Models of nuclear alpha cluster interacting with super-intense laser fields

English summary

In my research, I investigated the phenomenon of laser-assisted alpha decay by focusing on the laser-induced modification of the lifetime of alpha clusters formed in radioactive isotopes. During my research I considered alpha decay as a two-step process involving the formation of the alpha cluster (clustering) and its interaction with the residual nucleus culminating in tunneling through the Coulomb barrier. I discussed that, in leading order, the most pronounced effect of the laser field is displayed in the potential alteration of the Coulomb barrier, primarily influencing the tunneling process; the impact on the nuclear structure is not significant due to the strength of the nuclear forces.

In this dissertation, therefore, I investigated the tunneling phase of alpha decay in the case of heavy alpha-decaying isotone nuclei, concentrating on the alpha cluster in the mean-field potential of the surrounding nucleons. I conducted my study using non-relativistic quantum mechanics under the dipole approximation, ensuring the validity of this approach by analyzing the ponderomotive potential of the alpha cluster. The external laser field was represented as a classical vector potential with Guassian envelope function, and the interaction was realized through minimal coupling and considered as a perturbation.

Initially, for demonstrative purposes, I employed the WKB approximation and the Henneberger transformation to explore the effect of periodic laser fields. My numerical calculations for ^{210}Po demonstrated that the laser-modified decay width increases significantly for circularly polarized lasers. It shows that, even under significantly simplified conditions—considering a plane-wave laser and calculating the laser-modified decay width in a zeroth-order approximation—the effect of the laser is non-negligible. The model based on the Henneberger transformation is consistently applicable only in the case of laser fields with periodic time-dependence.

To extend my study to non-periodic laser pulses, I utilized non-Hermitian quantum mechanics (NHQM). By representing the alpha cluster as a quasi-stationary state with complex energy (the imaginary part of which yields the lifetime), I derived a first-order (t,t')-perturbative, analytical formula within the non-hermitian framework, that gives the shift in the complex energy due to some external, not necessarily time-periodic driving of the system in a quasi-stationary state. The complex energy was obtained by the diagonalization of the complex-scaled Hamiltonian. This allowed me to analyze the interaction between super-intense laser pulses and the alpha cluster. My calculations showed that circular polarization and short pulses yield the most pronounced effects, particularly for ^{212}Po (shortest lifetime) among the isotones studied. I also found the general result, that upon describing quasi-stationary states in NHQM-theory interacting with intense laser fields, characteristic gauges - the rE length-gauge and the pA radiation-gauge - cannot be considered, the physical gauge is the velocity gauge.

Additionally, I validated my NHQM and mean-field based theoretical framework by analyzing the even-even N=128, 130, and 132 isotonic chains. I computed mean-field tunneling widths through the complex spectral calculations and confirmed the fulfilment of the Geiger-Nuttall law, linking empirical trends to the real and imaginary parts of the complex energy eigenvalue. As a consequence, the decay is properly depicted by a non-perturbatively derived, single quantity.

As a future direction, the developed framework is readily adaptable to study super-intense laser-induced modifications to, for example, spontaneous fission or nuclear compound reaction rates; and could also serve as a fundament to investigate laser-assisted alpha decay in even-odd, deformed isotones, and potentially longer lifetime nuclei (for which advanced numerical precision and the more nuanced description of clustering is required).