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Lattice Location of Th in CaF_2 Using Channeling Techniques: Towards a Nuclear Clock

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The extremely low-energy ^{229}Th isomeric state has two possible decay channels towards the ground state: radiative decay and internal conversion (IC). Because of a 10^9 difference in half-life, IC is the dominant channel. Blocking the IC decay channel is critical for high-precision measurements of the transition energy and for the realization of an efficient solid-state nuclear clock. According to density functional theory calculations, doping ^{229}Th atoms into a CaF_2 crystal can block the IC decay channel if the thorium dopant takes its ground state configuration: Th^{4+} in a substitutional Ca site accompanied by two F^- interstitials for charge compensation. In this work we experimentally assess whether Th dopants occupy this ground state configuration in CaF_2 either doped during growth or with ion implantation. Because doping during growth is an equilibrium process, it is expected for the thorium dopants to occupy the ground state configuration. In contrast, other configurations might be occupied after doping with ion implantation, an out-of-equilibrium process during which abundant vacancies are produced.

Lattice positions of dopants in solids can be investigated using channeling techniques. The very large difference in mass between thorium and calcium allows to measure 2D Rutherford backscattering image scans of CaF_2 crystals doped with 1% Th (with respect to Ca) during growth. Doping with ion implantation is performed at ISOLDE, CERN. Here, a radioactive ion beam is implanted in CaF_2 and the lattice location of ^{229}Ac and ^{231}Th is determined with the emission channeling technique by measuring the anisotropic electron emission patterns upon the beta decay of ^{229}Ac and ^{231}Th, using a position sensitive detector. Analysis of both channeling techniques, hence both doping methods, reveals that the thorium dopants primarily occupy substitutional Ca sites, in accordance with the theoretical ground state configurations. Therefore, it is possible that a significant fraction of thorium dopants is in a configuration that can block IC decay.

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