Laser-assisted Z-boson decay

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1. Abstract

EXPERIMENTALISTS have long sought a method that allows them to control as they like the branching ratios of an unstable particle decay and direct some decay to follow one specific desired channel without another. The powerful laser could make this dream come true. In this poster and within the framework of the standard electroweak model, we investigate theoretically the laser effect on the branching ratios of different Z^0-boson decay modes by calculating analytically the Z^0-boson decay into a pair of fermion-antifermion $(Z^0 \to f\bar{f})$ in the presence of a circularly polarized electromagnetic field. See the full published paper : Laser Phys. Lett. **18**, 016002 (2021)

2. Introduction

HOW can the electromagnetic (EM) field change the behavior of particles and their properties in the various scattering and decay processes, is a question that was and is still receiving great interest by scientists and researchers, owing to the tremendous progress made by laser technology in recent times. Branching ratio (BR) is one of these properties that have not been sufficiently investigated in the decay processes that occur in the presence of the EM field, especially knowing that it is an experimentally measurable quantity. We study in this poster the decay of the Z^0-boson in the presence of an EM field, to explore the influence of the latter specifically on the BR of the different decay modes. In the standard model of electroweak interaction, the Z^0-boson, with mass $M_Z = (91.1876 \pm 0.0021)$ GeV and total decay rate $\Gamma_Z = (2.4952 \pm 0.0023)$ GeV [1], can decay into a pair of fermions $(Z^0 \to f\bar{f})$ excluding a pair of top quarks with a lifetime of about 3×10^{-25}sec. One of the important quantities measured by LEP and SLC colliders is associated with the invisible Z^0-boson decay rate Γ_{inv}, which is the partial decay rate to any final states that are rather difficult to detect by standard collider detectors. Γ_{inv} is interpreted, in the standard model, as the partial decay rate with respect to decay into neutrinos $\Gamma_{\text{inv}}(Z^0 \to \nu\bar{\nu})$. The Z^0-boson decay to a pair of charged fermions in a strong crossed EM field was calculated in 2009 by Kurilin in [2].

THE GOAL of this poster is to present what effects an EM field has on the BR of the different Z^0-boson decay modes. Natural units $c = \hbar = 1$ are used throughout the calculation.

3. Theory

We consider the decay of a Z^0-boson into a pair of fermions,

$$Z^0(q) \longrightarrow f(p_1) + \bar{f}(p_2). \quad (f = l, u, c, d, s, b) \tag{1}$$

We assume that this decay occurs in the presence of a circularly polarized monochromatic laser field, which is described by the following classical four-potential

$$A^\mu(\phi) = a_1^\mu \cos(\phi) + a_2^\mu \sin(\phi), \quad \phi = (k.x), \tag{2}$$

S-matrix element:
The lowest-order scattering S-matrix element for the laser-assisted Z^0 decay reads [3]

$$S_{fi}(Z^0 \to f\bar{f}) = \frac{-ig}{4\cos(\theta_W)} \int d^4x \overline{\psi}_f(x)\gamma^\mu \times (g_V - g_A\gamma_5)\psi_{\bar{f}}(x) Z_\mu(x), \tag{3}$$

Wave functions:
The wave function of the incoming Z^0-boson

$$Z_\mu(x) = \frac{\varepsilon_\mu(q,\lambda)}{\sqrt{2QV}} e^{-iq.x}, \tag{4}$$

The outgoing neutrinos are treated as massless particles described by Dirac spinors. The outgoing charged fermions are described by the relativistic Dirac-Volkov functions [4]

$$\begin{aligned}\psi_f(x) &= \left[1 + \frac{e\not{k}\not{A}}{2(k.p_1)}\right]\frac{u(p_1,s_1)}{\sqrt{2Q_1V}} \times e^{iS(q_1,x)},\\ \psi_{\bar{f}}(x) &= \left[1 - \frac{e\not{k}\not{A}}{2(k.p_2)}\right]\frac{v(p_2,s_2)}{\sqrt{2Q_2V}} \times e^{-iS(q_2,x)},\end{aligned} \tag{5}$$

where $e = -|e|$ is the charge of the electron, and

$$\begin{aligned}S(q_1,x) &= -q_1.x - \frac{e(a_1.p_1)}{k.p_1}\sin(\phi) + \frac{e(a_2.p_1)}{k.p_1}\cos(\phi),\\ S(q_2,x) &= -q_2.x - \frac{e(a_1.p_2)}{k.p_2}\sin(\phi) + \frac{e(a_2.p_2)}{k.p_2}\cos(\phi).\end{aligned} \tag{6}$$

Decay rate:

$$\Gamma(Z^0 \to f\bar{f}) = \sum_{s=-\infty}^{+\infty} \Gamma^s, \tag{7}$$

where s is the number of exchanged photons, and

$$\Gamma^s = \frac{G_F M_Z N_c}{16\sqrt{2}(2\pi)^2} \int \frac{|\mathbf{q}_1|^2 d\Omega_f}{Q_1 Q_2 g'(|\mathbf{q}_1|)} \overline{|M_{fi}^s|}^2, \tag{8}$$

where

$$\begin{aligned}g'(|\mathbf{q}_1|) &= \frac{|\mathbf{q}_1|}{\sqrt{|\mathbf{q}_1|^2 + m_{f*}^2}}\\ &+ \frac{|\mathbf{q}_1| - s\omega\cos(\theta)}{\sqrt{(s\omega)^2 + |\mathbf{q}_1|^2 - 2s\omega|\mathbf{q}_1|\cos(\theta) + m_{f*}^2}},\end{aligned} \tag{9}$$

and

$$\overline{|M_{fi}^s|}^2 = \frac{1}{3}\sum_\lambda \sum_{s_1,s_2} |M_{fi}^s|^2. \tag{10}$$

The quantity m_{f*} is the effective mass of the charged fermion inside the EM field.

$$\begin{aligned}m_{f*} &= \sqrt{m_f^2 - e^2a^2}\\ &= \sqrt{m_f^2 + e^2\mathcal{E}_0^2/\omega^2}\,),\end{aligned} \tag{11}$$

where $\mathcal{E}_0$ is the amplitude of the laser's electric and ω its frequency. The coupling constants g_V and g_A appearing in Eq. (3) are defined as

$$\begin{aligned}Z \to l^+l^- &: g_V = -1 + 4\sin^2(\theta_W)\ ;\ g_A = 1,\\ Z \to \text{up-quarks} &: g_V = 1 - \frac{8}{3}\sin^2(\theta_W)\ ;\ g_A = -1,\\ Z \to \text{down-quarks} &: g_V = -1 + \frac{4}{3}\sin^2(\theta_W)\ ;\ g_A = 1,\\ Z \to \text{neutrinos} &: g_V = g_A = 1.\end{aligned}$$

Lifetime τ_Z:

$$\tau_Z = \frac{1}{\Gamma_{\text{tot}}}, \tag{12}$$

where Γ_{tot} is the total decay rate of the Z^0-boson in the laser field given by

$$\Gamma_{\text{tot}} = \Gamma(Z \to \text{hadrons}) + \Gamma(Z \to l^+l^-) + \Gamma_{\text{inv}}, \tag{13}$$

where

$$\Gamma(Z \to \text{hadrons}) = \Gamma(Z \to \text{up-quarks}) + \Gamma(Z \to \text{down-quarks}), \tag{14}$$

and

$$\Gamma_{\text{inv}} = \Gamma(Z \to \text{neutrinos}). \tag{15}$$

Branching ratio:
We define the three (BRs) of the different Z^0-boson decay modes as follows

$$\text{BR}(Z \to \text{hadrons}) = \frac{\Gamma(Z \to \text{hadrons})}{\Gamma_{\text{tot}}}, \tag{16}$$

$$\text{BR}(Z \to l^+l^-) = \frac{\Gamma(Z \to l^+l^-)}{\Gamma_{\text{tot}}}, \tag{17}$$

$$\text{BR}_{\text{inv}}(Z \to \text{neutrinos}) = \frac{\Gamma_{\text{inv}}(Z \to \text{neutrinos})}{\Gamma_{\text{tot}}}. \tag{18}$$

Their experimental values in the absence of the laser field are [1]

$$\begin{aligned}\text{BR}(Z \to \text{hadrons}) &= (69.911 \pm 0.056)\%,\\ \text{BR}(Z \to l^+l^-) &= (10.099 \pm 0.011)\%,\\ \text{BR}_{\text{inv}}(Z \to \text{neutrinos}) &= (20.000 \pm 0.055)\%.\end{aligned} \tag{19}$$

4. Results and discussions

RESULT: It is found that, at high intensities, the Z^0-boson could only decay invisibly into neutrinos, and its decay into any other pair of charged fermions becomes impossible due to the increase in the effective mass that fermions acquire inside the electromagnetic field.

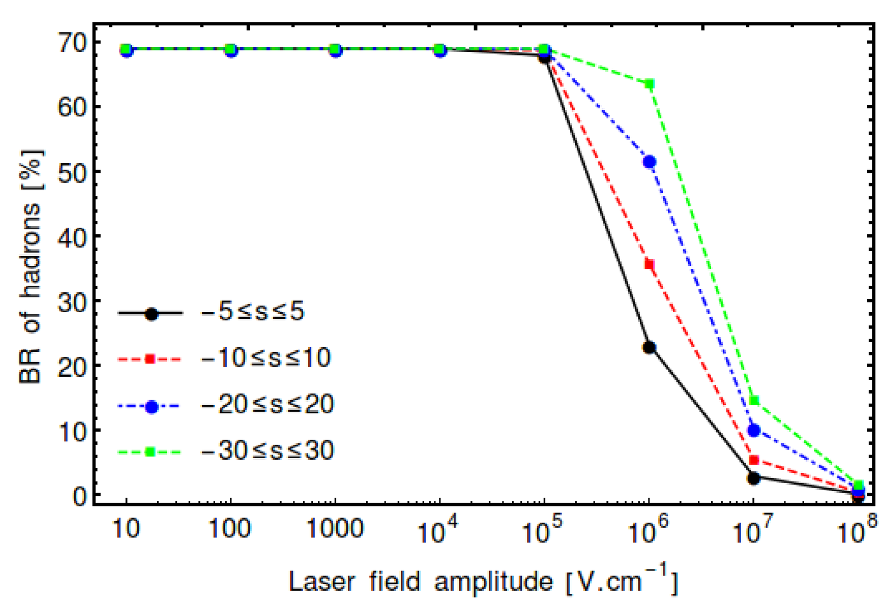

Figure 1: *The behavior of the BR (16) of the hadronic decay mode as a function of the laser field amplitude for different numbers of photons exchanged. The frequency of laser field is $\hbar\omega = 1.17$ eV.*

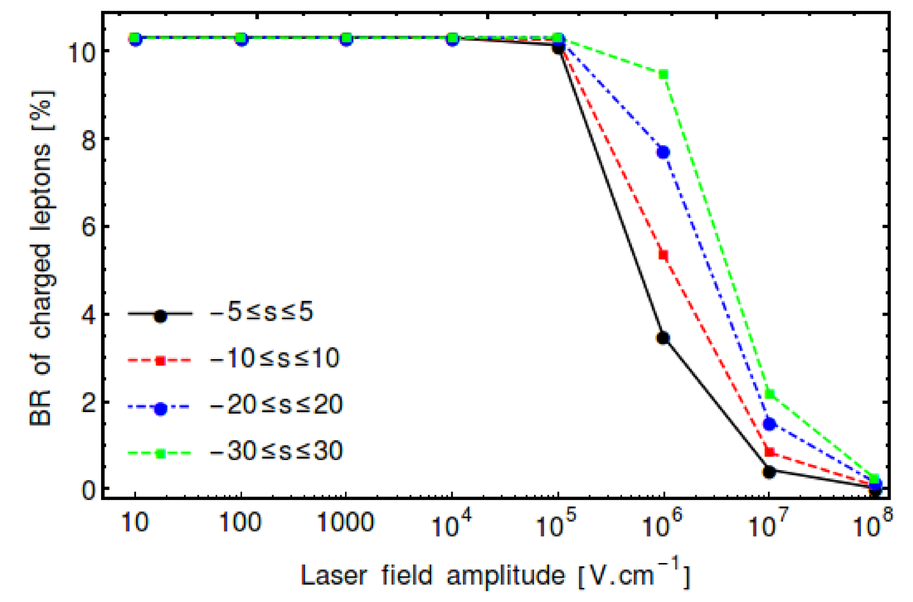

Figure 2: *The behavior of the BR (17) of the charged leptonic decay mode as a function of the laser field amplitude for different numbers of photons exchanged. The frequency of laser field is $\hbar\omega = 1.17$ eV.*

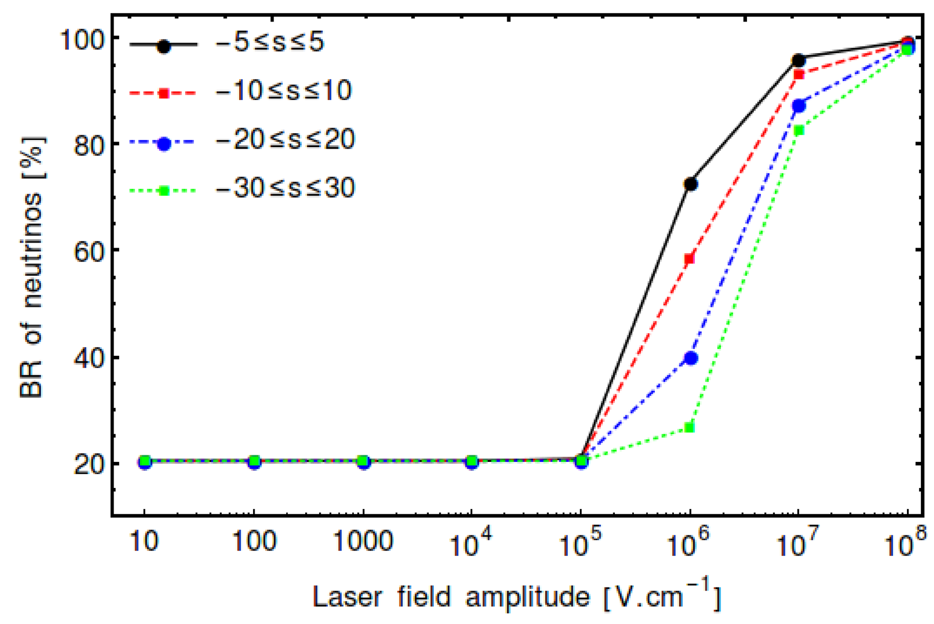

Figure 3: *The behavior of the invisible BR (18) as a function of the laser field amplitude for different numbers of photons exchanged. The frequency of laser field is $\hbar\omega = 1.17$ eV.*

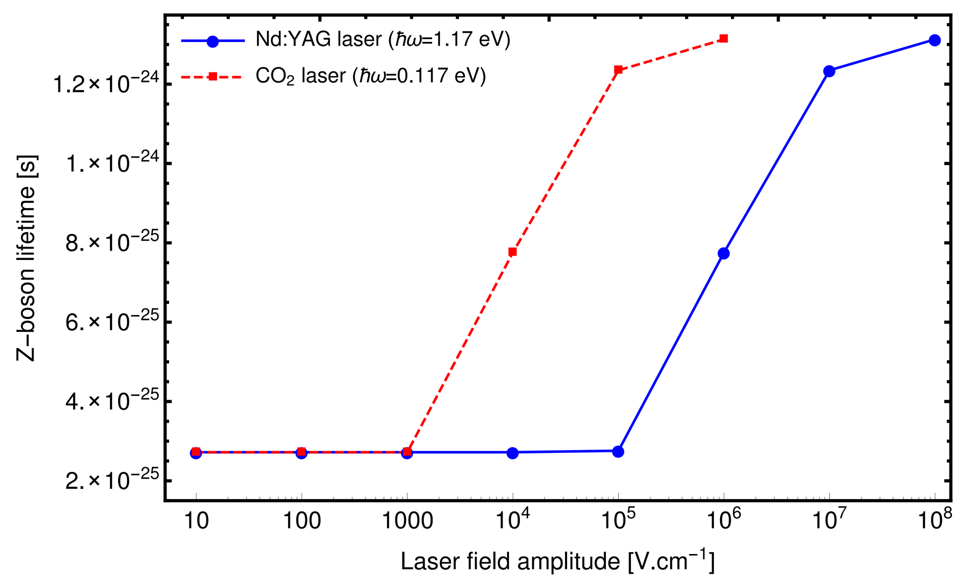

Figure 4: *The variations of laser-modified Z-boson lifetime as a function of the laser field amplitude for a Nd:YAG laser ($\hbar\omega = 1.17$ eV) and a CO_2 laser ($\hbar\omega = 0.117$ eV). The number of exchanged photons is taken as $-10 \le s \le +10$.*

5. Conclusion

Analytical calculations have been performed for the Z^0-boson decay in the presence of a circularly polarized laser field. It has been shown, theoretically, that the branching ratio of the invisible Z^0-boson decay mode can be enhanced by applying suitable laser fields. It is therefore time for experimentalists to take advantage of the powerful laser and consider it as a proposed technology allowing them to control branching ratios. We hope that this work will pave the way for other future works.

References

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