ON THE \(\beta^+\)-DECAY OF NEUTRON-DEFICIENT ISOTOPES

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Abstract

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The need for a definite preliminary orientation of experiments aimed at obtaining emitters of delayed protons, p- and $2p$-radioactive nuclei, and at interpreting their results, requires prediction of the properties of nuclei with a considerable neutron deficit as compared with β-stable nuclei. When information is available on mirror nuclei with an excess of neutrons, or on different isotopic states of other nuclei belonging to the isotopic multiplet under study, direct and quite accurate estimates are possible of the nucleon binding energy and the mass defect for neutron-deficient nuclei.

Thus, for example, the relation given in (^{1})

$$\Delta B_{\mathrm{np}} = B_n({}_N M_Z^A) - B_p({}_Z M_N^A) = \Delta B_0 =$$

$$= B_n({}_Z M_Z^{2Z}) - B_p({}_Z M_Z^{2Z}) \approx 1.2(Z-1)/(2Z)^{1/3}\ \mathrm{MeV} \qquad (1)$$

makes it possible, with good accuracy, to relate the binding energy of the Z-th proton B_p in a neutron-deficient nucleus ($Z > N$) to the binding energy of the Z-th neutron B_n in the mirror neutron-rich nucleus through the difference between the binding energies of the neutron and the proton in the isotopically self-conjugate nucleus containing Z neutrons and Z protons.

In (^{1}) another relation was also given, characterizing the mass difference of isotopically conjugate nuclei:

$${}_Z M_N^A - {}_N M_Z^A = (Z-N)\Delta M_0, \qquad (2)$$

where

$$\Delta M_0 = {}_{(A+1)/2} M_{(A-1)/2}^A - {}_{(A-1)/2} M_{(A+1)/2}^A \quad \text{for odd } A,$$

$$\Delta M_0 = \frac{1}{2}\left\{ {}_{A/2+1} M_{A/2-1}^A - {}_{A/2-1} M_{A/2+1}^A \right\} \quad \text{for even } A.$$

Comparing (2) with the formula widely used recently in the works of D. Wilkinson (see, for example, (^{2})),

$$M = a + bT_z + cT_z^2, \tag{3}$$

where a, b, c are constants of the given isotopic multiplet (i.e., for the given mass number A and total isotopic spin T), and M is the nuclear mass, we see that (for $T_{zp} = -1/2$ and $T_{zn} = +1/2$, as in Wilkinson) $b = -\Delta M_0$*.

The systematization of data and calculations of excitation energies of states with different isotopic spin for nuclei with $A \leq 80$ were recently given by Jänecke (^{3}).

When data on mirror neutron-rich nuclei are lacking, various semiempirical formulas are usually used, which represent developments of the well-known Weizsäcker—Fermi formula with allowance for shell corrections and for the generalized nuclear model. Very useful tables ($^{4-6}$) of the masses of atomic nuclei are based on such formulas. It is easy to see, however, that in a number of cases these tables contain erroneous values of the energy of positron β^+-decay and, consequently, of the mass defects of neutron-deficient nuclei. Indeed, proceeding from the principles of isotopi-

* Correspondingly $Q_{\beta^+}({}_ZM_N^A) = Q_{\beta^-}({}_NM_Z^A) + 2\Delta M_0$.

···of charge invariance, whose applicability has recently been confirmed experimentally (^{7}) even for such relatively heavy nuclei as Zr^{90}, the energy of positron β^+-decay

$$Q_{\beta^+} = {}_ZM_N^A - {}_{Z-1}M_{N+1}^A$$

is related to the difference of the Coulomb energies ΔE_{Coul} of the initial and final nuclei in the following way:

$$\begin{aligned} &\text{for } Z > N+1, \quad Q_{\beta^+} \geq \Delta E_{\text{Coul}} - 0.78\ \text{MeV},\\ &\text{for } Z = N+1, \quad Q_{\beta^+} = \Delta E_{\text{Coul}} - 0.78\ \text{MeV},\\ &\text{for } Z < N+1, \quad Q_{\beta^+} \leq \Delta E_{\text{Coul}} - 0.78\ \text{MeV}, \end{aligned} \tag{4}$$

where the difference

$$\Delta E_{\text{Coul}} - 0.78\ \text{MeV} = \Delta E_{\text{Coul}} - (m_n - m_p)c^2 = (Q_{\beta^+})_{\Delta T=0}$$

is the energy of superallowed β^+-decay, occurring without a change of isotopic spin: $\Delta T = 0$.

Fig. 1. Energies of positron β^+-decay. Points are data from Tables (^{4}) (a), (^{5}) (b), and (^{6}) (c).

Since

$$\Delta E_{\text{Coul}} \approx 1.2\,(Z-1)/A^{1/3}\ \text{MeV},$$

the curve shown in Fig. 1,

$$Q^0_{\beta^+} = 1.2\,\frac{Z-1}{(2Z-1)^{1/3}} - 0.78 \approx 0.95\,(Z-1)^{2/3} - 0.78\ \text{MeV},$$

separates the regions of β^+-decay energy values characteristic of nuclei with $Z > N+1$ and $Z < N+1$. For all nuclei with $Z \geq N+1$ (beginning with B^9), superallowed β^+-decay is possible, and, independently of other decay paths, they are distinguished by relatively short lifetimes. The β^+-decay energies of such nuclei, when daughter products are formed in the ground state, must lie above the curve $(Q_{\beta^+})_{\Delta T=0}$, and

$$Q_{\beta^+} = \Delta_{T'T} + (Q_{\beta^+})_{\Delta T=0} \approx \Delta_{T'T} + Q^0_{\beta^+}, \tag{5}$$

where $\Delta_{T'T}$ is the excitation energy of the state with isospin T' for nuclei with mass number A and ground-state isospin T ($T' > T$; for $\Delta_{T'T} < 0$ inversion of the levels of the parent nucleus occurs, and $Q_{\beta^+} \equiv (Q_{\beta^+})_{\Delta T=0} \approx Q^0_{\beta^+}$). The energy values $Q^0_{\beta^+}$ can be obtained from the data of Fig. 2A (even Z) and Fig. 2B (odd Z), where the compilation of calculations (curves) and experimental values (points) of $\Delta_{T'T}$ given by Jänecke ([3]) is used. Emission of delayed protons becomes especially probable when the proton binding energy in the daughter nucleus—the product of β^+-decay—satisfies

$$B_p < \Delta_{T'T}.$$

Only in the case where

$$Q_{\beta^+} \gg Q^0_{\beta^+} \quad (\text{i.e. } \Delta_{T'T} \gg Q^0_{\beta^+}),$$

which occurs at relatively small Z, may it be more probable for neutron-deficient nuclei with $Z \geq N+1$ to undergo not superallowed β^+-decay into an isotopically analogous state, but β^+-decay of another type into the ground or a weakly excited state. The lifetime of nuclei with $Z \geq N+1$ is always less than (or equal to) the time calculated using the characteristics of superallowed β^+-decay —energy $Q^0_{\beta^+}$ and $\log ft \approx 3.2$–3.5.

Among the already identified emitters of delayed protons with $Z \geq N+1$ there are 9 isotopes for which $Z = 2k+2$,

$N = 2k-1$ from $k = 2$ (C^9) to $k = 10$ (Ti^{41}). All these isotopes had been indicated earlier in the table given in (8), and for all of them, beginning with

Fig. 2

Figure 1: Fig. 2

Mg^{21}, superallowed β^+-decay predominates, followed by emission of protons from a state of the daughter nucleus isotopically analogous to the parent nucleus —in accordance with what was predicted in (8), and contrary to the assertion contained in (9) that in none of the observed cases of delayed-proton emission is there a superallowed β^+-transition to a proton-unstable level.

Fig. 2. Energies of positron β^+-decay for nuclei with even $Z = 2k + 2$ (A) and with odd $Z = 2k + 1$ (B). The decay energy $Q_{\beta^+} = Q^0_{\beta^+} + \Delta_{T'T}$, where $Q^0_{\beta^+} = 0.95 \times (Z - 1)^{2/3} - 0.78$ MeV, and the values $\Delta_{T'T}$ (calculated curves and experimental points are taken from the work of Jeneke) (3). $\Delta_{T'T} = \Delta_{10}$ (a); Δ_{21} (b); $\Delta_{3/2\,1/2}$ (c) and $\Delta_{5/2\,3/2}$ (d).

As can be seen from Fig. 1, the tabulated values of the β^+-decay energy of nuclei with $Z \geq N + 1$ in a number of cases turn out to be 3-4 MeV lower than the value $Q^0_{\beta^+}$. Various corrections to the Coulomb energy can hardly explain such large deviations, since the point at issue is not the change in the absolute value of the mass of one nucleus or another, but the mass difference of two neighboring nuclei. Analogous deviations of the tabulated values, indicating their incorrectness—this time upward from the values $Q^0_{\beta^+}$—are observed in a number of cases for nuclei with $Z < N + 1$.

Superallowed β^+-decay for nuclei with $Z \leq N$ from the ground state is possible only when $\Delta_{T'T} < 0$, i.e., when there is an inversion of the sequence of energy levels of states with different values of isotopic spin (for example, $Br^{70}(T = 1) \to Se^{70}$).

In the general case, however, the β^+-decay energies of these nuclei must lie below the curve $Q^0_{\beta^+}$, and their lifetimes considerably exceed the characteristic one for nuclei with $Z \geq N + 1$.

To date, four emitters of delayed protons have been discovered that belong to the class of nuclei for which superallowed β^+-decay cannot occur. These are the “heavy” emitter described in (9)—presumably an isotope of krypton or bromine with $A = 70$-72, with half-life $T_{1/2} = 23 \pm 4$ sec; the tellurium isotope Te^{108} with $T_{1/2} = 5.3 \pm 0.4$ sec (10); and two as yet unidentified isotope peaks, presumably also tellurium, with $T_{1/2} = 60 \pm 10$ sec and $T_{1/2} = 11 \pm 2$ sec (11). For the reasons indicated above, in identifying the “heavy” emitter the possibilities $Kr^{70,71}$ and Br^{70} are excluded; after comparison of the proton energies observed in (9) with the data of (4-6), only one possib-

···ness: Kr^{72} (or, perhaps, Kr^{73}—already outside the region $A = 70–72$). This conclusion has already been reported by us (^{12,13}), and we pointed out that the choice of the Kr^{70} variant in our earlier publication (^{14}), where the isotopes Br^{70-72} and Kr^{71} were correctly rejected, was a consequence of using tables (^{4})

without taking into account the considerations set forth above*.

Let us note that not only theoretical estimates, but also the experimental data concerning proton emitters produced in reactions with neon still require further refinement. Indeed, in the second of the experimental publications by V. A. Karnaukhov and co-workers (^{18}), the previously mentioned (^{19}) proton emitter with $T_{1/2} \approx 0.1$ sec gives way to two components of proton emission, one of which is characterized by a half-life of 0.5-1 sec. It is stated that proton emission was observed when nickel was bombarded not only with Ne^{20} ions, but also with B^{10} ions. This fact, seemingly very important for identifying the emitters, as well as the very discovery of some proton emitter with $T_{1/2} = 0.5$—1 sec, has received, however, neither confirmation nor refutation in subsequent publications.

It is natural to strive for a more detailed analysis of the results of all observations of delayed-proton emission, especially in those cases where the experimental results by themselves do not yet allow the nature of the proton emitters to be identified unambiguously; all the more so since, as has been shown here, the available tabulated data in a number of cases need a certain revision.

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* In work (^{11}), the question of identifying the "light" Dubna emitter with $T_{1/2} = 0.085 \pm 0.015$ sec (^{9}) is discussed. At the time (^{14}), having knowingly rejected from among the variants proposed by the authors (^{9}) the variant Mg^{20}, we noted that the Dubna "light" proton emitter is the isotope Ne^{17} or Mg^{21}. In the note submitted when correcting (^{14}), it was additionally indicated that, according to data that appeared that same year in the form of a preprint of work (^{15}), for Ne^{17} $T_{1/2} = 0.69 \pm 0.03$ sec, and that in light of the data (^{15}) the variant Mg^{21} remains for the Dubna "light" emitter. Later, the experimental work of D' Auria and Preiss (^{15}) proved to be erroneous. It was found (^{16,17}) that, in agreement with our preliminary estimates, $T_{1/2}(Ne^{17}) = 0.103 \pm 0.007$ sec and $T_{1/2}(Mg^{21}) = 0.118 \pm 0.004$ sec, after which the most natural (but still not directly identified) proposal is that the Dubna "light" emitter is Ne^{17}. The authors of (^{11}) have now also joined this conclusion, having now abandoned the Mg^{20} variant, although there are still no experimental data on the lifetime of Mg^{20}.

Note: Figure translations are in progress. See original paper for figures.