**Thesis argument map – Jacob Ross**

Noting that this work consists of four distinct but complete projects, the structure will vary from a traditional thesis. There are three complete measurements, and a report on the motivation and progress towards a project that was begun but eventually abandoned due to lack of resources. As such, there are three sections of the thesis - the introduction & background, the results of experiments in laser spectroscopy in Helium, and the results (& partial progress) of results in many-body physics with ultracold Helium. Each chapter will be somewhat self-contained, except where referring to concepts introduced in previous chapters. This structure may seem unconventional, but it seems impossible to construct a genuine unifying scientific motive. I would be happy to learn of a more parsimonious option. Instead, I will present the results in a narrative manner that loosely respects my original motivations for commencing this PhD: The emergence of complexity from simplicity. I am undecided whether, and how, to present an honest history behind what appears to be a fragmented collection of works with questionable motivation.

**Opening Hook**

In this thesis, we will get about as close to perfect stillness as is physically possible. The existence of zero-point energy - no quantum state can have precisely zero momentum - cements a simple fact: Nothing is stationary. Not to be deterred, I will describe measurements of ever weaker signals, converging on the determination of a wavelength for which matter becomes completely decoupled from light. I will describe detection of fluctuations in the vacuum of quasiparticles that emerge from a weakly interacting gas near zero kelvin, and then explore an emerging realm of experimental science describing strongly interacting systems whose dynamics pose fundamental challenges to classical notions of computability and complexity.

**Part I: Ultracold metastable Helium**

1. **General Background**

In this chapter, I provide a historical overview of the development of the field, and a minimal but sufficient discussion of the concepts required for all future chapters. I provide a summary of the context and contribution of each project. Details will be discussed in the relevant chapters as required.

1. Atomic theory, the death of classical physics, the quantum revolutions
2. Bose-Einstein condensation
   * Definition, history, key theory & experimental results
3. Ultracold atoms and metrology
   * Testbeds for our best theories
   * Gap: Historically bogus measurements, poorly constrained low-lying states
   * Contribution: QED is fine, but here are some cool techniques that leverage unique properties of Helium.
   * Gap: 413nm tuneout for test of QED
   * Contribution: QED is fine, but here is a cool new handful of measurement techniques.
4. Ultracold atoms for many body physics
   * Probing foundations of thermodynamics, exotic matter, and quantum simulation
   * Gap: Well, what happened in France?
   * Contribution: Theory might still be wrong, but it’s not \*that\* bad. Probably Bogoliubov is right, but something fishy happened here.
   * Gap: Momentum-space studies of strongly correlated gases, and why anyone would care (superfluidity perhaps)
   * Contribution: Well, it’s a work in progress, so will
5. **Getting to the ground state**

In this chapter, I describe the equipment I used throughout the projects described later in my dissertation, including:

1. The vacuum system
   * Architecture of the BEC machine
   * Environmental stabilization
2. Laser cooling and trapping
   * Basic atomic structure theory
   * Cooling and trapping techniques and their limitations
   * Optical molasses, Zeeman slowing, magneto-optical traps, magnetic traps, evaporative cooling
3. Diagnostics and detection
   * Ion production, Fluorescence imaging, absorption imaging, delay-line detector, atom lasers
4. Tunable laser system
   * Laser generation
   * Calibration, locking loop, Allan deviation
   * Beam control & alignment procedures

**Part II: Metrology**

1. **Precision measurement of weak electronic transitions in Helium**

Gap: Outstanding discrepancies between predictions of QED and experimental measurements (Martin, 1960; Luo, 201x; Vassen, 20xx)

Aim & scope: To constrain energy levels tied to the 23P2 state and the singlet-triplet interval in Helium, and to see how weak a transition we can actually measure.

Contribution: Constrain ionization energies of 53D and 51D levels to 150ppb, and 53S to 28ppb with novel (?) two-transition spectroscopic method with high sensitivity. Results consistent with predictions, correcting historical measurements. Detection of weakest electronic transition ever made in a neutral atom – results consistent with theory.

Method:

Excited-state transitions:

* Heating by two-photon scattering
* Illustrative model of evaporative cooling as transducer from initial temperature to final number
* Alignment method
* Experimental sequence
* Calibration
  + Polarization of light
  + Zeeman & Stark effect corrections
* Data processing pipeline

Forbidden transition:

* Line: Excitation & loss pathways
* Strength: Heating rate measurement
* Experimental sequences

Limitations, unresolved issues: Accuracy limited by wavemeter specs; potentially insufficient data to correct for Stark shift empirically, wavemeter drift

What next? Improved accuracy not necessarily meaningful, but technique could be applied to lower-lying states where theoretical uncertainties are greater

1. **Testing QED by measuring a tuneout wavelength in Helium**

Gap: Tuneout wavelengths are a test of QED independent of energy level predictions. The Helium atom is ideal because theory is more demanding than for Hydrogen, but has comparable accuracy. The 413nm tuneout is a particularly good choice. Previous measurements did not have the sensitivity to test QED.

Aim & scope: To measure the 413nm tune-out wavelength with sufficient accuracy to constrain QED.

Contribution: By using a new method for determining the frequency shift of a harmonic magnetic trap when disturbed by a probe beam, we present a method for precision determination of a tune-out wavelength. Our results are different from theoretical predictions but not with sufficient significance to

Method:

* Illustration of trap overlay method & ‘Clock shift’ analogy
* Three months of alignment?!
* Fixed-polarization tuneout determination
* Polarization dependence determination & extrapolation to nominal value
* Data processing pipeline

Limitations, unresolved issues: Sufficiently accurate to test QED, but accuracy limited by polarization calibrations

What next? Experiment could be improved (how?). The technique could be applied to ground state transitions in other elements.

Outlook for metrology in He\*

* Isotope shifts
* nuclear charge radii

**Part III: Many-body physics**

1. **Single-atom momentum spectroscopy of quantum depletion in a Bose-Einstein condensate**

Gap: Observations by another He\* lab in France were in disagreement with predictions based on otherwise exceptionally successful theories describing quasiparticles in condensates & their contribution to the single-particle momentum spectrum.

Aim & scope: I replicate the experiment to determine whether the theoretical description is accurate.

Contribution: I find evidence of quantum depletion that is consistently much closer to the theoretical predictions than the French result, but still statistically significantly different from the theory.

Method:

* Measurement & calibration sequences
* Data processing pipeline
  + Calibration, transformation & fitting
  + Empirical correlation functions

Limitations, unresolved issues: Sources of systematic error (stray counts, number mis-calibration, experimental drifts…)

What next? For more detailed study of the momentum spectrum, could use Raman spectroscopy (in-situ or during time of flight).

1. **Towards an optical lattice trap for ultracold metastable Helium**

Gap: In the field of quantum simulation, great effort has been expended towards quantum state control and readout via quantum gas microscopes. This only provides microscopic access to configurational information, less about quasiparticle formation or currents. Metastable helium promises a unique opportunity for *momentum microscopy*, opening a new avenue of study into quantum simulation of condensed matter.

Aim & scope: The aim of this project was to extend an existing apparatus quite considerably, achieve BEC, and then load and calibrate an optical lattice.

Contribution While this project is not complete, I contributed a great deal to the construction of the apparatus and laboratory infrastructure including

* Vacuum system extensions
* Two magneto-optical traps
* Construction and alignment of optical dipole traps
* Diagnostic imaging & data processing
* Simulation of small-scale system for preliminary predictions of experimental behaviour for calibration

Limitations, unresolved issues: The apparatus is currently in the hands of another group of students. There are potentially challenges maintaining vacuum quality, stabilization of the environment & mechanical vibration, and the loading sequence;

What next for this research/issue? Continued construction, addressing the issues above, studies of potential ways to extend He\* lattices (fermi-bose mixtures, quasirandom lattices)

**7. Conclusion**

The chapters are pretty self-contained. Not sure what belongs here.