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Time-Reversal Symmetry Breaking and Structural Evolution of Nuclei in Superstrong Magnetic Fields: A Covariant Density Functional Study

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Abstract

Extreme astrophysical environments, such as magnetars and core-collapse supernovae, host superstrong magnetic fields reaching $B \approx 10^{17} - 10^{18}$ G, which radically modify the quantum states of nuclear matter. In this study, we explore the structural response of finite nuclei to these intense fields, with a specific focus on critical waiting-point nuclei involved in r- and rp-process nucleosynthesis. Covariant Density Functional Theory (CDFT) is utilized to evaluate key bulk observables, including charge radii, quadrupole deformations (β_2), and total binding energies. To quantify model dependence and ensure theoretical reliability, self-consistent calculations are carried out using two independent parametrizations—the non-linear NL3* and the density-dependent DD-ME2 effective interactions—implemented within an axially symmetric, constrained relativistic mean-field framework.

The explicit inclusion of the magnetic field breaks time-reversal symmetry and lifts Kramers degeneracy [1]. This prompts a dramatic reorganization of the nuclear single-particle energy levels, contextualized alongside non-relativistic theoretical comparisons for finite nuclei [2]. Specifically, we identify critical level crossings at the Fermi surface that manifest at these extreme field strengths. This microscopic phenomenon triggers abrupt structural phase transitions, compelling transitional nuclei to shift from spherical configurations into oblate or prolate ground states. Furthermore, we systematically study the evolution of the nucleon density distributions and the neutron-proton density difference, noting a marked enhancement in total binding energy driven by the strong spin-alignment of nucleons.

These consistent structural and energetic shifts demonstrate that magnetically induced modifications critically impact stellar weak interaction rates. Macroscopic ground-state modifications directly influence electron emission and positron capture decay channels for exotic isotopes [3], while the extreme external magnetic field alters the electron phase space into quantized Landau levels [4]. Consequently, incorporating rigorous microscopic nuclear structure modeling is essential for the accurate simulation of weak rates and nucleosynthetic pathways

in extreme stellar environments.

References

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