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Precision Atomic Response Functions for Probing Dark Matter–Electron Scattering in Xenon and Germanium Detectors

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This work presents a comprehensive theoretical investigation of dark matter (DM)–electron interactions using atomic response functions (ARFs), with a focus on Germanium and Xenon—two widely employed detectors in direct detection experiments. Accurately modeling these interactions is essential for interpreting and guiding searches for light dark matter candidates, particularly in scenarios where DM particles interact with atomic electrons rather than nuclei.
Our goal is to develop a comprehensive set of ARFs at leading order (LO), derived using state-of-the-art atomic many-body methods. We show that the complex dynamics of DM-induced atomic ionization can be effectively described by four independent atomic response functions. These newly identified responses prove particularly significant in the context of light dark matter (LDM) scenarios, which we investigate using a model-independent effective field theory framework.
To achieve this, we employ the relativistic random-phase approximation (RRPA) and the relativistic frozen-core approximation (RFCA), enabling differential cross-section predictions with estimated accuracies of ~5% (RRPA) and ~20% (RFCA)[1,2, 3].
Using our computed ARFs, we set 90% confidence level exclusion limits on various DM-electron effective interaction operators by comparing with null results from current and ongoing experiments. In particular, our analysis is relevant to the CDEX and CDMSlite experiments, as well as xenon-based detectors such as XENONnT and other next-generation liquid xenon experiments. These detectors, with their increasing sensitivity to low-energy ionization signals, stand to benefit from the improved theoretical modeling provided by our atomic approach.
This study not only refines theoretical tools for interpreting DM-electron signals but also enhances the sensitivity of future searches. The results will be presented at an upcoming international conference.
[1] M. K. Pandey et al., Phys. Rev. D 102, 123025 (2020).
[2] C.-P. Liu et al., Phys. Rev. D 106, 063003 (2022).
[3] C.-P. Liu et al., arXiv:2501.04020."

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