Probing and controlling ultra-cold matter with light

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Non-destructive probing using the Faraday interaction: Spatially resolved non-destructive imaging of atomic ensembles is typically achieved using the dispersive light matter interaction (see Ref. [1] for a review), which relies on an atomic sample imparting a phase shift on imaging light by either the scalar or vector part of the interaction Hamiltonian. In our work we employ the latter (Faraday effect) $H^{\text{vec}} \approx \frac{\alpha^{\text{vec}}}{\Delta}\hat{F}_z(\hat{N}_+ - \hat{N}_-)$, in which the ensemble spin in the direction of light propagation, $\hat{F}_z$ imparts a differential phase on the two circular components of light, $\hat{N}_+$ and $\hat{N}_-$. As a results, incoming linearly polarized light is rotated by an angle proportional to the atomic magnetization, $\Theta \propto \hat{F}_z$. Since $\hat{F}_z$ is a constant of motion, measurement of the light polarization realizes a QND measurement of $\hat{F}_z$.

Characterizing dynamics of ultra-cold clouds: We employ the so-called Dark Field Faraday Imaging (DFFI) (see Fig. 1(a) and Ref. [1]). With this we send $\sim$ 1us off-resonant light pulses through ultra-cold clouds. The destructivity due to spontaneous emission is $\sim 10^{-4}$. This has allowed for up to 2000 spatially resolved images of the same cloud to be acquired. As illustrated in Fig. 2(a) this has allowed for an extremely precise determination of the trap frequency from an oscillating cloud.

Feedback stabilization Recently, we have we prepare ultra-cold clouds that are stabilized in atom number below the $\sim 10^{-3}$ level of Poissonian noise [2]. We use FPGA-based real-time analysis of high-precision non-destructive images and subsequently apply feedback to the ensuing evaporation procedure.

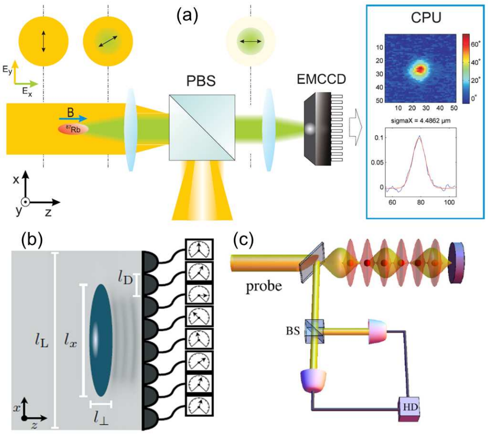

FIG. 1. The experimental setups for (a) Dark Field Faraday Imaging [1, 2, 5], (b) the probing of Bogoliubov excitations of condensates [3], and (c) QND detection of the SF-MI phase transition in optical lattices [4]

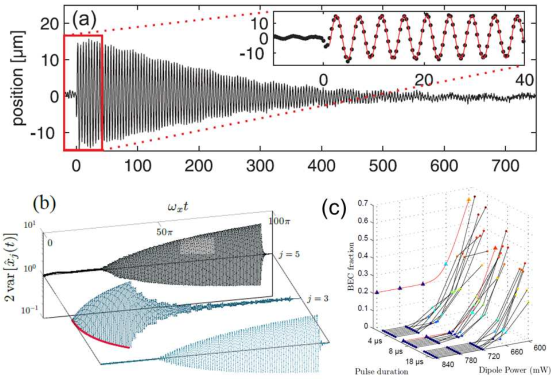

FIG. 2. (a) Non-destructive probing of an oscillating cloud. (b) Squeezing of selected Bogoliubov excitation modes [3]. (c) Single-shot probing of the phase transition to BEC.

Squeezing excitations of a BEC: The excitational spectrum of a BEC constitute density oscillations. With spatial Faraday imaging information of the population of each mode can be inferred, Fig. 1(b). By matching a stroboscopic probing to mode eigen-energies allows for selective squeezing and entanglement of modes, Fig. 2(b).

Characterizing quantum phase transitions: No probing at finite signal-to-noise is truly non-destructive [1]. Here, we investigate the fundamental accuracy-precision tradeoff when probing the phase transition to BEC with pulses of varying the probing field strength [5]. Figure 2(c) demonstrates increased precision of the determination of the critical point with increased probe duration at the expense of a systematic shift due to cloud heating. We have also realized multiple phase transitions in a single experimental run using conservatively induced transitions.

In Ref. [4] we demonstrate that spatially inhomogenous Faraday probing in optical lattices, Fig 1(c), can be used as a probe of the superfluid to Mott insulator transition.

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