Examiner's report on *"Metrology and Many-Body Physics with Ultracold Metastable Helium"* by Jacob A Ross.

The thesis presents a substantial body of experimental research on ultracold metastable He. It starts with laying down the context and significance of the work, then describes the development of the experimental setup, and presents solid experimental results, and the analysis thereof, in two different contexts. In the first context, which the author calls metrology, a number of atomic transitions in He* are studied either to measure for the first time, or with accuracies improved over previous measurements, the transition frequencies. The so-called tune-out frequencies for He* are then investigated with exquisite precision and over a broad range of settings for the probe light. In the second context, the phenomenon of quantum depletion in expanding He* Bose-Einstein condensates is studied, in particular the signatures of the large momentum tail in the expanding condensate, as predicted in the Tan-Bogoliubov theory.

The thesis opens with an 'Overview' chapter, giving historical perspectives on atomic spectroscopy, QED and BECs. Given that there was much scope for such details in the following chapters, I found these sections perhaps a bit overdone, but interesting to read at times.

Chapter 1 presents the theoretical background of a number of topics of relevance to the experiments. The classical theory of atom light interactions is outlined, and expressions for atomic polarizability, optical dipole potential and photon scattering derived. I believe some discussions of the real and the imaginary parts of the polarizability would be appropriate, especially their functional dependence on light detuning from an atomic resonance. A section introducing the helium atom and its properties follows. An atomic energy level diagram with singlet and triplet states would be very appropriate in this section as a reference point to fall back to. A section on the basic scattering theory with particular emphasis on He4 follows. The final section is a basic outline of the theory of Bose-Einstein condensation, the Bogoliubov theory and the Gross-Piteavskii description. Overall, the chapter is well organized and well written, but I found it very wordy at times – a more diagrammatic approach would probably be more useful.

Chapter 2 introduces the reader to the experimental apparatus. Section 2.1 describes the experimental steps to realize a magneto-optical trap and eventually trapping them in the Science chamber. The caption for Figure 2.1 is too long and very hard to follow- in particular in the absence of any subplot label, I did not know which of the beamlines I should be looking at while reading it. I believe that this section will confuse many of the intended readers (the examiners and the future grad students). I also suggest that the theory of laser cooling given in the subsection named 'Cooling Techniques' is moved to Chapter 1. Section 2.2 describes the laser systems used in the experiments and is generally well written. Section 2.3 describes the detection system. Although generally quite wordy, and there would certainly be scope to use diagrams to explain things better and save words, I still enjoyed reading this section.

Chapter 3 describes the progress towards an optical lattice trap for metastable Helium. Unfortunately I think that this chapter undermines the flow of the thesis. The motivation for optical lattices is given is the first two sections, which I think should have found their place in chapter 1 (theoretical background). Section 3 describes the painstaking work undertaken to realise the optically trapped helium atoms with a great deal of experimental details, while section 4 gives a brief outlook. I think sections 3 and 4 of this chapter would be best given as a chapter before the Conclusion (Chapter 7), as a prelude to the future experiments in this setup.

Chapter 4 is the first chapter in Part II of the thesis. The chapter is based on the publication ref. [353]. It describes precise measurements of the transition frequencies of five different transitions between the n = 2 to n = 5 levels, including a nominally forbidden singlet-triplet transition. These measurements have significance for the test of QED predictions, constancy of the fundamental constants such as the fine structure constant, and the so-called proton radius puzzle – which is presented in section 4.1. Section 4.2 outlines the measurement technique, and also presents results on the transition to the spin-forbidden singlet D state and spin-allowed triplet S state. Section 4.3 presents the measurements of the fine structure of the triplet D state. Section 4.4 describes the sources of line broadening and line shifts, as well the error budget. Section 4.5 draws some conclusions. I have some suggestions on this chapter

- In the measurement technique section, it is not clearly stated that probe and the pump beams are on simultaneously to induce atom losses. I think it should be made clear. Also the duration of the pulse (100ms) seems excessively long to me for the scattering rates (is the pump beam resonant?). It would be good to check.
- Is there an advantage of the measurement technique used here over direct optical detection of the atom number post/prior to evaporation? This should be discussed.
- Are BECs required, or just a convenient means to reduce broadening? This should be discussed.
- ‘Calibration shots’ are mentioned. The sensitivity of the final atom number with respect to the initial atom number can be tested by varying the former while keeping the evaporation sequence fixed. Is that what is meant by the calibration? Please explain.
- Can anything be said about the line strengths, maybe even the relative line strengths, of the transitions from these measurements?

Chapter 5 presents measurements on the precise determination of the tune-out frequency near 413nm in metastable helium. After some introductory remarks, section 5.1 discusses the concept of tune out frequencies and its relevance to the QED calculations to different orders. This is a very nicely done section, and I really liked figures 1 and 2 explaining the general physics (in general I missed figures like this in the thesis). Section 5.2 describes the measurement technique, which is based on combining an optical dipole trap with a magnetic dipole trap in their BiQuic setup followed by the trapping frequency measurements. The power of the dipole trapping beam is fixed, while its frequency is varied across the tune out frequency

– the assumption being that the at the tune out point, dipole beam will have no effect on the trapping frequency. The theory of the polarizability near the tune out point and its polarization dependence is given in two subsections, which I found to damage the flow of the chapter. I suggest that these discussions are either moved to chapter 1 (theoretical background) or given in a separate section in this chapter. Section 5.3 present the results of the experiments on tune out frequency measurements over a very wide range of polarization parameters, and validating the linear theory with these results. Section 5.4 present the analysis of the systematic effects in a thorough fashion, such as the polarization profile of the beam, birefringence of the glass cell, the effect of linearizing, and hyperpolarizability. I have a small number of additional suggestions on this chapter overall.

- It is not initially obvious why a purely optical trap, rather than a combined hybrid trap is more suited for these measurements. My understanding is that this is related to the spin-sensitive pulsed detection of outcoupled atoms from the magnetic trap. This should be motivated in the measurement technique section.
- Similarly the reason why BECs are used as opposed to cold thermal samples in these measurements should be explained.
- Is the anharmonicity of the dipole trap (inevitable for shallow dipole traps) a relevant factor?

Chapter 6, perhaps the most interesting chapter, presents experimental signatures and analysis of the evidence of quantum depletion in Bose-Einstein condensates with weakly interacting atoms in time-of-flight - contrary to the conventional hydrodynamic theory, and consistent with a previous experiment (ref 78). Section 6.1 introduces both the Bogoliubov and Tan theories of momentum distributions in the large k regime in the presence of quantum depletion in a condensate. In particular the N0n0 and k^-4 scalings for the total number of atoms in the large k tail are shown to be expected, although *in situ*. Section 6.2 presents the experimental and analysis procedures. Due to the limited range of k available during detection, it is argued that the fitting to a power law scaling leads to nonsensical values for the exponent, which seems to be a general problem where data range does not span several orders of magnitude for the independent variable. The upshot is that instead of the power law dependence, the focus was shifted to the dependence on N0n0. It was found that the dependence on N0n0 is valid, and independent dependence on N0 or n0 can be ruled out, lending evidence to the presence of quantum depletion. The observed slope however is found to be much larger that the predicted one. Numerical modelling of the dynamics of the momentum distributions during the time of flight is presented in section 6.3, this mapping from *in situ* to far-field is non-trivial due to host of reasons, so a conclusive evidence of quantum depletion is out of reach. However, the observations are found to be qualitatively consistent with the presence of quantum depletion, and the predictions also qualitatively consistent with the results presented in another study (ref 78). Section 6.4 summarizes the results.

- One small comment about physical models. The section of the power law fitting, perhaps unknowingly, gives the impression that one has to rule out all of the innumerably large alternative functional forms to establish one single functional form.

This of course is not true, as there is usually a very small of set of physically motivated functional form.

Chapter 7 gives a broad summary and overview of the thesis.

Overall, the thesis represents a substantial body of focused research work. The work presented precise measurements of a number of atomic transitions and a tune out frequency in He* and the phenomenon of quantum depletion in expanding condensates in a coherent manner and in significant depth and details. It has built considerably over the existing state of the affairs and produced a notable body of original results. I understand that three manuscripts based on the two parts of the thesis have emerged which are either published or are currently under peer-review. The thesis meets the international standard both in the contents of the research work and the presentation thereof. The candidate has clearly demonstrated a strong expertise of the subject and the due-diligence in reviewing the relevant literature and citing them where appropriate in the thesis (more than 450 entries in the bibliography is a testament to this).

Minor corrections

Chapter 2

- pp 44 line 5, “Bell-type” typo
- pp 45 line 4, “ molecular pumps” (extra fullstop)
- pp 45 line 5, fullstop missing
- pp 45 line 10, “faraday” should be Faraday. There are several more instances of this typo in this chapter.
- pp 45 line 13, LVIS should be defined.
- Fig.2.1 could be broken into two, each with a smaller caption.
- pp 59, line “…chapters ??..”

Chapter 3

- pp 91: “a.k.a.”
- pp 95: “faraday” should be “Faraday”
- pp 95: Is ETP the name of the manufacturer of the part?
- pp 103: “..1 0 ms delay ..” extra space in 10
- pp 104: “Unforunately..”, second para, second line, typo
- pp 104: “ NIM crate..” Is NIM defined?
- pp 106: First sentence: a larger range of momentum states does not necessarily mean a large phase space density.
- pp 107: “dipole fibers” is too colloquial.
- Fig 3.10 the caption and the diagram are too close to each other

Chapter 4

- pp.119 "…photon scattering signal…" what is it?
- Pp.121 "..transduction from photon scattering to…", the word "transduction" means something different.
- Fig. 4.3 Caption "Theory lines" do you mean the dotted lines? Also what are the vertical bars? Please mention that in the caption.
- pp121-122 The issue of the limitation of the dynamic range should be explained. Also the contradictory issues of SNR and saturation can be dealt with two different sets of measurements, right?
- Fig 4.3, 4.4, instead of cumbersome omega – 744…, could it be omega – omega_m, with omega_m defined in the caption and text to be 744…?
- Fig. 4.5. (b) axis label, there is a THz, MHz mix-up.
- The description of Fig.4.6 in the main text could be more elaborate.
- Pp130, The RF linewidth of the crystal oscillator of 300kHz sounds excessively large. Please check.
- Pp 126, uK in Roman font
- There are several instances in the chapter where a ½ space between a number and a unit is missing (e.g., 1.4kHz in page 126).

Chapter 5

- pp 134. An energy level diagram would be apt to help follow the text. "Section 5.3 gives…" needs a space.
- pp 135. "The tune-out frequency, where an atom does not interact with applied laser light…". It is not true that at tune out frequency atoms do not interact with light, in fact, the imaginary part of the polarizability does not cancel at the tune out point.
- Pp 136. "An equivalent model can be constructed using an LC circuit - the object of ultimate interest is the equation of motion,…" sounds very strange.
- Pp 151 "Connection to the experiment" should be emboldened (maybe just quote the section number).
- Secion 5.2.2: The first sentence is a bit unintelligible.
- Why was the probe dipole beam power not stabilized?
- Section 5.3.1. The exclusion criteria. Only one in 10000 shots was rejected, so was this necessary or useful?
- Fig 5.5 \omega_{net} is presumably an angular frequency, so one needs a 2\pi there.
- Pp 167. \chi^2/dof ~ 1 needs a space.
- Pp169: " 1140(20) MHz" should not italicized
- Pp 171: "also" twice..
- There are several of instances in the chapter where a ½ space between a number and a unit/symbol is missing (e.g., pp178 "~30\sigma).

Chapter 6

- The term "far-field" should be defined somewhere early.
- Fig 6.1: the caption encroaches into the diagram.
- Fig 6.1: where is the inset stated in the caption?
- Fig 6.2: Vertical scale unit should it be um^-3?
- pp192: "…alternative approach presented in section 6.2.1". It is section 6.2.1

- pp 194: “especially” spelt wrong.
- pp 197-198, the significance of p-value should be stated.