PREFERRED NUCLEAR ORIENTATION ARISING IN BETA DECAY IN A STEADY MAGNETIC FIELD

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Vestnik Moskovskogo Universiteta. Fizika,
Vol. 39, No. 6, pp. 67-69, 1984

UDC 539.12:539.172.2

A preferred spin orientation is shown to occur in nuclei arising from beta decay in a strong steady magnetic field. A study is made of the conditions under which the proton polarization in the reaction $n \to p + e + \tilde{\nu}$ is close to 100%.

It was suggested a long while ago that nuclear processes might be affected by strong electromagnetic fields, and in the 1920's it was actively discussed by Einstein in relation to the scope for producing induced radioactivity by bombarding matter with light quanta [1].

Here we discuss some consequences of applying a strong steady and homogeneous magnetic field of strength H in beta decay. Our results are essentially new by comparison with the early studies [2,3], since they provide not only a fairly complete picture of the beta-decay probability in magnetic fields but also the dependence on the energy released in decay $\varepsilon_0 mc^2$, as well as throwing light on the polarization characteristics of considerable experimental significance.

We use the standard scheme examined in detail in [3,4] for a probability of beta decay in a constant and homogeneous magnetic field, which gives us the following expression $(\hbar=c=1)$

$$W/W_0 = 2\mu\left\{\left[\frac{1+\zeta_n\zeta_p}{2}+\frac{2\alpha_0^2}{1+\alpha_0^2}\frac{1-\zeta_n\zeta_p}{2}\right]\left[\sum_{n=1}^{[N]} f(n)+\frac{1}{2}f(0)\right]+\right.$$
$$\left.+\zeta_n f(0)\frac{\alpha_0}{1+\alpha_0^2}\left[\frac{1+\zeta_n\zeta_p}{2}-\alpha_0\frac{1-\zeta_n\zeta_p}{2}\right]\right\}, \tag{1}$$
$$f(n)=\int\limits_{(1+2n\mu)^{1/2}}^{\varepsilon_0} dx\,(\varepsilon_0-x)^2(x^2-1-2n\mu)^{-1/2},\quad \mu=H/H_c,$$
$$H_c=m^2/e,\quad x=p_0/m,\quad p_0^2=m^2+2neH+p_3^2,\quad W_0=\frac{G^2m^5}{4\pi}(1+\alpha_0^2),$$

where G is the Fermi constant, $\alpha_0=|G^A/G^V|$, [N] is the integer part of $N=(\varepsilon_0^2-1)/(2\mu)$, and ξ_n and $\xi_p = \pm 1$ are the normalized projections of the spins of the initial and final nuclei correspondingly along the magnetic field and in the opposite direction.

We note that in deriving (1) we have considered a simple form of allowed beta decay, in which the difference in spectrum shape from the statistical one is due only to the external magnetic field. We have assumed also that the spins of the initial and final nonrelativistic nuclear states are 1/2. Then in this approximation, the description corresponds to a neutron going over to a proton and applies closely for example to transitions between mirror nuclei (such as $^3H \rightarrow {}^3He$) in which the numbers of protons and neutrons are interchanged. For definiteness, in what follows we consider the $n \rightarrow p$ transition on the assumption, however, that the energy released in beta decay ε_0 is arbitrary.

If the energy released in beta decay is small $(\varepsilon_0 - 1 \ll 1)$, we get from (1) up to terms quadratic in the field H that

$$W/W_0 = \frac{4(\varepsilon_0^2-1)^{7/2}}{105}\left\{\frac{1+\zeta_n\zeta_p}{2}\left[1+\zeta_n\frac{7\alpha_0}{1+\alpha_0^2}\mu^* + \frac{35}{12}\mu^{*2}\right] + \right.$$
$$\left. + \frac{1-\zeta_n\zeta_p}{2}\,\frac{2\alpha_0^2}{1+\alpha_0^2}\left[1-\zeta_n\frac{7}{2}\mu^* + \frac{32}{12}\mu^{*2}\right]\right\}, \quad \mu^* = H/[H_c(\varepsilon_0^2-1)]. \qquad (2)$$

We see from (2) that there is a difference from beta decay in the absence of the field, where the total probability is independent of the initial spin orientation, in that appreciable asymmetry occurs in a magnetic field. The different probabilities of transitions from the states $\xi_n = \pm 1$ may lead to the daughter nuclei acquiring a preferred orientation and $\zeta_n = \pm 1$ even though the parent nuclei on the whole are unpolarized and $n_\downarrow^{(1)} = n_\uparrow^{(1)} = n/2$ (where $n_\uparrow^{(1)}, n_\downarrow^{(1)}$ are the numbers of particles with spins directed along and against the field).

We integrate the kinetic equations describing this process to get that the limiting value of the polarization for magnetic fields $H \ll H_c(\varepsilon_0^2-1)$ in the case of small energy release is as follows for $t \gg \tau$, where τ is the characteristic decay time in the absence of the field:

$$\begin{pmatrix} n_\uparrow^{(2)} \\ n_\downarrow^{(2)} \end{pmatrix} = \frac{n}{2}\left\{1 \pm 14\frac{\alpha_0^2(1+\alpha_0)^2}{(1+3\alpha_0^2)^2}\mu^*\right\}. \qquad (3)$$

If the energy release is substantial, $\varepsilon_0 \gg 1 (H \ll H_c\varepsilon_0^2)$, the analogous characteristic is defined by

$$\begin{pmatrix} n_\uparrow^{(2)} \\ n_\downarrow^{(2)} \end{pmatrix} = \frac{n}{2}\left\{1 \pm 20\frac{\alpha_0^2(1+\alpha_0)^2}{(1+3\alpha_2^0)^2}\,\frac{\mu}{\varepsilon_0^2}\right\}. \qquad (4)$$

It follows from (3) and (4) that the difference between the numbers of nuclei formed by decay with spins directed along and against the field lies in the range $2(n_\uparrow^{(2)} - n_\downarrow^{(2)})/n = 10^{-6} \div 10^{-10}$, or $H = 10^5$ G for various known beta-active nuclides, the exact value being dependent on the energy released.

Therefore, the nuclear orientation arising from beta decay is extremely small at the magnetic fields attainable at present, but as regards order of magnitude it is comparable with the values characterizing nuclear paramagnetism, which can be observed by nuclear magnetic resonance methods.

The polarization increases linearly with the field strength and in fields $H \gg H_c(\varepsilon_0^2-1)/2$ it attains the value

$$n_\uparrow^{(2)}/n_\downarrow^{(2)} = (1-\alpha_0)^2/(1-2\alpha_0+9\alpha_0^2),$$

i.e., for realistic values α_0 of the order of one, the degree of polarization

Table 1

$S_n = -1/2$		$S_n = +1/2$
$S_p = +1/2$	$S_p = -1/2$	$S_p = +1/2$
$S_e = -1/2$	$S_e = -1/2$	$S_e = -1/2$
$S_{\tilde{\nu}} = -1/2$	$S_{\tilde{\nu}} = +1/2$	$S_{\tilde{\nu}} = +1/2$

$$(n_{\uparrow}^{(2)} - n_{\downarrow}^{(2)})/(n_{\uparrow}^{(2)} + n_{\downarrow}^{(2)})$$

is very close to 100%.

For example, in beta decay of the neutron ($\alpha_0 = 1.25$) in a magnetic field $H = 2.7\ H_c$, ~99.5% of the protons should have their spins oriented along the field. The formulas apply also for positron decay. In that case, the orientation is against the field in the final state to the same extent.

The asymmetry in the beta decay probability in a magnetic field of (1) can be illustrated for various projections of the nuclear spin on the field direction in the initial state ($S_n = \pm 1/2$) by enumerating the possible beta-decay channels for these cases. The asymmetry is most pronounced for fields $H \gg H_c(\varepsilon_0^2 - 1)/2$, as Table 1 shows. Here $S_n, S_p, S_e, S_{\tilde{\nu}}$ are the projections of the spins of neutron, proton, electron, and neutrino on the field direction.

There is no transition $S_n = 1/2 \rightarrow S_p = -1/2$ (Table 1) because of the momentum condition, which enables one to say that the initial state of a nucleus with its spin oriented along the magnetic field is more stable in relation to beta decay. Also, in the decay $H^3 \rightarrow He^3 + e + \tilde{\nu}$, the analogous effect of practically complete polarization in the daughter nuclei can be observed with a weak constraint on the field: $H \geq 1.6 \cdot 10^{12}$ G.

We are indebted to V. B. Braginskii, V. Chukhovskii, and A. V. Borisov for interest and valuable comments.

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5 March 1983 Theoretical Physics Department