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Rapidity-Spectral Decomposition and Spin Dynamics in Coupled Lorentz Spacetime Coordinates

We present a novel framework for parameterizing Lorentz spacetime coordinates using coupled rapidity parameters, extending classical special relativity with new insights into rapidity symmetries and spin effects. Building upon the Euler–Hamilton formalism, we introduce angular and transverse rapidities, enabling spectral decompositions of relativistic dynamics into elementary functions even when explicit analytic solutions are unavailable. A limiting process is developed to achieve this decomposition, providing new tools for modeling complex relativistic systems. We further expand the relativistic Hamiltonian and Lagrangian into rapidity spectra, yielding a new class of Lorentz coordinates with explicit rapidity dependence. These coordinates are applied to analyze charged particle dynamics in the fields of both plane monochromatic waves and pulsed laser beams. The kinetic energy and trajectory differences arising from the use of classical, rapidity-based, and Fermi-type coordinates are compared in detail. As a key advancement, we incorporate spin degrees of freedom into the rapidity-parametrized formalism. By coupling spin precession equations (via the Bargmann–Michel–Telegdi formalism) with rapidity variables, we derive new spin evolution equations for relativistic particles in 3+1 dimensions. The impact of the new spacetime parametrization on spin-orbit interactions and helicity conservation is analyzed. We also explore the structure of the proper Lorentz group SO(1,3) with coupled parameters, comparing transformations in old, new, and Fermi coordinates. Finally, as a special case, we demonstrate the applicability of our formalism to 1+1 dimensional relativistic hydrodynamics with spin, opening a path toward modeling spin-polarized relativistic fluids. These results contribute to the broader understanding of spin dynamics in high-energy particle and laser–plasma physics.

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