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Charged particle emissions in high-frequency alternative electric fields

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Abstract

Proton emission, α decay, and cluster radioactivity play an important role in nuclear physics. We show that high-frequency alternative electric fields could deform Coulomb barriers that trap the charged particle, and raise the possibility of speeding up charged particle emissions. They could also cause anisotropic effects in charged particle emissions, and introduce additional terms in the Geiger–Nuttall laws. Our study may further suggest that, for proton emitters like ^{166}Ir, when the electric field is strong, the dominant decay mode could be changed from α decay to proton emission. 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 of charged particle emissions in realistic laser fields.

Keywords: Alpha decay; Proton emission; Cluster radioactivity; Geiger–Nuttall law

Recent years witness great progress in studying proton emission, α decay, and cluster radioactivity [1–4]. Historically, modern theoretical nuclear physics originates from the explanation of α decay by Gamow, Gurney and Condon in 1928 [5,6]. Interests in alpha decay persist after that, and lots of interesting results have been obtained [7–36]. Later discoveries of proton emission in the 1960s [37,38] and cluster radioactivity in the 1980s [39,40] also make important contributions to deepening our understanding of nuclei lying near the border of nuclear stability.

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Recently, it is pointed out by Ref. [41–47] that, α decay, proton emission, and cluster radioactivity could be described systematically using unified decay rules. For a pedagogic introduction to charged particle emissions, we would like to recommend Ref. [1]. In the last few years, several works [50–56] are devoted to α decay in strong electromagnetic fields, partially inspired by the upcoming powerful laser facilities in the near future [48,49]. These studies provide some preliminary hints that strong laser fields could speed up α decays. This is not only interesting from the pure academic viewpoint, but also might be helpful for decontaminating α-radioactive nuclear wastes. In this note, we study charged particle emissions in high-frequency alternative electric fields, treating α decay, proton emission, cluster radioactivity in a unified approach inspired by Ref. [41–45,47,46]. By high-frequency alternative electric fields, we refer to alternative electric fields with frequencies (photon energies $\hbar\omega$) much higher than the Q values of charged particle emissions, which means $\hbar\omega \gg Q_\alpha \sim 10$ MeV, $Q_p \sim 1$ MeV, $Q_c \sim 50$ MeV for α decay, proton emission, and cluster radioactivity, respectively. High-frequency alternative electric fields correspond approximately to high-frequency laser fields in the dipole approximation. Therefore, our study could be viewed as a benchmark for future theoretical studies of charged particle emissions in realistic laser fields.

We start with the time-dependent Schrödinger equation

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

which describes the relative motion of the cluster and daughter nuclei in electromagnetic fields, with $\mathbf{A}(t) = \mathbf{A}_0 \sin\omega t$ giving rise to the alternative electric field [58]. $\mu = M_c M_d/(M_c + M_d)$ is the reduced mass of the two-body system, $Q_{\text{eff}} = eZ_{\text{eff}} = e(Z_c A_d - Z_d A_c)/(A_c + A_d)$ is the effective charge [52], and $V(\mathbf{r})$ is the original Coulomb potential between the cluster and daughter nuclei. Here, for simplicity, we adopt the natural unit $c = 1$. With the help of the Hennenberger transformation [57]

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

one obtains a Schrödinger-like equation for the new wave function $\Phi = \Omega_h(t)\Psi$

$$i\hbar\frac{\partial\Phi(\mathbf{r},t)}{\partial t} = \left[\frac{1}{2\mu}\mathbf{P}^2 + V(\mathbf{r} - \mathbf{S}(t))\right]\Phi(\mathbf{r},t),$$
$$\mathbf{S}(t) = \frac{Q_{\text{eff}}}{\mu}\int_{-\infty}^{t}\mathbf{A}(\tau)\mathrm{d}\tau. \tag{3}$$

We shall call the time-dependent potential $V(\mathbf{r} - \mathbf{S}(t))$ as the Hennenberger potential for convenience, and follow the convention of laser–atom physics and call $\mathbf{S}(t)$ as the quiver displacement for the charged particle moving in alternative electric fields [58].

We 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 case of high-frequency alternative electric fields [58]. Explicitly, the static component is given by

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