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Three-nucleon forces and shell structure of neutron-rich calcium isotopes

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Calcium isotopes are ideal to explore the evolution of the nuclear shell structure from stability to the neutron-rich extremes, which have very recently become experimentally available.
From a theoretical point of view, calcium isotopes are also the frontier for calculations consistently including nucleon-nucleon (NN), and three-nucleon (3N) forces. In the framework given by
chiral effective field theory (EFT), 3N forces have been shown crucial for a correct description of nuclear structure from the spectra of light nuclei to properties of medium-mass nuclei, such as the neutron dripline of oxygen and the appearance of the shell closure at N=28.
We perform calculations for medium-mass nuclei based on chiral NN+3N forces, employing many body perturbation theory (MBPT) to obtain an effective hamiltonian to be used in a valence-shell model calculations with a 40Ca core. The chiral EFT couplings are adjusted to three- and four-body systems. Single-particle energies and two-body matrix elements are calculated without any further modifications. The NN and 3N forces are included consistently to third order in MBPT.
We study in this framework the neutron-rich calcium isotopes up to 54Ca, calculating the ground state energies, excitation spectra and electromagnetic transitions, and compare to experiment. We find an overall good agreement for the measured properties and provide predictions for the exotic isotopes to be tested by future experiments.
In particular, the calculations show excellent agreement with the two-neutron separation energies (S2n) obtained in recent experiments for the neutron-rich Ca isotopes 51Ca, 52Ca, (measured at TRIUMF) and 53Ca and 54Ca (measured at ISOLTRAP). Of special importance is the S2n at 54Ca, which unambiguously establishes, both in the theoretical calculations and the new ISOLTRAP measurements, the subshell closure at N=32.
The lowest 2+ state in 54Ca, key for the determination of the N=34 subshell closure, is also predicted in reasonable agreement to the very recent experimental determination at RIKEN.

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