Space- and Time-Resolved Quantum Field Theory for Relativistic Tunneling with Extensions to Curved Spacetimes

Tunneling is one of the most intriguing quantum phenomena, underlying many important processes in nearly every area concerned by quantum physics. Recent literature, including theoretical works studying the tunneling of wave packets whose dynamics is governed by relativistic wave equations, and reports on experimental works using attoclocks, suggests that tunneling may exhibit superluminal effects. When considering the tunneling of relativistic wave packets, it is essential to account for the nonlinear effect of the creation of particle-antiparticle pairs due to vacuum excitation by the strong electromagnetic background—an effect expected to be observed in the upcoming intense laser experiments. Accounting for pair creation necessitates a quantum field theoretical approach. We demonstrate using computational quantum field theory (CQFT) that microcausality ensures fully subluminal propagation, precluding any superluminal or instantaneous propagation behaviors. We illustrate this result by propagating strictly localized Dirac wave packets that tunnel through potential barriers and show that they always remain inside the light cone. Finally, we extend CQFT to curved spacetimes, enabling the study of time evolutions of quantum fields in curved spacetime and, hence, the pair creation phenomena induced by spacetime curvature.