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Causality and quantum interference in time-delayed laser-induced nonsequential double ionization

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We perform a detailed analysis of the importance of causality within the strong-field approximation and the steepest descent framework for the recollision-excitation with subsequent tunneling ionization (RESI) pathway in laser-induced nonsequential double ionization (NSDI). In this time-delayed pathway, an electron returns to its parent ion, and, by recolliding with the core, gives part of its kinetic energy to excite a second electron at a time $t^{\prime}$. The second electron then reaches the continuum at a later time t by tunneling ionization. We show that, if $t^{\prime}$ and t are complex, the condition that recollision of the first electron occurs before tunnel ionization of the second electron translates into boundary conditions for the steepest-descent contours, and thus puts constraints on the saddles to be taken when computing the RESI transition amplitudes. We also show that this generalized causality condition has a dramatic effect in the shapes of the RESI electron momentum distributions for few-cycle laser pulses. Physically, causality determines how the dominant sets of orbits an electron returning to its parent ion can be combined with the dominant orbits of a second electron tunneling from an excited state. All features encountered are analyzed in terms of such orbits, and their quantum interference.

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