

Spatially Resolved Temperature Measurement Using Rydberg Doppler Broadening Thermometry

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We demonstrate a technique for spatially resolved temperature measurement utilizing Rydberg Doppler broadening thermometry. This method employs two focused laser beams arranged perpendicularly to excite laser-cooled atoms from the ground state to a Rydberg state via a two-photon absorption process. Temperature is obtained through Doppler broadening of the spectral line. The perpendicular configuration allows for selective probing of a specific position within the atomic cloud, enabling localized temperature measurement. This technique, in principle, offers a temperature resolution on the order of nK, attributed to the exceptionally narrow natural linewidth of the involved rubidium Rydberg transition line. Furthermore, the setup enables the measurement of position-velocity correlations within the cold atom ensemble. The velocity information is extracted through the Doppler shift, whereas the spatial information is inferred from the arrival time of ions detected by a channel electron multiplier detector. We use our method to measure the local temperature in a magneto-optical trap.

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Laser cooling and trapping are well-established techniques for preparing cold samples of atoms and molecules. Such samples are essential for applications including atomic clocks [1,2], the creation of Bose-Einstein condensates [3], and precision quantum sensing [4,5]. A large body of experimental work has investigated the properties of magneto-optical traps (MOTs) [6–10]. In particular, MOTs are known to exhibit rich dynamical behavior, including non-linear dynamics [11–13], phase transitions, and instabilities [14–16]. A key property of these ultracold ensembles is their temperature, a primary parameter that underpins coherence, their phase-space density, and the sensitivity of precision

measurements. Conventionally, temperature is measured using time-of-flight (TOF) expansion or release-and-recapture methods [17–23]. These methods are based on the assumption of a linear position-velocity correlation of atoms and typically require a large number of atoms to achieve a good signal-to-noise ratio. To overcome this limitation, one can instead use spectroscopic techniques based on the Doppler effect [24]. The application of this technique requires a transition with a natural linewidth significantly narrower than the Doppler width. Recent advances in two-photon excitation [25] to Rydberg states provide access to resonances with natural linewidths well below the Doppler width (typically kHz level) [26–28]. This allows, in principle, for temperature measurements with nK resolution (see Supplemental Material [29] for additional details). However, while previous studies have demonstrated Rydberg-based thermometry in MOTs [26–28,30], these approaches typically averaged over the entire atomic cloud, thus discarding local spatial information essential for studying nonequilibrium features such as heat transport [31] and Doppler heating [32]. Recently, spatially resolved temperature measurements have also been demonstrated using Raman spectroscopy [33,34]. While such Raman-based methods provide a powerful and complementary approach, they generally require comparatively large excitation volumes to maintain sufficient Raman transfer efficiency, which limits their applicability for microscopic local thermometry.

Here, we demonstrate spatially selective temperature measurements of an atomic cloud of ultracold ⁸⁷Rb atoms using Rydberg Doppler broadening thermometry. By

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addressing localized regions with laser beams an order of magnitude smaller than the dimensions of the atomic cloud, we can measure spatial variations in temperature across the sample. Beyond spatial resolution, our technique offers several additional advantages. We demonstrate temperature measurements over a broad range, from the μK to mK regime. Moreover, by probing atoms after a period of free expansion, we measure position-velocity correlations, an observable previously studied using complementary phase-space tomography techniques [35,36]. Our implementation provides a distinct route based on velocity-selective Rydberg excitation and field ionization detection.

In our experiments, we excite laser-cooled ^{87}Rb atoms to the $70S_{1/2}$ Rydberg state in a standard magneto-optical trap (MOT) containing $\sim 10^6$ atoms with a 1σ radius of $160\text{ }\mu\text{m}$ (Gaussian density profile). The excitation to the Rydberg state [37] is achieved through the two-photon absorption process (Fig. 1), in which atoms absorb photons from two linearly polarized laser beams at 420 nm and 1012 nm , respectively, arranged in a perpendicular configuration, to transition from $|5S_{1/2}\rangle$, $F=2$ to $|70S_{1/2}\rangle$ Rydberg state via the intermediate $|6P_{3/2}\rangle$, $F'=3$ state, detuned by $+200\text{ MHz}$. Depending on the measurement, we use different beam-waist configurations. For global thermometry, both excitation beams are expanded to waists of

1.6 mm (10 times the MOT radius). For position-velocity correlation measurements, we use a small 420 nm beam (waist $16\text{ }\mu\text{m}$) together with a large 1012 nm beam (waist 1.6 mm), providing spatial selectivity in one dimension. For local temperature measurements, both beams are small, with waists of $16\text{ }\mu\text{m}$ and $36\text{ }\mu\text{m}$ for 420 nm and 1012 nm beams, respectively. To detect Rydberg atoms, we employ a field ionization process [38–42]. The ions produced by field ionization are accelerated toward a channel electron multiplier (CEM) using the same electric field applied for ionization. Individual ions are detected as voltage peaks on an oscilloscope connected to the CEM and counted by a peak finding procedure in LabVIEW software with an overall detection efficiency of 40% [43]. The arrival times of the individual ions are also recorded and are used to infer the position of the Rydberg atoms.

The combination of using excitation beams in a perpendicular configuration and exciting atoms to Rydberg states allows us to probe the local dynamics of atoms in a small volume within the atomic cloud. Additionally, the small number of atoms in the selected region does not pose a limitation since only a few atoms excited to Rydberg states are sufficient to achieve a good signal-to-noise ratio.

In a single experimental cycle, after a loading time of 100 ms , we switch off the MOT magnetic field to minimize the Zeeman broadening. After $600\text{ }\mu\text{s}$ (at this point, the quadrupole field has decayed sufficiently; see Supplemental Material [29] for further details), the cooling beams are switched off, and the Rydberg excitation beams are pulsed on for $10\text{ }\mu\text{s}$. Excited atoms are then detected using field ionization. After the measurement, the cooling beams and magnetic field are switched on again to reload the MOT for the next experimental cycle. For each data point, the sequence is repeated 200 times to accumulate sufficient statistics.

To test our method, we first measure the global temperature of the atoms in the MOT using large excitation beams. Figure 2(a) shows the number of Rydberg atoms as a function of the laser detuning Δ_r for two different temperatures of the atomic cloud. The experimental data are fitted with a Gaussian profile to extract the total full width at half maximum (FWHM) Δf_{Total} . The measured linewidth contains contributions from Doppler broadening Δf_D , and non-Doppler mechanisms, dominated by laser-frequency jitter Δf_L (see Supplemental Material [29]). Additional contributions include power broadening, natural linewidth, and Zeeman broadening in the presence of magnetic fields. In our experiments, the excitation beam intensities are sufficiently low so that power broadening can be neglected (below 100 kHz). The largest peak intensities used in the experiment are about 2.5 W/cm^2 for the 420 nm laser and 46 W/cm^2 for the 1012 nm laser. The natural linewidth of the Rydberg transition, 0.95 kHz , is also negligible. Moreover, because the magnetic field is switched off before

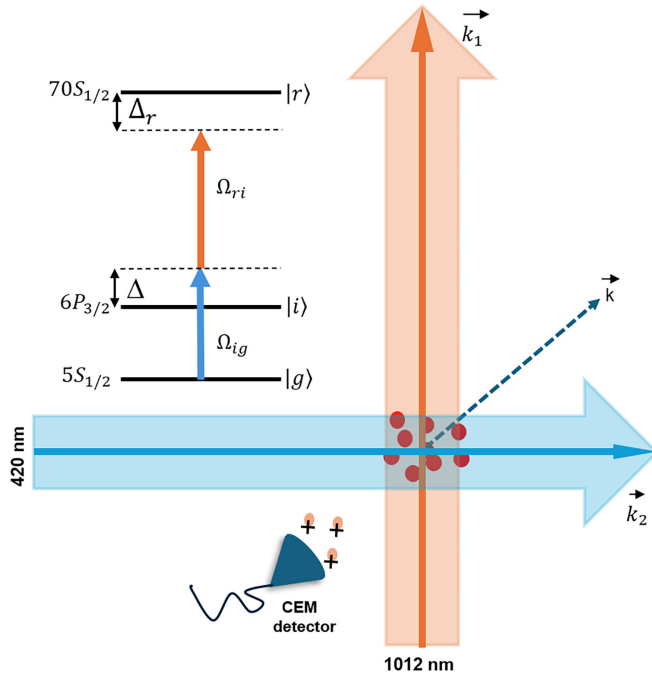


FIG. 1. Excitation and detection scheme. 1012 nm ($\vec{k}_1$) and 420 nm ($\vec{k}_2$) laser beams (large or small) are used in perpendicular configuration to excite the atoms into Rydberg state $|r\rangle$ from ground state $|g\rangle$ via an intermediate state $|i\rangle$. Δ , Δ_r are the detunings of 420 nm and 1012 nm laser beams, respectively, and Ω_{ig} , Ω_{ri} are the single photon Rabi frequencies. The angle between the effective wave vector $\vec{k}$ and $\vec{k}_2$ (blue laser) is 22.5° .

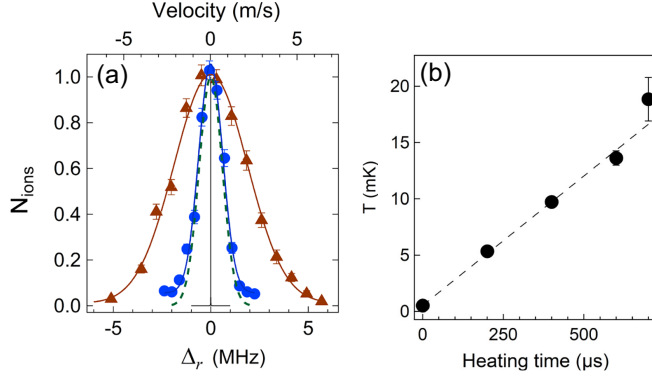


FIG. 2. Excitation spectrum and heating rate. (a) Number of Rydberg excitations ($70S_{1/2}$) as a function of excitation laser detuning Δ_r ; the corresponding atomic velocities are indicated on the top axis. Triangular and circular data points correspond to 4.8(2) mK and 210(50) μ K, respectively. The solid red and blue curves are Gaussian fits to the experimental data. The dashed curve shows broadening due to frequency jitter, and the narrow Lorentzian function indicates the natural linewidth. (b) Temperature of the atomic cloud versus heating time Δt . The dashed line is a linear fit, yielding a heating rate of 22.9(6) K/s.

the excitation pulse, Zeeman broadening is negligible, contributing less than 90 kHz as estimated from measurements of the residual magnetic-field decay. Consequently, the dominant non-Doppler broadening mechanism is the laser jitter Δf_L , which we measured to be 1.39(0.18) MHz by two independent methods: (i) the standard deviation of the peak position recorded by the LabVIEW-based laser-frequency stabilization feedback loop, and (ii) a comparison of spectra taken in co- and counterpropagating beam geometries (see Supplemental Material [29]). From method (ii), we can also infer that the laser jitter can be described by a Gaussian distribution. Consequently, the total FWHM linewidth is given by the quadrature sum of the two Gaussians, the Doppler, and laser broadening:

$$\Delta f_{\text{Total}} = \sqrt{\Delta f_D^2 + \Delta f_L^2}, \quad (1)$$

where the Doppler contribution is

$$\Delta f_D = \frac{\sqrt{\ln 2}}{\pi} |\vec{k}_1 + \vec{k}_2| U. \quad (2)$$

Here, U is the most probable thermal speed,

$$U = \sqrt{\frac{2k_B T}{m}}, \quad (3)$$

and $|\vec{k}_1 + \vec{k}_2|$ is the effective two-photon wave vector [27,28]. For two wave vectors $\vec{k}_1$ and $\vec{k}_2$ enclosing an angle β ,

$$|\vec{k}_1 + \vec{k}_2| = \sqrt{k_1^2 + k_2^2 + 2k_1 k_2 \cos \beta}. \quad (4)$$

Using Eq. (1), together with the measured Δf_{Total} and the independently measured laser-broadening contribution Δf_L , we obtain the Doppler width Δf_D and subsequently determine the temperature via Eq. (2). In Fig. 2(a), two scans are shown. In the first scan, the detuning of the MOT beams is kept at standard value used for MOT operation of -2Γ (where Γ is the natural linewidth of the transition $5S_{1/2} \rightarrow 5P_{3/2}$), resulting in a measured temperature of 210(50) μ K, compatible with typical values reported for ^{87}Rb MOTs [44–46] and with the Doppler temperature $T_D = 146$ μ K. The second scan was taken after switching the MOT beams to resonance for 200 μ s. In this case, the atomic cloud is heated to 4.8(2) mK by photon scattering. By varying this heating time, we also demonstrate the ability of our method to measure temperature over several orders of magnitude from ~ 100 μ K to 20 mK, as shown in Fig. 2(b). As expected, the measured temperature increases linearly with heating time, corresponding to a heating rate of 22.9(6) K/s. A simple theoretical estimate based on scattering-rate calculations predicts a heating rate of approximately 6 K/s. The difference from the experimentally observed value may be attributed to uncertainty in the exact resonance frequency of the cooling beams. In particular, a small blue detuning, on the order of 200 kHz, would give rise to anomalous Doppler heating [32,47], leading to an enhanced experimental heating rate.

The accessible temperature range is bounded from below by the laser-induced linewidth. Because the linewidths can only be measured with finite precision, the Doppler contribution must exceed its propagated uncertainty to be reliably resolved. Assuming a 10% uncertainty in both the measured total width and the independently determined laser broadening, we estimate a minimum accessible temperature of ~ 68 μ K for our setup. Experimentally, the lowest temperature we measure is 63(40) μ K, obtained for an optical molasses prepared with a cooling-laser detuning of -4Γ .

Our experimental setup also allows us to infer the position of Rydberg atoms using arrival times of the ions, and we can use this information to measure the position-velocity correlation of the atoms. Figure 3(a) shows the histogram of ion arrival times for two distinct velocity classes, -0.43 m/s and 0.53 m/s, corresponding to $\Delta_r = -1.21$ MHz and 1.5 MHz, respectively. The data were taken after heating the cloud for 400 μ s, followed by 1 ms of ballistic expansion. The peaks of the two arrival time distributions are separated in arrival time by 0.14 μ s. To calibrate the mapping between ion arrival time and position, we translated the MOT by shifting the magnetic-field zero by a known distance and measured the resulting change in arrival time (see Ref. [48] for details). Using this calibration, we infer that the two velocity classes are separated spatially by 636 μ m. To measure the correlation,

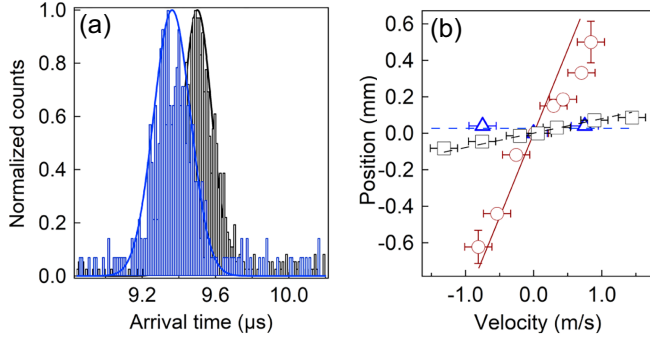


FIG. 3. Position-velocity correlation measurements. (a) Histogram of ion arrival times for two selected velocity classes. The measurement was performed after heating the cloud for 400 μs , followed by 1 ms of ballistic expansion. Two velocity classes, -0.43 m/s and 0.53 m/s, corresponding to the right peak (black bars) and left peak (blue bars), originate from positions $+0.19$ mm and -0.44 mm relative to the cloud center, respectively. (b) Relative position with respect to atoms with zero velocity as a function of the velocity component projected along the 420 nm beam, as inferred from the Doppler shift. The projected velocity was calculated by multiplying the measured velocity by $\cos(22.5^\circ)$. Triangles correspond to a sample in thermal equilibrium, while squares and circles denote the distributions measured immediately after resonant heating and after 1 ms of ballistic expansion, respectively. The dashed lines show linear fits to the data points, and the solid line represents the theoretically calculated position after 1 ms of expansion time.

we select a specific velocity class via the Doppler shift and then measure the number of atoms in that class, as well as their arrival time. Results are shown in Fig. 3(b). Triangular data points represent the measurement of the correlation without letting the cloud expand. As expected, no correlation is observed between the atomic position and velocity in the initial cloud, consistent with thermal equilibrium. After resonant heating for 400 μs (squares), a correlation begins to emerge. Letting the cloud undergo an additional 1 ms of ballistic expansion further enhances this correlation (circles) by approximately a factor of 12. The observed linear relation between position and velocity arises naturally during free expansion, as atoms with higher velocities travel farther from their initial positions. More generally, in situations where the position-velocity relation is not expected to be linear, this method can still be used to reconstruct the spatial distribution associated with different atomic velocity classes [32,47].

Finally, our method enables local probing of the atomic cloud using small excitation beams. To test this capability, we measured the ballistic expansion both globally and locally. For local measurements, we define a small probing volume (an order of magnitude smaller than the atomic cloud) near the center of the atomic cloud. An atomic sample with an initial temperature of ~ 2 mK is prepared by resonant heating, after which the MOT beams are switched off. After a variable expansion time up to 1500 μs , we

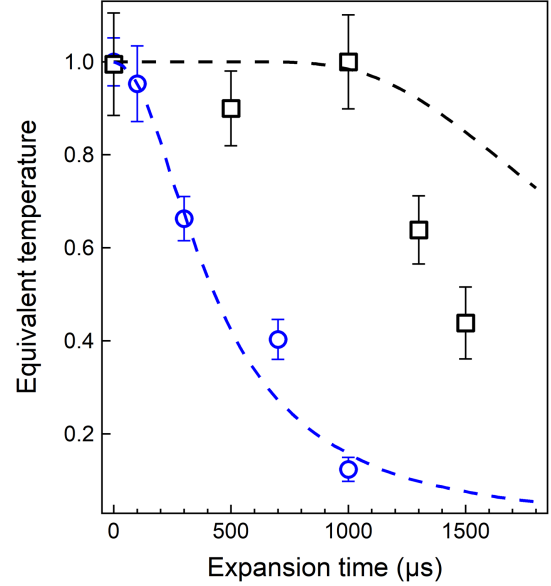


FIG. 4. Equivalent temperature as a function of expansion time. Circular and square data points represent the equivalent temperature measurement using small and large excitation beams, respectively. The temperatures are normalized to their values at zero expansion time. Dashed curves are the simulation results.

measure the velocity spread in the volume. Because the expanding cloud is out of thermal equilibrium, a unique thermodynamic temperature is not well defined; we, therefore, report an equivalent temperature, defined from the local mean velocity. Figure 4 shows the equivalent temperature as a function of the expansion time. For local probing (circles), the equivalent temperature decays rapidly. During ballistic expansion, only atoms with small velocity remain within the probe volume. In contrast, the global measurement with excitation beams 10 times larger than the MOT radius (squares) yields an almost constant equivalent temperature over the first millisecond, followed by a slower decay. The dashed lines in Fig. 4 represent simulation results that show good qualitative agreement with the experimental data. In these simulations, we generate an ensemble of particles whose velocities follow Maxwell-Boltzmann distribution and whose spatial density has a Gaussian profile. For simplicity, the excitation region is approximated by a spherical volume with a radius equal to the measured excitation beam waist, and the cloud expansion is then modeled using simple kinematic relations. This approximation could explain why there is deviation between the simulated and experimental decay of the equivalent temperature. Furthermore, uncertainty in the resonance condition could lead to Doppler heating (as discussed above) [32,47] and, hence, a larger width of the initial velocity distribution, resulting in faster decay of the measured equivalent temperature.

We then used this method to measure the temperature variation along a single dimension in the MOT using small

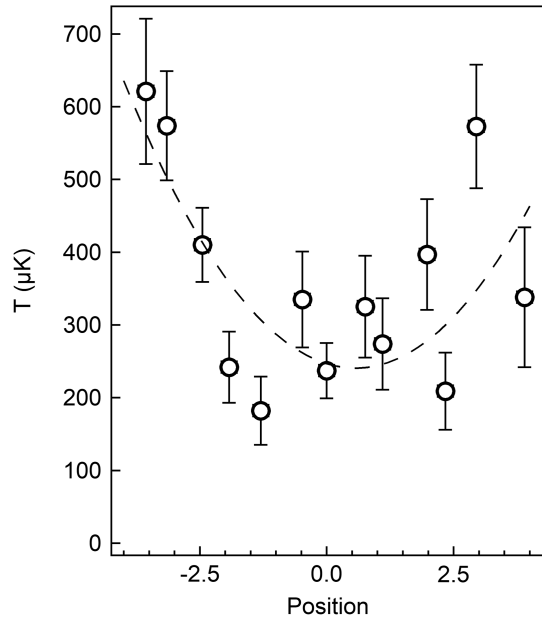


FIG. 5. Local temperature as a function of position across the MOT. The horizontal axis shows the position of the probed local volume in units of the MOT radius. Vertical error bars indicate the uncertainty in temperature due to error in total broadening measurements, and horizontal error bars indicate the uncertainty in determining the position of the excitation laser beam. The dashed curve is included as a guide to the eye.

excitation beams. A previous theoretical study [49] predicts that a temperature gradient must exist in the MOT for the density solution to remain physically valid. The measurement position within the MOT was selected by translating the 1012 nm excitation beam while keeping the 420 nm excitation beam fixed. The resulting beam displacement was monitored with a CCD camera positioned along the propagation direction of the translated beam. The results are shown in Fig. 5. The MOT temperature is clearly nonuniform and exhibits a spatial gradient, with higher temperatures in the wings and lower temperatures near the center. The temperature in the wings is approximately 3 times higher than that measured in the center of the MOT. A significant temperature difference becomes apparent beyond a distance of approximately 2.5σ from the center of the cloud.

We note here that similar measurements have been performed in optical molasses using Raman-based spectroscopy [33], which showed a similar inhomogeneous temperature distribution.

Local temperature fluctuations may arise from spatial inhomogeneities in the atomic density induced by interference fringes generated by counterpropagating cooling beams.

In conclusion, we have experimentally demonstrated that Rydberg Doppler-broadening thermometry enables precise, local measurements over a wide temperature range spanning from μK to mK . We use this technique to reveal

position-velocity correlations through spatially resolved Rydberg Doppler thermometry, complementing previous approaches based on phase-space tomography [35,36]. To confirm the method’s spatial locality, we then analyzed the ballistic expansion behavior for different excitation beam configurations. Finally, we validated the technique’s robustness by mapping the local temperature distribution across the MOT. Although the present Letter focuses on demonstrating the method, future experiments could use it to systematically investigate how local temperature gradients depend on MOT parameters, such as cooling-beam intensity, detuning, polarization, and magnetic-field gradient.

These results establish Rydberg Doppler thermometry as a powerful tool for spatially resolved thermometry in cold atom systems, with applications to nonequilibrium studies such as heat transport and Doppler-heating dynamics within the atomic cloud. Looking ahead, reducing the laser-frequency jitter that dominates the non-Doppler linewidth would lower the minimum accessible temperature and improve the resolution. In the limit of negligible laser-induced broadening, the intrinsically narrow Rydberg resonance would enable thermometry with nanokelvin resolution.

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