α-radioactivity in an ultra-intense laser field from heavy and superheavy nuclei

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1. Introduction

Nowadays, the study of laser-nucleus interaction has gained much attention in nuclear physics research. Utilizing WKB approximation within the framework of the α-decay precluster model, the possibilities to control α-decay channel at multipetawatt and exawatt laser intensities are investigated [1]. Similarly, the chirped Pulse Amplification (CPA) technique is also used for the study of laser-nucleus interactions [2] which can be utilized to facilitate the phenomenon of fission in heavy nuclei and fusion in light nuclei.

Our work systematically studies α-decay in doubly-even and doubly-odd nuclei under the influence of an ultra-intense laser field for nuclei with atomic numbers Z ranging from 83 to 118.

2. Theoretical framework

Alpha-decay half-life of an α-radioactive nucleus can be calculated as:

$$T_{1/2}^{\alpha} = \frac{\ln 2}{P_\alpha \left(\frac{1}{2}\int_0^{\frac{\pi}{2}} \nu(\theta) P(\theta)\ \sin\theta\ d\theta\right)}. \qquad (1)$$

Here, $P_\alpha = 0.34$ for even-even nuclei and for doubly-odd nuclei $P_\alpha = 0.15$. "θ" is the orientation angle of the emitted α particle to the symmetric axis of the deformed daughter nucleus. The penetrability ($P(\theta)$) and the assault frequency $\nu(\theta)$ of the α particle are given as:

$$P(\theta) = \exp\left(-\frac{2}{\hbar}\int_{a'(\theta)}^{b'(\theta)} \sqrt{2\mu(V(r,\theta) - Q_\alpha)}\ \ dr\right)$$

$$\nu(\theta) \sim \frac{(G + \frac{3}{2})\hbar}{1.2\pi\mu R_p(\theta)^2}$$

Here G is the global quantum number, Q_α is the α-disintegration energy, $a'(\theta)$ & $b'(\theta)$ are classical turning points. μ is the reduced mass of α-particle and the daughter nucleus also, $R_{d,p}(\theta) = R_0\left(1 + \beta_2^{d,p} Y_{20}(\theta) + \beta_4^{d,p} Y_{40}(\theta)\right)$ fm $\ni R_0 = 1.18\ A_{d,p}^{1/3}$. The total two-body interaction potential is given as $V(r,\theta) = V_C(r,\theta) + V_N(r,\theta) + \frac{\hbar^2}{2\mu r^2}\left(l + \frac{1}{2}\right)^2$. To incorporate $V_N(r,\theta)$ in eq.(2), we have utilized the energy density functional (EDF) of the Skyrme force to consider the interaction of the point-like α particle with the nucleons of the core of decaying nucleus [3] :

$$\begin{aligned} V_N(r,\theta) = \alpha\rho_N(r,\theta) + \beta(\rho_n^{5/3}(r,\theta) + \rho_p^{5/3}(r,\theta)) \\ + \gamma\rho_N\epsilon(r,\theta)(\rho_N^2(r,\theta) + 2\rho_n(r,\theta)\rho_p(r,\theta)) \\ + \delta\frac{\rho_N{}'(r,\theta)}{r} + \eta\rho_N{}''(r,\theta) (2) \end{aligned}$$

$\rho_{n,p,N}$ are the density profiles of nucleons ($\rho_N = \rho_n + \rho_p$), and $V_C(r,\theta)$ is given as:
$V_C(r,\theta) = \frac{Z_d Z_\alpha e^2}{r}\left(1 + \frac{3R_0^2}{5r^2}\beta_2^d Y_{20}(\theta) + \frac{3R_0^4}{9r^4}\beta_4^d Y_{40}(\theta)\right)$

3. Results and Discussion

The interaction of the electromagnetic field with the radioactive system is given as:

$$V_L(\vec{r},t,\Theta) = -Z_{eff}\ \vec{r}\cdot\vec{E(t)} = \frac{Z_\alpha A_d - Z_d A_\alpha}{A} r E(t) (3)$$

Where Θ is the angle between the electric field $\vec{E(t)}$ and radial vector $\vec{r}$, Z_{eff} is the effective charge.

$$E(t) = \sqrt{\frac{2I_0}{c\epsilon_0}}\exp\left(-\frac{c^2t^2}{x^2\lambda^2}\right)\sin\omega t.$$

$$\dot{E}_0[\mathrm{MeVfm}^{-1}] = 27.44{\times}10^{-19}[I_0(\mathrm{Wcm}^{-2})]^{1/2}.$$

Such that, $V_{wL}(r,\theta) = V(r,\theta) + V_L(\vec{r},t,\Theta)$. By choosing the laser's wavelength (λ) of 200

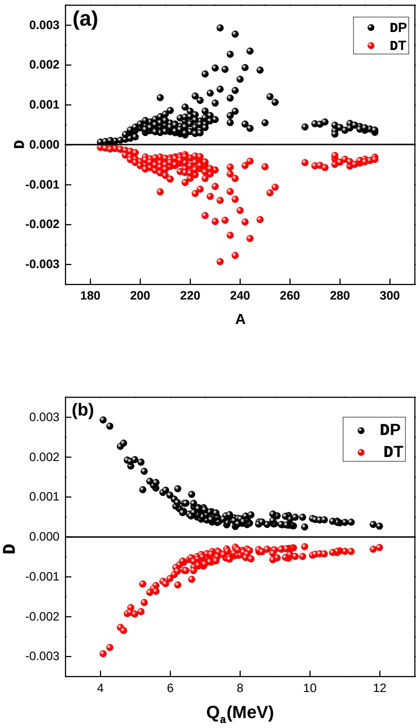

FIG. 1: (a) Black and red points represent the relative change of penetration probabilities (ΔP) and α-decay half-lives (ΔT) and (b) the variation in ΔPs and ΔTs with disintegration energies of α-decay process.

nm, peak intensity of 10^{24} W/cm^2, Θ=0, and for x=5, the relative rate at which the α-decay half-life (ΔT) and the penetration probabilities are changing (ΔP), and can be expressed as:

$$\Delta T = \frac{T(E) - T(E=0)}{T(E=0)}, \Delta P = \frac{P(E) - P(E=0)}{P(E=0)}. \tag{4}$$

Fig. 1 (a) shows the relative rate of change in penetration probability and α decay half-life for chosen nuclei in the presence of a laser field. We can see from Fig. 1 (b) the disintegration energy Q_α is found to be negatively related to the relative rate of change of the penetration probability. The sequence of Gaussian chirped-pulse with chirping parameter b, with

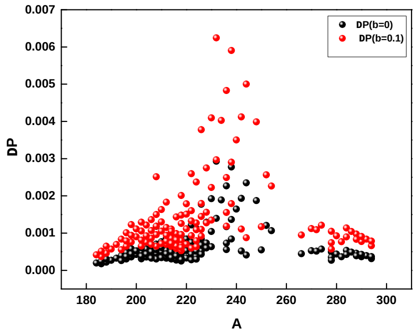

FIG. 2: The black and red points represent the relative change in penetration probability of α-particle without chirping (b=0) and with b=0.1 introduced in Gaussian electric field $E(t)$, respectively.

an envelope function can be written as [4]:

$$E(\omega t, b) = \sqrt{\frac{2I_0}{c\epsilon_0}} \exp\left(-\frac{c^2t^2}{\lambda^2x^2}\right) \sin\left(\omega t + \frac{b\omega^2t^2}{2\pi}\right). \tag{5}$$

The fig. 2 clearly shows the increase in ΔP values when a positive chirp ($b = 0.1$) is introduced in the laser's field. We can see how ΔP values change when b is slightly changed from 0 to 0.1.

4. Conclusion

Our results show that the laser affects the $P(\theta)$ and $T^{\alpha}_{1/2}$ of α-radioactive nuclei to some finite extent. The ΔP ranges from 0.006 % to 0.293 %. The Q_α is found to be negatively related to the ΔP. Positive chirping increases the penetration probability of α-particle. Introducing the chirp in laser's field modified ΔP which ranges from 0.0368 % to 0.624 %.

References

[1] A. P´alffy et al., Phys. Rev. Lett. **124**, 212505 (2020).
[2] J.-H. Cheng et al., Phys. Revi. C **105**, 024312 (2022)
[3] E. Shin et al., Phys. Rev. C **94**, 024320 (2016).
[4] X. Zhang et al., Phys. of Plas. **19** (2012).