Nonclassical Motional State Excitation in Bose-Einstein Condensates

Khemendra Shukla*[1], Ngo Thi Hoang Loc[1], Yi-Wei Liu[1]
[1]Department of Physics, National Tsing Hua University, Hsinchu, Taiwan
*Tel:+886-3-574-2561, Fax: 886-3-572-3052, E-mail: s105022858@m105.nthu.edu.tw

Abstract: We present the experimental observation of macroscopic excited motional states in Bose-Einstein condensates. The interference of the states exhibits a non-smooth density distribution. Unlike the conventional collective oscillation modes, the perturbative approach is not applicable for its dynamics. In our protocol of the trap frequency jumping, the condensate is self excited by lowering the potential well allowing it to release the chemical potential to the kinetic energy. To observe and enhance the obtained effects, we transferred BECs to a quasi-2D potential well with a chirped trap frequency, and then effectively converted the 3D atomic ensemble to a sequence of 2D slices. We have observed the cloud deformation as a non-Gaussian wave packet, and then its revival. The excited atomic cloud undergoes coherent superposition and possesses collective oscillation among excited motional states. The momentum space observation (time-of-flight imaging) provides a strong implication of squeezing. Our method can be applied for the matter-wave propagation and manipulation of nonclassical motional states.

Motivation

Spatial density or phase modulation upon the ground state order parameter, the topological state, can be realized by coherently manipulating the quantum system, such as coherent matter-wave, i.e. Bose-Einstein condensates (BECs).
We present the excitation of BECs using the trap frequency jumping technique, which has been employed in nonclassical motional squeezed states of trapped ions [1, 2] and cold atomic ensembles [3]. Although the number squeezed states [8] and the spin squeezed states [5] of BECs have been reported for decades, the demonstration of macroscopic squeezed motional states has not yet been realized to the best of our knowledge. The trap frequency jumping method is expected to coherently manipulate the motional states for macroscopic wave-packet squeezing in phase space.

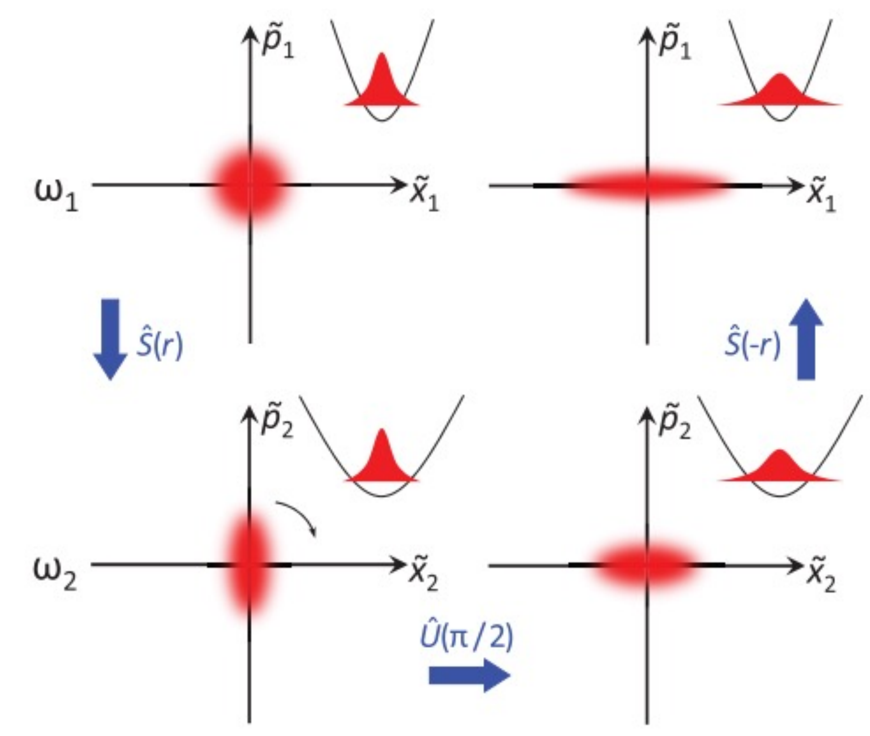


Fig. 1. Illustration of the frequency jump squeezing protocol in a harmonic oscillator in phase and real (inset) spaces. The sequence starts with atoms in the vibrational ground state (upper left). A sudden jump of the oscillation frequency transforms the atomic wave function into a squeezed state in the new oscillation frequency eigenstates basis (lower left).

Experimental Setup

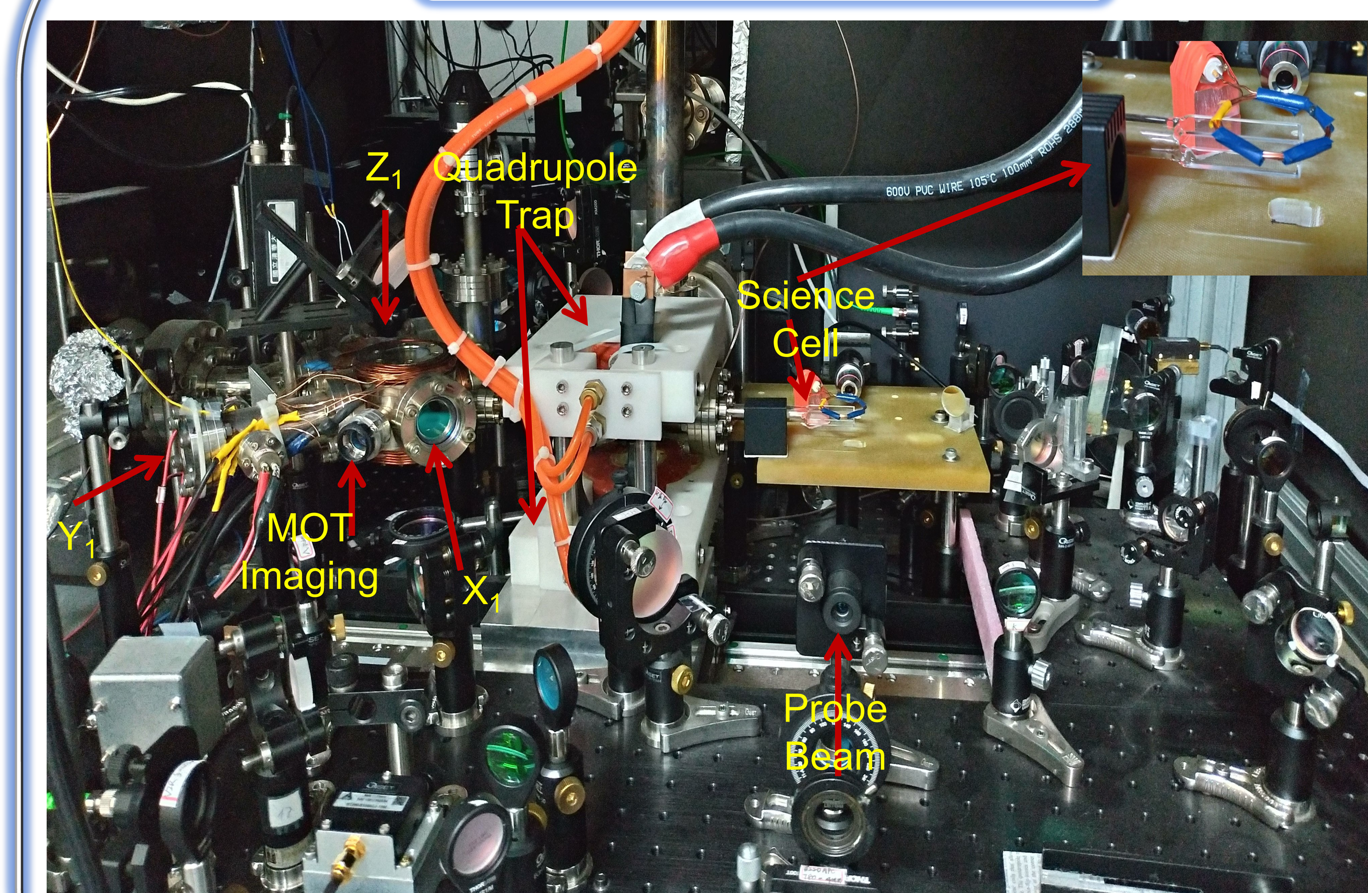


Fig. 2. Experimental setup shows the MOT chamber and UHV science cell. ^{87}Rb atoms are loaded into MOT and transferred to science cell.

Method

The potential formed by magnetic quadrupole trap is given by,

$$U(\rho, z) = (U_0' - mg)(z + z_0) + \frac{U_0'\rho^2}{8(z+z_0)} - \frac{U_0'\rho^4}{64(z+z_0)^3}$$

Rearranging the above equation, we get

$$U = (U_0' - mg)(z + z_0) + \frac{1}{2}m\omega_\rho^2\rho^2 + \frac{1}{4}\beta\rho^4$$

The trap frequency ω_ρ can be written as,

$$\omega_\rho^2 = \frac{1}{m}\frac{\partial^2 U}{\partial \rho^2} = \frac{U_0'}{4m(z+z_0)} = \frac{z_0}{z+z_0}\omega_0^2$$

where $\omega_0 = \sqrt{U_0'/4mz_0} = 2\pi \times 23.4$ hz

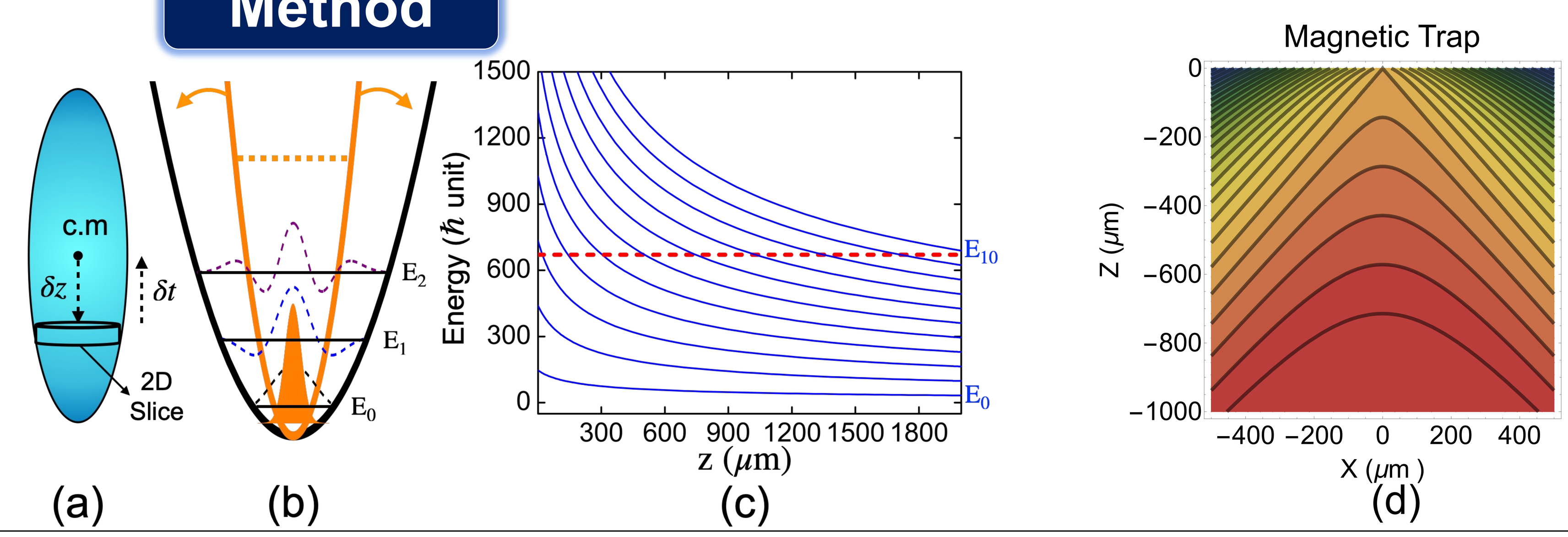


Fig. 3. (a) Schematic of a 2D BEC slice at δz below the center-of-mass (c.m.). (b) The BEC wave packet (orange) in the hybrid trap was transferred to the magnetic trap (black) by turning off Optical Dipole Trap. (c) The energy levels of the MT under the harmonic approximation. (d) Equipotential curve of the magnetic quadrupole trap.

Results and Discussion

The dynamics is related to the accumulated oscillation phase of the density distribution,

$$\phi(t) = 2\int \omega_\rho dt$$

At $z = a_z t^2/2 + v_z t\_z_0$ with reduced acceleration $a_z = g - U_0/m$, oscillation phase can be written as,

$$\phi(t) = \phi_{c.m.}(z_{c.m.}, t) + \delta\phi(\delta z, t) + \phi'$$

For c.m., $v_z = 0$, then

$$\phi(z_{\text{c.m.}}, t) = 2\omega_0\sqrt{\frac{2z_0}{a_z}}\ln[2\sqrt{\frac{z_{\text{c.m.}}}{z_0}}] + \phi'$$

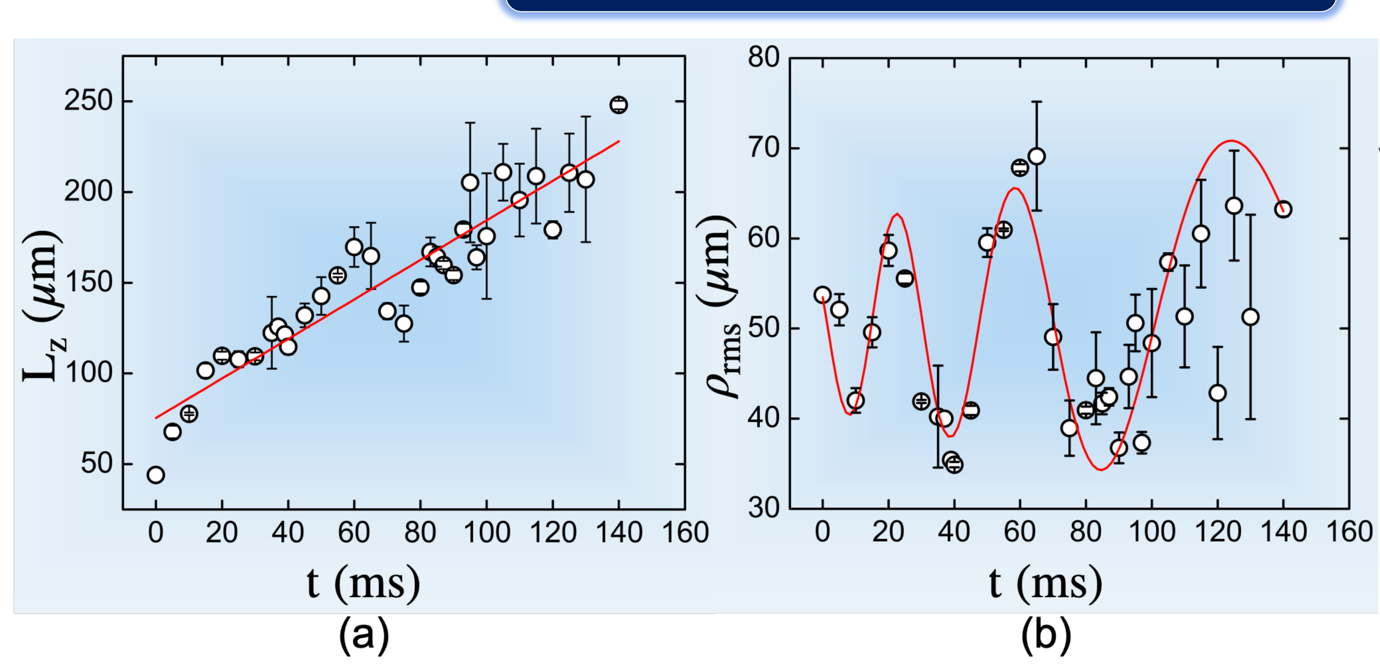


Fig. 4. Dynamics of the BEC in the Magnetic Trap. (a) The r.m.s. width of atomic cloud in z-direction, L_z . (b) Oscillation of the radial r.m.s. width of atomic cloud, $\rho_{r.m.s.}$.

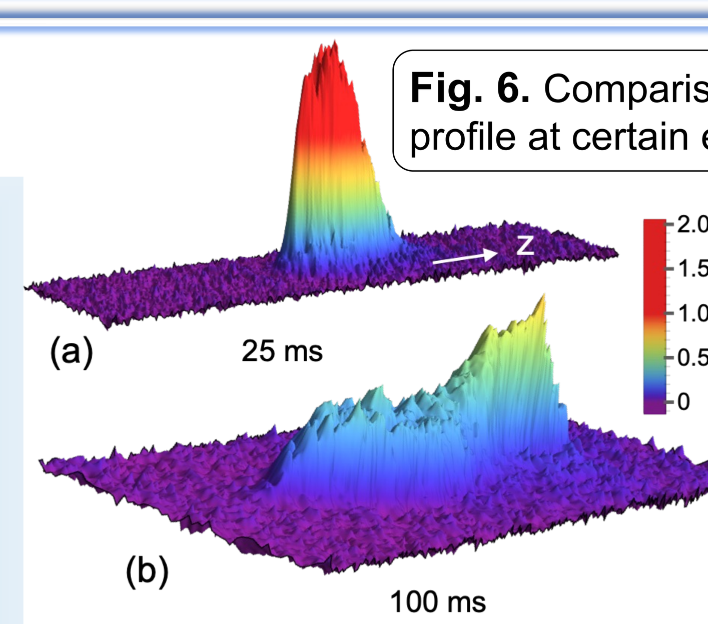


Fig. 6. Comparison of density profile at certain evoluton time.

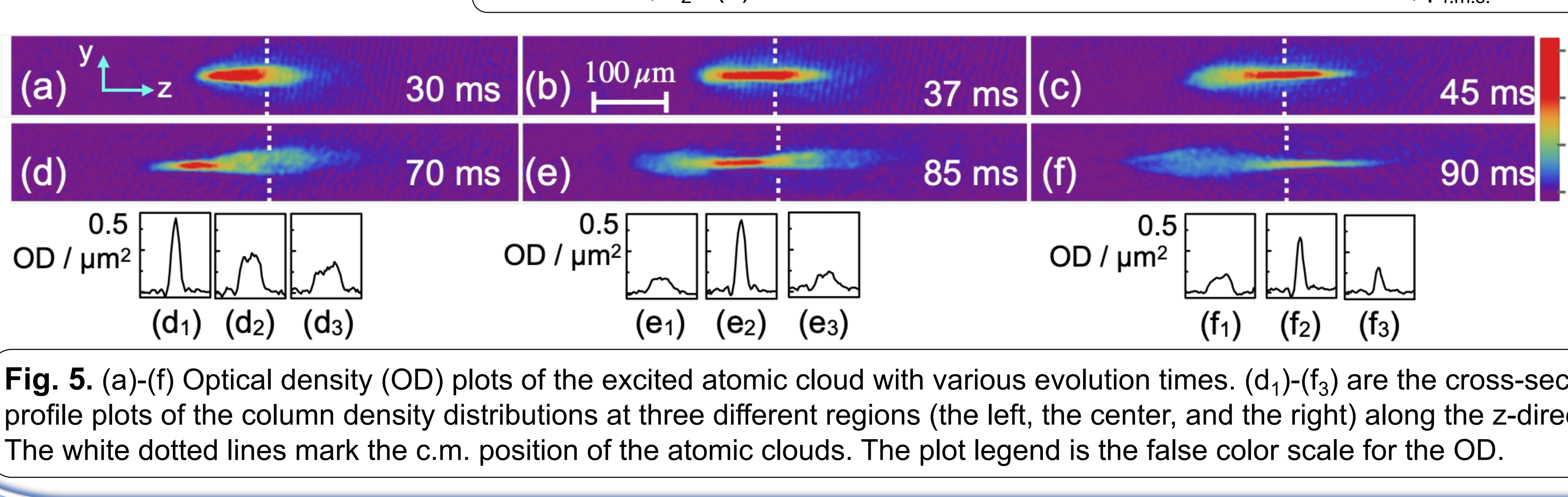
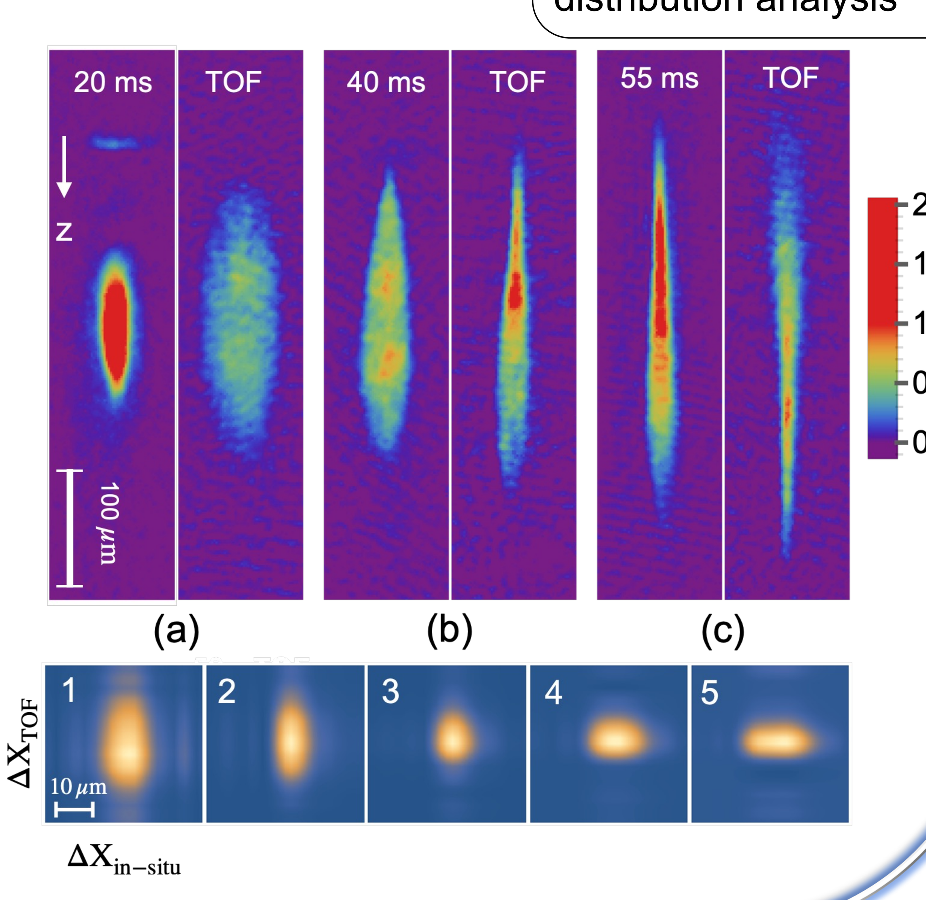


Fig. 5. (a)-(f) Optical density (OD) plots of the excited atomic cloud with various evolution times. (d_1)-(f_3) are the cross-section profile plots of the column density distributions at three different regions (the left, the center, and the right) along the z-direction. The white dotted lines mark the c.m. position of the atomic clouds. The plot legend is the false color scale for the OD.

Fig. 7. Momentum space absorption images and density distribution analysis



Conclusion and Future Work

- The macroscopic quantum degenerate gas, BEC, was coherently excited to the motional states, whose interference led to a peculiar non-smooth density distribution.
- This phenomenon was confirmed and enhanced by transferring BEC to a quasi-2D anharmonic well with a chirped trap frequency, which converted the 3D atomic ensemble to a sequence of 2D slices.
- We have demonstrated the oscillating dynamics among the states in- volved, and the wave-packet collapse and revival. The momentum space projection revealed a strong implication of matter-wave squeezing.
- In the future, the applications on matter-wave optics, quantum simulation, and squeezing can be expected with more sophisticated trap potential control.

References

[1] D. M. Meekhof, C. Monroe, B. E. King, W. M. Itano, and D. J. Wineland, Physical Review Letters 76, 1796 (1996).
[2] J. G. Bohnet, B. C. Sawyer, J. W. Britton, M. L. Wall, A. M. Rey, M. Foss-feig, and J. J. Bollinger, Science 352, 1297 (2016).
[3] M. Xin, W. S. Leong, Z. Chen, Y. Wang, and S. Y. Lan, Physical Review Letters 127, 183602 (2021).
[4] C. Orzel, A. K. Tuchman, M. L. Fenselau, M. Yasuda, and M. A. Kasevich, Science 291, 2386 (2001).
[5] J. Est`eve, C. Gross, A. Weller, S. Giovanazzi, and M. K. Oberthaler, Nature 455, 1216 (2008).

Acknowledgements

This work was supported by the Taiwan Ministry of Science and Technology and National Tsing Hua University.