

論文 / 著書情報
Article / Book Information

題目(和文)	結晶中の単一希土類イオンの低温分光測定
Title(English)	Spectroscopy of a single rare-earth ion in a crystal at cryogenic temperature
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出典(和文)	学位:博士(理学), 学位授与機関:東京工業大学, 報告番号:甲第9708号, 授与年月日:2015年3月26日, 学位の種類:課程博士, 審査員:松下 道雄,奥田 雄一,上妻 幹旺,村上 修一,旭 耕一郎,細谷 暁夫
Citation(English)	Degree:., Conferring organization: Tokyo Institute of Technology, Report number:甲第9708号, Conferred date:2015/3/26, Degree Type:Course doctor, Examiner:,,,,,
学位種別(和文)	博士論文
Category(English)	Doctoral Thesis
種別(和文)	論文要旨
Type(English)	Summary

論文要旨

THESIS SUMMARY

専攻 : Department of	物性物理学	専攻	申請学位 (専攻分野) : Academic Degree Requested	博士 (理学)
学生氏名 : Student's Name	中村 一平		指導教員 (主) : Academic Advisor(main)	松下 道雄
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要旨 (英文 800 語程度)

Thesis Summary (approx.800 English Words)

Centuries after ancient Greek philosophers pondered over the conceptual idea of atom to explain the universe, the concept of atom revived in France to establish stoichiometry. Nowadays, atoms and molecules are no longer conceptual ideas but their existence is a solid fact. Real atoms and molecules drive scientists to observe and to control behavior of individual atoms and molecules. Observation of photo-activity of a single quantum system in condensed media, so-called single-molecule spectroscopy, has initiated in 1989. Today, the single-molecule spectroscopy has enormous significance in the context of quantum information technologies, where the observation and the control of a quantum system are inseparable from each other.

This thesis describes the single-ion spectroscopy of Rare-Earth (RE) ion doped in crystal. When cooled down to a few kelvins, the nuclear spin transition of RE ions doped in a crystal is known to be detected using its optical transition. RE ions have forbidden optical transitions between two $4f$ electronic configurations with a long radiation lifetime reaching to 100 μ s. The hyperfine splitting about 10 MHz due to the nuclear spin appears on the spectral line of the ions, whose linewidth narrows down to 10 kHz of its lifetime-limited width at a few K.

Aiming at the optical detection and manipulation of a single RE nuclear spin quantum state, the author has consulted on the low-temperature spectroscopy of single praseodymium ions doped in a lanthanum trifluoride crystal ($\text{Pr}^{3+}:\text{LaF}_3$).

Spectroscopy of a single Pr^{3+} requires the sensitivity enough to detect the weak luminescence due to the long radiation lifetime and the frequency resolution close to the narrow spectral linewidth of the ion. Thus, the author needed to build the cryogenic confocal microscope dedicated to carry out the single-ion spectroscopy of $\text{Pr}^{3+}:\text{LaF}_3$. A high performance objective for the cryogenic microscopy was newly developed with the numerical aperture of 0.97 and the detection efficiency of the confocal setup was as large as 0.48%. The excitation lightsource consists of a commercial continuous-wave diode laser and an optical Fabry-Perot cavity as the stable laser frequency reference. The laser linewidth was made narrower than 0.4 MHz and the long-time stability of the output frequency was ± 0.018 MHz/day.

Photo-luminescence excitation measurement of individual Pr^{3+} ions was demonstrated with a bulk crystal of 0.05% Pr^{3+} -doped LaF_3 cooled down at 1.5 K. Spectral lines of the 3H_4

→ 3P_0 transition of individual Pr^{3+} ions were resolved as luminescence peaks with intensities of 20-30 cps and the full-width at half-maximum of approximately 3 MHz at an excitation intensity of 80 W cm^{-2} . The population transfer of a single Pr nuclear spin was demonstrated via the optical pumping process of the ion.

This study is the first success of the single-RE spectroscopy with a bulk crystal sample which contains multiple RE ions in the microscopic volume. It benefits future implementation of multi-qubit operations based on the ion-ion interaction to address the individual ions close in the sub-micrometer distance by the inhomogeneous distribution of their transition frequency. In application to nuclear spin qubit, qubit manipulation is conducted under the magnetic field to use Zeeman sub-levels. Because the Zeeman effect is anisotropic, the orientation of the magnetic field must be accurately controlled with respect to the host crystal. The experiment using the bulk crystal sample paves the way for the optical access to a single ion under the Zeeman field. The author believes this study established the first step to utilizing the RE-doped crystal as the solid-state quantum-information processor.

This thesis is organized into five chapters. Chapter 1 introduces the significance and also the difficulty of the spectroscopy of single RE ions doped in a crystal. Chapter 2 covers physical and chemical properties of the sample material $\text{Pr}^{3+}:\text{LaF}_3$ and the spectroscopic method to resolve individual Pr^{3+} ions abundantly contained in the bulk crystal sample. Chapter 3 describes the development of the home-build cryogenic confocal setup to carry out the single-ion spectroscopy. Chapter 4 includes the results of the photo-luminescence excitation spectroscopy of $\text{Pr}^{3+}:\text{LaF}_3$ at 1.5 K and the discussion about the success of the single- Pr^{3+} detection and origins of observed spectral widths of individual ions. Chapter 5 summarizes the entire study and declares the outlook of quantum information processing using a RE-doped bulk crystal.

備考：論文要旨は、和文 2000 字と英文 300 語を 1 部ずつ提出するか、もしくは英文 800 語を 1 部提出してください。

Note: Thesis Summary should be submitted in either a copy of 2000 Japanese Characters and 300 Words (English) or 1 copy of 800 Words (English).

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