Chapter 1

Introduction

During my tenure at Berkeley, there has been a palpable shift in the ultracold atom "community" to progress from studies *of* Bose-Einstein condensates (BECs) to studies *with* them. While much work continues in the understanding of more exotic systems such as spinor condensates [1, 2, 3, 4, 5], lower dimensional systems [6, 7, 8, 9], dipolar BECs [10, 11], and bosons in lattices [12, 13], *scalar* Bose condensates are now primarily thought of as "sources" of coherent beams of ultracold atoms. This shift is analogous to the history of the laser, where what began as an object of research and rapidly became a ubiquitous component in the experimental physicist's toolbox. Some of the prominent work which makes use of a BEC as a bright source of ultracold atoms include measurements of fundamental constants [14], studies of sympathetic cooling of fermions [15] (which itself resulted in a secondary BEC of molecules [16, 17] and high-T_c fermionic superfluidity [18]), and even magnetometery [19].

The work described in this thesis should be considered firmly in this context, as while the early chapters of this thesis are concerned with the design and construction of an apparatus to make BECs, the remaining four chapters are concerned with how we used and studied ultracold atoms after their humble origins as a BEC in a simple magnetic trap. The last two chapters especially represent this "second generation" thinking, as the first experiments with loading ultracold atomic ensembles into a strongly coupled cavity QED system are presented.

1.1 Exploring Frontiers with Ultracold Atoms

To begin, we examine the state of matter that describes Bose condensates[1]. A gas of N bosons at zero temperature forces all particles to occupy the same spatial wavefunction $\phi(\mathbf{r})$, under the Hamiltonian [20]

$$\mathcal{H} = \sum_{j=1}^{N} \left(-\frac{\hbar^2}{2m} \nabla_j^2 + U(\mathbf{r}_j) \right) + \mathcal{U}_o \sum_{j<k} \delta(\mathbf{r}_j - \mathbf{r}_k) \,, \tag{1.1}$$

where $U(\mathbf{r}_j)$ is the external potential and the point-like interaction strength is $\mathcal{U}_o$. We may also define the condensate wavefunction $\psi(\mathbf{r}) = \sqrt{N}\,\phi(\mathbf{r})$, and the energy of the system is then readily computed to be

$$E(\psi) = \int \left(\frac{\hbar^2}{2m} |\nabla \psi(\mathbf{r})|^2 + U(\mathbf{r}) |\psi(\mathbf{r})|^2 + \frac{N\mathcal{U}_o}{2} |\psi(\mathbf{r})|^4 \right) d^3\mathbf{r} \,, \tag{1.2}$$

where we assume $N \gg 1$. This equation is written as a functional on ψ, the complex conjugate of which can be exploited as a variational parameter subject to the normalization constraint $\int \psi^*(\mathbf{r})\psi(\mathbf{r})\, d^3\mathbf{r} = N$. With the chemical potential μ serving as the Lagrange multiplier which enforces particle conservation, the quantity $E - \mu N$ is minimized at a fixed chemical potential and we arrive at the Gross-Pitaevskii equation [22, 23]:

$$\left(-\frac{\hbar^2}{2m} \nabla^2 + U(\mathbf{r}) + \mathcal{U}_o |\psi(\mathbf{r})|^2 - \mu \right) \psi(\mathbf{r}) = 0 \,. \tag{1.3}$$

Extensions of this equation will be encountered in Chapter 5, but the crucial point is that the Bose-condensed system is a product of N identical wavefunctions $\psi(\mathbf{r})/\sqrt{N}$, with the form of $\psi(\mathbf{r})$ given by Equation (1.3) and the particular experimental parameters $U(\mathbf{r})$ (determined by the external trapping potential), $\mathcal{U}_o$ (determined by the atom/molecule of the system), and N (number of particles in the condensate). Regardless of the value of the particular experimental parameters, the solution to Equation (1.3) can be written, in complex polar form, as

$$\psi(\mathbf{r}) = \sqrt{n(\mathbf{r})}\, e^{i\vartheta(\mathbf{r})} \,, \tag{1.4}$$

where $n(\mathbf{r})$ is the density and $\vartheta(\mathbf{r})$ is the spatially varying phase. That a single phase function characterizes the system is the basis for considering a BEC as a coherent source.

[1] As the statistical mechanics of BECs has been explored extensively elsewhere [20, 21], we refer the reader to these references for theoretical justification of the statements and equations in this subsection.

In most instances, one seeks to maximize atom number to enhance the experimental signal[2]. This leaves just $\mathcal{U}_o$ and $U(\mathbf{r})$ as an experimentalist's tuning parameters. $\mathcal{U}_o$ is adjusted by either choosing a boson with the desired scattering properties [26] or cleverly adjusting the interactions between atoms/molecules with external fields [27]. This thesis is, to a degree, a story of the second approach as we employ various new containers $\mathcal{U}(\mathbf{r})$ to house a condensate of the most commonly used atom for BEC experiments, rubidium-87.

As is the case with the vast majority of experimental ultracold atom experiments, our rubidium BEC is *formed* in a harmonic trap:

$$U(x_1, x_2, x_3) = \frac{1}{2}m\left(\omega_1^2 x_1^2 + \omega_2^2 x_2^2 + \omega_3^2 x_3^2\right). \tag{1.5}$$

As will be described in this thesis, the magnetic trap used for this work has an uncharacteristically wide tuning range for the trapping frequencies $\omega_1, \omega_2, \omega_3$, but the BEC is nonetheless ordinary in its beginnings. There are certainly more interesting containers than that of Equation (1.5), including optical lattice potentials [28], quasi-lower dimensional trapping [9], and even a box-like potential [29].

In this line of thinking, two "new" potentials will concern this thesis. The first is a circular waveguide, with an idealized potential of the form

$$U(z, \rho) = \frac{1}{2}m\omega_z^2 z^2 + \frac{1}{2}m\omega_\rho^2(\rho - \rho_o)^2, \tag{1.6}$$

expressed in (z, ρ, θ) cylindrical coordinates. This is harmonic about the waveguide center, but perfectly flat in the θ dimension. Quantum degenerate matter in this system must obey periodic boundary conditions, a consequence of Equation (1.6) representing a multiply connected geometry (as opposed to the simply connected geometry of Equation (1.5)).

The second "new" potential is perhaps more exotic than the first, with a form

$$U(z, \rho) = U_1\,\phi_1(\rho)\,\sin^2 k_1 z + U_2\,\phi_2(\rho)\,\sin^2 k_2 z, \tag{1.7}$$

also expressed in cylindrical coordinates. This is an equation for overlapping optical standing wave potentials, where $\phi_{1,2}(\rho)$ are the transverse mode functions, $k_{1,2}$ are the respective wavevectors, and $U_{1,2}$ are the optical potential depths (dependent on the light intensity, polarization, detuning from atomic resonance, etc.). There is nothing immediately exotic

[2] The work of Oberthaler *et al.* [24, 25] is a notable exception.

about this potential, as many studies of ultracold atoms in one-dimensional optical lattices were carried out over the last decade [30, 31]. The novelty of Equation (1.7) comes if one or both of the optical fields is sensitive to the quantized nature of the electromagnetic field. This comes about when the influence of a single photon is energetically relevant as compared to the other energy scales of the system. This is a case not found in free space, and manufacturing a system where the energy contribution per photon is relevant for an ultracold atomic system leads us to the following section.

1.2 Cavity Quantum Electrodynamics (CQED)

Some seventy years after Einstein's resurrection of the idea of corpuscular light, advances in lasers and non-linear optics allowed the exploration of correlation experiments with light [32] which definitively proved the existence of the photon, leaving "quantum optics" as the only viable theory of light. The detection of a single photon is usually[3] a destructive process whereby a photon is absorbed by some material and detected either through heat or electric current generation. While the creation and destruction of photons is integral to the theory of quantum electrodynamics, it remains dissonant with the more familiar quantum mechanical notion of unitary evolution of a system under a Hamiltonian.

At its core, cavity QED is the attempt to make the influence of single photons felt *coherently*, in that a quantum system undergoes unitary evolution due to the action of the quantized electromagnetic field. Typically this quantum system is an atom, though recent CQED experiments have utilized other quantum systems such as quantum dots [34] and superconducting circuits [35, 36]. As the quantum system is presumably sensitive to the electric field, e.g. through a Hamiltonian such as $\mathcal{H} = -e\hat{\mathbf{r}}\cdot\mathbf{E}$, the difficulty in realizing this goal is mainly one of scale. In free space the electric field of a monochromatic single photon is infinitesimally small, and cavity QED seeks a regime where the interaction between a photon and a quantum system is at least a significant, if not the dominant, part of the Hamiltonian evolution.

Interestingly, the idealized case of cavity QED is encountered immediately when the

[3]To date, only cavity QED has demonstrated the completely non-destructive detection of a photon [33]. High-energy photons may be detected without full absorption (e.g. Compton scattering), but the original photon is "destroyed" in lieu of another photon of lower energy.

quantization of electromagnetic field is considered theoretically, a brief treatment of which will be presented in Chapter 6. It is from this point that we begin to develop the theoretical framework necessary to motivate the use of ultracold atoms to explore novel many-atom cavity QED regimes.

1.2.1 Experimental CQED, ca. 2001

Reaching the strongly coupled CQED regime may be achieved by working with a dipole transition with large dipole moment d, utilizing a cavity of small mode volume V, or both. Pioneering work in the Haroche group [37] made use of superconducting cavities and large dipole Rydberg atomic states with microwave transition frequencies. Optical cavity QED involves the use cavities with very small mode volume; the fundamental work in this implementation has been led by Kimble *et al.* [38, 39, 40, 41, 42, 43], but numerous other groups have made important contributions in the last six years [44, 45, 46, 47, 48, 49, 50].

The mm-scale[4] optical cavities which have proven useful in this cavity QED incarnation had, at the time that the work presented in this thesis began, only been used with atoms delivered ballistically from laser-cooled thermal sources [38, 51]. Efforts to trap atoms inside a cavity was nearly operational [41], and other groups [49] were working on the delivery of atomic samples to optical cavities with far off-resonance optical traps (FORTs).

It is in this context that our experimental endeavor began in early 2002. In an attempt to make use of the established techniques of laser cooling, magnetic trapping, and evaporative cooling of atomic ensembles, we sought to use a magnetically trapped, ultracold gas as a reservoir of quantum objects for optical cavity QED. The central goal was the repeatable delivery of cold atoms to a strongly coupled cavity, allowing access to many unexplored regimes of cavity QED. The reliable delivery of many atoms, perhaps even precisely determined numbers of atoms, to a cavity could eliminate the stochastic nature of the current generation of cavity experiments. Single atom CQED could potentially be restored by a controlled promotion from weakly coupled states[5], allowing *multiple* CQED

[4]The millimeter-scale is in reference to the size of the optical element used to make the cavity, i.e. the outer diameter of the mirror substrate is $\sim 3\,\mathrm{mm}$. The optical *mode* has a scale better represented by 10's of μm, as this is the typical size scale of the cavity mode waist and length.

[5]The decoupling of the ensemble may be accomplished either by physical placement of the atoms in very

experimental cycles for each atom cooling cycle. Finally, with its single atom sensitivity, the cavity could be used as a new probe of many-body physics.

1.3 "E2" - A History

Upon my arrival at Berkeley in June 2001, James Higbie and Lorraine Sadler were already hard at work on the construction of the basic hardware for a Rubidium-87 BEC machine. While still a little disoriented after completing two years in West Africa with the Peace Corps (and somewhat inconvenienced by a persistent case of giardiasis), I began my work in the nascent Stamper-Kurn group on this first experimental effort. By luck of the draw, I got to tackle the implementation of the homemade external cavity diode laser (ECDL) systems used for rubidium laser cooling. My youthful dabblings left many dead diodes, PZTs, and circuit boards in my wake, but thankfully I stayed below the maximum allowable screw-ups to remain in the group. As 2001 gave way to 2002, Keshav Dani and I began the process of designing the second experiment (E2, as it came to be known). As we sketched out the design for the required magnetic trapping system (outlined in Chapter 3), we acknowledged that the millimeter scale magnetic trap was a substantial technical challenge requiring a few extra months work beyond that required to assemble a more standard design. While there were many scheduling underestimates and deadlines missed in my graduate career, none were as significant as the underbid time to construct what came to be known as the "millitrap." Throughout the many dark days of trial and error, I was blessed with an outstanding cadre of individuals who shared my agony on the millitrap project. Keshav and I worked through the summer and into the fall of 2002, a time when it dawned on all of us just how difficult this project was going to be. Into 2003, we were lucky enough to steal theorist Ken Brown away from the Whaley group for a few months, with the upshot that, together, he and I were finally able to put the first viable version of the millitrap into the chamber and achieve ultra-high vacuum conditions (UHV). I owe Ken Brown a special debt of gratitude, as not only was he a fantastic lab mate and natural physicist, but his ear for indie music and willingness to bring in mix CDs

weakly coupled parts of the cavity or outside the mode entirely. Utilizing internal states which are weakly coupled to the cavity is also possible, although the collective action of large ensembles can still significantly affect the cavity resonances even in the far-detuned limit.

packed with Pavement, The Pixies, and Guided By Voices opened up to me to the world of pretentious music criticism/snobbery, a religion to which I have since converted with a fundamentalist's zeal.

In 2003, E2 was very lucky to sign a first round rookie draft pick in Tom Purdy, who proved himself the consummate experimental physicist in every way. He suffered the musical dominance that Ken and I cast over 75 LeConte without complaint and, when Ken left for a post-doc at MIT, Tom signed on as the fourth (and thankfully last) grad student thrown at the millitrap project. With his eye for detail and impressive mechanical aptitude, we finally turned the tide on the project and, with the help of the pros in the Physics Machine Shop (most notably Dave Murai and the very missed Armando Baeza), we put together the second generation millitrap which now resides in the main science chamber of B167 Birge.

And, of course, while the operation the millitrap was a critical part of the experiment, parallel to this effort was the required assembly of an entire lab full of optics, electronics, computer control, and vacuum equipment. In the summer of 2003, E2 was again blessed with two incredible personnel additions. Kater Murch, renaissance man extraordinaire, arrived and immediately began proving his immense worth by assembling the power supply interlock system at a staggering clip. With this in place we were able to observe the lab's first collection of cold atoms in a magneto-optical trap (fed by a rubidium dispenser). As summer waned, the long-awaited arrival of E2's post-doc – Dr. Subhadeep Gupta – finally came to pass. With his "Deep"[6] expertise, the next few months involved an attempt to magnetically trap and transfer a significant population of cold atoms into the 1^{st} generation millitrap region. After much investigation and many depleted rubidium dispensers, we came to the conclusion at the end of 2003 that the current implementation of the system (a getter-loaded MOT[7] and vertical magnetic transfer from the paired quadrupole traps) was simply inadequate to deliver large populations of atoms to the millitrap. As the second generation millitrap was complete and ready for installation, we decided to take the opportunity for a major overhaul of the entire system. The rubidium dispenser was

[6] He also Deep-ly loves puns.

[7] Our work with the rubidium dispensers was not completely fruitless, as it resulted in the group's first experimental publication (KLM *et al.*, RSI **76**, 023106 (2005)) and is included in Appendix E.

eliminated in favor of an oven/Zeeman-slower system, the magnetic transfer coils were redesigned to provide tighter and more versatile trapping, we invested in more laser power via a home-built tapered amplifier system and, most critically, we changed the orientation of the entire vacuum system from a vertical transfer to the millitrap to a horizontal transfer. This proved a very fateful decision as, besides the factor of two improvement in field gradient, it inadvertently made possible the ultracold atom storage ring work presented in Chapters 4 and 5. This change was did have the downside of reducing the versatility of the CQED work in Chapter 6 and 7 due to the preclusion of long time-of-flight imaging out of the cavity, but on the whole the overhaul was a huge win for the experiment.

In the blindingly fast winter of 2003, E2 became nearly unrecognizable compared to its first incarnation. By the end of summer the atom number in the reworked MOT exceeded a few billion atoms and the new millitrap was installed and had passed all heat/field tests with flying colors. While we had lost Tom to E3 (the planned atom chip-based replacement for E2), the final roster of Kater, Deep and I plowed ahead into the fall. On October 28th, 2004, the millitrap captured its first collection of cold atoms in a spherical quadrupole trap, and within a month we had achieved a Bose-Einstein condensate of over a million atoms in an Ioffe-Pritchard trap. Just a few short weeks later, Kater and I (somewhat academically) lowered the current in the gradient bars and made the astonishing discovery that the atoms not only remain trapped but that they filled in a circular-looking shape. We quickly realized what the source of this circular trapping was (presented in Chapter 4), and in short order worked how this "quadrupolar ring" trap could be modified to produce a Bose condensate in the circular geometry. The subsequent nine months were unbelievably productive, with the millitrap proving well worth the trouble by resulting in four publications [52, 53, 54, 55] in the course of $1\frac{1}{2}$ years.

The design for the cavity system necessarily had occurred in parallel with the millitrap, predating Deep Gupta's arrival in the group. Working within the constraints of the mechanical pieces that I designed and that Dave Murai had constructed, Deep had assembled and tested the cavity in parallel to all of the the millitrap/ring work[8]. By fall of 2005, it was time to finally make E2 whole with the integration of the high-finesse optical

[8]Indeed, Deep's influence is felt throughout this thesis, but nowhere more so than in Chapter 6 where the experimental elements of the cavity system are discussed.

cavity system. In September, we officially closed the book on the ring trap and cracked the vacuum chamber to add the cavity (described in Chapter 6). By January 2006, the cavity system was functional and we were poised to finally realize the experimental goals laid out four years prior. We found reconfiguring the millitrap to make a time-orbiting potential (TOP) trap was the best method for this application. By May we were reliably transferring Bose-condensates of $40,000+$ atoms into the heart of the high-finesse optical cavity. With these early explorations we found even more uncharted territory when we discovered the efficient transfer of the magnetically trapped atoms to optically trapped atoms (bound by the red-detuned potential from the 850 nm cavity locking light). This was well into the wilderness of a completely new physical system, with tens of thousands of $\sim 1\,\mu$K atoms interacting with a strongly coupled cavity QED system. As discussed in Chapter 6, the atomic cooperativity[9] was over two orders of magnitude larger than any other reported system [49, 56]. The subsequent six months involved many all-nighters and Kingpin runs ("But the cavity is quieter at night!") in an attempt to get a handle on the system. As my graduate career draws to a close, E2's history is still very much being written, but with two papers on the verge of submission and two bulky chapters at the end of this thesis, the future looks as bright as it can when you're dealing with fluxes of only 10^4 photons/sec.

1.4 Outline

The structure of this thesis closely mirrors the chronology of my graduate work. I have been fortunate enough to have the opportunity to encounter a variety of physical systems in my graduate career, and the relative diversity amongst the chapters is reflective of this. The construction and operation of the hybrid BEC-CQED apparatus will be presented in chapter 2. The operation, performance, and capabilities of the most unique technical part of this apparatus, the "millitrap," will be presented in chapter 3. In chapter 4, the use of this device to form a circular magnetic waveguide for ultracold atoms will be discussed, as well as future prospects for utilizing this technique for Sagnac atom interferometry and Bose condensation of ultracold atoms in a fully circularized magnetic trap. A close

[9] The atomic cooperativity is a measure of the coherent evolution of the many-atom cavity system.

experimental and theoretical consideration of the state of the propagating atom laser in the circular waveguide is discussed in chapter 5, including a new technique for diagnosing atom beams which is not restricted to our particular experiment. In chapter 6, the theoretical basis for CQED with many atoms is outlined, and the relevant experimental elements necessary to access this system are detailed. Finally, in Chapter 7 the first experimental results from the BEC-CQED apparatus will be presented, with a look toward the future of many-atom cavity QED in the system described herein. Crucial design drawings, as well as the relevant publications for this work are included in the Appendices.