Abstract: The most accurate time and frequency measurement devices existing today are atomic clocks. State-of-the-art devices such as bosonic fountain clocks have limited accuracies due to the interactions between atoms. An atomic clock based on ultracold fermions on a microchip has the advantage of superior accuracy by essentially eliminating atom-atom interactions. The Ultracold Atomic, Molecular, and Optical Physics Laboratory at the College of William and Mary is constructing such a clock in our dual-species apparatus designed for cooling and trapping rubidium and potassium bosons and fermions. As of the fall semester 2013, we are excited to report that we have reached Bose-Einstein condensate (BEC) on a microchip with approximately $1 \times 10^4$ $^{87}$Rb atoms. Other milestones leading to this achievement and aiding in the advancement of our potassium capabilities include: 1) magnetically trapping $^{39}$K atoms (in addition to $^{87}$Rb atoms), 2) magnetically transporting both $^{87}$Rb and $^{39}$K atoms to the microchip, 3) loading $^{87}$Rb atoms onto the microchip, and 4) evaporative cooling of $^{87}$Rb atoms. We present this progress towards a $^{40}$K fermion atomic clock on a microchip with potential application in NASA’s Deep Space Network (DSN).

I. Introduction

Atomic clocks are used in any application which requires extremely accurate time or frequency measurement, including digital communications and satellite navigation systems. Due to the widespread use and success of these applications, there is continuing demand to develop smaller and more accurate devices. Currently, the most accurate atomic clock is a cesium fountain clock operated by the National Institute of Standards and Technology. This clock reaches accuracies of a few parts in $10^{15}$ to $10^{16}$ but requires a height of 2 meters over which to drop the bosonic cesium atoms$^{1,2}$. Alternatively, magnetic microchip traps have produced ultracold bosonic rubidium atomic clocks which can reach accuracies of a few parts in $10^{13}$ with the potential for miniaturization$^3$. However, each of these types of clock suffer from the limiting atom-atom interactions$^2$. We are building a fermion atomic clock on a microchip which has the advantage of reaching exceptional accuracies by essentially eliminating the atom-atom interactions$^4$.

II. Application

In its current form, NASA’s DSN tracks spacecraft using Doppler shifted frequencies from the two-way path between ground station and spacecraft (see Fig. 1)$^5$. This scheme requires the use of one dedicated DSN antenna for each spacecraft being tracked for the entire 7-8 hour period that the signal is sent and received. A reliable frequency source (such as an atomic clock) placed on the spacecraft would allow for one-way DSN navigation, effectively cutting time in half and allowing each ground station to track multiple spacecraft at a time.
One such possibility for an on-board frequency source is a microchip fermion atomic clock with their potentially compact size and accuracy. An alternative candidate is a mercury ion clock, however, the large atomic samples permitted by fermion atomic clocks can provide larger signal-to-noise than the ion clock counterparts.

As an additional capability, implementing two independent atomic clocks within a few centimeters of one another on one spacecraft allows one to exploit their sensitivity to magnetic fields and create a simple gradient magnetometer. Space Technology 5 and the Mars Global Surveyor Magnetic Field Investigation are two of several NASA missions to date concerned with mapping the magnetic fields of moons and planets, including Earth. With an on-board gradient magnetometer, the spacecraft navigating via the DSN would be capable of tracking changes in the magnetic environment as they travel.

**III. Background**

Atomic clocks are based on the energy difference between two levels of an atom and the corresponding frequency of a photon which connects those two levels (see Fig. 2). Since atoms of the same species have identical energy level structures, the resonant frequency can be used to develop an extremely reliable and reproducible frequency standard. Atomic clocks use this frequency standard to tune a local oscillator to the resonant frequency of the atom.

All atoms can be characterized as either bosons or fermions (see Fig. 2), each of which obeys different quantum statistical laws. Bosons have integer spin and can simultaneously occupy the same quantum state as any number of other bosons. When cooled to extremely low temperatures, bosons form a state of matter called BEC in which nearly all atoms occupy the lowest energy level possible. On the other hand, fermions have half-integer spin and are forbidden from occupying the same quantum state as an identical fermion. At extremely low temperatures, fermions form degenerate Fermi gases (DFGs) and have the advantage of strongly suppressing interactions between atoms.

Due to the sensitivity of the atoms, both BECs and DFGs are suitable tools for performing precision measurements. However, an atomic clock based on a microtrapped DFG promises to provide more

![Fig. 1. NASA’s DSN uses Doppler data to track spacecraft. Each ground station can track only one spacecraft at a time, which can take 7-8 hours for a signal to be sent and received. An on-board fermion atomic clock cuts this time in half and allows each ground station to track multiple spacecraft orbiting a planet.](image)

![Fig. 2. a) 2-Level Atom: The photon connecting ground state $|g\rangle$ and excited state $|e\rangle$ will have a frequency $f$ associated with the energy difference $\Delta E$ by the relation $\Delta E=hf$ where $h$ is Planck’s constant. b) Bosons vs. Fermions. Any number of bosons can simultaneously occupy the same energy state. No two identical fermions can occupy the same energy state.](image)
accurate time and frequency measurements than one based on a BEC due to the suppressed atom-atom interactions\textsuperscript{4}.

**IV. Methods**

We are constructing a fermion atomic clock with ultracold $^{40}\text{K}$ atoms. The clock will operate between the $F=9/2$ and $F=7/2$ hyperfine ground states. Due to the Zeeman shift, we can choose two magnetic hyperfine sublevels that are both trappable and experience the same energy shift at a particular “magic” magnetic field. While there are several of these types of transitions, we will initially operate our clock on the $|F=9/2, m_F=7/2\rangle \leftrightarrow |F=7/2, m_F=-7/2\rangle$ transition at 0.717 G. A fermion atomic clock operating at this frequency has an expected stability of $10^{-12}$ to $10^{-14}$. In a microgravity environment, operating our clock on the alternative $|F=9/2, m_F=1/2\rangle \leftrightarrow |F=7/2, m_F=-1/2\rangle$ transition at 0.041 G could produce stabilities on the order of $10^{-15}$.

The atomic clock will function as follows (see Fig. 3). We will magnetically trap approximately $10^4$ ultracold $^{40}\text{K}$ atoms in the $|F=9/2, m_F=7/2\rangle$ state in a microchip trap. We use a $\pi/2$ pulse generated on the microchip to put the atoms into a superposition of the clock states. While in the superposition, the atoms will precess for sometime $T$ measured by the local quartz oscillator. After this time, another $\pi/2$ pulse in reverse places the atoms in a combination of ground and excited states. We can measure the number of atoms in each state by spatially separating the two states and imaging them. The length and accuracy of the precession time $T$ will determine how many atoms end up in the ground state vs. the excited state. We can use the ratio of the atoms in these states as a feedback to tune the local oscillator more closely to the atomic transition.

Since the clock is sensitive to magnetic fields, we can place two clocks next to each other to form a gradient magnetometer. The changes in the environmental magnetic fields will manifest as a difference in timing between the clocks, leading to a different ratio of atoms in ground/excited states between the two clocks.

**V. Current Status and Outlook**

Atomic clock experiments with fermions require exquisite atomic and optical control. Therefore, we are implementing our clock in a series of steps to ease troubleshooting along the way. We are currently pursuing demonstration of a proof-of-principle bosonic atomic clock so we can tackle experimental difficulties before moving to the more challenging fermionic system. The bosonic clock allows us to optimize our optical dipole trap and test pulse frequencies and imaging techniques on a more simplified system. In the meantime, we continue to advance our potassium atom capabilities so we can smoothly transition to fermions when we have confidence in our bosonic system.

The standard path to BEC is as follows:

1. Atoms are initially cooled and trapped in a magneto-optical trap (MOT) which consists of six counter-propagating red-detuned laser beams overlapping at the center of a
quadrupole magnetic trap created by a pair of anti-helmholtz coils (see Fig. 4). We have achieved $^{87}\text{Rb}$ MOTs of around $10^8$ atoms at ~30 $\mu\text{K}$ and smaller $^{39}\text{K}$ MOTs at comparable temperatures.

Fig. 4. Portion of Ultracold Atom Apparatus. Our apparatus consists of two ultra-high vacuum chambers oriented in an L-shape. Initial cooling and trapping occurs in the MOT chamber. Atoms are then transported via a magnetic transport system to the second chamber containing the atom chip where they are further cooled to degeneracy.

2. Atoms are further cooled during a brief (~6 ms) molasses stage by further detuning the lasers while the magnetic trap is turned off. We can further cool $^{87}\text{Rb}$ to temperatures as low as 4 $\mu\text{K}$. In our current status, further cooling of $^{39}\text{K}$ is not yet necessary for the following steps.

3. After the molasses stage we turn off the lasers and quickly turn on our magnetic trap. A short (~1 ms) pulse of circularly polarized light before the magnetic trap pumps our atoms into the desired trappable magnetic hyperfine sublevel. We have loaded both $^{39}\text{K}$ and $^{87}\text{Rb}$ atoms into the magnetic trap, both individually and simultaneously.

4. While in the magnetic trap, our atoms are magnetically transported from the initial vacuum cell to a second vacuum cell containing the microchip (see Fig. 4). During the past year, we were able to transport atoms for the first time in our magnetic transport system. We are currently capable of transporting both $^{87}\text{Rb}$ and $^{39}\text{K}$ atoms, both individually and simultaneously, to the microchip.

5. Once at the microchip, the atoms are transferred to the magnetic trap produced by the chip. Here, the atoms undergo the final evaporative cooling step in order to reach BEC. For the evaporative cooling, we apply and sweep an RF field at our atoms, thereby ejecting the hottest atoms from our trap. As of September, we are able to evaporatively cool approximately $1x10^4$ $^{87}\text{Rb}$ atoms to BEC (see Fig. 5). We are in the process of loading the $^{39}\text{K}$ atoms into the microchip magnetic trap.

Fig. 5. Bimodal distribution of ultracold $^{87}\text{Rb}$ as atoms go from thermal cloud to BEC with absorption image as inset and corresponding temperatures (top to bottom). a) Entirely thermal distribution just above the critical temperature. b) The BEC begins to emerge from the thermal distribution at the critical temperature ~ 480 nK. c) Quasi-pure BEC achieved.

A summary of these achievements can be found in the table below.
Table of accomplishments since renewal of award

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In addition to our achievement of BEC and progress towards potassium on the microchip, we have also been advancing our dipole trapping capabilities. We currently have a $^{87}$Rb dipole trap in our MOT cell that is operational and in the process of being optimized. We also have the design and equipment prepared to begin installing a second dipole trap at the chip. Both the MOT chamber dipole trap and the chip chamber dipole trap are sufficiently far-detuned to trap rubidium and potassium atoms.

Although we are primarily interested in potassium, the rubidium bosons are much more abundant and easier to cool and trap than $^{39}$K bosons or $^{40}$K fermions. Optimizing our alignment and loading schemes for rubidium will ease the transition to potassium atoms.

Once our $^{39}$K atoms are loaded into the dipole trap, we can implement a proof-of-principle bosonic clock. After optimizing the timing and pulsing system, we can move to the more difficult fermionic clock with $^{40}$K.

VI. References