward to the right) shows the difference between the values of S_{2n} and S_{2p}. If a point is positioned below this curve, it corresponds to a two-proton instability of the corresponding isotope.

The positions of the points on the S_{2n} curves below the $\Delta B_{2n,2p}$ curve clearly correspond to a negative binding energy of proton pairs in the isotopes of even elements, whose charges and symbols are shown along the abscissa. The numbers of neutrons are equal to the charges of the elements on the original experimental curves of S_{2n} (Ref. 8).

Let us consider a numerical example. The value of S_{2n} for the neutron-rich iso-

TABLE I. Expected decay characteristics of the decay of 2p-radioactive isotopes.

Isotope	^{22}Si	^{31}Ar	^{39}Ti	^{42}Cr
Q_{2p}, MeV	0.15	0.25	0.75	0.4
τ_{2p}, s	10^2	10^4	10^{-5}	10^4
$E_\beta +$ (max), MeV	14.4	15.9	15.3	13.4
$E_\beta + (\Delta T = 0)$, MeV	3.8	5.3	6.2	6.7
$E^*(\Delta T = 0)$, MeV	10.6	10.6	9.1	6.7
$\tau_\beta + (\Delta T = 0)$, s	2	0.5	0.3	0.2
Decay chain after β^+ $(\Delta T = 0)$	$\beta^+ pp$	$\beta^+ pp$	$\beta^+ pp$	$\beta^+ pp$

tope $^{22}_{8}O_{14}$ is 10.5 MeV (Ref. 8), and the sum $\Delta B_0(^{28}_{14}Si_{14}) + \Delta B'_0(^{26}_{13}Al_{13})$ is about 10.65 MeV. Accordingly, the isotope $^{22}_{14}Si_8$ has a negative—although numerically extremely small—proton-pair binding energy (about 0.15 MeV), and it should be perceived experimentally as stable (or nearly stable) with respect to two-proton decay. Here β^+ represents an active isotope, in accordance with the data of a recent paper.[12] Over the entire interval from oxygen to chromium we would expect to find nine "boundary" (2p-unstable) isotopes: ^{12}O, ^{16}Ne, ^{19}Mg, ^{22}Si, ^{26}S, ^{31}Ar, ^{34}Ca, ^{39}Ti, and ^{42}Cr (we are saying nothing about the even more unstable and very short-lived neighbors of these nine, e.g., ^{30}Ar and ^{38}Ti).

Taking $\tau \approx 10^{-12}$ s as a lower limit on the lifetime of radioactive nuclei, we reach the conclusion that it would be possible to observe a two-proton radioactivity for the following four isotopes, whose decay characteristics are listed in Table I: ^{22}Si ^{31}Ar, ^{39}Ti, and ^{42}Cr.

We conclude with a few brief comments and an explanation of Table I.

Since τ_{2p} depends very strongly on the energy of the 2p decay, Q_{2p}, the numerical values of τ_{2p} are crude estimates. Shown along with the total (max) kinetic energy of the positrons in β^+ decay (the third row) are values of $E_{\beta^+} = 1.2[(Z-1)/A^{1/3} - 1.8$ MeV, which correspond to a superallowed transition without a change in isospin $(\Delta T = 0)$. The lifetime for this transition (the sixth line) corresponds to a value logft = 3.5. Since the daughter nucleus in the case of a superallowed β^+ transition is highly excited—by an amount E^* $(\Delta T = 0)$, shown on the fifth row—there is the possibility here of a chain of decays involving the successive emission of two more protons (which would definitely not be paired, in contrast with the decay of ^{22}Al and ^{26}P; Refs. 5 and 6) after the β^+ decay. This circumstance might hinder an unambiguous identification of a decay accompanied by the emission of a pair of protons as a manifestation of a true two-proton radioactivity.

The four isotopes listed in Table I hardly exhaust all possibilities for observing a two-proton radioactivity (among the heavier 2p-active nuclei we might cite, for example, ^{55}Zn, ^{59}Ge, and ^{108}Xe), but for an analysis of the decays of heavier nuclei we do not have the same sort of detailed data on the binding energies of neutron pairs in neutron-rich isotopes as we were able to borrow from Ref. 8 for the elements from beryllium to scandium.

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