Effect of an intense electromagnetic wave on forbidden nuclear β decays

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The possibility that an intense monochromatic electromagnetic wave will change the total probability for a forbidden β transition is discussed.

Reiss[1,2] has recently analyzed the effect of an intense electromagnetic wave on forbidden nuclear β decays. Specifically, he analyzed the possibility that the forbiddenness might be lifted if the nucleus absorbed from the wave (or emitted into it) n dipole photons, so that an angular momentum of n units could be transferred to the nucleus, and the selection rules for an n-fold forbidden transition could be changed to an

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allowed transition. He considered many-photon interactions of an electron produced in β decay with an external field. Reiss[1,2] concluded that when the field amplitude F and the field frequency ω in the wave satisfy $z\equiv(eFR/\omega)^2\sim n$ (R is the radius of the nucleus) there could be a substantial increase in the probability for the process. Calculations carried out for the singly forbidden transition $^{90}Sr\rightarrow{}^{90}Y$ yielded a decrease in the decay half-life by a factor of 3.8. The corresponding decrease for the triply forbidden transition $^{87}Rb\rightarrow{}^{87}Sr$ was by five orders of magnitude, while the prediction for the quadruply forbidden transition $^{113}Cd\rightarrow{}^{113}In$ is a decrease of the decay half-life by 12 orders of magnitude. Reiss subsequently published[3] some corrections to the calculations in Refs. 1 and 2 but did not reexamine the basic results of those papers. In the present letter we show that these results are completely wrong.

The wave functions used in Refs. 1 and 2 for a nucleus in an external electromagnetic field are gauge-equivalent to a complete neglect of the interaction of the nucleus with the field, and for this reason they cannot describe a lifting of forbiddenness. As in the case of allowed β transitions,[4-9] taking the effect of the field on the wave function of the electron into account may lead to only small corrections of order χ^2 ($\chi = eF/\sqrt{2m\epsilon_0}2\epsilon_0$, where m is the mass of the electron, and $\epsilon_0 = M_i - M_F - m$ is the kinetic energy evolution). The pronounced change in the probabilities for forbidden β decays in a wave which was predicted in Refs. 1 and 2 is a consequence of the neglect of the factor $e^{i\mathbf{qr}}$ in the amplitude for the process ($\mathbf{q}$ is the resultant momentum of the electron and the neutrino): Because of this neglect, the matrix element for the process, M, a function of $\mathbf{q} - e\mathbf{A}$, is replaced by $M(-e\mathbf{A})$ in an external field. The cancellation of two large contributions in the expression for the probability for the process is disrupted, and the result is an incorrect conclusion. This cancellation is a consequence of gauge invariance, which is disrupted when $M(\mathbf{q} - e\mathbf{A})$ is replaced by $M(-e\mathbf{A})$.

The parameter $z^{1/2}$ of Refs. 1 and 2 represents the ratio of the classical energy acquired by a particle charge e in a field F at a distance R, on the one hand, to the photon energy ω, on the other. This parameter ignores the fact that the nucleus is a quantum-mechanical system and cannot absorb photons continuously. In actuality, the forbiddeness may be listed in the following way: We assume that the decaying nucleus has an excited state $|1\rangle$, whose spin and parity allow a β transition to the final state $|f\rangle$. The parent nucleus can then undergo a virtual transition to the $|1\rangle$ state through the absorption of one or several photons from the wave (or the emission of photons into the wave); the $|1\rangle$ state will then undergo an allowed β decay. A similar situation arises if there is a $|2\rangle$ state in the daughter nucleus with quantum numbers which allow the β transition $|i\rangle\Rightarrow|2\rangle$ followed by the electromagnetic transition $|2\rangle\Rightarrow|f\rangle$.

Let us consider the simple case of unique, singly forbidden β transitions which are described by the single nuclear matrix element $B_{ij} = \langle f|\sigma_i x_j + \sigma_j x_i - (2/3)(\sigma\mathbf{r})\delta_{ij}|i\rangle$. The matrix element of the hadron current is $\langle f|J_\mu|i\rangle = \delta_{\mu i}B_{ij}q_j$; $i, j = 1,2,3$. The selection rules for unique, singly forbidden β transitions are $\Delta J^{\Delta\pi} = 2^-$. The $|1\rangle$ state must be coupled to the $|i\rangle$ initial state by an electric dipole transition; the $|1\rangle\Rightarrow|f\rangle$ transition will be an allowed Gamow-Teller transition with $\Delta J^{\Delta\pi} = 1^+$. There will be a corresponding situation for a transition through a $|2\rangle$ virtual state of the daughter nucleus.

As we will show below, the effect of an external field on the characteristics of a forbidden β decay intensifies the energy evolution ϵ_0; we will accordingly examine the nonrelativistic case, $\epsilon_0 \ll m$. Working by the simple method of Ref. 8 for calculating the probabilities for quantum-mechanical processes in an intense electromagnetic wave (see also Refs. 7 and 9), we easily find an expression for the total probability of a forbidden β decay in the field of a wave.

As in Refs. 1 and 2, we assume $eFR/\Delta\epsilon_{1,2} \ll 1$ ($\Delta\epsilon_1 = \epsilon_1 - \epsilon_i$, $\Delta\epsilon_2 = \epsilon_2 - \epsilon_f$), so that we can treat the interaction of the nucleus with the wave by perturbation theory. Since $R \lesssim (5\text{–}7)\times 10^{-13}$ cm and $\Delta\epsilon_{1,2} \gtrsim 10$ keV, this condition can be satisfied with an ample margin by fields that can be produced in the laboratory. The interaction of the electron with the external field is taken into account exactly.

As expected, the corrections to the total probability for the process which stem from the lifting of forbiddenness are of the order of

$$\left[\frac{eFR}{\Delta\epsilon_{1,2}}\frac{1}{\sqrt{2m\epsilon_0}R}\right]^2 \sim \left(\chi\frac{\epsilon_0}{\Delta\epsilon_{1,2}}\right)^2 .$$

Here is the result for the total probability for the process in the case in which the lifting of the forbiddenness occurs through the $|1\rangle$ excited state of the decaying nucleus, in lowest order in the parameters χ^2 and $(\chi\,\epsilon_0/\Delta\epsilon_1)^2$, and with allowance for the terms which depend on the field frequency ω of order up to ω^2 inclusively:

$$W = W_1 + W_2 ,$$

$$W_1 \cong W_0\left\{1 + \frac{315}{8}\chi^2\left[1 + \frac{23}{90}\left(\frac{\omega}{2\epsilon_0}\right)^2\right]\right\}, \tag{1}$$

$$W_2 \cong \left(\chi\frac{\epsilon_0}{\Delta\epsilon_1}\right)^2\left(\frac{G_A^2}{2}\right)\frac{1}{(2J_i+1)(2J_1+1)}\frac{4}{3}\,|\langle J_f\|\,\sigma^1\,\|J_1\rangle|^2|\langle J_1\,\|\,d^1\,\|J_i\rangle|^2 \cdot$$

$$(2m\epsilon_0)(2m)^{3/2}\pi^{-3}(8/105)\epsilon_0^{7/2}\left\{1 + \frac{35}{2}\left(\frac{\omega}{2\epsilon_0}\right)^2 + 14\left(\frac{\omega}{2\epsilon_0}\right)\left(\frac{\omega}{\Delta\epsilon_1}\right) + 3\left(\frac{\omega}{\Delta\epsilon_1}\right)^2\right\}.$$

Here $W_0 = (G_A^2/2)(2J_i+1)^{-1}|\langle J_f||B^{(2)}||J_i\rangle|^2(2m)^{5/2}\pi^{-3}(2/945)\epsilon_0^{9/2}$ is the probability for a unique, singly forbidden transition in the absence of a field; the reduced matrix elements for the quantity B_{ij}, the dipole operator **d**, and the spin operator $\vec{\sigma}$ are defined in accordance with Ref. 10. The expression for W for the case in which the transition occurs through a $|2\rangle$ virtual state of the daughter nucleus is similar in form.

The component W_1 of the total probability corresponds to a direct transition $|i\rangle \Rightarrow |f\rangle$ with allowance for the corrections for the effect of the external field on the electron wave function; the component W_2 corresponds to a transition through a $|1\rangle$ virtual state. In other words, this second component describes the lifting of forbiddenness. In principle, there could be an interference of the direct transition with the transition $|i\rangle \Rightarrow |1\rangle \Rightarrow |f\rangle$, but the corresponding component of the probability, $W_3 \sim \mathrm{Im}\{\langle J_f||B^{(2)}||J_i\rangle\langle J_i||d^1||J_1\rangle\langle J_1||\sigma^1||J_f\rangle\}$, vanishes because the corresponding reduced matrix elements are real.

It follows from this expression that the corrections to W_0 in an external field are exceedingly small. The value of χ for the record high intensities of laser fields is of the order of $\chi \sim 10^{-3}$–10^{-4} at $\epsilon_0 \cong 20$ keV and falls off rapidly with increasing ϵ_0. The parameter $(\epsilon_0/\Delta\epsilon_1)$ would be of the order of unity according to the most optimistic estimates (with $\Delta\epsilon_1 \sim 10$ keV). In reality, $\Delta\epsilon_1$ could at best be of the order of tens to hundreds of keV. As examples we might cite the unique, singly forbidden transitions between nuclear ground states $^{112}Ag(2^-) \to {}^{112}Cd(0^+)$ ($\epsilon_0 = 3960$ keV; the ^{112}Ag nucleus has a 1^+ level with an energy $\Delta\epsilon_1 = 18.5$ keV) and $^{79}Se(7^+/2) \to {}^{79}Br(3^-/2)$ ($\epsilon_0 = 159$ keV; the ^{79}Se nucleus has a $5/2^-$ level with an energy $\Delta\epsilon_1 = 364.5$ keV). The power level of the available sources of electromagnetic radiation is thus not high enough for any significant change in the total probabilities for forbidden β transitions.

Our analysis has focused on unique, singly forbidden transitions, but it is simple to see that the situation could only be worse for doubly forbidden, triply forbidden, etc., transitions.

Interestingly, the coefficient of χ^2 in the expression for W_1 is an order of magnitude greater than the corresponding coefficient in the case of allowed β decay.[4–9] This circumstance means that unique, singly forbidden transitions are more promising than allowed transitions for a study of the effect of an intense electromagnetic wave on the total probability for β decay. A transition of particular interest is $^{187}Re(5^+/2) \to {}^{187}Os(1^-/2)$, for which the energy evolution is very low, $\epsilon_0 = 2.64$ (4) keV. If the maximum laser intensity can be raised two orders of magnitude, the increase in the probability for the process in a field will reach $\sim 10\%$, according to expression (1).

However, some serious technical difficulties will have to be resolved before such an experiment can be carried out.

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