IL NUOVO CIMENTO **45 C** (2022) 10
DOI 10.1393/ncc/i2022-22010-3

Colloquia: SoUP 2021

Laser effect on unstable particle decay

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received 4 November 2021

Summary. — This paper is intended to briefly expose the effect of lasers on the decay processes of some unstable particles and present some of the important results we have obtained.

1. – Introduction

The matter in the universe is composed of microscopic constituents, known as elementary or fundamental particles whose composition is not yet known. Each particle has characteristic properties like: mass, electric charge, spin and lifetime. What interests us a lot among these properties here is the lifetime. This term ”lifetime” is often used when we talk about the decay of particles. There is a universal principle that says: every particle decays into lighter particles, unless prevented from doing so by some conservation law. An important thing is that the nuclear decay should not be confused with particle decay. Here, we are interested in particle decay. Our contribution in this area of research is to apply the electromagnetic field to the decay processes in order to investigate its effect on the calculated experimentally measurable quantities which are the total decay rate, lifetime and branching ratio. Decay processes in the presence of an electromagnetic field can be divided into two main categories: first, laser-assisted processes that also exist in the absence of the field but can be modified by the laser. Second, laser-induced processes that can only occur when a background field is present, providing an additional energy reservoir. Recently, we have conducted a serie of studies to know and understand the effect of the laser field on experimentally measurable quantities during electroweak

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decay processes. We have calculated the pion [1], Z-boson [2] and W^--boson [3, 4] decays in the presence of an electromagnetic field in an attempt to contribute to enriching the debate on this area of research. These investigations have some interest in particle physics as looking for new phenomena in unusual surrounding of intense electromagnetic environment, which can be supplied experimentally by applying a high-intensity laser beam [5]. The rest of the paper is structured as follows. In sect. **2**, we will give brief notes about the employed theoretical approach. In sect. **3**, we will present and discuss some of the results obtained. Finally, the conclusion of this study is given in sect. **4**. In this work, relativistic formalism and natural units $c = \hbar = 1$ are used throughout.

2. – Theoretical approach

Theoretically, we consider the laser field "monochromatic" (*i.e.*, includes only rays of one color and one frequency), well polarized (for example here we consider circular polarization), defined mathematically by the following classical four-potential (in the case of circular polarization):

$$A^\mu(\phi) = a_1^\mu \cos(\phi) + a_2^\mu \sin(\phi), \quad \phi = (k.x). \tag{1}$$

This laser field is characterized by two parameters which are field strength and frequency.

The theoretical calculations is performed within the framework of the standard model of electroweak interactions by using the method of exact solutions for charged particle states in the presence of a circularly polarized electromagnetic wave field [6, 7]. This approach is well known in particle physics as the Furry picture [8] of non-perturbative interactions with the external electromagnetic field.

When we talk about decay, we have three important experimentally measurable quantities which must be calculated.

The first is the decay rate Γ [eV] which measures the probability of a decay. It can be written generally as follows:

$$\Gamma(1 \to 2 + 3 + ... + n) = \frac{1}{2m_1} \int \underbrace{\mathrm{d}\Phi}_{\text{Phase space of final states}} \times \overbrace{|\mathcal{M}_{fi}|^2}^{\text{Matrix element}}, \tag{2}$$

where m_1 is the mass of the decaying particle.

The second quantity that comes immediately after is the lifetime τ [sec] which is defined simply as the inverse of the decay rate

$$\tau = \frac{1}{\Gamma}. \tag{3}$$

The third and last quantity is the branching ratio BR[%] which is calculated if there are several decay modes

$$\mathrm{BR}_i = \frac{\Gamma_i}{\underbrace{\sum_i \Gamma_i}_{\Gamma_{tot}}}. \tag{4}$$

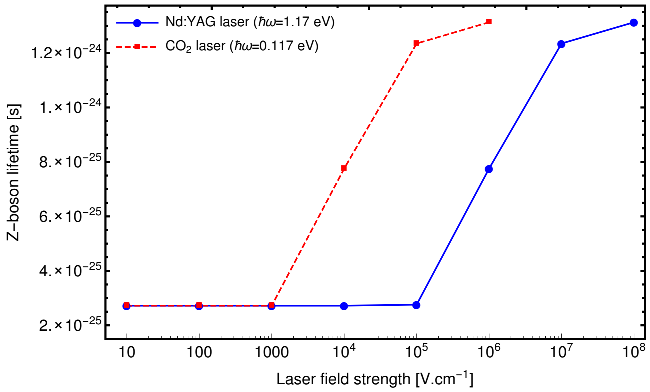

Fig. 1. – The variations of laser-modified Z-boson lifetime as a function of the laser field strength for a Nd:YAG laser ($\hbar\omega = 1.17$ eV) and a CO$_2$ laser ($\hbar\omega = 0.117$ eV).

The reader can refer to our previous works [1-4] for more details on how to calculate each of these quantities above in the presence of a laser field. Because of its cumbersome and heavy expressions, we did not include it here.

3. – Numerical results and discussion

Here, we present one of the most important results we obtained in our work on the decays of some unstable particles. We found that the decay rate decreases with the laser field strength, which leads to a longer lifetime of the decaying particle. For example, we illustrate, in fig. 1, the variations of Z-boson lifetime as a function of laser field strength for two different frequencies (Nd:YAG laser: $\hbar\omega = 1.17$ eV and CO$_2$ laser: $\hbar\omega = 0.117$ eV). We note that the Z-boson lifetime expands and lengthens, and changes nonlinearly with increasing laser field strength. For the effect of the laser frequency, it appears that at high frequencies, the effect of the laser on the lifetime diminishes with a similar behavior to the case of the pion [1] and muon [9] lifetimes. Figure 2 shows the same thing for the laser-assisted W-boson lifetime [4].

The debate about the laser effect on the total decay rate and lifetime began for the first time in the 1970s [10, 11] and was revived at the beginning of the 21st century [12-14] to the present day. The effect of the laser field on the lifetime of the muon was studied by Liu *et al.* by embedding the decaying muon in a strong "linearly" polarized electromagnetic field [9]. It was found that the muon lifetime decreased and became shorter (specifically from its normal value 2.2×10^{-6} sec to a value of less than 5×10^{-7} sec). In our calculation, we have adopted the same theoretical approach as Liu *et al.*. The difference in behavior that we observed is due to the nature of the field polarization applied to the decay process. Those who have worked with linear polarization have found that the lifetime decreases, and we who worked with circular polarization found it increasing. Thus, it cannot be denied that the polarization of the laser field plays a major role in the contrast of the results. However, this difference in lifetime behavior in both cases of polarization can be reasonably accepted with reference to the quantum Zeno effect [15, 16] or the anti-Zeno effect [17, 18], depending on whether the decay is decelerated or accelerated. Concerning the result we obtained, which is the increase of the lifetime, we interpreted it as a kind of the quantum Zeno effect. It means that the application of repeated measures

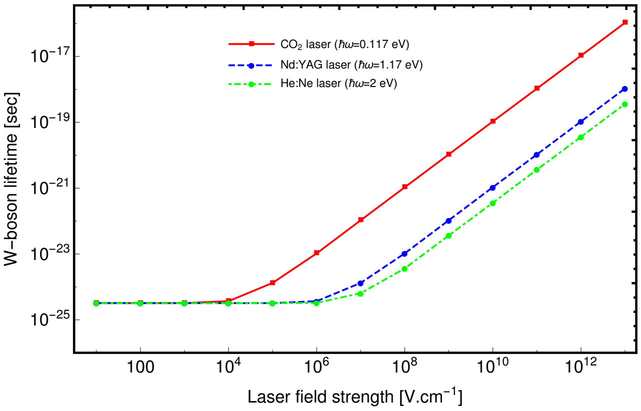

Fig. 2. – The variations of laser-assisted W-boson lifetime as a function of the laser field strength for a CO_2 laser ($\hbar\omega = 0.117$ eV), a Nd:YAG laser ($\hbar\omega = 1.17$ eV) and a He:Ne laser ($\hbar\omega = 2$ eV).

blocks the evolution of the system in time and keeps it in the fundamental level. In our case, the external electromagnetic field plays the role of a measurement device. In other words, an unstable particle which is continuously illuminated by an intense laser field of appropriate frequency to see whether it decays will never be found to decay.

Now, let us see how an electromagnetic field can influence the branching ratios (BR) or contribute to their enhancement or suppression.

In the Z-boson decay, we have three decay modes whose experimental values in the absence of laser are as follows [19]:

$$\begin{aligned} \mathrm{BR}(Z \to \text{hadrons}) &= (69.911 \pm 0.056)\%, \\ \mathrm{BR}(Z \to l^+l^-) &= (10.099 \pm 0.011)\%, \\ \mathrm{BR}_{\mathrm{inv}}(Z \to \text{neutrinos}) &= (20.000 \pm 0.055)\%. \end{aligned} \tag{5}$$

It has been shown theoretically that the branching ratio of the invisible Z-boson decay mode $\mathrm{BR}_{\mathrm{inv}}(Z \to \text{neutrinos})$ can be considerably enhanced by applying suitable laser fields [2]. The enhancement of the invisible decay mode is offset, on the other hand, by the suppression of hadronic and charged leptonic decay modes.

In W^--boson decay, we have two decay modes whose experimental values in the absence of laser are as follows [19]:

$$\begin{aligned} \mathrm{BR}(W^- \to \text{hadrons}) &= (67.41 \pm 0.27)\%, \\ \mathrm{BR}(W^- \to \text{leptons}) &= (32.58 \pm 0.16)\%. \end{aligned} \tag{6}$$

We have found that the laser has increased the branching ratio of hadrons from its normal value of 67% to about 85% resulting in a decrease in that of leptons by the same extent [4].

This significant change in BRs when the laser field is present is a very important and unusual result.

To the best of our knowledge, there are no experimental results currently available in the literature to compare with.

4. – Conclusion

As a conclusion, we have seen, through the study of some laser-assisted decay processes, how an electromagnetic field can change the behavior and properties of elementary particles. However, these results presented here are purely theoretical and need an experimental study to confirm them in order to meet the needs of the scientific community in the future in parallel with the remarkable development of laser technology.

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