Dynamic of Kerr Spacetime: Geodesics, Frame Dragging, and the Penrose Process

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Kerr black holes, or rotating black holes, are central to understanding spacetime curvature around massive rotating bodies; the Penrose process offers a theoretical framework for extracting a black hole's rotational energy by utilizing the frame-dragging effect and the unique geometry of Kerr black holes. The precise geometric and physical conditions necessary for the Penrose process to be viable in astrophysical settings remain largely unexplored, though. Our study aimed to optimize energy extraction efficiency via the Kerr metric’s geometric properties and specific particle splitting parameters. Utilizing the Boyer-Lindquist coordinate system, we developed a visualization model of black hole geometry. Our model suggests that a rapidly spinning black hole (a=0.90) is the optimal condition for the Penrose process. Building on our findings, we further hypothesize that a strict kinematic threshold must be met to achieve a net energy efficiency gain. We utilize the local 4-momentum conservation and the Euler-Lagrange method to model the parent particle’s geodesics and its disintegration as a three-stage hybrid event: infalling, splitting, and a subsequent escape phase. While our model identifies the optimal splitting parameters at an angle of 90 and a radius of 1.9M, the result further characterizes that the Penrose process is governed by a strict kinematic threshold: the relative velocity between split fragments must exceed 0.7c to generate a net energy gain. Our work lays the groundwork for evaluating high-energy relativistic phenomena such as the Bañados-Silk-West (BSW) effect, with the potential for excavating the relativistic gravitational slingshot mechanism.

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