

Non-invasive way to feel density of atoms can provide a new window into the Quantum World

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A new technique developed by scientists can enable local density measurements of cold atoms in real time, without significantly disturbing them. This could prove instrumental in the development of near-future applications in quantum computation and quantum sensing, where real-time detection of atoms and their quantum state is of paramount importance.

In conventional cold atom experiments, where kinetic energy of atoms are reduced to near absolute zero temperatures by means of laser cooling and trapping techniques, the quantum properties of the atoms are more evident. These cold atoms can then be used as resources for quantum computers and quantum sensing. In order to detect the quantum state of these atoms, methods such as absorption and fluorescence imaging are widely used. However, these techniques have inherent limitations. Absorption imaging struggles while imaging dense atomic clouds because the probe beam cannot penetrate sufficiently to provide accurate density measurements. Fluorescence imaging, on the other hand, requires longer exposure times to collect scattered photons, and both approaches are often destructive, altering the state of the atoms during measurement.

Researchers at the Raman Research Institute, an autonomous institute of the Department of Science and Technology (DST), Government of India, demonstrated a technique called Raman Driven Spin Noise Spectroscopy (RDSNS), that overcomes these challenges by combining spin noise spectroscopy, which detects natural fluctuations of atomic spins by detecting the polarisation fluctuations of a laser light passing through the atomic sample. This method also uses two additional laser beams to coherently drive atoms between two adjacent spin states.

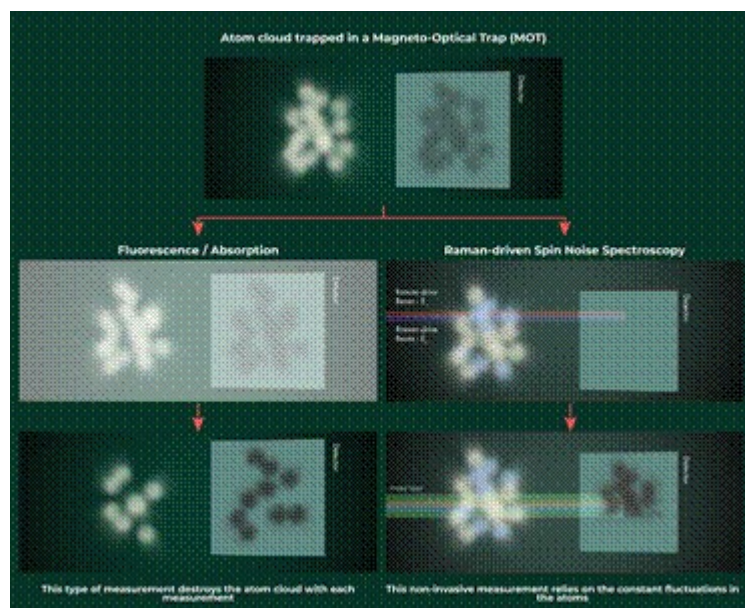


Fig. RDSNS is a non-invasive measurement that enables us to probe the atom cloud in high temporal and spatial resolution

These Raman beams drive transitions between atomic states and dramatically boost the signal – by nearly a million times. The probing volume is 0.01mm^3 which is achieved by focusing the probe to just 38 micrometers, targeting a tiny region of the atom cloud encompassing about 10,000 atoms. Importantly, the measured signal provides a direct measure of local density rather than merely the total atom number.

The team used RDSNS to study potassium atoms in a magneto-optical trap (MOT), and observed that the central density of the atomic cloud saturated within one second, whereas the total atom count, measured via fluorescence, took nearly twice as long.

This highlights a key difference-- fluorescence reveals global atom counts, while RDSNS shows how tightly atoms are packed locally.

“The technique is non-invasive, as the probe is far-detuned and operates at low power, allowing even microsecond-scale measurements to achieve accuracy within a few percent,” Bernadette Varsha FJ & Bhagyashri Deepak Bidwai, Research Assistants, QuMIX lab at RRI pointed out.

“Real-time nondestructive imaging methods are a great quantum sensing and computing candidate. It uncovers many-body dynamics by capturing the transient microscopic density fluctuations. It can be used to benchmark theoretical models with spatially resolved data.”, said Sayari, a PhD researcher at RRI and the study's lead author.

To validate RDSNS, the team compared local density profiles with results obtained using the inverse Abel transform applied to fluorescence images. The agreement was remarkable. Unlike the Abel transform, which requires axial symmetry, RDSNS performs robustly even in asymmetric or dynamically evolving atomic clouds.

The broader significance of this work is invaluable for quantum technologies; fast, precise, and non-invasive density measurements are helpful in devices like gravimeters, magnetometers, and other sensors that depend critically on knowing atom density with precision. By enabling micron-scale local probing without disturbing the system, RDSNS opens pathways to study phenomena such as density wave propagation, quantum transport, to name a few.

“We anticipate that this technique will find broad applications in real time diagnostics of cold atom experiments especially in context of quantum computing with neutral atoms and quantum simulations with cold atoms, and in domains such as exploring transport phenomena, non-equilibrium dynamics etc.”, said Prof. Saptarishi Chaudhuri, who leads the Quantum Mixtures (QuMIX) lab at RRI.

Supported under India's National Quantum Mission, this breakthrough positions RRI at the forefront of precision measurement in quantum research, underscoring a broader lesson: progress often comes not from looking harder, but from finding gentler, smarter ways to look.

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