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Toward Positronium Bose-Einstein Condensation: Laser Cooling in Vacuum and Challenges in Nanoporous Materials

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Positronium (Ps), a purely leptonic bound state of an electron and a positron, offers a unique platform for testing fundamental physics, including gravity on antiparticles [1] and a gamma-ray laser [2]. Achieving Bose-Einstein condensation (Ps-BEC) would be a breakthrough, requiring ultracold temperatures (approximately 10 K) and a dense state (around 10^{18} cm^{-3}) Ps within its short lifetime of 142 ns [3]. As a first step toward Ps-BEC, we recently demonstrated one-dimensional laser cooling of Ps in vacuum, reducing its velocity spread to ~1 K within 100 ns using a chirped laser pulse train [4]. This achievement marks the first successful laser cooling of Ps. To achieve Ps-BEC, laser cooling must be applied to dense Ps confined in nanoporous materials. While silica aerogels allow efficient Ps formation and thermalization [5,6], we found that Ps excited to the 2P state exhibits unexpectedly short annihilation lifetimes in nanopores, hindering cooling cycles [7]. We will present an overview of our Ps-BEC project, including the vacuum laser cooling experiment, the challenges of 2P-Ps annihilation in confinement and the ongoing development of nanoporous media optimized for Ps formation, condensation, and cooling. These advances pave the way toward Ps condensation and, ultimately, a gamma-ray laser.
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