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## Laser-assisted decay of $W^-$ and $Z^0$ vector bosons

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- **Strong field physics** is the general research area of the laser-matter interaction.
- New Physics can be developed from the interaction of intense laser fields with atoms, molecules and particles.
- How can the **behavior** and **properties** of particles change in the presence of an **electromagnetic** (EM) field ?
- What is the effect of the EM field (provided by a laser) on the evolution of a **quantum system** in time ?
- **Example** of a quantum system :
  - **Decay process** of an unstable particle ( $A \rightarrow B + C + \dots$ )
- The recent development of laser technology has contributed to the advancement of **theoretical** studies in this field, despite the delay in **experimental** studies.
- **N.B.** : **Natural units**  $c = \hbar = 1$  are used throughout.

- Decay processes in the presence of an EM field :
  - 1 Laser-**assisted** processes
  - 2 Laser-**induced** processes
- The **monochromatic circularly** polarized laser field is described by the following 4-potential :

$$A^\mu(\phi) = a_1^\mu \cos(\phi) + a_2^\mu \sin(\phi) \quad (1)$$

- $\phi = (k \cdot x)$  : Phase
- $k = (\omega, \mathbf{k})$  : wave 4-vector ( $k^2 = 0$ )
- $a_1^\mu = |\mathbf{a}|(0, 1, 0, 0)$  and  $a_2^\mu = |\mathbf{a}|(0, 0, 1, 0)$  : Polarization 4-vectors

$$(a_1 \cdot a_2) = 0; \quad a_1^2 = a_2^2 = a^2 = -|\mathbf{a}|^2 = -(\mathcal{E}_0/\omega)^2, \quad (2)$$

where  $\omega$  is the laser frequency and  $\mathcal{E}_0$  is the laser field strength.

- Lorentz gauge condition :  $k_\mu A^\mu = 0, \implies (k \cdot a_1) = (k \cdot a_2) = 0.$
- Characteristic parameters of the EM field :
  - Electric field strength  $\mathcal{E}_0$  : [V/cm] or [eV<sup>2</sup>] in N.U
  - Frequency  $\hbar\omega$  [eV]

# Measurable quantities to be calculated

- ① **Decay width  $\Gamma$  [eV]** : The decay width of a particle of mass  $m$  to  $n$  bodies, expressed in its rest frame, is given by :

$$\Gamma = \frac{(2\pi)^4 \delta^4(P - \sum_{i=1}^n P_i)}{2m} \int \underbrace{d\Phi_n(P_1, \dots, P_n)}_{\text{Phase space}} \times \overbrace{|\mathcal{M}_{fi}|^2}^{\text{Matrix element}}, \quad (3)$$

where

$$d\Phi_n(P_1, \dots, P_n) = \prod_{i=1}^n \frac{d^3 p_i}{(2\pi)^3 2E_i},$$

with  $P = (m, 0)$  and  $P_i = (E_i, \vec{p}_i)$  for  $i = 1, \dots, n$

- ② **Lifetime  $\tau$  [sec]** :

$$\tau = \Gamma^{-1} \quad (4)$$

- ③ **Branching ratio (BR) [%]** : If we have several decay modes  $\Gamma_i$ .

$$\text{BR}_i = \frac{\Gamma_i}{\underbrace{\sum_i \Gamma_i}_{\Gamma_{\text{tot}}}} \quad (5)$$

- Dirac equation in the **absence of EM field** :

$$\boxed{(\gamma^\mu \hat{p}_\mu - m)\psi(x) = 0.} \quad (6)$$

- Dirac equation in the **presence of EM field** :

$$\text{1}^{\text{st}} \text{ order : } \boxed{[\gamma^\mu (\hat{p}_\mu - eA_\mu) - m]\psi(x) = 0} \quad (7)$$

$$\text{2}^{\text{nd}} \text{ order : } \boxed{[(\hat{p} - eA)^2 - m^2 - \frac{ie}{2} F_{\mu\nu} \sigma^{\mu\nu}]\psi(x) = 0} \quad (8)$$

where  $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$  and  $\sigma^{\mu\nu} = \frac{1}{2}[\gamma^\mu, \gamma^\nu]$ .

- Dirac-Volkov** wave functions :

$$\psi(x) = \left[ 1 + \frac{e\mathbf{k}\cdot\mathbf{A}}{2(k\cdot p)} \right] \frac{u(p, s)}{\sqrt{2QV}} \times \exp \left[ -i(p\cdot x) - i \int_0^{k\cdot x} \left( \frac{e(p\cdot A)}{(k\cdot p)} - \frac{e^2 A^2}{2(k\cdot p)} \right) d\phi \right]. \quad (9)$$

- For a **circularly polarized** EM field :

$$\psi(x) = \left[ 1 + \frac{e\mathbf{k}\cdot\mathbf{A}}{2(k\cdot p)} \right] \frac{u(p, s)}{\sqrt{2QV}} \times \exp \left[ -i(q\cdot x) - \frac{e(a_1\cdot p)}{(k\cdot p)} \sin(\phi) + \frac{e(a_2\cdot p)}{(k\cdot p)} \cos(\phi) \right], \quad (10)$$

where

$$q = p - \frac{e^2 A^2}{2(k\cdot p)} k$$

- Matrix element  $S_{fi}$

$$S_{fi}(Z \rightarrow f\bar{f}) = \frac{-ig}{4\cos(\theta_W)} \int d^4x \bar{\psi}_f(x) \gamma^\mu (g_V - g_A \gamma_5) \psi_{\bar{f}}(x) Z_\mu(x). \quad (11)$$

$$S_{fi}(W^- \rightarrow q\bar{q}') = \frac{ig}{2\sqrt{2}} \int d^4x \bar{\psi}_q(x) \gamma^\mu (1 - \gamma_5) \psi_{\bar{q}'}(x) W_\mu^-(x), \quad (12)$$

- Decay width in the presence of an EM field

$$\Gamma(W^- \rightarrow q\bar{q}') = \sum_{n=-\infty}^{+\infty} \Gamma^n(W^- \rightarrow q\bar{q}'), \quad (13)$$

where  $n$  is the number of exchanged photons, and

$$\Gamma^n(W^- \rightarrow q\bar{q}') = \frac{g^2 |V_{qq'}|^2 N_c}{64 p_0} \overbrace{\int \frac{d^3 q_1}{(2\pi)^3 Q_1} \int \frac{d^3 q_2}{(2\pi)^3 Q_2}}^{\text{Phase space}} \times (2\pi)^4 \delta^4(q_1 + q_2 - q - nk) |\overline{\mathcal{M}}_{fi}^n|^2, \quad (14)$$

where  $N_c = 3$  is the number of color, and

$$|\overline{\mathcal{M}}_{fi}^n|^2 = \frac{1}{3} \left( -g^{\mu\nu} + \frac{p^\mu p^\nu}{M_W^2} \right) \text{Tr} \left[ (\not{p}_1 + m_q) \Lambda_\nu^n (\not{p}_2 - m_{q'}) \bar{\Lambda}_\mu^n \right], \quad (15)$$

- The trace calculation is performed with the help of FeynCalc.

- **Lifetime**  $\tau_W$  :

$$\tau_W = 1/\Gamma_W^{\text{tot}}, \quad (16)$$

where

$$\Gamma_W^{\text{tot}} = \Gamma(W^- \rightarrow \text{leptons}) + \Gamma(W^- \rightarrow \text{hadrons}), \quad (17)$$

with

$$\Gamma(W^- \rightarrow \text{leptons}) = \Gamma(W^- \rightarrow e^- \bar{\nu}_e) + \Gamma(W^- \rightarrow \mu^- \bar{\nu}_\mu) + \Gamma(W^- \rightarrow \tau^- \bar{\nu}_\tau),$$

and

$$\Gamma(W^- \rightarrow \text{hadrons}) = \Gamma(W^- \rightarrow \bar{u}d) + \Gamma(W^- \rightarrow \bar{c}s).$$

- **Branching ratios** :

$$\text{BR}(W^- \rightarrow \text{hadrons}) = \Gamma(W^- \rightarrow \text{hadrons})/\Gamma_W^{\text{tot}}, \quad (18)$$

$$\text{BR}(W^- \rightarrow \text{leptons}) = \Gamma(W^- \rightarrow \text{leptons})/\Gamma_W^{\text{tot}}.$$

- **Experimental values** in the absence of the laser field : [PDG2020]

$$\text{BR}(W^- \rightarrow \text{hadrons}) = (67.41 \pm 0.27)\%, \quad (19)$$

$$\text{BR}(W^- \rightarrow \text{leptons}) = (32.58 \pm 0.16)\%.$$



- **Lifetime**  $\tau_Z$  :

$$\tau_Z = 1/\Gamma_Z^{\text{tot}}, \quad (20)$$

where

$$\Gamma_Z^{\text{tot}} = \Gamma(Z \rightarrow \text{hadrons}) + \Gamma(Z \rightarrow \ell^+ \ell^-) + \Gamma_{\text{inv}}, \quad (21)$$

with

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

and

$$\Gamma_{\text{inv}} = \Gamma(Z \rightarrow \text{neutrinos}).$$

- **Branching ratios** :

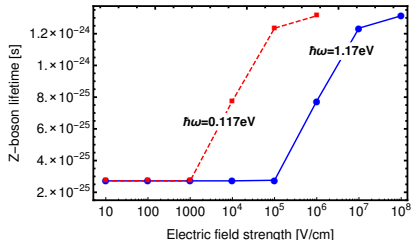
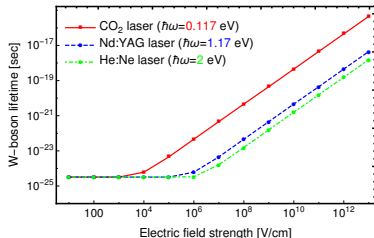
$$\begin{aligned} \text{BR}(Z \rightarrow \text{hadrons}) &= \Gamma(Z \rightarrow \text{hadrons})/\Gamma_Z^{\text{tot}}, \\ \text{BR}(Z \rightarrow \ell^+ \ell^-) &= \Gamma(Z \rightarrow \ell^+ \ell^-)/\Gamma_Z^{\text{tot}}, \end{aligned} \quad (22)$$

$$\text{BR}_{\text{inv}}(Z \rightarrow \text{neutrinos}) = \Gamma_{\text{inv}}(Z \rightarrow \text{neutrinos})/\Gamma_Z^{\text{tot}}.$$

- **Experimental values** in the absence of the laser field : [PDG2020]

$$\begin{aligned} \text{BR}(Z \rightarrow \text{hadrons}) &= (69.911 \pm 0.056)\%, \\ \text{BR}(Z \rightarrow \ell^+ \ell^-) &= (10.099 \pm 0.011)\%, \\ \text{BR}_{\text{inv}}(Z \rightarrow \text{neutrinos}) &= (20.000 \pm 0.055)\%. \end{aligned} \quad (23)$$

- We have performed **3** theoretical studies for the decay of **3** particles <sup>1</sup> :
  - ①  $\pi^- \rightarrow \ell^- + \bar{\nu}_\ell$ , ( $\ell = e, \mu$ ) [Phys. Rev. D **102**, 073006 (2020)]
  - ②  $Z^0 \rightarrow f + \bar{f}$ , ( $f = \ell, u, c, d, s, b$ ) [Laser Phys. Lett. **18**, 016002 (2021)]
  - ③ Decay of boson  $W^-$ 
    - Leptonic channel :  $W^- \rightarrow \ell^- \bar{\nu}_\ell$  [arXiv:2101.00224]
    - Hadronic channel :  $W^- \rightarrow q\bar{q}'$  [Chin. J. Phys. (2021)]



- **Reduction of the width  $\Gamma$**   $\implies$  **Longer lifetime**
- **What does it mean ?** & **How to interpret it physically ?**
- $\implies$  **Quantum Zeno effect**

<sup>1</sup>See also for laser-assisted kaon decay : Baouahi et al., Laser Phys. Lett. **18**, 106001 (2021)

# Numerical results : Branching ratios

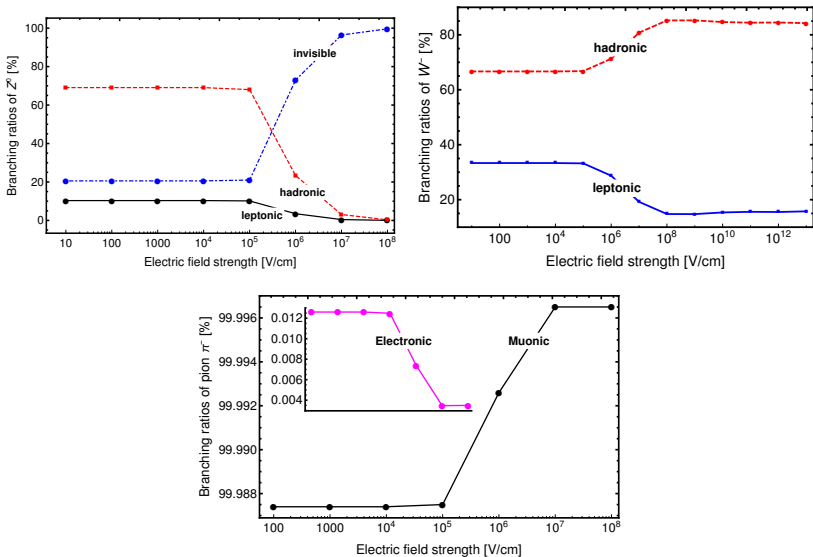


Figure: Branching ratios for 3 particles as a function of the electric field strength  $\mathcal{E}_0$ . The laser frequency is  $\hbar\omega = 1.17$  eV.

# Conclusion

- We have studied **theoretically** the **decay processes** in the presence of a **circularly** polarized EM field.
- Influence of the laser field on measurable quantities :
  - **Decrease** in **total decay width**
  - **Extension** of the **lifetime**
  - **Modification** of the **branching ratios**

## Limitations : Experimental !!

- These results require experimental investigation 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.
- It was time to take advantage of the powerful laser and consider it a promising technology.

## Perspectives :

- Apply the same concept to other decay processes.
- Check other laser field polarization : linear and elliptic.

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**Thank you for your attention**

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