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Quantum Mechanical Numerical Model of XHe–Nucleus Interaction and Direct Dark Matter Searches

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While Standard Model extensions such as Supersymmetry have long provided promising candidates, the absence of supersymmetric particle signals at the LHC and contradictory results from direct detection experiments motivate exploration of alternative scenarios. The hypothesis of composite dark atoms — electrically neutral atom-like bound states formed by stable doubly negatively charged particles with primordial helium nuclei — offers a promising framework to address the challenges in direct dark matter detection. We present self-consistent quantum-mechanical numerical model for describing the three-body interaction between X-helium (XHe) dark atoms and nuclei of ordinary matter, bridging cosmoparticle physics, nuclear physics, and experimental dark matter searches. The methodology incorporates nuclear, Coulomb, centrifugal, and Stark interaction potentials, enabling precise reconstruction of the effective interaction potential for XHe with sodium and iodine nuclei. Our results reveal a crucial selectivity: while the effective potential for sodium supports the radiative capture of the sodium nucleus by the dark atom into a single low-energy bound state with binding energy in the 1–6 keV range, consistent with the DAMA/LIBRA annual modulation signal, the corresponding radiative capture rates for iodine are substantially suppressed. This selectivity of modulation signal generation in the detector depending on the target nucleus naturally explains the observed signal in NaI detectors and its absence in experiments using heavier target nuclei, while satisfying experimental constraints on high-energy gamma emission. The results obtained validate the dark atom hypothesis as a coherent resolution to long-standing puzzles in dark matter direct searches. The developed model establishes a framework for interpreting experimental results and for future investigations of composite dark matter candidates.

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