RADIATION BY A TUNNELING PARTICLE: A TIME-DEPENDENT DESCRIPTION

C.A. Bertulani, D. T. de Paula, and V. Zelevinsky

We study the bremsstrahlung radiation of a tunneling charged particle in a time-dependent picture. This problem can shed light on basic and still controversial quantum-mechanical problems as tunneling times, tunneling in a complex and nonstationary environment, preformation of a tunneling cluster in a many-body system and so on. α-decay offers a unique possibility to address these fundamental questions. We study the bremsstrahlung in high energy α-decays, for which the decay time is treatable numerically. This allows us to pay attention to qualitatively new aspects of the bremsstrahlung in decay processes, and compare with stationary approaches.

We solve the time-dependent Schrodinger equation for the alpha-particle in a potential well + Coulomb barrier, and calculate the radial momentum $p_r(t)$ and corresponding dipole radiation from the radial part of the total wavefunction. Initially, we have an s-wave wavefunction for an alpha particle confined in a radial well $V(r) = -V_0$ for $r < R_0$, and $V(r) = -V_0 + 2Ze^2/R_0$ for $r \geq R_0$. At $t = 0$ we switch the potential to a spherical square well with depth $-V_0$ for $r < R_0$ and a Coulomb potential $2Ze^2/r$ for $r \geq R_0$ which triggers the tunneling. The quantum-mechanical momentum increases slower than the classical one, due to the extended nature of the particle's wave function. As a consequence, the Fourier transform of the quantum momentum has its higher frequencies suppressed, as compared to the classical case.

Another interesting feature is a wiggling pattern associated with the interference of neighboring quasistationary states of the particle inside the nucleus. The leaking of the inner part of the wave function creates an effective oscillating dipole, which emits radiation. The same leaking creates the perturbation mixing different resonance states. The Fourier transform of the particle momentum should therefore contain appreciable amplitudes associated with this motion as can be confirmed by the calculation for the case with no Coulomb post-acceleration. Asymptotically, the momenta calculated in all different ways coincide at large times.

Since the quantum-mechanical momentum of the particle increases slower than the classical one, the spectrum at larger photon energies is suppressed in comparison with the classical one. However, at very large photon energies the spectrum shows a peak, revealing the interference between the different components of the wave function in the well. The width ΔE of the peak is related to the lifetime of the quasistationary state. The lower part of the energy spectrum is solely due to the tunneling through the barrier, while the peak at higher energies is due to the interference of the resonances during the tunneling process. The bremsstrahlung peaks associated with quantum beats are present in any dynamical tunneling process, since an initial localized state always has some overlap amplitude with neighboring states of the open well. Until now it is poorly known how an alpha-particle is preformed inside a nucleus. The possible manifestations of virtually excited clusters in nuclei are predicted to be seen in knock-out reactions induced by protons or electrons. The study of bremsstrahlung in the tunneling process can provide an additional information. Indeed, the initial wave function must be of a localized nature, thus having a nonzero amplitude of carrying a part of the wave function of an adjacent resonance. For high-lying states this leads to the pronounced peaks in the bremsstrahlung spectrum. The observation of those peaks would be valuable for inferring the content of the initial wave function of a preformed alpha-particle (or fission products). Thus, the aproaches based on perturbation theory miss an important piece of information, namely, the time-dependent modification of the particle wavefunction in the well during the decay time. This leads to substantial emission of photons with frequencies close to those of quantum beats between neighboring resonances. This effect should be relevant in radiation emitted during α-decay in nuclei. In a more general case, the time dependence of the wave function of a tunneling particle seems to deviate substantially from the spectrum calculated by using perturbation theory with semiclassical wave functions. More experimental data on bremsstrahlung by a tunneling particle would be very welcome for learning more about preformation states and dynamics of quantum beats.

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