Charged Particle Emissions in High-Frequency Alternative Electric Fields

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Reference

Dong Bai, **Daming Deng**, and **Zhongzhou Ren**,
Charged Particle Emissions in High-Frequency Alternative Electric Fields, arXiv:1805.02379 (to appear on Nuclear Physics A)

Outline

1. Introduction
2. Formalism
3. Results
4. Summary

Charged Particle Emissions + $\cdots$

Charged particle emissions play an important role in nuclear physics.

- α **decay**: discovered in 1899; first application of Quantum Mechanics in nuclear physics;
  Phenomenological approach: density dependent cluster model, coupled channels method, etc;
  Microscopic approach: cluster-configuration shell model; quartetting wave function approach, etc.
- **Proton emission**: discovered in the 1960s.
- **Cluster radioactivity**: discovered in the 1980s.

α decay, proton emission, and cluster radioactivity could be described systematically using unified decay rules. (see, e.g., Ni, Ren, Dong, and Xu, 2008)

$\cdots$ + High-Frequency Alternative Electric Fields

Recently, a few works have been devoted to α decays in strong electromagnetic fields, partially inspired by the upcoming powerful laser facilities in the near future.

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3. S. Misicu and M. Rizea, Open Phys. **14**, 81 (2016).
4. I. V. Kopytin and A. S. Kornev, Phys. At. Nucl. **77**, 53 (2014).
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6. H. M. Castañeda Cortes, etc, Phys. Lett. B **723**, 401 (2013).

In our work, we study charged particle emissions in high-frequency alternative electric fields. By "high frequency", we mean the frequencies of alternative electric fields (photon energies $\hbar\omega$) are much higher than the Q values of charged particle emissions, i.e.

- $\hbar\omega \gg Q_\alpha \sim 10$ MeV for α decay,
- $\hbar\omega \gg Q_p \sim 1$ MeV for proton emission,
- $\hbar\omega \gg Q_c \sim 50$ MeV for cluster radioactivity.

High-frequency alternative electric fields correspond approximately to high-frequency laser fields in the **dipole approximation**. Our study could be viewed as a benchmark for future theoretical studies of charged particle emissions in realistic laser fields.

Formalism

We start with the time-dependent Schrödinger equation

$$i\hbar\frac{\partial\Psi(\mathbf{r},t)}{\partial t}=\left[\frac{1}{2\mu}\left(\mathbf{P}-Q_{\text{eff}}\,\mathbf{A}(t)\right)^2+V(\mathbf{r})\right]\Psi(\mathbf{r},t), \qquad (1)$$

with $\mathbf{A}(t)=\mathbf{A}_0\sin\omega t$ giving rise to the alternative electric field, $\mu=M_cM_d/(M_c+M_d)$ being the reduced mass, $Q_{\text{eff}}=eZ_{\text{eff}}=e(Z_cA_d-Z_dA_c)/(A_c+A_d)$ being the effective charge, and $V(\mathbf{r})$ being the Coulomb potential.

Hennenberger Transformation

By using the **Hennenberger transformation**

$$\Omega_h(t) = \exp\left[\frac{i}{\hbar}\int_{-\infty}^{t}\left(-\frac{Q_{\mathrm{eff}}}{\mu}\mathbf{A}\cdot\mathbf{P} + \frac{Q_{\mathrm{eff}}^2}{2\mu}\mathbf{A}^2\right)\mathrm{d}\tau\right], \qquad (2)$$

we could obtain a new equation for the new wave function $\Phi = \Omega_h(t)\Psi$

$$i\hbar\frac{\partial\Phi(\mathbf{r},t)}{\partial t} = \left[\frac{1}{2\mu}\mathbf{P}^2 + V(\mathbf{r}-\mathbf{S}(t))\right]\Phi(\mathbf{r},t),$$

$$\mathbf{S}(t) = \frac{Q_{\mathrm{eff}}}{\mu}\int_{-\infty}^{t}\mathbf{A}(\tau)\mathrm{d}\tau. \qquad (3)$$

$V(\mathbf{r}-\mathbf{S}(t))$ is known as the Hennenberger potential. $\mathbf{S}(t)$ is known as the quiver displacement for the charged particle moving in alternative electric fields.

High-Frequency Limit

- We can expand the Hennenberger potential $V(\mathbf{r}-\mathbf{S}(t))$ in terms of Fourier series. It is well-established in theoretical laser-atom physics that, it is the static component that dominates over the rest Fourier components in the high-frequency limit.
- Explicitly, the static component is given by

$$V_0(\mathbf{r}) = \frac{1}{T}\int_0^T V(\mathbf{r}-\mathbf{S}(t))\mathrm{d}t. \tag{4}$$

In the following, we work with only the static component $V_0(\mathbf{r})$.

Differential Penetrability

The differential and total penetrabilities are calculated by using the WKB approximation. The differential penetrability is given by

$$P(\Theta, \theta_\lambda) = \exp\left(-2\int_{R_t(\theta_\lambda)}^{R(\Theta)} \sqrt{\frac{2\mu}{\hbar^2}[U(r) - Q]}\mathrm{d}r\right), \qquad (5)$$

$$U(r) = \frac{\hbar^2}{2\mu r^2}L(L+1) + V_0(r, \Theta, \theta_\lambda, S_0). \qquad (6)$$

Θ is the angle between $\mathbf{r}$ and $\mathbf{S}(x)$. Here, we consider the possibility of the cluster or daughter nucleus to be axially deformed. θ_λ measures the angle between $\mathbf{r}$ and the symmetric axis of the deformed nucleus.

Total Penetrability

The total penetrability could be estimated by

$$P = \frac{1}{4} \int_0^{\pi} \mathrm{d}\theta_\lambda \sin\theta_\lambda \int_0^{\pi} \mathrm{d}\Theta \sin\Theta \, P(\Theta, \theta_\lambda). \tag{7}$$

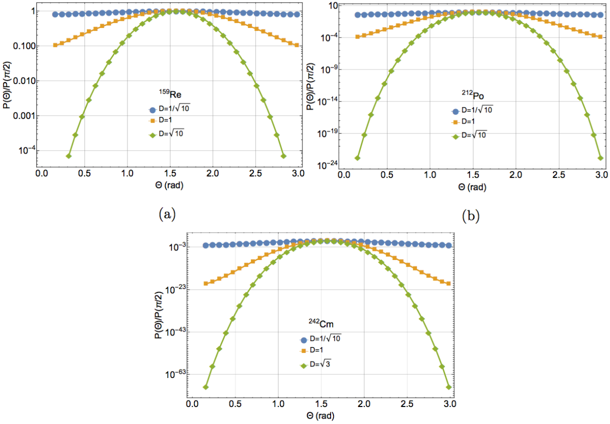
Results

- We present numerical results concerning the impacts of high-frequency alternative electric fields on **proton emission**, α **decay**, and **cluster radioactivity**.
- Adimensional parameter D:

$$D = S_0/R_{d0} \propto \frac{Z_{\text{eff}}}{\mu R_{d0}} \frac{\sqrt{I}}{\omega^2}, \tag{8}$$

with S_0 the quiver amplitude, R_{d0} the average radius of the daughter nucleus, Z_{eff} the effective charge, μ the reduced mass, I the intensity of the electric field, and ω the frequency.

Anisotropic Effects

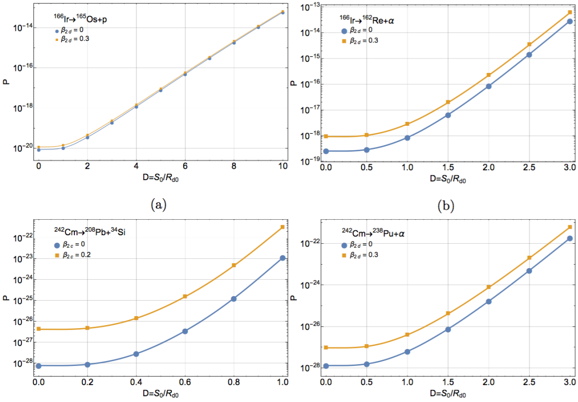


(a) (b)

(c)

FIG. 1: Differential barrier penetrability normalized to its maximal value at $\Theta = \pi/2$ with different values of D for (a) the proton emitter ^{159}Re with the orbital angular momentum $L = 5$, (b) the α emitter ^{212}Po, and (c) the ^{34}Si emitter ^{242}Cm.

Total penetrability versus *D*

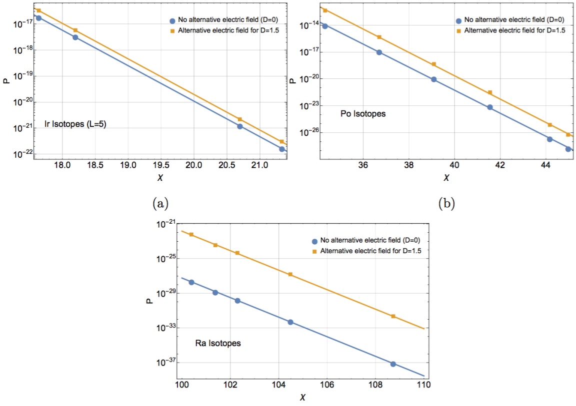


(a) (b)

(c) (d)

FIG. 2: Total penetrability versus $D = S_0/R_{d0}$ with different assumptions on their deformations for (a) the proton-emission channel of ^{166}Ir with the orbital angular momentum given by $L = 2$, (b) the α-decay channel of ^{166}Ir, (c) the ^{34}Si-radioactivity channel of ^{242}Cm, and (d) the α-decay channel of ^{242}Cm.

Shifted Geiger-Nuttall Law



(a) (b)

(c)

FIG. 3: Total penetrability versus the Coulomb-Sommerfeld parameter χ for (a) Ir isotopes as proton emitters, (b) Po isotopes as α emitters, and (c) Ra isotope as ^{14}C emitters in the absence of alternative electric fields ($D = 0$) and in the presence of alternative electric fields with $D = 1.5$.

Competition Between Decay Modes

We also study the competitions between different decay modes.

- α **decay** *vs* **proton emission**:
  For ^{166}Ir, the branching ratios of the α-decay and proton-emission channels being 93% and 7%, respectively. When switching on strong high-frequency electric fields, the D values for these two decay channels satisfy approximately $D_p/D_\alpha \sim 15$. Take $D_\alpha \approx 0.5$. When put in such strong high-frequency alternative electric fields, the total penetrability of the α-decay channel of ^{166}Ir remains roughly to be at the same orders of magnitude, while for the proton-emission channel we have $D_p \approx 7.5$, corresponding to the total penetrability being enhanced by about five orders of magnitude. The results here indicate that, when ^{166}Ir is placed in strong high-frequency alternative electric fields, its dominant decay mode may be changed from α decay to proton emission.

- α **decay** *vs* **cluster radioactivity**:
  For ^{242}Cm, the D values for the ^{34}Si-radioactivity and α-decay channel satisfy $D_c/D_\alpha \sim 0.17$. Take $D_\alpha \approx 3$. The total penetrability of the α-decay channel is increased by about five orders of magnitude. Correspondingly, $D_c \approx 0.5$, and the total penetrability of the ^{34}Si-radioactivity channel is enhanced by a factor less than one order of magnitude. Therefore, the ^{34}Si-radioactivity channel becomes even more suppressed in the presence of strong high-frequency alternative electric fields.

Summary

In this work, we study charged particle emissions in high-frequency alternative electric fields, including

- anisotropic effects induced by high-frequency alternative electric fields,
- the relation between total penetrabilities and the D values,
- shifted Geiger-Nuttall laws,
- competition between different decay modes.

As high-frequency alternative electric fields correspond to high-frequency laser fields in the dipole approximation, our study could be viewed as a benchmark for future theoretical studies.

Thanks!