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Quantum Technologies

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QUANTUM TECHNOLOGIES

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Abstract

This is the final report of a two-year, Laboratory-Directed Research and Development (LDRD) project at the Los Alamos National Laboratory (LANL). Recent developments in atomic and optical physics involving trapped ions and atoms have revolutionized our ability to control and manipulate quantum-mechanical systems. Using this new technology we have undertaken fundamental quantum mechanical experiments to study: quantum computation with laser-cooled calcium ions; all-optical quantum computation; "interaction-free" measurements, parity violation in nuclear beta decay; and the ultrasensitive detection of selected species of environmental and nonproliferation interests.

Background and Research Objectives

Recent developments in laser cooling and trapping of atomic species and in the fields of atomic physics and quantum optics have made a variety of innovative scientific and technological uses of quantum systems experimentally accessible. During the last two years the "Quantum Technologies" project was funded to develop these new experimental techniques. Several examples that show the power of quantum technologies are now in progress:

a) Laser manipulation of the quantum states of trapped calcium ions provides an environment for investigating quantum computation. The massive computational parallelism afforded by the superposition principle provides quantum computation with the potential to render "public key" encryption systems insecure;

b) Linear optical systems can simulate simple quantum algorithms;

c) "Interaction-free" measurements allow an object to be detected without scattering or absorbing any radiation;

d) Entangled photon pairs produced by the process of down-conversion of a laser beam in a non-linear crystal allow unprecedented tests of quantum-mechanical non-locality;

e) Trapped and polarized radioactive atoms enable a new high-precision test of the Standard Model of electroweak interactions and parity violation;

f) New ultrasensitive detection methods which promise to be 100 times more sensitive than existing techniques are being developed to measure selected isotopic species of interest to environmental and nuclear nonproliferation concerns.

Importance to LANL's Science and Technology Base and National R&D Needs

In the past few years there have been advances in the experimental study of the foundations of quantum mechanics, photonics, and atomic physics that make it possible: to produce non-classical two-photon states; to laser cool atoms or ions to their quantum mechanical ground states; and to optically manipulate their quantum states. These revolutionary methods have opened up a wide-variety of novel concepts in previously inaccessible physical domains to experimental investigation. During the past two years our collaboration has jointly developed experimental techniques whose common goal is to exploit these capabilities. (At the purely technical level, common themes which encompass these activities are: traps, laser cooling, laser excitation of selected states, and fluorescence readout with narrow linewidth lasers and frequency up- and down-conversion.) These breakthrough technologies have opened up a wide range of research that is important to the

Laboratory in three main areas: basic science; quantum computation and information assurance; and nonproliferation and international security.

There are several reasons why this research is important to the Laboratory. This research program builds on our existing multi-divisional expertise in: atomic and nuclear science, quantum optics, laser technology, separation chemistry, and security applications. It is well aligned with the STB and NIS program office missions, and the core competencies of Nuclear Science, Plasmas & Beams and Theory, Modeling & High Performance Computing. The work is innovative science with real-world applications that expand our capabilities and strengthen our science and technology base. Moreover, the proposed research offers to produce new technologies for: information security in optical networks and satellite communications; information warfare (code breaking) and information assurance (security of US cryptosystems); advanced computation; and ultra-sensitive detection capabilities for nuclear proliferates. These technologies are of great interest to and address urgent needs in the intelligence and defense communities.

Scientific Approach and Accomplishments

1. Quantum Information Science

The representation of information by classical physical quantities such as the voltage levels in a microprocessor is familiar to everyone. But over the past decade, quantum information science has been developed to describe binary information in the form of two-state quantum systems, such as photon polarization states. (A single bit of information in this form has come to be known as a "qubit.") Remarkable new capabilities in the world of information security have been predicted that make use of quantum-mechanical superpositions of information, a concept that has no counterpart in conventional information science. For example, a quantum computer would make use of logical operations between many qubits and would be able to perform many operations in parallel. Certain classically intractable problems, such as factoring large integers, could be solved efficiently on a quantum computer.

1.1. Quantum Computation: Introduction

With two or more qubits it becomes possible to consider quantum logical-"gate" operations in which a controlled interaction between qubits produces a (coherent) change in the state of one qubit that is contingent upon the state of another. These gate operations are the building blocks of a quantum computer (QC), which in principle is a very much more powerful device than any classical computer because the superposition principle allows an extraordinarily large number of computations to be performed simultaneously. In 1994 it was shown that this "quantum parallelism" could be used to efficiently find the prime factors of composite integers. Integer factorization and related problems that are computationally intractable with conventional computers are the basis for the security of modern public-key cryptosystems. However, a quantum computer running at desktop PC speeds could break the keys of these cryptosystems in only seconds (as opposed to the months or years required with conventional computers). This single result has turned quantum computation from a strictly academic exercise into a subject whose practical feasibility must be urgently determined.

The architecture of a quantum computer is conceptually very similar to a conventional computer: multiqubit, or "multibit," registers are used to input data; the contents of the registers undergo logical-gate operations to effect the desired computation under the control of an algorithm; and, finally, a result must be read out as the contents of a register. The principal obstacles to constructing a practical quantum computer are: (1) the difficulty of engineering the quantum states required; (2) the phenomenon of "decoherence," which is the propensity for these quantum states to lose their coherence properties through interactions with the environment; and (3) the quantum measurements required to read out the result of a quantum computation. The first proposals for practical quantum-computation hardware, based on various exotic technologies, suffered from one or more of these problems. However, in 1994 it was proposed that the basic logical-gate operations of quantum computation could be experimentally implemented with laser manipulations of cold, trapped ions: a qubit would comprise the ground (S) state (representing binary 0) and a suitably chosen metastable excited (D) state (to represent binary 1) of an ion isolated from the environment by the electromagnetic fields of a linear radio-frequency quadrupole (RFQ) ion trap. Figure 1 shows schematically how the constituent parts of an ion trap quantum computer come together.

The principal components of this technology are already well developed for frequency-standard and high-precision spectroscopy work. Existing experimental data suggest that adequate coherence times are achievable, and a read-out method based on so-called "quantum jumps" has already been demonstrated with single trapped ions. We are developing an ion-trap quantum-computer experiment using calcium ions, with the ultimate objective of performing multiple gate operations on a register of several qubits (and possibly small computations) in order to determine the potential and physical limitations of this technology.

The heart of our experiment is a linear RFQ ion trap with cylindrical geometry in which strong radial confinement is provided by radio-frequency potentials applied to four "rod" electrodes and axial confinement is produced by a harmonic electrostatic potential applied by two "end caps." After laser cooling on their 397-nm S-P transition, several calcium ions will become localized along the ion trap's axis because their recoil energy (from photon emission) is less than the spacing of the ions' quantum vibrational energy levels in the axial confining potential. Although localized to distances much smaller than the wavelength of the cooling radiation, the ions nevertheless undergo small amplitude oscillations, and the lowest frequency mode is the axial center of mass (CM) motion in which all the ions oscillate in phase along the trap axis. The frequency of this mode, whose quantum states will provide a computational "bus," is set by the axial potential. The inter-ion spacing is determined by the equilibrium between this axial potential, which tends to push the ions together, and the ions' mutual Coulomb repulsion. For example, with a 200-kHz axial CM frequency, the inter-ion spacing is on the order of 30 μm.

Because of its long radiative lifetime (~1 s), the S-D transition has such a narrow width that it develops upper and lower sidebands separated from the central frequency by the CM frequency. With a laser that has a suitably narrow linewidth and is tuned to the lower sideband, an additional stage of laser cooling is used to prepare the "bus" qubit (CM vibrational mode) in its lowest quantum state ("sideband cooling"). On completion of this stage, the QC is prepared with all qubits in the $|0>$ state, ready for quantum computation.

The narrow-linewidth laser tuned to the S-D transition is the essential tool for changing the contents of the quantum register of ions and performing quantum logical-gate operations. By directing this laser at an individual ion for a prescribed time, we will be able to coherently change the value of the qubit that the ion represents through the phenomenon of Rabi oscillations. An arbitrary logical operation can be constructed from a small set of elementary quantum gates, such as the so-called "controlled-NOT" operation, in which the state of one qubit is flipped if a second qubit is in the "1" state but left unchanged if the second qubit is in the "0" state. This gate operation can be effected with three laser operations, using quantum states of the ion's CM motion as a computational bus to convey quantum information from one ion to the other. The result of the quantum computation can be read out by turning on the S-P laser. An ion in the "0" state will fluoresce, whereas an ion in the "1" state will remain dark. So, by observing which ions fluoresce and which are dark, a value can be obtained.

1.2. Experimental Ion Trap Quantum Computation

We have succeeded in trapping and laser cooling calcium ions to rest in our ion trap and imaging them with a charge-coupled device (CCD) camera. The localized string of cold ions forms a quantum register (see Figure 2).

We have also designed and constructed several types of diode laser systems for laser cooling of calcium ions to form crystalline strings. In particular, for effective laser cooling on the 397-nm transition it is also necessary to apply light at 866-nm, so as to keep the ion from entering a long-lived electronic state that does not participate in the cooling transition. We have also developed a diode laser system for producing the 397-nm light be frequency doubling 794-nm diode laser light. First, we built several diode laser systems for 794-nm and 866-nm operation that employ a feedback grating and extended cavity design so that the laser linewidth can be narrowed sufficiently for our experiments. Second, because there are no frequency standards near those we require, we built three reference cavities that can be used for arbitrary frequencies. We stabilize our lasers by locking them to a reference cavity, and in turn stabilize the cavity by locking it to a narrow linewidth helium-neon laser. Third, we built a system to amplify the 794-nm diode laser beams after their frequency has been stabilized and their linewidth narrowed. This system, called a MOPA ("master oscillator power amplifier") by optical engineers, produces a 300mW output beam from our 5mW diode laser beam. Finally, we built a power build-up cavity with a frequency doubling crystal to convert 794-nm infrared light from a diode laser into the 397-nm ultraviolet light we need for cooling the calcium ions in the ion trap.

We have operated all the components individually and together as a fully solid-state laser diode/MOPA/frequency doubling system. We already use the 866-nm diode lasers for our research on a daily basis. We are engineering the full system so that it too can be used daily. These diode laser systems are useful because they can replace Titanium::Sapphire laser systems that are more complex (23 optical components rather than 3), more expensive ($200K rather than $15K), larger (600 lbs. rather than 1 lb.), less efficient (use 50 kW rather than 1 W) and require a clean room environment and gallons of cooling water. Another attractive aspect of this work is that every single component can and has been used for other experiments in the Quantum Technologies project, so it has proven very useful to develop this technology base at Los Alamos.

1.3. Theory Of Ion Trap Quantum Computation

The theoretical work conducted under this project was to investigate all aspects of the physics of cold trapped ions, as it pertains to the development of quantum computation. We carried out studies in three general areas, namely feasibility studies of quantum computation with cold trapped ions, investigations of the errors that place fundamental limits on computational capacity, and the effects of stray electromagnetic fields causing "heating" of the ions and how these effects might be nullified.

First, we examined the dynamics of strongly coupled cold trapped ions from first principles, and we analyzed the nature of the laser-ion interaction specific to the calcium system that we adopted [DFVJ-1, 2]. We also performed a detailed study of the spacing between ions in long crystalline chains, comparing theoretical, numerical and experimental results.[DFVJ-3]

We examined a number of different error mechanisms and how they limit quantum computational capacity. These mechanisms included: spontaneous emission from ions, cross-talk between adjacent ions due to finite resolving power of the laser focal spot and the lack of resolution in frequency space due to the short duration of laser pulses. These effects, when taken in combination, result in specific limits on the size of numbers that could be factored using a quantum computer (without quantum error correction). The results were encouraging: on the order of one hundred thousand quantum gate operations could be performed on registers of up to 50 or so ions, and so even without error correction it should be possible to factor numbers up to 10 bits in length. Furthermore, these investigations were useful in allowing one to determine optimal values for various experimental parameters. [DFVJ-4, DFVJ-5, DFVJ-6]

Experiments carried out to date, both at LANL and elsewhere, have revealed the single most daunting technological challenge to be overcome in the development of ion trap quantum computers is the effect of stray random electromagnetic fields degrading the fragile quantum ground state of the ions motion, whose purity must be preserved for successful computations to take place. To understand this problem fully, we undertook a detailed theoretical study which revealed an unexpected result that the "heating" occurs predominantly in a single mode, the other oscillatory modes remaining relatively pure. [DFVJ-7] From this study we determined how the heating rate depends on critical parameters such as the trap dimensions and frequencies. Further investigations into an alternative computational scheme were carried out [DFVJ-8], suggesting that the problem of heating might be overcome entirely by suitable application of techniques such as stimulated Raman adiabatic passage.

1.4. Development Of Algorithms For Quantum Computers

It is of great interest to determine the class of problems that are amenable to more efficient solution on a quantum computer than on classical computers. Integer factorization is a particular instance of the more general problem of finding a "hidden" subgroup of an Abelian group, given a function that takes on constant but distinct values on the cosets of the subgroup. We have been investigating the generalization of this problem to non-Abelian groups and believe that the techniques we have developed will open up new applications for quantum computational algorithms. We have also investigated the implications of quantum computation for the security of public-key cryptography. [RJH]

1.5. Interaction Free Measurements

In 1993 Elitzur and Vaidman (EV) showed that the wave-particle duality of light could allow “interaction-free” quantum interrogations of classical objects, in which the presence of a non-transmitting object is ascertained seemingly without interacting with it

[EV], i.e., with no photon absorbed or scattered by the object. Two drawbacks to their technique are that the measurement result is ambiguous at least half of the time, and that the fraction of measurements which are interaction-free is at most 0.5. Along with collaborators at the University of Innsbruck, we proposed that one could circumvent these limitations by incorporating a weak, repeated interrogation technique [PGK1], basically an optical version of the quantum Zeno effect [MS,AP]. Employing a specific embodiment (developed here at LANL) based on an inhibited polarization rotation, we made the first observation of >50% "efficiency".

We have made much progress in the investigation of "interaction-free measurements". In 1997 we made a complete theoretical study of the effects of losses on system efficiency and confirmed the results experimentally [PGK2]. Last year, using a fast switching system, we have produced true efficiencies of interaction-free measurement up to 73%, and demonstrated the feasibility of up to 85% efficiency [PGK3]. Also, we performed a series of experiments investigating the practical implementation of interaction-free "imaging", where the techniques are used to take a (pixellated) 1D image of an object, again with the goal of negligible absorption or scattering [PGK4]; a resolution of less than 10 microns has been achieved in a simple system looking at thin wires, optical fibers, hairs, etc. Finally, one of the most exciting prospects is the ability to couple to a quantum object, such as a single atom or ion, which can be in a superposition state. We have begun a complete theoretical treatment of this fairly complicated problem, demonstrating, for example, that the quantum state of the object can be transferred to the interrogating light, allowing the production of macroscopic entangled states of light and Schrödinger cat states [PGK5].

1.6. Wave-Particle Duality

We have performed the world's first comprehensive test of the wave-particle duality in which the relationship between the amount of wave-like (interference) and particle-like (definite trajectories) behavior is quantified by the inequality $V^2 + D^2 > 1$, relating fringe visibility V and path distinguishability D [PGK6]. With a single-photon Mach-Zehnder interferometer in which the photon polarization is used to label the paths, we have investigated this duality relation for various situations, and demonstrated that, contrary to popular belief, lack of particle-like information does not necessarily imply wave-like behavior and vice-versa. Using a unique tunable source of quantum states, we have also been able to examine pure, mixed, and partially-mixed input states. In addition, we have demonstrated several novel types of "quantum erasers", in which wave-like behavior can be recovered if one erases the particle-like information [PGK7]. Curiously, it was demonstrated that even for mixed states, where no particle-like information exists, one can still recover interference. These studies have direct relevance to the growing field of quantum information, specifically quantum computation, where proposals for error correction based on quantum erasure rely on an understanding of the phenomenon when non-pure states are involved.

1.7. Optical Simulation Of A Quantum Computer

We have designed and demonstrated the first *all-optical* implementation of a quantum circuit [PGK8,PGK9]. Recently it was shown that all of the essential operations of a quantum computer could be accomplished using only standard linear optical elements (e.g., beamsplitters, waveplates, polarizers, etc.) [PGK10]. In this technique, the individual bits are represented by different spatial or polarization modes of light. This summer we realized a simple optical implementation of Grover's quantum algorithm for efficiently searching an unstructured database. In our example, a database of four elements is searched with a single query, in contrast to the classical expected value of 2.25 queries. Whereas an exact one-to-one correspondence with Grover's algorithm would require at least 24 optical elements, our "compiled" version required only 12. It is seen that the quantum computer is essentially an interferometer, albeit a complicated one. The difference from a genuine quantum computer with *distinct* entangleable registers is that the optical implementation requires a number of elements which grows exponentially with the number of bits. Nevertheless, the all-optical schemes may readily implement algorithms involving several bits.

1.8. "Entangled" Photon Pairs And Quantum Mechanical Non-Locality

Using the process of spontaneous parametric down-conversion in a novel two-crystal geometry, we have generated a source of polarization-entangled photon pairs which is more than ten times brighter, per unit of pump power, than previous sources, with another factor of 30 to 75 expected to be readily achievable [PGK11]. We have measured a high level of entanglement between photons emitted over a relatively large collection angle and over a 10-nm bandwidth. As a demonstration of the source capabilities, we obtained a world-record 242 standard deviation violation of Bell's inequalities in less than three minutes and observed near-perfect photon correlations when the collection efficiency was reduced. In addition, both the degree of entanglement and the state purity should be easily tunable.

2. Experiments with Trapped Radioactive Atoms

By combining the latest in optical and magnetic trapping techniques with our existing capabilities of handling and separating radioactive materials, we are developing a unique capability to trap, manipulate, and investigate radioactive atoms. In a synergistic fashion, we are applying this new capability to undertake three very different projects – (1) a high-precision study of parity violation in the beta-decay of polarized nuclei; (2) the ultra-sensitive detection of selected species for environmental and nuclear nonproliferation concerns; and (3) the study of atomic collisions and Fermi-degeneracy at very cold temperatures. These projects and the progress that we have made are highlighted below.

2.1 Parity Violation in the Beta Decay of Polarized ^{82}Rb

Theories of fundamental processes must develop in tandem with our understanding of the relationship between symmetry principles and the invariance of physical laws under specific transformations in space and time. Of the four fundamental forces in nature (strong, electromagnetic, weak, and gravity), the weak interaction is unique in that it violates parity, or space-reflection symmetry. Four decades have passed since the first suggestion by Lee and Yang [LY] that parity could be violated in weak interactions, and the subsequent discovery by Wu et al. [WU] of parity violation in the beta decay of polarized ^{60}Co. Today, maximal violation of parity is described in the standard model the unified electroweak interaction between leptons and quarks. This model is based on empirical data established by nuclear and particle physics experiments during the second half of this century. Nonetheless, the origin of parity violation and how it is related to other conservation laws and physical processes is unresolved and marks one of the central mysteries of modern physics. Low-energy physics experiments that exploit nuclear beta decay continue to offer a means to probe the fundamental origin of parity violation and, more generally, the helicity structure of the electroweak interaction.

Parity violation is manifest in nuclear beta decay as an asymmetry in the angular correlation of the emitted beta particles relative to the spin orientation of the parent nucleus. Pure Gamow-Teller (GT) transitions offer a direct route to study this asymmetry since they proceed solely through the axial-vector couplings responsible for parity violation. Historically, however, studies of pure GT transitions have been limited by the lack of good candidates, namely reasonably long-lived species that can be produced in high yields and which have suitable allowed (unhindered) transitions. In the cases where good candidates have been realized, modern experiments are limited in precision due to the fact that solid samples are employed with limited nuclear polarization. It is now possible, however, to envision a new generation of pure GT experiments by exploiting optical and magnetic traps for radioactive atoms.

At Los Alamos, we are working to exploit magnetically trapped ^{82}Rb in a new generation of fundamental symmetry experiments. ^{82}Rb, an allowed GT β-decaying nucleus, has the appropriate atomic structure and lifetime ($t_{1/2}$ = 75 s) to be exploited in a magneto-optical trap (MOT). We are in the process of mounting a prototype experiment to measure the positron-spin correlation coefficient (**A**) from polarized ^{82}Rb in a magnetic TOP (Time-Orbiting-Potential) trap. In this case, an essentially massless source of highly polarized sample of atoms are confined to a localized cloud of ~1 mm in diameter with the alignment of the nuclear spin being controlled by the application of a rotating magnetic bias field. Consequently, this rotating beacon of spin-polarized ^{82}Rb nuclei can be exploited to measure the parity-violating correlation as a continuous function of the positron energy and emission angle relative to the nuclear spin orientation. Our initial goal is to undertake a 1% measurement of the beta-asymmetry **A** coefficient which would match the world's best measurements and then we intend to push the precision down to the 0.1% level. In the future, recoil detectors will be added to the experiment so that other beta-neutrino-nuclear spin correlations can be measured, further testing, in a self-consistent fashion, our understanding of electroweak interactions in nuclei.

The initial challenge in undertaking this experiment is to trap a sufficiently large number of radioactive atoms. This requires the use of a strong source and the efficient introduction and trapping of these species in a trap. As magneto-optical traps (MOTs) are currently the strongest traps for neutral atoms, our approach involves the coupling of a mass separator to a MOT. In particular, our idea is to isotopically separate and implant ^{82}Rb into a catcher foil which is located within the trapping cell of a MOT (see Figure 1). Upon heating the implanted ^{82}Rb atoms diffuse out of the catcher foil and are trapped in a standard MOT composed of three, orthogonal, circularly-polarized laser beams that are retro-reflected back through the cell. In this way we have been able to efficiently introduce and trap ^{82}Rb for the first time. Using this apparatus with a 9 mCi source of ^{82}Sr ($t_{1/2}$ = 25 d) produced at LANSCE isotope production facility and chemically extracted in our hot cells, we where able to trap 6 million atoms of ^{82}Rb fed by the electron capture of ^{82}Sr (see [V1, V2] for details). This represents a two order of magnitude improvement in the number of trapped atoms over all previous radioactive atom trapping work throughout the world. Since this initial work, we have gone on to measure the hyperfine structure of the $5P_{1/2}$ and $5P_{3/2}$ atomic states as well as the isotope shift of the D_1 transition in ^{82}Rb [V3]. This information is needed for the optical pumping (polarization) step of the experiment (see below).

After the successful trapping and measurements of ^{82}Rb in the MOT, the next step in the parity violation experiment is to transfer the atoms to a second MOT using a laser push beam and magnetic guide approach (see Figure 3). Typical results from this trap, transfer, and retrap sequence are shown in Figure 4. After optimization we obtained a single-shot transfer efficiency of ~50%. Because the second MOT has a much better vacuum than the first MOT, the lifetime in the second MOT was considerable better (~500 s in MOT II compared to ~30 s in the MOT I). This long lifetime made it possible to accumulate atoms in the second MOT by running in a multi-shot transfer mode.

The next steps in undertaking the β-asymmetry experiment are: (a) the optical pumping (polarization) of the atoms into the desired weak-field-seeking, spin-aligned magnetic substate; (b) the loading of the time-orbiting-potential (TOP) magnetic trap (8); and (c) the detection of the positrons. For the most part, the first two steps will employ techniques that have already been developed, however, in our case a premium will be placed on optimizing the efficiency of the loading process and in maintaining a high degree of nuclear polarization once trapped. Both are critical to the success of our experiment. As of this time, we have done extensive modeling of the TOP trap performance as rotating source of spin–polarized nuclei, constructed our own TOP trap system, and demonstrated that it works with stable rubidium atoms. An initial trapping lifetime of ~70 s was obtained with little optimization. We now know how to improve the system further and are prepared to implement the optical pumping step. A first-generation positron telescope has been extensively modeled and tested. Everything is now in place and we are looking forward to loading our first samples of polarized ^{82}Rb into the TOP trap and beginning our first beta-asymmetry measurements.

2.2 Ultra-sensitive Detection Using Optical Traps

Examining the capabilities of optical traps, one finds many desirable features which are well matched to the needs of ultra-sensitive detection. These include its high-selectivity, high-sensitivity, and large dynamic range. High selectivity results from the fact that the trapping process involves the repeated near-resonant absorption and fluorescent emission ("scattering") of thousands of photons within a fraction of a millisecond (the time it takes for an atom to traverse the trapping cell). High sensitivity results from the fluorescent detection of the trapped cloud of atoms where the signal is highly leveraged by the "scattering" of millions of photons per second per trapped atom. And finally, without the space charge limitations as in ion traps, neutral atom traps are capable of trapping large numbers of atoms (10^8 atoms or more) within a relatively small cloud size (~2 mm diameter) making large dynamic range measurements possible. With the trapping of many different species (mostly alkali, alkali earth, and noble gas elements so far) and the ability to detect a single trapped atoms already demonstrated, optical traps are a natural candidate for ultra-sensitive detection. The main challenge in applying this new technology is in obtaining high trapping efficiencies.

The problems associated with achieving high trapping efficiencies are multifold. They include: (1) the introduction of the sample without degrading the ultra-high vacuum of the trap; (2) enhancing the time the atoms of interest spend in the vapor state as compared to being "stuck" on the walls of the trapping cell; and (3) optimizing the trapping light field with respect to beam intensity, detuning, magnetic field, and geometry of the MOT. Given the relatively weak trapping potential of optical traps (at least compared to ion traps), atom-atom collisions with hot (room temperature) gas atoms or molecules represent a significant loss mechanism. In general, the trapping lifetime scale directly with the pressure in the trap. In the case of trapping rubidium atoms, a pressure in the 10^{-9} torr range is needed to achieve a trapping lifetime of ~10 seconds. As mentioned above, our approach solves the sample introduction problem by using a mass separator to implant the species of interest directly into a small catcher foil located within the trapping cell itself. Upon subsequent heating of the catcher foil, the implanted atoms are released and trapped with a minimum of gas loading. To address the second problem, we have adopted the approach of using a special nonstick coating on the inside of the trapping cell to reduce wall "sticking" times. Following the work of Stephens *et al*. [SW], we have used a dryfilm coating to increase the trapping efficiency. For stable cesium we have measured a trapping efficiency of 20% using such a coating [V2]. Finally, there are several good studies that have investigated the trapping efficiency optimization of a MOT. Herein, we employ large diameter trapping beams and a cubic trapping cell geometry to obtain reasonably high trapping efficiencies.

In our initial work, we have concentrated on the trapping of ^{82}Rb ($t_{1/2}$ = 75 s) because: (1) a convenient mother source of ^{82}Sr ($t_{1/2}$ = 25 d) was readily available; (2) gamma-ray counting techniques could be used to characterize the efficiency of each step in the process; (3) the possibility of long-term contamination of our system was eliminated; and (4) the efficient trapping of ^{82}Rb was synergistic with the beta-asymmetry experiment as described above. To date we have been able to detect trapped ^{82}Rb atoms at the 4,000 atom level in MOT I [V4]. This was derived from the fluorescent signal from the trapped cloud of atoms that are imaged onto a photo-detector. Although we used a modulation / lock-in technique to extract this small signal, this approach is limited by the large background of scattered light coming from the walls of the cubic trapping cell. To reduce the scattered light problem, we have explored another method in which the atoms are transferred to a second MOT wherein there is much less scattered light and a better light collection geometry can be used. Using this MOT I – MOT II transfer approach (see figures 3 and 4), we have been able to detect as few as 20 atoms of ^{82}Rb in MOT II. Given the transfer efficiency of ~50%, this represents a two order of magnitude improvement in our detection sensitivity.

In the future we are interested in extending this technique to the trace detection of ^{135}Cs, ^{137}Cs, and possibly ^{90}Sr as these radioactive species are of high importance to environmental monitoring and nuclear proliferation concerns. Ultimately, our goal is to demonstrate the utility of optical traps as a new ultra-sensitive analysis tool with the capability of making quantitative isotopic ratio measurements at the 10^4 atom level – two orders of magnitude better than existing techniques.

2.3 Cold Atomic Collision and Fermi Degeneracy in Rubidium Isotopes

One of the most exciting events in recent years was the awarding of the 1997 Nobel Prize in physics to Steve Chu (Stanford Univ.), Claude Cohen-Tannoudji (ENS, Paris), and Bill Phillips (NIST, Gaithersburg) for the development of many of the atomic trapping and cooling techniques that we are currently employing. Moreover, the physics community has been enthralled by the recent discovery of Bose-Einstein condensation (BEC) in dilute alkali vapor of ^{87}Rb, ^{23}Na, and ^{7}Li. Although BEC has been observed earlier in superfluid ^{4}He, there densities were so high that atom-atom interactions became so strong that perturbative approaches could not be used to understand the system. In the dilute alkali BEC systems, however, the densities and experimental conditions of the BEC are more easily controlled and perturbative methods can be applied to understand the Bose-Einstein quantum mechanical nature of these very cold systems.

Beyond BEC there is presently a growing interest to explore Fermi degenerate systems which are made of up atoms with half interger total spin. In nature, there are only two stable alkali isotopes that are fermionic – ^{6}Li and ^{40}K. However, both of these species appear to be less than ideal for these studies and it is not know if either has the desired collision properties that are needed to reach Fermi degeneracy. Consequently, we have explored the possibility of using radioactive rubidum isotopes for such studies. In particular, recent theoretical calculations [BB] indicate that ^{84}Rb and possibly ^{86}Rb have favorable collision properties and both appear to be excellent candidates for Fermi degeneracy investigations. We have thus developed an experiment to trap ^{84}Rb (^{86}Rb) atoms in a TOP trap (as mentioned above) and to sympathetically cool them down to the Fermi degenerate regime using an overlapping cloud of ^{87}Rb BEC. A separate LDRD/ER proposal to undertake this experiment has recently been funded and within the last few weeks we have been successful in trapping ^{84}Rb and demonstrating the simultaneous trapping of 84Rb + 87Rb in a magneto-optical trap. This experiment promises new insight into the quantum mechanical nature of such weakly interacting Fermi degenerate systems which at a sufficiently low temperature are expected to form Cooper pairs and undergo a transition to a BCS-type superfluid state.

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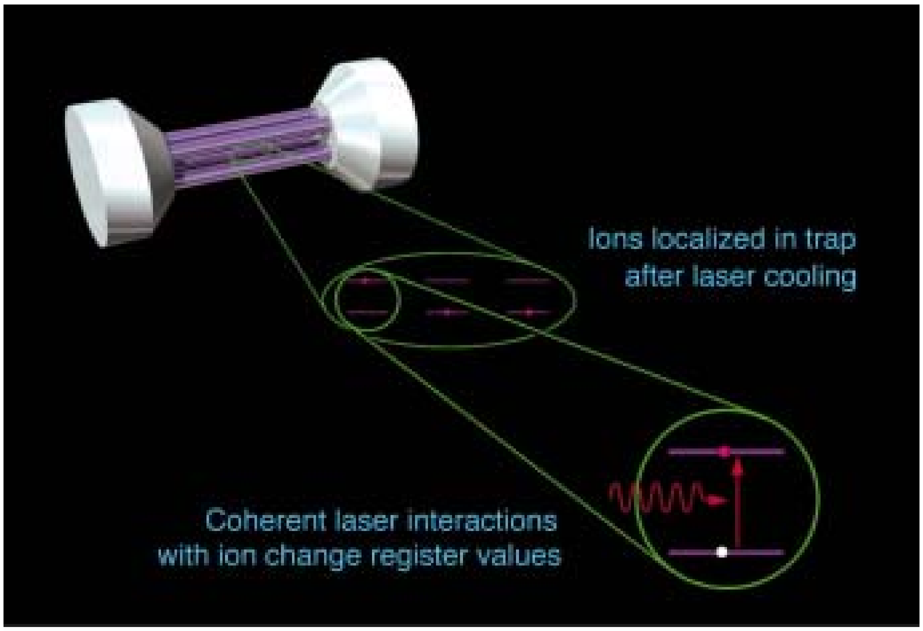

Figure 1. A schematic representation of an ion trap quantum computer.

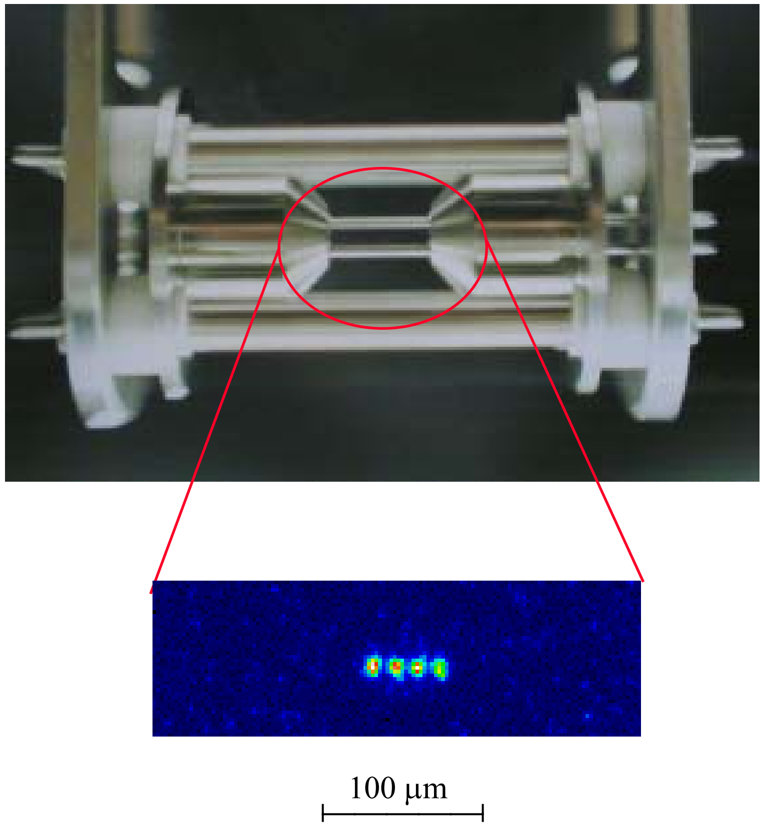

Figure 2: A string of four calcium ions localized by laser cooling in the LANL ion trap. The trapping region is about 1 cm long by 1.8 mm high. The image is formed by the ion fluoresence in the 397-nm cooling laser beam.

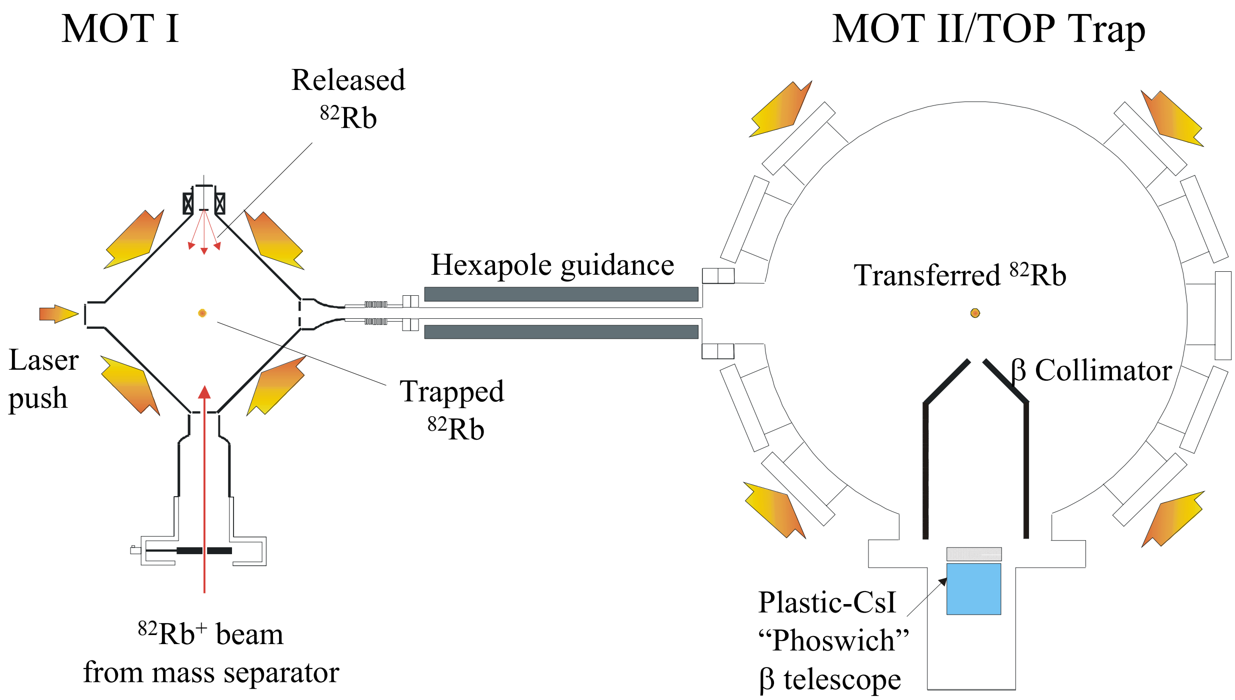

Figure 3: Layout of a double MOT system. $^{82}Rb^{+}$ ions are implanted into a ytterium foil located internally to the MOT I trapping cell. Upon heating the rubidium is release and trapped in MOT 1. After trapping the atoms are "pushed" over to the MOT II chamber through a hexapole quide tube. Retrapped in MOT II, the atoms are then optically pumped into the desired spin-aligned magnetic state and loaded into a TOP trap to measure the parity violating beta-decay of polarized 82Rb using a β-telescope detector.

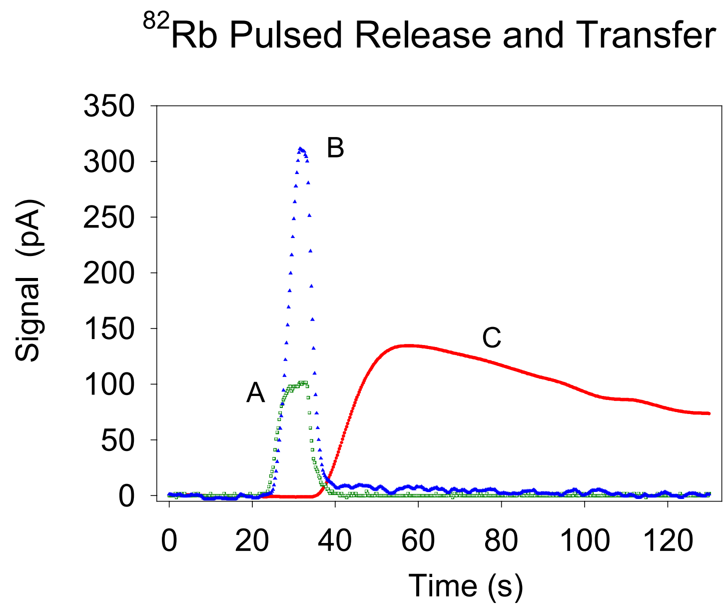

Figure 4: Pulsed release, trapping and transfer of ^{82}Rb in a double MOT system. Trace A gives the optical pyrometer readout of the foil temperature which is rapidly heated to a temperature of 700 ^{o}C for ~10 s. Trace B shows the lock-in trapping signal from MOT I. At the ~35 s mark, MOT I is switched off and the atoms are rapidly "pushed" using another laser beam over to MOT II where they are retrapped. Trace C shows the MOT II lock-in trapping signal.