Laser assisted two-proton radioactivity

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1. Introduction

Two-proton radioactivity is a rare and exotic form of nuclear decay in which a nucleus spontaneously emits two protons. This process is significant because it challanges our understanding of nuclear stability and the traditional rules governing nuclear decay. Experimental observations [1–3] of two-proton radioactivity are rare but have been made in certain heavy, proton-rich nuclei in which the balance of nuclear forces can be disrupted, leading to the possibility of proton emission.

This radioactivity is a manifestation of the quantum mechanical phenomenon known as tunneling. Many theoretical models, have been developed to describe and predict the probabilities of two-proton radioactivity [3–5]. These models take into account the nuclear structure, energy levels, and the complex interplay of nuclear and electrostatic forces.

2. Theory

The study of two-proton radioactivity in the presence of a laser field is fascinating and relatively new area of research in the field of nuclear physics. In the presence of an intense laser field, several significant effects can be observed like enhanced decay rates, quantum tunneling effects etc. due to additional energy provided by laser fields to the protons, making it easier for them to overcome the electrostatic repulsion within the nucleus. The laser field can also modify the pathways by which the protons are emitted. Studying these effects involves complex quantum mechanical calculations and experiments in highly controlled environments. Researchers in this field use theoretical models, simultations and advanced experimental techniques to investigate the interplay between intense laser fields [7, 8] and nuclear decay processes like two-proton radioactivity.

We have considered that the two-proton decay can be explained as the penetration of the two protons through the interaction potential barrier, comprising the coulomb potential and nuclear potential i.e,

$$V(r) = V_N(r) + V_C(r) \tag{1}$$

where $V_N(r)$ [6] is a short-range nuclear potential which is given as:

$$V_N(r) = -1100\exp\left[-\left(\frac{r-1.17A^{1/3}}{0.574}\right)\right]\ \text{MeV} \tag{2}$$

and $V_C(r) = 2\frac{Z_d 1.44}{r}$ MeV. Here, A is the mass number of parent nucleus and Z_d is the atomic number of daughter nucleus. Moreover, the interaction between the laser electric field and the nucleus is given as [7]:

$$V_I(\overrightarrow{r},t) = -Z_{eff}\overrightarrow{r}\cdot\overrightarrow{E}(t) = -Z_{eff}\,rE(t)\cos(\theta) \tag{3}$$

where, θ is the angle between $\overrightarrow{r}$ and $\overrightarrow{E}(t)$ and $Z_{eff} = \frac{(A-Z)}{(A-1)}$ is an effective charge while the electric field $\overrightarrow{E}(t) = E_0\cos(\omega t+\phi)$, $E_0 = \sqrt{\frac{8\pi I}{c}}$ and $I = 10^{24}$ W/cm^2. The penetrability of 2p through potential barrier can be calculated using the Wentzel-Kramers-Brillouin(WKB) method as $P = \exp\left(-\frac{2}{\hbar}K\right)$, where

$$K(\theta,t) = \int_{R_{in}}^{R_{out}}\sqrt{2\mu[V(r)-Q+V_I(r,\theta,t)]}\,dr. \tag{4}$$

Here, μ is the reduced mass of the daughter products while Q is the 2p-disintegration energy. R_{in} and R_{out} are the turning points.

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3. Results and Discussion

In this article we mainly look into the relative change of the penetrability induced by the laser field which is defined as

$$\Delta = \frac{P(E) - P(E=0)}{P(E=0)} \tag{5}$$

where E is the laser field strength. Δ is also understood as a function of the emission angle θ and time t. In FIGs. 1-3, we have plotted Δ w.r.t t for ^{52}Zn, ^{42}Cr and ^{34}Ca respectively at spatials angles $\theta = 0°$, $45°$ and $90°$. The disintegration energies are obtained from [9] for ^{42}Cr and ^{34}Ca while for ^{52}Zn, Q is obtained using [10]. From these figures, it is concluded that the modifications in the penetrabilities are strongest along $\theta = 0°$ and no modifications are seen along $\theta = 90°$. ^{42}Cr has the lowest disintegration energy among the considered nuclei and from our calculations, modifications are found to be of greater magnitude in this nucleus when compared to other ones.

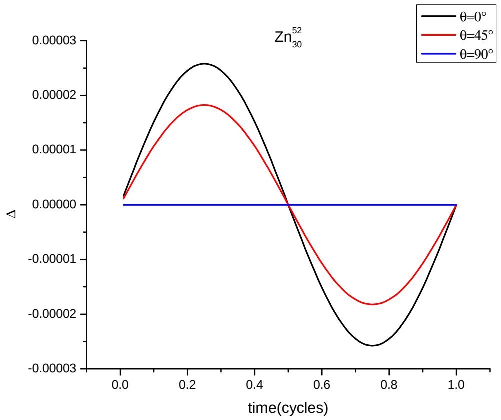

FIG. 1: Time dependent modification to 2p penetrability for three spatial angles for $^{52}Zn_{30}$.

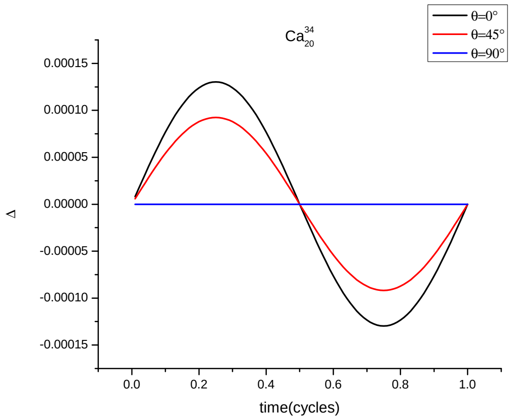

FIG. 2: Time dependent modification to 2p penetrability for three spatial angles for $^{34}Ca_{20}$.

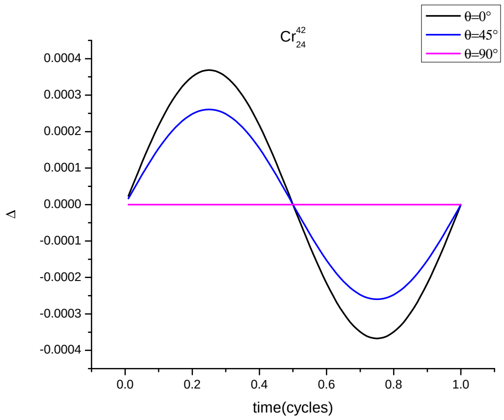

FIG. 3: Time dependent modification to 2p penetrability for three spatial angles for $^{42}Cr_{24}$.

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