氏　　　　名	管　明（Guan Ming）
授与した学位	博　士
専攻分野の名称	理　学
学位授与番号	博甲第　　　７３７７　　　号
学位授与の日付	２０２５年　９月　２５日
学位授与の要件	自然科学研究科　　　　学際基礎科学専攻 （学位規則第４条第１項該当）
学位論文の題目	The X-ray induced quenching of the thorium-229 isomer states in a CaF_2 crystal host （CaF_2 結晶ホスト中におけるトリウム 229 アイソマー状態の X 線誘起消光）
論文審査委員	教授　池田　直　　　教授　笠原　成　　　准教授　小汐　由介

学位論文内容の要旨

The first excited energy level of the thorium-229 nucleus lies at approximately 8.356 eV and is referred to as thorium isomeric state, denoted as ^{229m}Th. This isomeric state is remarkably low in energy compared to typical nuclear excited states, which often involve gamma radiation in the keV to MeV range. In contrast, the photon emitted during the de-excitation of the ^{229m}Th isomer has a wavelength of about 148 nm, placing it in the vacuum ultraviolet (VUV) region of the electromagnetic spectrum. The lifetime of the isomer is very sensitive to the environment and it charge compensation. The ^{229m}Th lifetime has been measured to be 10 μs in neutral thorium atoms, ~10 and ~30 minutes in thorium ions doped in wide-bandgap crystal hosts and in ion trap, respectively

In the crystal environment, our experiment works demonstrated that the thorium isomer states can quenched. Here, the term quenching refers to an effective reduction of the ^{229m}Th lifetime and corresponding signal yield, due to the controllable decay channel in the crystal environment. This thesis aimed to explore the microscopic mechanism regarding how and why the Th-229 isomeric state quenched in the ^{229}Th:CaF_2 crystals host, which serve as the state-of-the-art platform for solid-state nuclear clocks in the future. The structured of the thesis is as follows.

Chapter 1 provides an overview of why the ^{229}Th isomeric state is considered unique in the field of nuclear physics, and how it can serve as the basis for constructing a nuclear clock. Several applications of the nuclear clock are demonstrated.

Chapter 2 presents a brief review of the research history of the ^{229}Th isomeric state, offering readers a foundational understanding of the development and evolution of this research field, from both the aspect of experimental and theoretical works.

Chapter 3 introduces the experimental setups developed to excite the ^{229}Th isomeric state and to detect the radiative signal from its decay. Furthermore, the setup was upgraded to enable crystal cooling, allowing for the investigation of temperature-dependent effects. Using this improved setup, we observed the temperature dependence of X-ray-induced isomer quenching. The instrument works was published in the M. Guan *et. al.*, NIMB **562**, 165647 (2025).

Chapter 4 provides essential information about the crystals used in this study, including their synthesis, transmission properties, and application within our research group. In addition, a detailed literature review on crystal defects is presented, along with experimental results on the luminescence properties of the target crystals.

Chapter 5 presents the experimental results, including those from the NRS, VUV, and XIQ experiments. Chapter 6 concludes the thesis with a summary of the main findings and their implications.

論文審査結果の要旨

GUAN 氏はトリウム 229 アイソマーのクエンチ現象の精密観測を実現するために、極低温まで結晶を冷却し真空紫外光を観測できる実験装置を考案し、その設計から組み上げ、稼働を行った。ここでクエンチ現象は X 線照射によりアイソマーの寿命が短くなる現象である。この装置を用いて真空紫外光観測を実施し、その結果、極低温領域において問題となっていた結晶表面に不純物が付着して真空紫外光の透過度が減少する問題を解決し、クエンチ現象の観測を可能にした。

SPring-8 放射光 X 線を用いて生成したトリウム 229 アイソマーを用いた実験では、X 線強度、温度を変化させながら、アイソマー生成量、クエンチ効果、結晶からの紫外光の発光を系統的に観測し、クエンチ現象が X 線照射により結晶中に生ずる格子欠陥とその移動度によることを見いだし、その理論的モデルを構築して説明を試みた。

以上の成果は、結晶中のトリウム 229 を用いる、固体原子核時計の実現に大きく貢献するものであり、基礎科学への重要な貢献に加え、超精密時間標準の実現の可能性を極めて高いところに導いた成果である。

審査会において論文内容を明瞭に報告し、すべての質疑において的確に応答したことから、本審査委員会は本論文を博士（理学）の学位に値するものであると判断する。