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13. ABSTRACT (Maximum 200 words) This grant has supported an extensive effort aimed at using laser cooled Cs atoms trapped in optical lattices as qubits, and to demonstrate basic single- and two-qubit quantum gates. During the grant period we have made significant progress towards these goals. We have: (i) Refined or developed new essential diagnostic tools for atomic qubits, including Stern-Gerlach analysis and real-time QND measurements. (ii) Developed techniques to trap atomic qubits in 3D optical lattices, and to cool and initialize them in one of the logical basis states. (iii) Developed techniques for robust single-qubit manipulation based on plain or composite microwave pulses. In addition, new conceptual developments have occurred and our perspective on two-qubit gates and experiments to test them have evolved considerably. During the coming year we hope to demonstrate a non-separable two-atom phase gate based on controlled ground state collisions, and to observe a new phenomenon known as a trap-induced shape resonance that may provide new freedom to design high-fidelity quantum logic.				
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4. Statement of the Problem Studied

This grant has provided support for an extensive effort aimed at using laser cooled Cs atoms trapped in optical lattices as qubits, and to demonstrate basic single- and two-qubit quantum gates. During the grant period we have made significant progress towards these goals. We have developed essential diagnostic tools for atomic qubits, techniques to trap, cool and initialize them, and techniques for robust single-qubit manipulation. In addition, new conceptual developments have occurred and our perspective on two-qubit gates and experiments to test them have evolved considerably. In the “Summary of Results” section below, we describe each of these accomplishments in detail. For a review of our original proposal for neutral atom QIP see refs. [1] and [2], for a short review of our current perspective see ref. [3].

5. Summary of Results

Conceptual Developments

The basic premise of quantum information processing (QIP) in the neutral atom/optical lattice is that quantum information – qubits – can be encoded in pairs of hyperfine states in the atomic ground electronic manifold. Due to the generally weak and short range interaction between neutrals, such qubits can be collected in large ensembles without perturbing each other. Long coherence times, well developed tools for microwave/Raman laser manipulation, and powerful cooling and trapping techniques make such atomic ensembles excellent candidates for quantum memory. On the downside, weak interatomic interactions make the implementation of two-qubit entangling gates *the critical element* of neutral atom QIP. Following our first proposal [1], we originally planned to encode two separate “species” of qubits, and to use the

state-sensitive nature of the optical lattice potential to transport one species relative to the other. This would allow us to bring pairs of qubits very close together, where a controlled interaction could be mediated by the dipole-dipole interaction induced by the trap light or a separate “catalysis laser”, and allow us to implement a non-separable two-qubit phase gate. It was well understood from the outset that the fidelity of such a gate is limited by radiative transitions to excited molecular states, and that such errors can be suppressed only by working with very tightly localized wavepackets in very deep optical lattices. A separate proposal by Cirac & Zoller [4] considered a simpler encoding and qubit transport scheme, wherein a qubit pair was brought together for a ground state collision only for one out of the four two-qubit logical basis states. This again allows the implementation of a non-separable two-qubit phase gate. In a seminal experiment Bloch, Hänsch and coworkers successfully used the Cirac-Zoller scheme to entangle strings of Rb atoms, but were unable to isolate two-qubit interactions and to systematically study two-qubit gate performance [5].

The atomic level structure of Cs – in particular the large hyperfine splittings – is a considerable advantage when cooling, trapping and manipulating atomic qubits. At the start of our project (2001), however, little was known about the collisional physics of Cs, and experts suspected that inelastic spin-flip collisions might prevent a Cirac-Zoller gate from operating. (In contrast, the favorable collisional physics of atomic Rb was established early on from work on atomic Bose-Einstein condensates). Dipole-dipole interactions between Cs atoms were better understood at the time, and detailed modeling by our very close theory collaborators in the group of I. H. Deutsch at the University of New Mexico led to predictions of dipole-dipole gate fidelities in excess of 0.9, for optical lattice depths that seemed marginally feasible in the laboratory [6]. This was the main rationale behind our original focus on Cs dipole-dipole gates in very deep and tightly confining lattices. In the past few years, Deutsch and co-workers have studied Cs ground state collisions in much greater detail. This has led to quantitative predictions for the likelihood of inelastic spin-flip collisions in a Cirac-Zoller gate for Cs, and indicated that such a gate might function with fidelities as good as 0.99. Equally important, this work has identified a new collisional phenomenon known as a trap-induced shape resonance, wherein the light shift in an optical trap is used to tune a trap state into resonance with a bound molecular state [7]. The result is much stronger molecular interactions at larger interatomic separations, plus extra freedom to “engineer” the precise details of the collision. Further developments are necessary, but we are hopeful that this will allow the design of gate protocols that are more robust to errors, such as imperfect control of the atomic center-of-mass degrees of freedom. For these reasons we have shifted our current goals towards the demonstration of Cirac-Zoller type gates and the observation of trap induced shape resonances. It is worth noting that trap induced shape resonances become important when the ground state scattering length is comparable to the extent of the trap ground state, a condition easily reached with Cs even in quite shallow lattices but out of reach for Rb except in lattices that are much deeper than currently possible. The prospects of working at moderate lattice depths removes a very considerable restraint on the experiment, and has been a key element in our most recent progress on single-qubit control.

Diagnostic Tools

Good diagnostic tools are extremely important when one seeks to implement accurate quantum state preparation and control in a new physical system. The development of such tools

has consistently proven one of the most important enablers for this project. Various types of time-of-flight (TOF) measurements have long been a workhorse of cold atom research. In our setup we can easily and accurately measure the momentum distribution of an atomic sample along the vertical axis by releasing the atoms, letting them fall under gravity, and observing the distribution of arrival times at a probe beam located ~ 5 cm below the cooling and trapping region. From the momentum distribution we can determine the degree of vibrational excitation and the ground state population in our optical lattice traps, with accuracies better than a few percent. Unfortunately our setup does not allow us to use TOF analysis to access the horizontal degrees of freedom with similar convenience and accuracy, a shortcoming which has so far prevented us from diagnosing and optimizing our qubit preparation as well as we would like.

Over the past several years we have steadily improved our use of TOF analysis to access hyperfine spin degrees of freedom. These measurements are cold-atom versions of the classic Stern-Gerlach experiment - we let the atoms fall in a strong magnetic field gradient and observe the separate arrival time distributions for atoms with different magnetic quantum number m_F . Using probes tuned to the $F = 3 \rightarrow F'$ and $F = 4 \rightarrow F'$ transitions we can further separate the signals from atoms in the $F = 3, 4$ hyperfine manifolds, for straightforward and accurate measurements of all magnetic populations in the entire ground manifold. This is a very powerful way to optimize optical pumping or diagnose problems such as leakage of population outside the qubit basis states. In the past we have even used the technique to perform complete quantum state tomography in a hyperfine manifold of given F . For a detailed description of cold atom Stern-Gerlach analysis, see ref. [8].

While Stern-Gerlach analysis yields unprecedented and easy-to-interpret information about the ground hyperfine degrees of freedom, it is poorly suited as a tool to observe dynamics in real time. We have used Stern-Gerlach measurements to track qubit Rabi oscillations, but this requires a separate run of the experiment, with TOF data acquisition and analysis, for each sampling point. As a result, mapping out e. g. a spin-echo pulse sequence has required a full days work – clearly impractical when we seek to perform a simultaneous many-parameter optimization of the optical lattice trap and a composite-pulse single-qubit gate. We have solved this problem by developing and implementing a continuous, non-destructive optical probe of atomic pseudo-spins. The technique originally grew out of NSF-funded effort to use Faraday rotation of a probe beam to perform real-time measurements of the z -component of a hyperfine spin-angular moment [9,10]. As part of that project we developed a thorough understanding of the full tensor interaction between alkali atoms and optical probe or trapping fields, and leveraged that knowledge to engineer a coupling between the z component of the Stokes vector (polarization ellipticity) of a probe beam and the σ_z component of a qubit pseudo-spin. A measurement of the probe ellipticity then yields a quantum non-demolition (QND) measurement of σ_z , and can be made non-perturbing by tuning the probe to one of two “magic” frequencies where the probe-induced light shift is identical for both qubit states. Ref. [11] describes the measurement technique in more detail, and reports on its use to observe Rabi oscillation of a qubit encoded in the $F = 3, 4$, $m_F = 0$ atomic clock doublet in Cs. We have made extensive use of the technique to track the time evolution of qubits in the Cirac-Zoller encoding scheme, ($|0\rangle = |F = 3, m_F = 3\rangle$, $|1\rangle = |F = 4, m_F = 4\rangle$), and to evaluate the fidelity and robustness of composite-pulse single-qubit gates (see below). This effort will be reported in an upcoming publication.

Because we have found real-time, non-destructive measurements to be absolutely crucial to the evaluation and optimization of quantum information components and protocols, we have invested a modest effort in the development of such a tool also for quantum state tomography. In Ref. [12] we and our theory collaborators propose the use of continuous, optical probe measurements to experimentally reconstruct the density matrix for a spin ensemble, in a way that in principle can be both real-time and non-destructive. The basic idea is to perform a continuous, real-time measurement of some observable associated with the ensemble-averaged hyperfine spin-angular momentum, while at the same time using the tensor light shift and a time-dependent magnetic field to drive the atomic spins. Because one can implement arbitrary unitaries, it is possible to use a carefully designed evolution to continually map new information about the original quantum state onto the measured observable. Provided the system is sufficiently controllable to explore all of state space before decoherence sets in, one can then in principle determine the initial density matrix from the measurement record. We are now working to implement the method in the laboratory, as part of NSF and ARO/ARDA funded projects.

Atom Trapping in Far-Off-Resonance Optical Lattices

The use of optical lattices to trap and move atomic qubits is an integral part of most proposals for neutral atom QIP, and has been a consistent theme throughout this project. We have purchased and set up an MBR 110/Verdi V10 Titanium Sapphire laser system, with sufficient single-mode output power to form the deep and far-detuned optical lattices required for QIP. We have set up 3D optical lattices consisting of three 1D optical lattices of slightly different optical frequencies (to avoid interference between the component lattices). These lattices have been routinely loaded with Cs atoms from a conventional magneto-optic trap/optical molasses source, at densities corresponding to one atomic qubit per $\sim 10^2$ lattice sites. After loading, atom numbers typically decay with lifetimes of several hundred ms, while the populations of individual hyperfine states relax in several tens of ms. These timescales are consistent with the rate of heating and optical pumping in deep lattices with detunings of order 100 GHz.

It is of key importance that we be able to precisely measure and control the lattice parameters, in particular the mechanical oscillation frequency in the lattice microtraps along each of the three lattice dimensions. We have routinely used resonant parametric heating of the trapped sample to determine the trap frequency along the vertical direction, and found excellent agreement with calculations based on lattice beam intensity and detuning. While accurate, this method does not provide access to the horizontal trap frequencies, nor does it provide a useful real-time tool to diagnose and minimize the spread of trap frequencies in an inhomogeneous lattice. We now use microwave spectroscopy to measure the AC Stark shift of the qubit transition frequency in the presence of one or more of the 1D lattices, from which the trap frequencies can be readily determined.

To be used for QIP, an optical lattice setup must lend itself to precise manipulation of both center-of-mass and spin degrees of freedom. In alkali atoms the ground hyperfine angular momentum comes with a magnetic moment of one Bohr magneton, making spin states relatively sensitive to magnetic fields. As an example, qubits in the maximally field-sensitive Cirac-Zoller encoding undergoes a transition frequency shift of $\sim 2.5 \text{ kHz/mG}$, and therefore require control of background and applied magnetic fields to much better than a mG . This is particularly

challenging because a complete sequence of lattice loading, qubit initialization and QIP operations requires complex, time dependent fields of widely varying magnitude and direction, which can result in problematic eddy currents and transient magnetization of vacuum components and other hardware. We are currently using a stainless steel vacuum chamber with non-magnetic windows, and external coils to apply control fields and cancel ambient fields. The design does result in undesirable transient behavior when fields are switched, but at a level which appears to be acceptable for now. Our entire experiment is synchronized to the 60 Hz power-line cycle, which ensures that the ambient fields can be adequately compensated during the few ms required for a quantum gate experiment. Better performance be achieved with a magnetically shielded system, but we have so far considered the accompanying loss of optical access to be unacceptable in a first generation research apparatus. Finally, much better control of the applied fields can be achieved if atoms are trapped in an all glass vacuum cell, as demonstrated in the setup designed and used in a separate project on quantum control in spin ensembles.

Raman Sideband Cooling & Qubit Initialization

During the first half of the grant period a major part of our effort was directed towards initialization of atomic qubits in our optical lattice. The goal has been to prepare atoms in the 3D ground vibrational state of the optical lattice potential associated with a single ground hyperfine state, with a fidelity that will be useful for tests of single- and two-qubit gate protocols. To this end we have employed a variation of the Raman sideband cooling technique developed in our original work, wherein the Raman coupling required for cooling is provided by the lattice potential itself and a magnetic field is used to tune the system to the “red” (cooling) sideband [13]. We have found that it is relatively straightforward to achieve substantial cooling with this approach, but quite challenging to tweak its performance to achieve very near unit population of the target state. This, we now believe, is mainly due to our lack of good diagnostic tools with which to simultaneously measure vibrational excitation along all three lattice dimensions. TOF analysis is readily used to measure excitation along the vertical dimension, and has allowed us to optimize cooling and achieve populations in the vertical ground vibrational state of $\sim 98\%$. If extrapolated to 3D this would correspond to ground state populations of $\sim 92\%$. Separate Stern-Gerlach measurements typically show $>95\%$ population in the $|F = 3, m_F = 3\rangle$ magnetic sublevel, for a total population of the $|F = 3, m_F = 3\rangle \otimes |n = 0\rangle$ target state of $\sim 90\%$. If true, this is probably quite good enough for initial experiments with Cirac-Zoller collisional gates. Unfortunately, we have so far been unable to perform accurate measurements of the vibrational excitation along the horizontal dimensions, and based on these we can set only a lower bound of $\sim 70\%$ on the 3D ground vibrational population. If this lower bound does in fact hold up, then the quality of our qubit initialization is probably insufficient for the demonstration of a high-fidelity two-qubit gate, at least of the Cirac-Zoller type gate where the collisional phase shift depends critically on the shape and extent of the center-of-mass wavepackets. We remain optimistic that Raman sideband cooling can be made to work as well for trapped neutrals as for ions, but have decided to postpone further efforts until a microwave spectroscopy-based direct measurement of the 3D ground vibrational population can be implemented. This problem is closely related to the development of robust control techniques for single-qubit manipulation, and now seems tractable in light of our recent progress on that front.

Robust Single-Qubit Gates

Our main focus during 2004-2005 has been to implement coherent manipulations of qubits on the Bloch sphere. The most recent results of this work has not been discussed in an annual progress report, and is therefore described in detail here. More details and results will be reported in a forthcoming publication. At the start of our grant period we envisioned that qubit manipulation would be accomplished with Raman laser pulses, in part because this seemed necessary to drive $\Delta m_F > 1$ transitions (required for the encoding used on our original QIP proposal), and in part because the Raman laser beams can be focused on a micron scale and so might lend themselves more easily to addressing individual atoms in a large-period optical lattice. For this purpose we designed and built a diode based Raman laser system consisting of a master laser frequency-modulated at 4.6 GHz (half the Cs ground hyperfine splitting), and two slave lasers injection locked to each their separate modulation sideband. However, as we shifted our focus to the Cirac-Zoller encoding ($\Delta m_F = 1$), we decided to drive the qubits directly with microwaves at the ~ 9.2 GHz transition frequency between the $F = 3, 4$ manifold. This eliminated the extra complication of a Raman laser system, and allowed us to focus immediately on composite-pulse techniques to implement robust and very high fidelity single-qubit gates.

To establish a baseline for single-qubit gate performance, we have worked for some time with qubits encoded in the $F = 3, 4$, $m_F = 0$ clock doublet of untrapped Cs atoms. This largely rules out degradations of the gate performance due to background magnetic fields and uncontrolled AC Stark shifts from the optical lattice potential. As it turns out, we are now able to control magnetic fields well enough that there is no discernible difference between the clock and Cirac-Zoller encodings in this respect, and our most recent work has therefore used the latter throughout.

The most basic single-qubit gate is a plain rotation of the Bloch vector by an angle θ about a predetermined axis. As a measure of our ability to do such rotations we typically prepare our qubit ensemble in the logical- $|0\rangle$ state and apply a series of successive π rotations around the x -axis of the Bloch sphere (X gates in QIP terminology). We define the fidelity of n successive gates as the overlap of the actual and target states, $F = |\langle \psi | i \rangle|^2$, where $|i\rangle, i = 0, 1$ is one of the logical basis states. A series of successive plain X gates is simply Rabi oscillation between the qubit basis states, and the fidelity of a sequence of gates can be determined directly from the time dependent populations of those states. Fig. 1 shows continuous optical probe measurements of the logical- $|1\rangle$ populations, averaged over an ensemble of qubits that are either untrapped or trapped in a lattice. Several aspects of these data sets are worth noting. First, there is no simple way to determine what absolute signal level correspond to unit population in one or the other qubit basis state. Secondly, even if this calibration problem is addressed, the measurement signal-to-noise ratio (though quite good) is insufficient to reliably detect errors below 10^{-2} in a single gate operation. This is the fundamental motivation for considering successive gate operations. In practice we extract a fidelity estimate by fitting the observed signal to a realistic model for an ensemble of Rabi oscillating qubits. The model accounts for expected spatial variations in the microwave power and effective microwave detuning (caused by magnetic fields or AC Stark shifts) across the ensemble, and includes among the free parameters χ (resonant Rabi frequency), $\delta\chi$ (rms spread in χ), Δ (detuning) and $\delta\Delta$ (rms spread in Δ). Also included in the model is the effect of optical pumping due to the scattering of probe light, which causes both the signal amplitude and mean to decay on long time scales. This decay can be determined

independently and does not enter as a fit parameter. Based on fits to Rabi oscillations we estimate $<0.5\%$ spread in the microwave power, whereas the spread in detuning is $\sim 1\%$ for free atoms and $\sim 10\%$ for atoms trapped in a lattice. Once these parameters are known we can then determine the fidelity of a *single* plain X gate, including degradation due to the errors (spread) in microwave power and detuning across the ensemble. This yields a fidelity estimate of $F = 0.9998$ for free atoms, and $F = 0.988$ for atoms in the lattice. We are currently in the process of obtaining good error bars for these estimates. It must be noted that these values are based on a two-state analysis. In reality the microwave field will off-resonantly drive transitions to other magnetic sublevels in the ground manifold. We have measured the Rabi frequencies

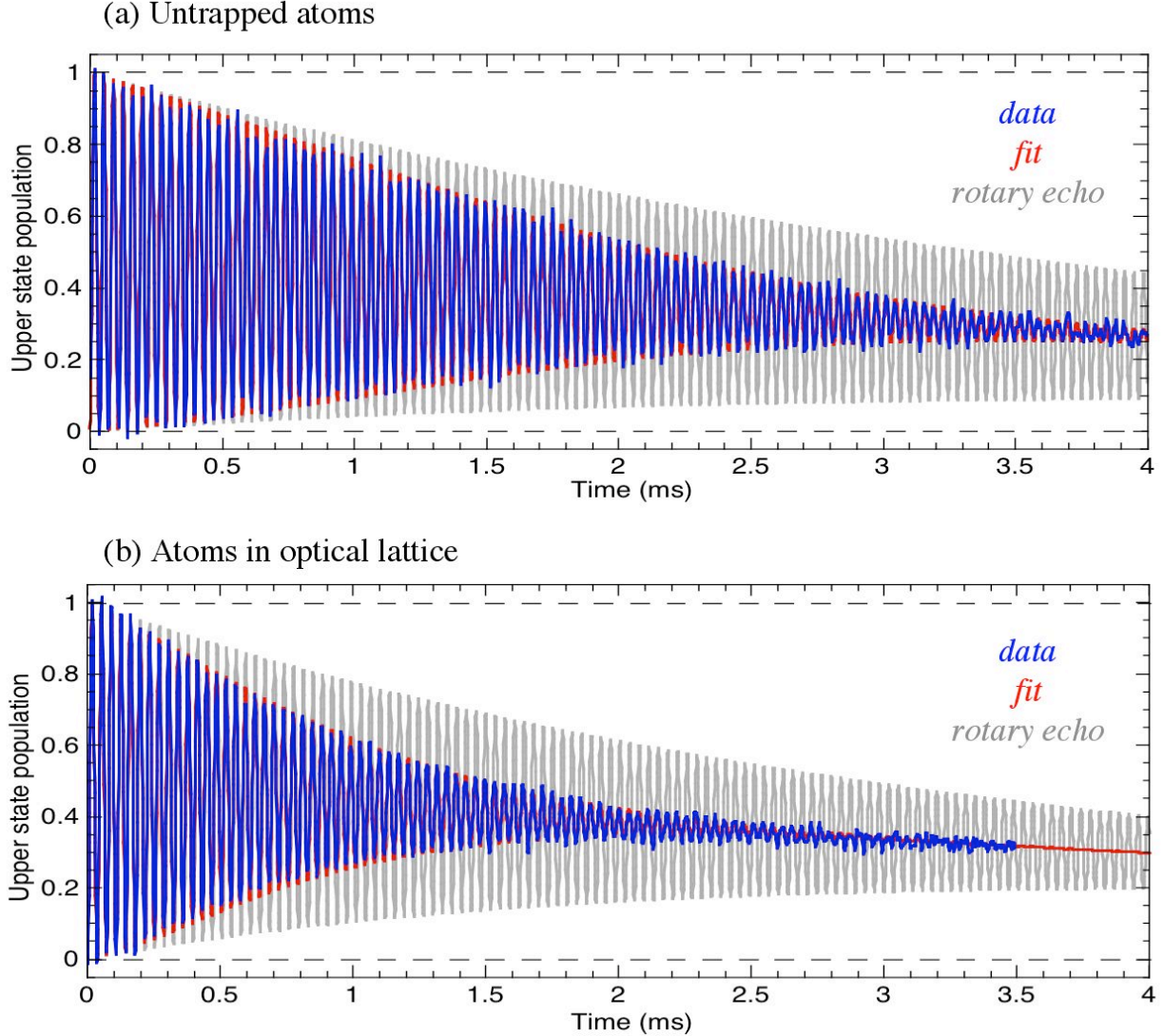


Figure 1. (a) Rabi oscillations of untrapped qubits. (b) Rabi oscillations of qubits trapped in a lattice with an oscillation frequency of ~ 40 kHz and a detuning of ~ 130 GHz. Blue: data from a continuous QND measurement of the population in the logical- $|1\rangle$ state. Red: best fit, including ensemble inhomogeneities and decoherence from optical pumping. Gray: Fit to a 2π rotary echo signal for identical parameters.

and detunings for these transitions, and estimate that less than 10^{-3} of the populations leak to these states during the operation of an X gate.

In the absence of probe or lattice light, the fidelity degradation of a plain X gate is dominated by errors in the microwave power and detuning, predominantly in the form of spatial variations across the qubit ensemble. It is well known from NMR that such errors can be compensated through the use of composite pulses, allowing one to implement single qubit gates in a robust fashion. We have implemented a number of composite pulse schemes in our system, both to determine the underlying coherence times and to implement robust gates. One highly successful tool is the so-called 2π rotary echo, which consists of a series of successive 2π rotations around the x and $-x$ axes. One can show (and we have confirmed in our experiments) that this sequence compensates for errors in power or detuning in a highly efficient manner. Thus, a continuous optical probe measurement of the logical- $|1\rangle$ population becomes indistinguishable from Rabi oscillation in the absence of any inhomogeneities. The grey lines in fig. 1 are fits to such rotary echoes, and provide a reliable experimental measure of the decoherence due to photon scattering from the probe and optical lattice. Extrapolating such measurements to zero probe power, we have estimated our coherence times to be at least 20 ms for untrapped qubits (at that point the atoms have fallen out of the probe beam), and ~ 5 ms for qubits trapped in an optical lattice (fig. 2). We do not believe the ~ 5 ms coherence time for trapped qubits to be in any way fundamental, and are now working to track down and remove the cause.

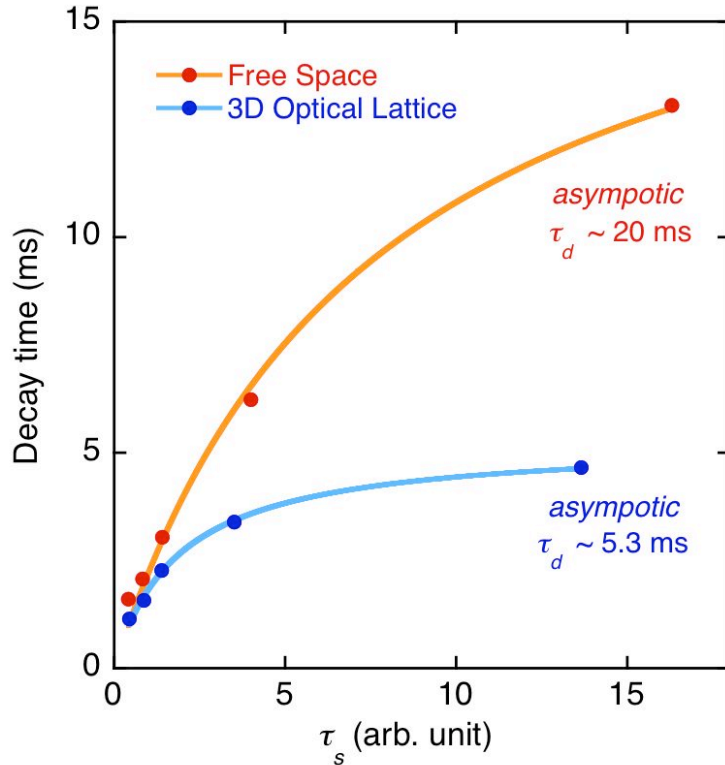


Figure 2. Decay time constants for the rotary echo signal as function of probe photon scattering time (in arbitrary units), for free and trapped atoms. Fits to the data indicate coherence times of ~ 20 ms and ~ 5 ms, respectively.

To improve gate performance in the optical lattice we have implemented several well known universal composite pulses, including CORPSE (Compensation for Off-Resonance with a Pulse Sequence) and SCOFULOUS (Short Composite Rotation for Undoing Length Over and Under

Shoot) [14]. The CORPSE sequence improves tolerance against detuning errors, and is expected to compensate for the significant spread in effective detuning that occurs in an optical lattice. We are in the process of completing a detailed study of CORPSE based X gates, along the lines described for plain pulses above. Preliminary indications are that this can produce gate fidelities around 0.999, which is more than adequate for the foreseeable future. The SCROFULOUS sequence improves tolerance against microwave power and timing errors, which are not a major problem in our setup. Furthermore, it has proven difficult to evaluate the fidelity of SCROFULOUS-based gates from multiple- X gate sequences, as these are similar to 2π rotary echoes and prevent pulse errors from accumulating.

Continuing Research Plans

Our considerable success with composite-pulse microwave manipulation suggests a number of interesting applications in our system. We have discussed robust pulse techniques with experts in the field (Navin Khaneda, Isaac Chuang), and are beginning to appreciate the extraordinary power of the underlying tools for quantum control. As an example, it appears straightforward to design microwave pulses that have good immunity against errors in both Rabi frequency and detuning, and at the same time sharply suppress off-resonance transitions to states outside the qubit basis. The performance of such pulses is constrained only by the overall pulse duration, and optimal solutions can be derived for situations when this is limited by decoherence. One can also consider the application of control theory to the problem of reliably addressing individual atoms in a lattice. In such an approach a focused laser beam might be used to locally shift the qubit transition frequency into resonance with a driving microwave field, and a designer pulse used to implement a desired rotation on a particular target atom while leaving the neighbors untouched. We intend to pursue further research in various aspects of quantum measurement and robust control as part of projects funded by ARO/ARDA, ONR and NSF.

Our most important goal for the coming year is to apply the laboratory techniques developed so far to an experiment aimed at demonstrating a Cirac-Zoller type phase gate, and hopefully observe the existence of trap induced shape resonances. We plan to detect collisional phases by “inserting” a controlled collision in one arm of a simple atom interferometer/Ramsey interrogation. This is essentially the method used by Bloch and Hänsch in [15,5], but with a few key differences. First, we are working with a highly underfilled lattice, where only $\sim 1\%$ of atoms in the ensemble will have collisional partners. With high-fidelity microwave pulses, it is straightforward to design the Ramsey interrogation so that “un-paired” atoms start and end up in the logical- $|0\rangle$ state with very high fidelity, while those who undergo pairwise collisions end up with measurable probability amplitude in the logical- $|1\rangle$ state. This will allow us to detect the signal from pairs without any substantial background from un-paired atoms. At the same time the occurrence of atom “triplets” is of order $\sim 10^{-4}$ and can be ignored, thereby eliminating the longer atom-chains that complicated interpretation of the Bloch-Hänsch experiment. All major hardware for this experiment was acquired as part of this grant, and we are hope to complete the project with modest support currently received from ARO/ARDA via subcontract from NIST.

6-2. Listing of Publications

(a) Refereed papers

- A. Silberfarb, P. S. Jessen and I. H. Deutsch, *Quantum State Reconstruction via Continuous Measurement*, Phys. Rev. Lett. **95**, 030402 (2005).
- P. S. Jessen, I. H. Deutsch and R. Stock, *Quantum Information Processing with Trapped Neutral Atoms*, Quant. Inf. Proc. 3, 15 (2004).

Publications in non-refereed journals

- H. Deutsch and P. S. Jessen, *Quantum Information Processing in Optical Lattices: Cold Atomic Qubits in a Virtual Crystal of Light*, IEEE LEOS Newsletter **16**, No 2, 3 (2002).

(c) Manuscripts presented at meetings but not published

- P. S. Jessen, *Weak Optical Measurement and Control of Atomic Spin Ensembles*, 2005 meeting of the APS Division of Atomic and Molecular Physics, Lincoln, Nebraska, 17-21 May 2005. (Invited)
- B. Mischuck, W. Rakreungdet, and P. S. Jessen, *Robust Manipulation of Neutral Atom Qubits*, 2005 meeting of the Division of Atomic and Molecular Physics, Lincoln, Nebraska, May 17-21, 2005.
- G. A. Smith, A. Silberfarb, and P. S. Jessen, *Density Matrix Reconstruction of a Large Angular Momentum by Continuous Weak Measurement on Cold Cs Atoms*, 2005 meeting of the Division of Atomic and Molecular Physics, Lincoln, Nebraska, May 17-21, 2005.
- S. Chaudhury, G. A. Smith, K. Schulz, and P. S. Jessen, *Continuous Measurement of the 133 Cs Clock Transition Pseudo-spin*, 2005 meeting of the Division of Atomic and Molecular Physics, Lincoln, Nebraska, May 17-21, 2005.
- P. S. Jessen, *Elements of QIP with Trapped Neutrals at the University of Arizona*, NIST Workshop on Quantum Information with Optically Controlled Neutral-Atom Qubits, Gaithersburg, Maryland, 28-29 April 2005.
- G. A. Smith, S. Chaudhury and P. S. Jessen, *Probing the Spin Degrees of Freedom of Cold Atom Ensembles*, Seventh Annual SQuInT Workshop, Tucson, Arizona, February 18-20, 2005. (Invited)
- P. S. Jessen, *Continuous Optical Measurement and Control of Atomic Spin Ensembles*, PRACQSYS'04, California Institute of Technology, Pasadena, California, 21-24 August 2004. (Invited)
- P. S. Jessen, *Optical Measurement and Control of Atomic Spin Ensembles*, QUEST 2004 Summer Workshop, Santa Fe, New Mexico, 9-13 August 2004. (Invited)
- P. S. Jessen, *Quantum Computing with Trapped Neutral Atoms*, Computing Beyond Silicon Summer School, California Institute of Technology, Pasadena, California, 7 July 2004. (Invited)

- P. S. Jessen, *Elements of QIP with Trapped Neutrals at the University of Arizona*, NIST Workshop on Quantum Information with Optically Controlled Neutral-Atom Qubits, Gaithersburg, Maryland, 10-11 June 2004.
- W. Rakreungdet, K. F. Lee and P. S. Jessen, *Quantum Control of Atomic Qubits in a 3D Optical Lattice*, 2004 meeting of the Division of Atomic and Molecular Physics, Tucson, Arizona, May 25-29, 2004.
- P. S. Jessen, *Errors in Neutral Atom QIP*, Workshop on Scalable Quantum Information Processing via Error Control, Chicago, Illinois, 7 May 2004. (Invited)
- P. S. Jessen, *Coherent Manipulation of Trapped-Atom Qubits: Progress Towards Optical Lattice QIP*, DARPA QUIST PI Meeting, Chicago, Illinois, 3-6 May 2004.
- W. Rakreungdet, K. F. Lee and P. S. Jessen, *Initializing and Manipulating Atomic Qubits in a 3D Optical Lattice*, Fifth Annual SQuInT Workshop, San Diego, California, February 20-22, 2004. (Poster)
- P. S. Jessen, *Towards a Trapped-Atom Quantum Processor*, DARPA FoQuS Workshop, Falls Church, Virginia, 28-29 January 2004.
- P. S. Jessen, *Two-qubit QIP: Fantasy vs. reality. Optical Lattices (QIP with Trapped Neutral Atoms)*, DARPA QUIST PI Meeting, Ft. Lauderdale, Florida, 12-14 November 2003. (Invited)
- P. S. Jessen, *Qubit Initialization and Manipulation in an Optical Lattice*, DARPA QUIST PI Meeting, Beverly Hills, California, 23-25 June 2003.
- W. Rakreungdet, L. Harrison and P. S. Jessen, *Sideband Cooling and Qubit initialization in a 3D Optical Lattice*, 2003 meeting of the Division of Atomic and Molecular Physics, Boulder, Colorado, May 20-24, 2003.
- W. Rakreungdet and P. S. Jessen, *Raman Sideband Cooling in a 3D Optical Lattice*, Fifth Annual SQuInT Workshop, Santa Fe, New Mexico, February 7- 9, 2003. (Poster)
- P. S. Jessen, *Qubits and Quantum Gates in Optical Lattices*, Joint IPAM/MSRI Workshop on Quantum Computing, Los Angeles, California, 21-23 October 2002. (Invited)
- P. S. Jessen, *Elements of a Neutral Atom Quantum Processor*, DARPA QUIST Meeting, Cambridge, Massachusetts, 9-13 September 2002.
- P. S. Jessen, *Elements of a Neutral-Atom Based Quantum Processor*, DARPA QUIST Kickoff Meeting, Dallas, Texas, 26-29 November 2001.

(d) Manuscripts submitted, but not published

- S. Chaudhury, G. A. Smith, K. Schulz and P. S. Jessen, *A Continuous Non-demolition Measurement of the Cs Clock Transition Pseudo-spin*, quant-ph/0506158, submitted to Phys. Rev. Lett. (2005).

7. List of all participating scientific personnel, including degrees earned.

Poul S. Jessen
K. I. Cheong
L. B. Harrison (graduate student) x
K. F. Lee (postdoctoral fellow) x
B. E. Mischuck (graduate student) x
W. Rakreungdet (graduate student) x
S. Thekkiniathu

8. Report of Inventions

None

9. Bibliography

- [1] *Quantum Logic Gates in Optical Lattices*, G. K. Brennen, C. M. Caves, P. S. Jessen and I. H. Deutsch, Phys. Rev. Lett. **82**, 1060 (1999).
- [2] *Quantum Computing with Neutral Atoms in an Optical Lattice*, I. H. Deutsch, G. K. Brennen and P. S. Jessen, Fortschritte der Physik **48**, 925 (2000).
- [3] *Quantum Information Processing with Trapped Neutral Atoms*, P. S. Jessen, I. H. Deutsch and R. Stock, Quant. Inf. Proc. **3**, 91 (2004).
- [4] *Entanglement of Atoms via Cold Controlled Collisions*, D. Jaksch, H.-J. Briegel, J. I. Cirac, C. W. Gardiner, and P. Zoller, Phys. Rev. Lett. **83**, 1975 (1999).
- [5] *Controlled collisions for multi-particle entanglement of optically trapped atoms*, O. Mandel, M. Greiner, A. Widera, T. Rom, T.W. Hansch, and I. Bloch, Nature **425**, 937 (2003).
- [6] *Quantum Logic for Trapped Atoms via Molecular Hyperfine Interactions*, G. K. Brennen, I. H. Deutsch, and C. J. Williams, Phys. Rev. A **65**, 022313 (2002).
- [7] *Quantum State Control via Trap-induced Shape Resonance in Ultracold Atomic Collisions*, R. Stock, E. L. Bolda, and I. H. Deutsch, Phys. Rev. Lett. **91**, 183201 (2003); see also Ph. D. Dissertation by Rene Stock
- [8] *Measuring the Quantum State of a Large Angular Momentum*, G. Klose, G. Smith, and P. S. Jessen, Phys. Rev. Lett. **86**, 4721 (2001).
- [9] *Faraday Spectroscopy in an optical lattice: a continuous probe of atom dynamics*, G. A. Smith, S. Chaudhury and P. S. Jessen, J. Opt. B: Quantum Semiclass. Opt. **5**, 323 (2003).
- [10] *Continuous weak measurement and nonlinear dynamics in a cold spin ensemble*, G. A. Smith, S. Chaudhury, A. Silberfarb, I. H. Deutsch and P. S. Jessen, Phys. Rev. Lett. **93**, 163602 (2004).
- [11] *A Continuous Non-demolition Measurement of the Cs Clock Transition Pseudo-spin*, S. Chaudhury, G. A. Smith, K. Schulz and P. S. Jessen, quant-ph/0506158, submitted to Phys. Rev. Lett. (2005)
- [12] *Quantum State Reconstruction via Continuous Measurement*, A. Silberfarb, P. S. Jessen and I. H. Deutsch, to appear in Phys. Rev. Lett. (2005).
- [13] *Resolved-sideband Raman cooling to the ground state of an optical lattice*, S. E. Hamann, D. L. Haycock, I. H. Deutsch and P. S. Jessen, Phys. Rev. Lett. **80**, 4149 (1998).

-
- [14] *Tackling systematic errors in quantum logic gates with composite rotations*, H. K. Cummins, G. Llewelly, and J. A. Jones, Phys. Rev. A **67**, 042308 (2003).
 - [15] O. Mandel, M. Greiner, A. Widera, T. Rom, T. W. Hansch, and I. Bloch, “Coherent Transport of Neutral Atoms in Spin-Dependent Optical Lattice Potentials”, Phys. Rev. Lett. **91**, 010407 (2003).