Overview on Laser-assisted Decay Processes

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Plan

Introduction

- 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 ($A \to B + C + \ldots$)
- 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.

Laser configuration

- 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 :

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

- $\phi = (k.x)$: 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

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

  where ω is the laser frequency and $\mathcal{E}_0$ is the laser field strength.
- Lorentz gauge condition : $k_{\mu}A^{\mu} = 0, \Longrightarrow (k.a_1) = (k.a_2) = 0.$
- Characteristic parameters of the EM field :
  - Electric field strength $\mathcal{E}_0$: [V/cm] or [eV^2] in N.U
  - Frequency $\hbar\omega$ [eV]

Measurable quantities to be calculated

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

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

where

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

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

2. **Lifetime τ [sec]** :

$$\tau = \Gamma^{-1} \tag{4}$$

3. **Branching ratio (BR) [%]** : If we have several decay modes Γ_i.

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

Dirac equation and wave function

- Dirac equation in the absence of EM field :

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

- Dirac equation in the presence of EM field :

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

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

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 :

$$\psi(x) = \left[1 + \frac{e\not{k}\not{A}}{2(k.p)}\right]\frac{u(p,s)}{\sqrt{2QV}} \times \exp\left[-i(p.x) - i\int_0^{k.x}\left(\frac{e(p.A)}{(k.p)} - \frac{e^2A^2}{2(k.p)}\right)d\phi\right]. \tag{9}$$

- For a circularly polarized EM field :

$$\psi(x) = \left[1 + \frac{e\not{k}\not{A}}{2(k.p)}\right]\frac{u(p,s)}{\sqrt{2QV}} \times \exp\left[-i(q.x) - \frac{e(a_1.p)}{(k.p)}\sin(\phi) + \frac{e(a_2.p)}{(k.p)}\cos(\phi)\right], \tag{10}$$

where

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

- Matrix element S_{fi}

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

$$S_{fi}(W^-\to q\bar{q}')=\frac{ig\;V_{qq'}}{2\sqrt{2}}\int d^4x\overline{\psi}_q(x)\gamma^\mu(1-\gamma^5)\psi_{\bar{q}'}(x)W^-_\mu(x), \quad (12)$$

- Decay width in the presence of an EM field

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

where n is the number of exchanged photons, and

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

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

$$|\overline{\mathcal{M}^n_{fi}}|^2=\frac{1}{3}\Big(-g^{\mu\nu}+\frac{p^\mu p^\nu}{M_W^2}\Big)\mathrm{Tr}\Big[(\not{p}_1+m_q)\Lambda^n_\nu(\not{p}_2-m_{q'})\overline{\Lambda}^n_\mu\Big], \quad (15)$$

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

- **Lifetime** τ_W :

$$\tau_W = 1/\Gamma_W^{\text{tot}}, \tag{16}$$

where

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

with

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

and

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

- **Branching ratios** :

$$\begin{aligned} \text{BR}(W^- \to \text{hadrons}) &= \Gamma(W^- \to \text{hadrons})/\Gamma_W^{\text{tot}}, \\ \text{BR}(W^- \to \text{leptons}) &= \Gamma(W^- \to \text{leptons})/\Gamma_W^{\text{tot}}. \end{aligned} \tag{18}$$

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

$$\begin{aligned} \text{BR}(W^- \to \text{hadrons}) &= (67.41 \pm 0.27)\%, \\ \text{BR}(W^- \to \text{leptons}) &= (32.58 \pm 0.16)\%. \end{aligned} \tag{19}$$

- **Lifetime τ_Z :**

$$\tau_Z = 1/\Gamma_Z^{\text{tot}}, \tag{20}$$

where

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

with

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

and

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

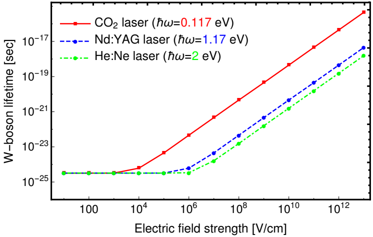
- **Branching ratios** :

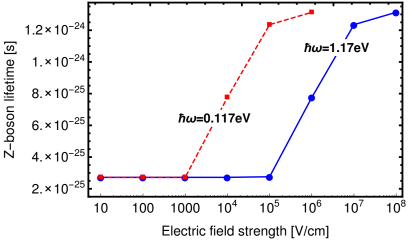
$$\begin{aligned} \text{BR}(Z \to \text{hadrons}) =& \Gamma(Z \to \text{hadrons})/\Gamma_Z^{\text{tot}}, \\ \text{BR}(Z \to \ell^+\ell^-) =& \Gamma(Z \to \ell^+\ell^-)/\Gamma_Z^{\text{tot}}, \\ \text{BR}_{\text{inv}}(Z \to \text{neutrinos}) =& \Gamma_{\text{inv}}(Z \to \text{neutrinos})/\Gamma_Z^{\text{tot}}. \end{aligned} \tag{22}$$

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

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

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





- **Reduction of the width Γ** $\Longrightarrow$ **Longer lifetime**
- What does it mean ? & How to interpret it physically ?

$\Longrightarrow$ **Quantum Zeno effect**

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

Numerical results : Branching ratios

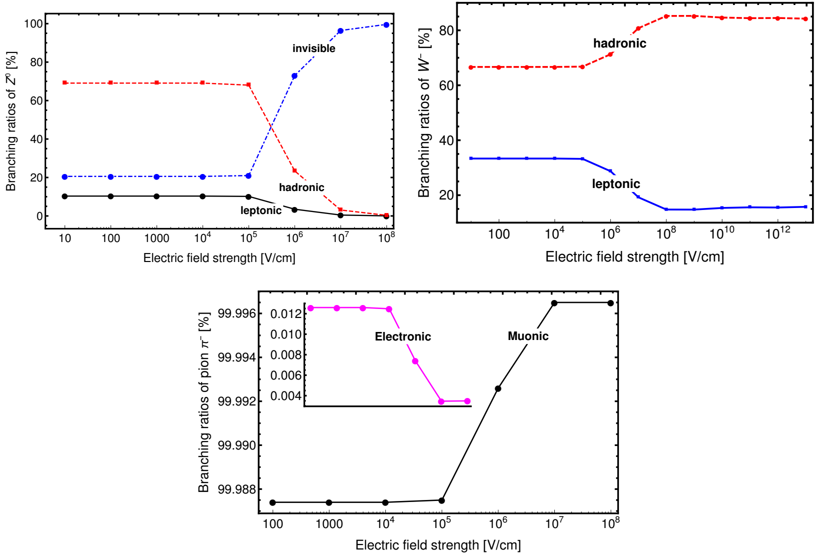


Figure: Branching ratios for 3 particles as a function of the electric field strength $\mathcal{E}_0$. The laser frequency is $\hbar\omega = 1.17$ eV.

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.

Thank you for your attention