（ 続紙 1 ）

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論文題目	High-sensitivity *in situ* imaging of atoms in an optical lattice with narrow optical transitions （狭線幅光学遷移を用いた光格子中の原子の高感度その場イメージング）		

（論文内容の要旨）

Development of laser cooling techniques in recent decades has enabled us to study neutral atoms in a quite controlled way. Cold neutral atoms have been used as a platform to study intriguing quantum many-body phenomena such as Bose-Einstein condensation and Bardeen-Cooper-Schriefer- Bose-Einstein condensation crossover. The excellent controllability of a cold atom system allows us precise measurements with unprecedented accuracy, which provides wide applications, such as an atomic clock. Another important application of cold atoms is quantum information processing. Internal degrees of freedom of a trapped cold atom can be regarded as a well-defined quantum bit (qubit) and quantum gate operations are realized by moderate internal or external interaction.

In such cold atom research, a probing method plays an important role. In fact, one of the advantages of cold atom research is the ability to “see” atoms directly by taking images of the atoms via resonant or near-resonant light to the atoms. Among various developments in probing techniques, high-sensitivity detection is of particular importance, especially in the study of a simple system of a few atoms.

While high-sensitivity detection and imaging were demonstrated with alkaline metals, there has been increasing interest on a different kind of atomic species. One attractive atomic species is ytterbium. Ytterbium is an alkaline-earth-like-metal atom and has several unique features, such as the rich variety of isotopes of two fermions and five bosons, and the existence of long-lived metastable electronic states. These features offer various possibilities in quantum many-body physics research and are also advantageous to quantum information processing as well as precision measurement. Therefore, a high-sensitivity imaging of ytterbium atoms will bring about a significant development in cold atom research.

Under these backgrounds, this thesis reports on the successful demonstration of high-sensitivity *in situ* imaging of ytterbium atoms in a two-dimensional optical lattice. The applicant demonstrated fluorescence imaging of ytterbium atoms in an optical lattice using optical molasses with a narrow optical transition of the wavelength 556 nm (“green molasses”), providing the Doppler cooling limit temperature low enough compared to the typical optical lattice depths. The applicant successfully observed a spatial modulation of fluorescence intensity with a period of approximately 6 μm as a result of the interference between the lattice period of 266 nm and the period of the standing-wave optical molasses of 278 nm. This pattern indicates that the temperature was sufficiently lower than the lattice potential so that the atoms emitted fluorescent photons around the bottom of the lattice sites during fluorescence imaging.

The applicant also proposed and demonstrated fluorescence imaging in the combination of two different kind of optical molasses ("dual molasses"). In the dual molasses method, the optical molasses by a broad transition is applied as a probe because it provides better imaging resolution due to its short wavelength of 399 nm. The green molasses is simultaneously applied to keep the atom temperature low. In the dual molasses experiment, the applicant again observed the spatially modulated fluorescence pattern with a period of 6 μm, which proves the cooling effect by the green molasses in the dual molasses configuration. The applicant obtained a signal intensity high enough for a single atom detection during an exposure time of 50 ms, during which hopping or loss is essentially negligible. This result is promising for the realization of the site-resolved detection of individual ytterbium atoms in a Hubbard-regime optical lattice, which is attractive in that it can be used to study various systems including a fermionic system in a close relation with electrons in a solid.

The applicant further developed a powerful probing method, "spectral imaging", in which the spectral information at every spatial position is obtained. By combining the high-resolution spectroscopy via the ultra-narrow optical transition and the *in situ* imaging with high-sensitivity, the applicant performed spectral imaging of ytterbium atoms in a two-dimensional optical lattice and obtained position-dependent spectra originated from inhomogeneous light shift due to the Gaussian profile of the optical lattice beams. The spectral imaging technique demonstrated in this thesis will be used to explore subtle local energy shifts in a quantum gas.

Finally, the applicant proposed a scalable quantum computation scheme using 171 ytterbium atoms in an optical lattice. In the scheme, the nuclear spin of a 171 ytterbium atom in a single lattice site serves as a qubit with a long coherence time. A multi-qubit operation, which is a key component for quantum computation, is possible to be performed by exciting atoms to a magnetic metastable state to induce the magnetic-dipole interaction. Thus, the decoherence intrinsic to the interaction for performing multi-qubit operations can be reduced and high scalability is achievable. This scheme, combined with the experimental results in this work, will be a key to the realization of an atom-based quantum computer.

（続紙　２　）

（論文審査の結果の要旨）

近年、中性原子のレーザー冷却技術が開発され、マイクロケルビン台の極低温の原子集団を用意することが可能になり、物性、量子情報、原子時計、その他様々な研究に用いられている。さらに、ボース・アインシュタイン凝縮体やフェルミ縮退などの量子気体が生成され、その物性研究が盛んに研究されている。こうした研究では、光と原子の相互作用を駆使して、高感度に原子をプローブする方法が特に重要であり、これにより少数個の原子を観測することが可能になる。

このような背景のもと、本論文では、光格子に閉じ込められた2次元量子気体のイッテルビウム原子について、高感度なその場観測の手法を開発したことを報告している。まず、イッテルビウム原子に特有の線幅の狭い光学遷移を駆使して、原子を冷却しながら、高感度かつ高空間分解能で、原子を観測することに成功し、いわゆるモアレ空間構造を観測することに成功している。さらに、より高い空間分解能が得られる光学遷移を組み合わせた「2重モラセス」法を考案し、実証することに成功した。さらに、高空間分解能のイメージング法と高周波数分解能の分光法を組み合わせた「スペクトラルイメージング法」を新たに開発することに成功し、光格子ポテンシャルのわずかな不均一性に起因するスペクトルの空間依存性を捉えることに成功した。さらに、これらの手法に関連して、光格子中のイッテルビウム原子を用いた、拡張性のある量子計算の方法を提案している。

以上の結果は、光格子中の冷却原子という新しい量子多体系に関する重要な発展をもたらすものであると認められる。これらは、世界に先駆けたもので、すでに学術雑誌や国内・国際会議などを通して、国の内外を問わず脚光を浴びている。今後、光・原子物理学、量子情報処理、量子エレクトロニクス、など、多くの研究分野への貢献も多大であり、高く評価できる。

よって、本論文は博士（理学）の学位論文として価値あるものと認める。また、平成２５年９月１９日、論文内容とそれに関連した事項について諮問を行った結果、合格と認めた。

なお、本論文は、京都大学学位規程第１４条第２項に該当するものと判断し、公表に際しては、当該論文の全文に代えてその内容を要約したものとすることを認める。

要旨公表可能日：２０１４年４月１日以降