The possibility of experimental verification of the effect of a magnetic field on β decay of tritium

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The effect of different electromagnetic fields on the rate of β decay of nuclei as a function of the magnitude of energy liberation is analyzed. It is shown that the effect of a constant magnetic field ~ 10 T can be detected experimentally in observations of β decay of polarized tritium nuclei.

The study of the effect of various kinds of external actions on the course of nuclear processes is one of the old problems of the physics of this century, which was mentioned in the works of Einstein.[1] The many unsuccessful attempts to observe such an effect, for example, on the β activity of nuclei, indicate the constant striving of experimentalists to apply constantly improving technical capabilities to the solution of this fundamental problem.

In this paper we want to call attention to the results of an analysis of the effect of different electromagnetic fields on the rate of β decay and to single out situations that are now experimentally realizable. As will be demonstrated below, in order to solve this problem, the action of a strong magnetic field on polarized β-active nuclei with small energy liberation is most suitable.

Our calculations[2–4] show that when intense laser radiation acts on β-active nuclei, the total decay time depends on the amplitude of the field (E) quadratically

$$\tau = \tau_0 \begin{cases} 1 - \dfrac{35}{8}(E/\tilde{H}_c)^2, & \epsilon_0 - 1 \ll 1, \\ 1 - 10(E/\tilde{\tilde{H}}_c)^2 \left(\ln 2\epsilon_0 - \dfrac{4}{3}\right), & \epsilon_0 \gg 1, \end{cases} \tag{1}$$

where τ_0 is the decay time in the absence of the field, ϵ_0 is the energy liberated in the decay, expressed in units of the rest mass energy of the electron, and the quantity $H_c = m^2c^3/(e\hbar) = 4.41\times 10^{13}$ G, $\tilde{H}_c = H_c(\epsilon_0^2 - 1)^{3/2}$, $\tilde{\tilde{H}}_c = H_c\epsilon_0^2$. Allowance for the polarization of the initial state of the decaying nuclei leads only to an insignificant change in the numerical coefficient in front of the squared term in Eq. (1).

We also obtained similar results for the case of so-called constant crossed fields ($|E| = |H|$, $E \perp H$).

In our calculations, only allowed β-transitions were examined and in examining the polarization dependences it was assumed that the spin of the nucleus is 1/2. These characteristics, in particular, correspond to β-decay of the neutron, as well as tritium. As is evident from expression (1), nuclei with small energy liberation are most strongly affected by the laser field. However, for the record laser beam intensities achieved in recent years, the field-dependent correction to the time constant of β-decay of tritium amounts to $\Delta\tau/\tau_0 \lesssim 10^{-10}$.

The experimental difficulties related to the observation of such small electromagnetic corrections apparently can be overcome only by creating lasers whose intensity will be another several orders of magnitude higher than the level achieved today. Under such conditions, it may be very interesting to investigate the unique β decay of the nucleus Re^{187}, which is characterized by very small energy liberation $\epsilon_0 = 1.004$.

For β decay of unpolarized nuclei in a constant magnetic field, the situation for experimentally verifying the effect of the external action on the decay rate becomes even worse.[5] The characteristic parameter of the perturbation expansion is now H/H_c^*:

$$\tau = \tau_0 \begin{cases} 1 - \frac{35}{12}(H/H_c^*)^2, & \epsilon_0 - 1 \ll 1, \\ 1 - 5(H/\widetilde{\widetilde{H}}_c)^2 (\ln 2\epsilon_0 - 1), & \epsilon_0 \gg 1, \end{cases} \tag{2}$$

where $H_c^* = H_c(\epsilon_0^2 - 1)$. It is easy to see that a magnetic field with intensity $H = H_c^*$ for the β decay of tritium nuclei is 3.22×10^{12} G while in a constant crossed field, the characteristic value $\widetilde{H}_c = 8.76 \times 10^{11}$ G.

However, if the β decay of polarized nuclei occurs in a sufficiently stong, constant magnetic field, then a correlation between the electron spin and the direction of the magnetic field will yield a correction to the decay probability which depends linearly on the field,

$$\tau = \tau_0 \begin{cases} 1 - \frac{7}{2} aS_n(H/H_c^*), & \epsilon_0 - 1 \ll 1, \\ 1 - 5aS_n(H/\widetilde{\widetilde{H}}_c), & \epsilon_0 \gg 1, \end{cases} \tag{3}$$

where $S_n = \pm 1$ characterizes the projection of the spin of the nucleus (1/2) in the initial state on the direction of the magnetic field, $a = 2\alpha_0(1 - \alpha_0)/(1 + 3\alpha_0^2)$; $\alpha_0 = |G^A/G^V|$ is the ratio of the axial and vector constants of the model for the interacting weak currents.

Numerical estimates of the β decay of tritium and of the neutron with $\alpha_0 = 1.25$, using Eq. (3), give $\tau_1 = \tau_0(1 + 1.19 \times 10^{-13}\ S_n\ H(\text{G}))$ and $\tau_2 = \tau_0(1 + 1.94 \times 10^{-15}\ S_n H(\text{G}))$, respectively. The first value indicates that in magnetic fields with intensity of the order of 10 T, the effect of the magnetic field on the total probability of the decay of tritium, although small, amounts to about 10^{-8}. Since the literature has examples of successful storage of hydrogen in a magnetic bottle in a chamber whose walls are covered by superfluid helium at a temperature of about 0.3 K, and of hydrogen containment for several hours, and since there are also some justifiable assumptions that the conditions for holding tritium are analogous to some extent,[6] we hope that it will be possible to observe the effect described above.

Calculations show that in order to achieve the required measurement accuracy, 10^{15}–10^{16} events must be recorded. In the decay of ^3H these events can be accumulated over a time of about 10^7 sec.

In summary, we might note that recent vigorous experimental efforts to measure the rest mass of the neutrino have given rise to a discussion of the different β-active nuclei, of which tritium is still the most important one.[6-8] In one of the experiments it was suggested that a spectrometer with a longitudinal magnetic field of the order of 10^5 G be used to study the β decay of atomic polarized tritium.[6] The great care required in performing the measurements of the rest mass of the neutrino and observations of the effect of an external magnetic field on the course of β decay, as well as the general nature of the object being studied and the basic aspects of the technique used to perform the measurements, could lead to a consolidation of efforts in solving a number of technical problems.

We also note that the loss, in terms of the magnitude of the effect, in working with nuclei, whose β decay liberates a large amount of energy $\epsilon_0 \gg 1$, is partially cancelled out by the more rapid accumulation of the required number of events. The actual limit is imposed only by the existing counting rates of the detectors.

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