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14. ABSTRACT

With the long-term goal of understanding high-temperature superconductivity (whose explanation has remained elusive since its 1987 discovery), we have worked towards site-resolved, spin-sensitive imaging of a two-dimensional square lattice of ultra-cold atoms. Such an approach may reveal the microscopic struggle between magnetism and superfluidity in square lattices. En route to this goal, we have constructed an ultra-high vacuum system, assembled laser cooling systems, tested high-resolution microscopes that are compatible with our system,

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Report Title

Site-resolved quantum simulation of fermion lattice problems: final report

ABSTRACT

With the long-term goal of understanding high-temperature superconductivity (whose explanation has remained elusive since its 1987 discovery), we have worked towards site-resolved, spin-sensitive imaging of a two-dimensional square lattice of ultra-cold atoms. Such an approach may reveal the microscopic struggle between magnetism and superfluidity in square lattices. En route to this goal, we have constructed an ultra-high vacuum system, assembled laser cooling systems, tested high-resolution microscopes that are compatible with our system, developed a new wavelength for laser cooling and probing, and successfully trapped roughly 500 million atoms of fermionic potassium.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Number of Papers published in peer-reviewed journals: 0.00

(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

Number of Papers published in non peer-reviewed journals: 0.00

(c) Presentations

July-Aug 2010 (period between last interim report and this final report):

Michigan Quantum Summer School (2-13 August 2010, Ann Arbor): J. H. Thywissen, Tutorial lectures on Quantum Simulation with Ultracold Atoms.

ICAP, The International Conference on Atomic Physics (25-30 July 2010, Cairns, Australia): A. Bardon, "Two-frequency dynamics in a double-well BEC"

Number of Presentations: 2.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

(d) Manuscripts

Number of Manuscripts: 0.00

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED
David McKay	0.10
FTE Equivalent:	**0.10**
Total Number:	**1**

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Karl Pilch	0.10
FTE Equivalent:	**0.10**
Total Number:	**1**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
Alex Piggott	0.10
FTE Equivalent:	**0.10**
Total Number:	**1**

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

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The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME	
Michael Sprague	
Hai-Jun Cho	
Total Number:	**2**

Names of personnel receiving PHDs

NAME	
Total Number:	

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

See Attachment

Technology Transfer

Site-resolved quantum simulation of fermion lattice problems
Contract number W911NF-08-01-002
U. S. Army Research Office
Nov 15, 2007 - Feb 15, 2010

PI: J. H. Thywissen, University of Toronto

Final Technical Report

TABLE OF CONTENTS

PROJECT DESCRIPTION

Site-resolved quantum simulation of fermion lattice problems

1. Introduction

Ultracold atoms are particularly well suited to a sub-class of quantum computation called Quantum Simulation (QSim). The basic idea is to use a quantum system to answer questions unreachable for classical computers because of memory, speed, and size limitations. However unlike a universal quantum computer, a QSim experiment is dedicated to a specific Hamiltonian.

One outstanding problem of technological and intellectual significance that can be addressed with QSim is the explanation of high temperature superconductivity (HTSC). The simplest model of electrons moving and interacting in a lattice is the Hubbard model (HM) with repulsive on-site interactions. This model is also a strong candidate model to explain HTSC. Unfortunately, although the HM is simple, finding its ground state has eluded both analytical and computational approaches.

Possible progress can be made on this problem by quantum simulation. In particular, since there is little controversy that the HM explains neutral fermionic atoms on a lattice, the properties of the atomic system can teach us about the physics contained in the Hubbard model [Demler02]. If successful, it would be the first example of a useful quantum calculation. Perhaps more importantly, it could revolutionize our understanding of HTSC, by either rejecting or supporting the claim that HTSC could be explained by the Hubbard model.

2. Project Summary

Quantum simulation with neutral atoms in optical lattices is currently being pursued in several laboratories. Among the most exciting prospects is a realization of the repulsive Fermi Hubbard model, with possible implications in the field of high-temperature superconductivity. In optical lattices, d-wave superfluidity may occur at extremely low temperatures and at incommensurate fillings. This poses several challenges that will be addressed in this proposal: (A:) How can ultra-low temperatures be achieved and measured in a lattice? (B:) How can incommensurately filled (and thus disordered) fermion lattice phases be observed?

As of 2007, the state-of-the-art for imaging cold fermions was a spatial resolution of several microns, and thus single-site addressing is only compatible with large site-to-site separations of 5μm or greater. In such a lattice, simulations which rely upon tunneling would need to take place at unrealistically low temperatures (as low as 50 pK). Our system improves the state of the art by an order of magnitude, making possible in-situ imaging of lattices appropriate for quantum simulation of condensed matter systems, ie, for small-period lattices. Methods include a dedicated vacuum architecture with sub-millimeter working distances; the use of ultraviolet light to image atom, instead of standard infrared wavelengths; and exploitation of cutting-edge biomedical techniques, developed for high-resolution single-molecule imaging.

In-situ imaging will be used to measure spin and occupation statistics of fermions loaded into optical lattices. How to "cold load" fermions into a lattice -- or cool in situ -- is currently one of the most challenging obstacles to quantum simulation of the Fermi Hubbard model. In-situ imaging will allow us to make statistical measurements of entropy, the quantity which is invariant under compression. The proposed method will also be able to measure double occupancy, which is the key quantity in Polmeranchuk cooling. Furthermore, local probes will be able to study the spatial structure of lattice occupation in the presence of a background trapping potential, which is essential for cold atom experiments. Recent theoretical work suggests that entropy is spatially localized at the edges of commensurate filling zones, as in Mott insulating phases of bosonic atoms.

Both local and non-local probes will be used to investigate lattice fermions at a variety of fillings. Significantly, while simple diffraction can observe periodic filling (such as a zero temperature anti-ferromagnetic ordering), it will not extend to disordered states. Thus new probes are required for incommensurate fillings, where high-temperature superconductivity is observed in cuprate materials.

In sum, this project enables not only the development of much-needed cooling techniques, but also the probing of intrinsically disordered states which will address open questions about the Fermi Hubbard Model.

3. Context: Cuprates and the Hubbard Model

All known high-T_c compounds consist of stacks of copper-oxygen planes with the copper ions forming a square two-dimensional (2D) lattice on which electrons move. Figure 1 shows a schematic summary of the measured cuprate phase diagram. The axes of this phase diagram are temperature and doping, where the latter corresponds to the number of additional electrons per copper atom added to the copper-oxygen planes by the adjacent plane composition. At low doping, cuprates are observed to be insulating anti-ferromagnets (AF). At higher positive or negative doping, a superconducting (SC) phase is observed. The technological importance of these phases is that their critical temperature (T_c) can be over 100K, above the temperature of liquid nitrogen. The intellectual importance of the high-temperature superconducting phase is that its explanation is as yet to be discovered.

The simplest model that may explain HTSC is the single-band Hubbard model on a 2D square lattice:

$$H = -t \sum_{\langle i\, j \rangle, \sigma} a^\dagger_{i\sigma} a_{j\sigma} + U \sum_i n_{i,\uparrow} n_{i,\downarrow}$$

where $a^\dagger$ and a are the creation and anihilation operations, n is the number operator $a^\dagger a$, i and j refer to lattice sites, the first sum is over all adjacent pairs of sites, and σ refers to spin states of the fermions. The unique strength of ultra-cold atoms for quantum simulation is the knowledge and control over parameters of the HM. Changing the lattice beam intensity controls the tunneling strength t in each

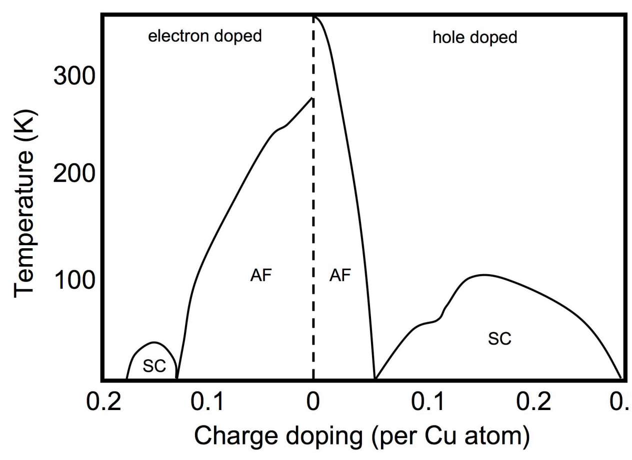

Figure 1. Schematic phase diagram of high-T_c superconducting cuprates. Hole-doping is represented on the right and electron-doping on the left; zero doping indicates half-filling. Anti-ferromagnetic (AF) and superconducting (SC) phases are indicated. [From Bonn06]

spatial direction and compresses each site, increasing on-site interaction strength *U*. Since *t* decreases more quickly than *U* as the lattice is raised, the ratio *U/t* can be chosen arbitrarily. *U* can also be controlled independently by the ambient magnetic field.

The ground state of the strongly repulsive HM on a half-filled (ie, zero doping) square lattice is an antiferromagnetic Mott-insulator, consistent with observations in the cuprates. However calculation of the ground state away from half filling is a subject of controversy in the theoretical community. If a neutral atom system can faithfully be described by the HM, and brought to low enough temperature, then the presence or absence of superconductivity would be an important step forward in the understanding of HTSC.

3.1 Temperature requirements

Since the HM is amenable to computational solutions at half-filling, we can use theoretical results for the AF phase as a guide to determine the relevant temperature scale at which to search for HTSC. The transition from paramagnet to anti-ferromagnet is called the Néel temperature, and estimated to be $0.04T_F$ [Tremblay07], where T_F is the Fermi energy divided by the Boltzmann constant. Assuming the ratio of T_c to the Néel temperature is the same as observed in the cuprates, the transition to superfluidity would be expected roughly a factor of four below this, at $0.01T_F$, which is approximately 5 nK for typical experimental parameters.

Reaching this temperature will be challenging for neutral fermions in optical lattices, where the lowest measured temperature to date is $0.2T_F$.Various methods have been proposed [Georges05,Cirac07] to realize these temperatures, which include "algorithmic cooling". An important part of this proposal is the development of temperature and entropy probes to evaluate temperature and cooling techniques for fermions in optical lattices.

Another important consequence of the low transition temperatures in the HM is that small lattice spacings are desirable. A two-dimensional lattice at half-filling will have a Fermi energy of *4t*, where *t* is the tunneling strength between wells. As lattice spacing *d* increases, the tunneling strength decreases exponentially if all other parameters are fixed -- and at best like $1/d^2$, if the ratio of lattice depth to recoil energy is held constant. Even using the conservative estimate, a 5-µm lattice spacing will have a Néel temperature 100 times lower than a 500 nm lattice spacing. Thus large-period lattices are not compatible with QSim of the Hubbard model.

4. Technical proposal

4.1 System overview

A two-chamber cold atom apparatus has been built: one chamber for atom collection from a vapor using a magneto-optical trap (MOT), and the second chamber designed to enable high-resolution imaging. Potassium 40 (^{40}K) is trapped and cooled using a dark SPOT, and then transported in a magnetic trap from the MOT chamber to the UHV chamber. There, atoms will be trapped optically and cooled evaporatively in an optical dipole trap (ODT). In order to maintain thermal equilibrium, a spin mixture will be used [Jin99]. At sufficiently low temperatures, an optical lattice will be turned on adiabatically. The optical lattice has a period of 530nm. In the horizontal direction beams create a square lattice (similar to the copper sites in cuprates); in the vertical direction the lattice slices the cloud into planes.

4.2 Imaging single lattice sites
Our approach to this problem combines state-of-the-art optical engineering, imaging in the ultraviolet band, and state-sensitive readout.

Ultraviolet imaging line. Potassium has so far only been imaged using 766.7nm light, probing the strongest dipole transition (4S-4P) of the atom. This wavelength is also used for efficient laser cooling and trapping, and is the resonance nearest to the trapping light we will use. However, since imaging resolution is proportional to the imaging wavelength, we gain a factor of 1.9 in resolution by probing along the 404.5 nm (4S-5P) transition. Fortuitously, 405 nm is a wavelength of technological interest for "Blu-ray Disc" data storage, and thus strong diode laser sources have been developed in the past several years. The biomedical industry uses the same wavelength for UV microscopy, and thus 405 nm is a common design wavelength for microscope objectives. These applications open up a new opportunity for high-quality imaging of atomic potassium.

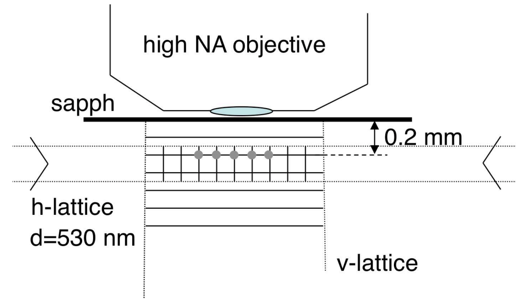

Figure 2. Imaging geometry. A single plane of a 1064nm vertical lattice is occupied with ^{40}K. Four 760nm beams (two shown) create a 2D horizontal lattice. Atoms are imaged through a Sapphire vacuum window at a short working distance from a high NA objective.

State of the art optical engineering. Figure 3 shows our imaging configuration. Atoms are trapped close to a thin (200 µm) sapphire window, which serves as one wall of the vacuum system, as a mirror for the vertical axis of the optical lattice, and as a thin window for imaging. This configuration eliminates the long working distances (~5 cm) and thick optical view ports (3-5 mm) which has made ultra-high resolution imaging impossible in previous experiments. Instead, we realize a situation quite close to biomedical microscopy through a cover slip (typically 170-µm-thick quartz), where sub-wavelength resolution is routine.

In a scanning confocal microscopy configuration, excitation with 405 nm and measurement at 767 nm could provide a further enhancement of signal-to-noise and resolution. Again, such techniques are routine in biomedical imaging, but have never been applied in cold atom physics. The diffraction-limited resolution of our setup is 250 nm in a confocal configuration.

4.3. Probe techniques and read-out
State and number measurements. State measurement is important in fermion lattice problems, since interaction only occurs between spin-up and spin-down fermions. When imaging along a cycling transition, this degree of freedom can be mapped to the hyperfine state and preserved during imaging, however 4S-5P imaging will scramble the hyperfine degree of freedom.

Figure 4 shows one possible read-out scheme. We measure the state of the atom by transferring all of one spin species to an adjacent (unoccupied) lattice plane. After imaging both planes, we will be able to distinguish between four possibilities for a site occupation: (1.) zero atoms, (2.) one spin-up atom, (3.) one spin-down atom, or (4.) two atoms of opposite spins. Any other configuration would require excitation across the band gap, and are thus highly suppressed. Note that the interplay between double- and single-occupancy sites leads to the Polmeranchuk cooling mechanism [Georges05,Tremblay07]. Spin sensitive imaging will enable spin-spin correlation measurements, sensitive to antiferromagnetic fluctuations.

Nonlocal probes. Superfluidity is a delocalized transport phenomenon which cannot be observed directly by local probes. Thus non-local probe techniques complementary to in-situ imaging will also be developed. Among the most promising candidates is Raman spectroscopy [Dao07], which will reveal the d-wave nature of pairing in the lattice, if it exists in the HM. This type of probe will only be important at an advanced stage of the project, after we have verified using in-situ probes that the entropy of the system is low enough to search for superfluidity.

4.4 Spatial structure of inhomogeneous traps

Although solids are uniform systems, trapped atoms exist in non-uniform traps. There is thus spatial structure, which can be understood approximately by considering a density which is highest at the trap center, and vanishes at the edge of the cloud. Comparison with uniform solid systems can be accomplished with local probes, able to make measurements in without averaging across the inhomogeneity of the full trapped gas. Alternately, such probes can be used to *pre-select* constant density regimes, if addressing capabilities are added to the system.

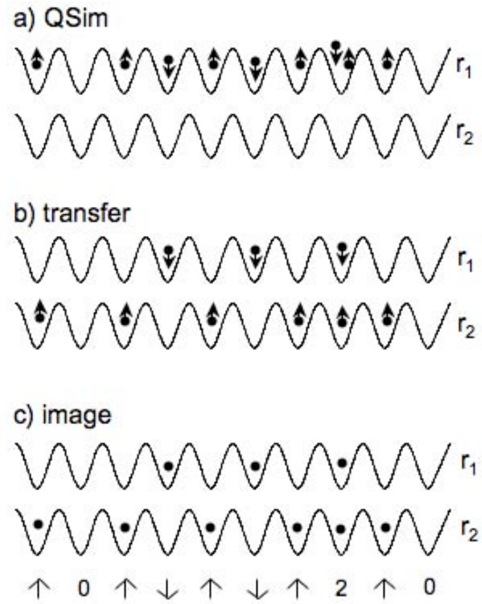

Figure 3. State and number measurement. (a) Quantum simulation occurs in a single 2D plane. (b) Before imaging, all of one spin species is transferred to an adjacent plane. (c) Even though imaging destroys spin information, occupation of the two "registers" r_1 and r_2 can be used to reconstruct the state and occupancy.

Although at first inhomogeneity of the trap seems to be a disadvantage, it could be exploited to our advantage. First, entropy of incommensurate doping will be concentrated at several spatial shells in the trap. This could provide a mechanism to cool the gas [Ho07]. Second, a single sample shows a variety of densities, which corresponds to a variety of dopings. Properly probed, this could be a powerful way to use a single sample to explore the physics of many average densities. Such an approach depends on the validity of a local density approximation, and thus the gradients in density must be small -- a motivation for carefully controlled background potentials.

5. Summary of project description

We have outlined the key elements of the system constructed, and discussed its ability to address fermion lattice problems.

RESULTS

The goal of this project was to create a local probe for ultra-cold neutral fermions in a two dimensional optical lattice. Ultimately, this new tool will enable quantum simulation of the Hubbard Model and other condensed matter lattice models.

The research team working on this project consists of four graduate students (two senior and two junior students), two postdoctoral fellows (both of whom moved to other positions in December 2009), one technician, several undergraduates, and the PI. Funds from ARO were used in acquiring equipment and supplies, and thus salaries of the team were supported from other sources. However travel of the team for ARO purposes (eg, to DARPA program reviews) were billed to this account, and I have thus reported a fractional support for some team members.

Near-ultra-violet light at 405nm will be used for imaging atoms in the lattice. This line (the 4S-5P resonance in potassium) may also be useful for laser cooling, for two reasons. First, the line width is narrower, and thus the Doppler temperature may be five times lower. Second, the smaller absorption cross-section may reduce re-scattered light, which is a density-limiting process in magneto-optical traps.

We have done saturation spectroscopy on a heated vapor cell, and more recently locked the laser on an atomic line. High-power (100mW) diodes have been acquired for injection and power boosting. We estimate that 30mW of light would be required to make a magneto-optical trap, and thus a single injected laser should be sufficient. A cold box has been constructed to pull free-running diodes down to the required wavelength.

We have developed several demanding tests for commercial microscope objectives. We find that although the Zeiss Plan Neofluar 63x can give sub-micron resolution at both 405nm and 767nm (the two resonances for potassium), the 405nm is not diffraction limited. Spherical aberrations limit the resolution to 600nm, which would be diffraction-limited half the numerical aperture that we are using. Thus a custom microscope objective has been commissioned from Special Optics LLC, which is predicted to be diffraction limited at 405nm and a NA of 0.6, giving a resolution of 400nm.

A third revision of the MOT collection cell has been installed. Earlier versions suffered from wall chemistry and source damage. A vacuum change was made in the early 2010, resulting in more than a hundred million atoms in the MOT.

A magnetic field stabilization circuit has been designed and built to address the Feshbach resonances at 200G and 225G in 40K. Using this resonance, interactions between atoms can be tuned. This is a powerful tool to model lattice problems with cold atoms, since accomplishing the equivalent in condensed matter systems would require tuning the charge of the electron. We will use Feshbach resonances both in evaporatively cooling atoms and, later in the experimental cycle, to tune the interaction strength U of the Hubbard Hamiltonian.

In summary, we have constructed a system for site-resolved quantum simulation of fermion lattice problems.

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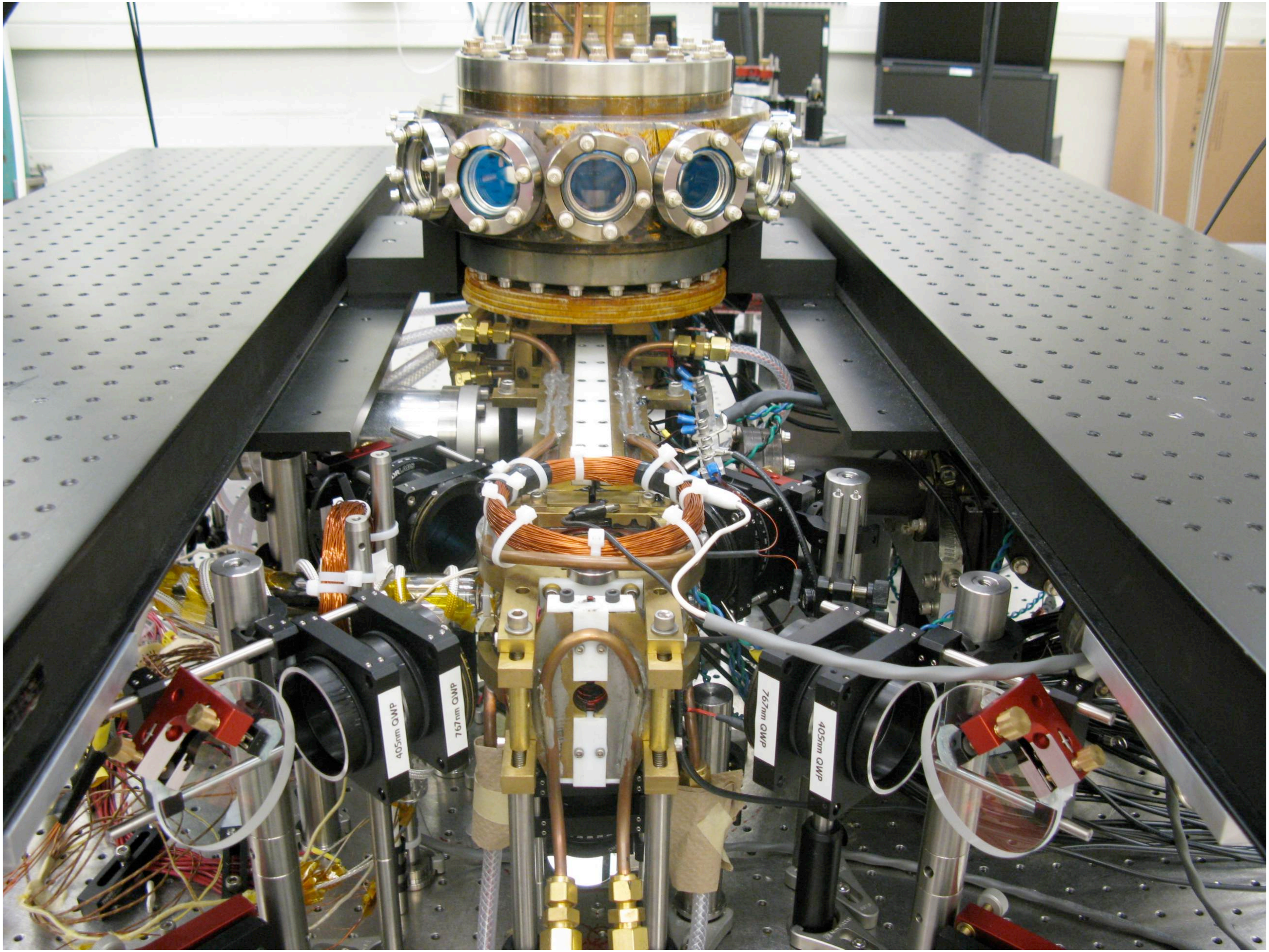
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