Fast loaded dual species magneto-optical trap of cold Sodium and Potassium atoms with light-assisted inter-species interaction

Sagar Sutradhar, Anirban Misra, Gourab Pal, Sayari Majumder, Sanjukta Roy, and Saptarishi Chaudhuri

Raman Research Institute, C. V. Raman Avenue, Sadashivanagar, Bangalore 560080, India

(*Electronic mail: srishic@rri.res.in)

(Dated: 23 August 2023)

We present the design, implementation and detailed experimental characterization and comparison with numerical simulations of two-dimensional Magneto-optical traps (MOT) of bosonic $^{23}$Na and $^{39}$K atoms for loading the cold atomic mixture in a dual-species 3DMOT with a large number of atoms. We report our various measurements pertaining to the characterisation of the two 2D $^+$ MOTs via the capture rate in the 3DMOT and also present the optimised parameters for the best performance of the system of the cold atomic mixture. In the optimised condition, we capture more than $3 \times 10^{10}$ $^{39}$K atoms and $5.8 \times 10^8$ $^{23}$Na atoms in the 3DMOT simultaneously from the individual 2D $^+$ MOTs with the capture rate of $5 \times 10^{10}$ atoms/sec and $3.5 \times 10^8$ atoms/sec for $^{39}$K and $^{23}$Na, respectively. We also demonstrate improvements of more than a factor of 5 in the capture rate into the 3DMOT from the cold atomic sources when a relatively high-power ultra-violet light is used to cause light-induced atomic desorption in the 2D $^+$ MOT glass cells. A detailed study of the light assisted interspecies cold collisions between the co-trapped atoms is presented and interspecies loss coefficients have been extracted to be, $\beta_{NaK} \sim 2 \times 10^{-12}$ cm$^3$/sec. The cold atomic mixture would be useful for further experiments on Quantum simulation with ultra-cold quantum mixtures in optical potentials.

I. INTRODUCTION

Ultra-cold quantum gases in optical potentials offer a versatile platform for Quantum Simulation[1,2] precision measurements[3] and Quantum Technologies[4] due to the high degree of controllability of such systems such as inter-atomic interaction, dimensionality, spin states and external potentials. This makes ultra-cold atomic ensembles an ideal ‘quantum toolbox’ leading to unprecedented progress in this research field.

Quantum gas mixtures with dual atomic species has attracted considerable interest since they offer a wealth of novel possibilities. Quantum degenerate mixtures realized by using single atomic species in different Zeeman sub-level[5,6], multiple isotopes of same species or different atomic species[7,8,9] can be used to investigate novel quantum phases hitherto unexplored in single atomic species. For example, the physics of impurities coupled to degenerate gas[10,11] is of fundamental importance in condensed matter systems. Novel exotic quantum phases such as quantum droplets in a spin mixture of Bose gases have recently been proposed[12] and observed in homo- and hetero-nuclear quantum mixtures[13,14,15]. Quantum mixtures can also be used to create hetero-nuclear stable polar molecules[16,17] which is useful to study controlled ultra-cold chemistry[18] as well as long-range anisotropic dipolar interaction[19,20,21].

A Quantum degenerate mixture of sodium and potassium is an attractive combination for a hetero-nuclear quantum mixture experiment. Both the Bose-Bose mixture ($^{23}$Na-$^{39}$K, $^{23}$Na-$^{41}$K) and Bose-Fermi mixture ($^{23}$Na-$^{40}$K) can be obtained opening up a myriad of possibilities for exploring the many-body physics arising due to the interplay between interspecies and intra-species interaction with quantum statistics playing a significant role. Another important advantage of the combination of sodium and potassium for the hetero-nuclear quantum mixture is that the Na-K ground-state polar molecule[22,23] are chemically stable as compared to other combinations of inter-species hetero-nuclear molecules with a large dipole moment of $\sim 2.72$ Debye paving the way to explore long-range dipolar interaction for quantum simulation[24].

In this article, we describe our experimental setup to realize an ultra-cold atomic mixture of $^{23}$Na and $^{39}$K atoms in a dual-species magneto-optical trap (3DMOT) loaded from cold atomic beams produced via two independent, compact and efficient two-dimensional magneto-optical traps (2D $^+$ MOTs) of $^{23}$Na and $^{39}$K. We also present the detailed characterisation of the performance of the cold atom sources of both $^{23}$Na and $^{39}$K atoms to obtain the optimised experimental parameters for the best possible performance of the cold atomic beam sources.

The various sections in this article are organised as follows: In section II we provide a detailed description of the experimental system including the ultra-high vacuum assembly and laser systems. In section III we focus on the characterisation and performance of the cold atomic beam sources. In section IV we give a detailed theoretical description of the numerical simulations performed in order to compare with the experimental results of the atomic sources. We have provided a complete system performance study in section V. Finally, we discuss about the interspecies light-assisted collisions between hetero-nuclear cold atoms in section VI.

II. EXPERIMENTAL SETUP

In this experimental setup, a large number of $^{23}$Na and $^{39}$K atoms are simultaneously captured in a dual-species 3DMOT from two independent sources of the cold atomic beams. There are stringent requirements on the design of the apparatus such as good optical access for trapping laser beams as well as detection, ultra-high vacuum to ensure longer trap lifetime of the atoms and high magnetic field gradient for mag-
A schematic of the vacuum assembly. The two-species MOT is loaded from two independent 2D+ MOTs as sources of cold $^{23}$Na and $^{39}$K atoms. The dual-species 3DMOT is produced in a spherical octagonal chamber. The UHV side is pumped by three large-capacity ion pumps whereas the two independent source regions are pumped with two 20 l/s ion pumps. Coils made of hollow-cored water-cooled copper tubes placed outside 3DMOT chamber are used to generate the quadrupole magnetic field for trapping of atoms. A single-arm magnetic transport allows transferring the cloud to the ‘science cell’ with large optical access.

Our experimental setup is designed and built up to fulfill these requirements and enable further experiments on the quantum degenerate mixture in both magnetic and optical potentials.

A. Vacuum assembly

A schematic view of our vacuum system is shown in Fig. 1. A spherical octagon-shaped chamber for 3DMOT, made with non-magnetic stainless steel (Kimball physics-MCF600-SphOct-F2C8) placed at the centre of the vacuum manifold is attached with two independent 2D+MOT glass cells (Precision Glassblowing, Colorado, USA). For both $^{23}$Na and $^{39}$K atoms, the vacuum chamber of the 2D+ MOT consists of a cuboidal glass cell (dimensions 85 mm $\times$ 40 mm $\times$ 40 mm), whose longitudinal axis is aligned horizontally and placed along the axis of a differential pumping tube connecting the 2D+ MOT glass cell and the 3DMOT chamber. The atomic beam is prepared along the longitudinal axis of the glass cell. The differential pumping tube was made from a single block of oxygen-free highly conductive (OFHC) copper. One end of the tube is a 45$^\circ$-angled polished mirror with a round surface of diameter 18 mm and placed inside the glass cell. The other end of the tube has a disk shape of diameter $\approx$ 48 mm and a thickness of 10 mm. This disk acts as a gasket between the two CF40 flanges of the 2D+ MOT and the 3DMOT chamber. The 45$^\circ$ surface of the copper tube allows the alignment of the longitudinal cooling laser beams as described later in this article.
The differential tube has a hole which originates at the center of the 45° surface and runs along the axis of the tube and ends up at the UHV side of the 3DMOT chamber. The differential pumping hole starts with a diameter of 2 mm and then widens up in two steps over a total distance of 270 mm. The hole reaches a diameter of 8 mm (6 mm) after the first 20 mm length and subsequently widens up to 14 mm (12 mm) after the next 120 mm length for $^{23}$Na ($^{39}$K) tubes.

The differential pumping tube has a conductance of 0.043 l/s (0.038 l/s) for the $^{23}$Na ($^{39}$K) side. The two 2D$^+$ MOT glass cells are individually pumped using two 20 l/s Ion pumps. The 3DMOT chamber is pumped by a 75 l/s Ion pump, and the cells are individually pumped using two 20 l/s Ion pumps. The 2D$^+$ MOT and the 3DMOT sides is cut at an angle of 45° and mirror-polished to facilitate the passage of the retarding beam. An additional pushing beam is used to direct the cold atomic beam to the 3DMOT chamber through the differential pumping hole.

Additionally, our experimental system includes a magnetic transport tube and a glass cell (‘science cell’) of dimension 85 mm × 30 mm × 30 mm pumped by two more Ion pumps with 40 l/s and 75 l/s pumping speeds. We also occasionally use a Titanium Sublimation pump to maintain the base pressure below $10^{-11}$ mbar near the ‘science cell’. The base pressure near the 3DMOT chamber is measured using an ionisation gauge to be $\sim 7 \times 10^{-11}$ mbar which is also consistent with our observed cold atom trap lifetime of $\sim 48$ s. On the other hand, both the 2D$^+$ MOT glass cells are maintained at a base pressure below $10^{-9}$ mbar.

We have used a natural abundance source (ingot) of sodium (Sigma Aldrich(262714-5G)). The ingot is placed inside a CF16 full nipple and attached to the glass cell through a CF16 angle gate valve (MDC vacuum). Heatings tapes are wrapped around the full nipple and the gate valve in such a way that, we could maintain a temperature gradient from the oven towards the glass cell, which ensures the sodium drifts into the cell and remains there. The purpose of the gate valve is two-fold, first, it determines the amount of flow of sodium vapour into the glass cell and, second, during replenishment of the source it would allow us to isolate the oven from the rest of the vacuum system.

We have also used a natural abundance source (ingot) of potassium from Sigma Aldrich (244856-5G) as the source for loading atoms in the $^{39}$K 2D$^+$ MOT. The design of the potassium oven is similar to the sodium one. Here we have kept natural abundance potassium and enriched $^{40}$K (10% enrichment, from Precision Glassblowing, USA), inside two different CF-16 full nipples, followed by respective CF-16 angle gate valves. These two ovens are connected and integrated with the 2D$^+$ MOT glass cell.

### B. Laser systems

The cooling and repumping beams for the laser cooling of sodium atoms were derived from a frequency-doubled Diode laser system (Toptica TA-SHG pro) which typically gives a total output power of 1100 mW at 589 nm ($^{23}$Na D2 transition). The laser beam from the TA-SHG pro is divided into several beams. A low-power beam (typically 5 mW) is fed into an AOM (AA optics, centre frequency 110 MHz) double-pass assembly and subsequently directed into the saturation absorption spectroscopy (SAS) setup. The spectroscopy for sodium is realized using a vapour cell of length 75 cm from Triad technologies (TT-NA-75-V-P), which is heated to 150°C to create a sufficiently high vapour pressure for absorption.

The cooling beams for the 2D$^+$ MOT as well as the 3DMOT are generated using two independent AOM (Isomet 110 MHz) double-pass setups and tuned appropriately red-detuned from the $3^2S_{1/2}(F = 2) \rightarrow 3^2P_{3/2}(F' = 3)$ transition. The repumping beams are tuned in resonance with the transition $3^2S_{1/2}(F = 1) \rightarrow 3^2P_{3/2}(F' = 2)$, by passing the cooling beams through two independent Electro-optic modulators (EOM) (QuBig-EO-Na1.7M3). The EOMs are powered by two independent drivers (QuBig-E3.93KC), and each side-band has typically 20% of the power of the carrier (cooling) frequency. The co-propagating cooling and repumping beams are injected into their respective polarization-maintaining (PM) fibers and transferred to the experimental optical table for the realization of the 2D$^+$ MOT and the 3DMOT.

For potassium atoms, we use two independent External Cavity Diode Lasers (ECDL) from Toptica Photonics for deriving the cooling (DL pro) and repumping (DL 100) laser beams. Each of these laser outputs is amplified using two independent tapered amplifiers (Toptica BoosTA pro) with a maximum output power reaching 2 W. The output of each of the Potassium lasers is divided into two beams, the one with low power $\approx 5$ mW is fed into the SAS setup. The spectroscopy is realized with a glass vapour cell of length 5 cm, in which a K-sample with natural abundance is heated to 50°C.
The other output beams from the two Potassium lasers are injected into the Tapered Amplifiers (TA). The amplified output beams of the TAs are split into several beams and sent through the corresponding AOM (AA Optics, 200 MHz) double pass configurations to prepare the beams at the appropriate frequencies to be used as the cooling and repumping beams for the 2D$^+\text{MOT}$ and the 3DMOT. The K$^+$ cooling laser is offset-locked to the $4S_{1/2}[F = 2] \rightarrow 4P_{3/2}[F' = 3]$ transition of $^{39}\text{K}$ atoms, while the repumping laser is locked to the $4S_{1/2}(|F = 1\rangle, |F = 2\rangle) \rightarrow 4P_{3/2}$ crossover transition.

The laser beams transferred to the main experimental table using PM fibers (Schafter-Kirchhoff GmbH) are out-coupled by the corresponding fiber-collimators, which provides a collimated Gaussian beam of $1/e^2$ diameter of 12 mm.

III. ATOMIC BEAM SOURCE

The 3DMOT can be loaded efficiently from a cold atomic beam with a high capture rate of atoms. The preparation of an atomic beam requires high atomic vapour pressure (in the range, of $10^{-8}$-$10^{-6}$ mbar). Generally, it is prepared in a section spatially separated from the 3DMOT section (which requires a UHV environment). The atomic beam is directed through a differential pumping tube into the 3DMOT section, which maintains a pressure difference of a few orders of magnitude between the 2D$^+\text{MOT}$ region and the UHV 3DMOT region. This atom loading scheme not only keeps the 3DMOT in a UHV range to minimize the collisions with the room-temperature atoms but also loads the 3DMOT with a large number of atoms. This creates a favourable starting point for proceeding towards evaporative cooling of the cold atomic mixture to quantum degeneracy.

We have employed two independent and spatially separated 2D$^+\text{MOTs}$ as the cold atomic beam sources for $^{23}\text{Na}$ and $^{39}\text{K}$, which provide cold collimated atomic beams to load the 3DMOT in the UHV chamber through two opposite ports.

A. 2D$^+\text{MOT}$

The 2D$^+\text{MOT}$ is created by two orthogonal retro-reflected elliptical (circular) laser beams in presence of a two-dimensional quadrupole magnetic field for $^{39}\text{K}$ ($^{23}\text{Na}$) atoms. The elliptical beams are chosen slightly convergent with $1/e^2$ diameter of incident beams to be 36 mm (24 mm) along the atomic beam direction and normal to the atomic beam axis is 24 mm (24 mm) at the 2D$^+\text{MOT}$ cloud position for $^{39}\text{K}$ ($^{23}\text{Na}$) atoms. The circularly polarised transverse cooling beams are retro-reflected using right-angled prisms which preserves the helicity of the beams via two total internal reflections. The degree of convergence has been chosen to accommodate the reflection of the uncoated glass cell surfaces (typically, each surface has 4 per cent reflectance), such that we obtain the same intensities of the incident and the retro-reflected beam at the position of the atomic cloud. The 2D quadrupole magnetic field is realized by two pairs of racetrack coils in an anti-Helmholtz configuration which creates a line of zero magnetic fields along the centre of the magnetic coil configuration. The atoms cooled in the transverse direction are confined around the zero magnetic field line of the 2D quadrupole magnetic field.

The performance of the 2D$^+\text{MOT}$ is enhanced by integrating a pair of counter-propagating laser beams with Gaussian width of 12 mm along the atomic beam direction which forms a longitudinal optical molasses cooling configuration. In this configuration, the optical molasses reduces the longitudinal velocities which allow the atoms to spend more time in the transverse cooling region. This reduces the transverse velocities of the atoms thereby reducing the divergence of the cold atomic beam. As a result, the atoms go through the differential pumping tube without much loss of atoms thereby increasing the cold atomic beam flux loading the 3DMOT. The longitudinal cooling beams are referred to as the pushing and the retarding beams as shown in Fig. 2. The retarding beam is aligned counter-propagating to the direction of the cold atomic beam. The longitudinal cooling using optical molasses reduces the longitudinal velocity of the cold atomic beam within the capture velocity of the 3DMOT in the UHV chamber thereby increasing the atoms captured in the 3DMOT. The retarding beam has a dark cylindrical region due to the hole in the mirror overlapping with the pushing beam in the counter-propagating direction which creates an imbalance of radiation pressure along the shadow region and helps in pushing the cold atomic beam to the UHV chamber through the differential pumping hole. An additional pushing beam with a Gaussian width of 1.15 mm (1.3 mm) for $^{23}\text{Na}$ ($^{39}\text{K}$) was aligned along with the pushing and retarding beams which pushes the atomic cloud into the 3DMOT chamber.

Two pairs of race-track-shaped magnetic coils in the anti-Helmholtz configuration are placed around the 2D MOT glass cell symmetrically. The transverse magnetic field gradient is 21 G/cm/A (12 G/cm/A) for $^{23}\text{Na}$ ($^{39}\text{K}$).

We use LabVIEW interfaced PXIe system (NI PXIe 1062Q chassis) containing a digital card (NI 6535) and an analog card (NI 6538), to precisely control the intensity as well as the detuning of the cooling and repumping laser beams through AOMs. Also, all the trigger lines (required for the camera trigger, RF switches and IGBT gate trigger for magnetic field switching) are drawn from the digital channels which have 100 ns time resolution. Acquisition of experimental images is done through Thorlabs scientific camera (Thorlabs CS2100M) of high quantum efficiency (61% at 600nm), integrated with the LabVIEW.

IV. NUMERICAL SIMULATION

A numerical simulation has been performed to model the characteristics of the 2D$^+\text{MOT}$ as an atom source to load atoms in the 3DMOT in the UHV. In this simulation, the trajectory of each particle captured from background vapour is calculated using their equations of motion. The initial position of the atoms is chosen randomly within the 2D$^+\text{MOT}$ glass cell excluding the portion containing the copper tube’s end that protrudes into the glass cell. The velocities
of the atoms are chosen according to Maxwell-Boltzmann distribution at a certain temperature \( T \) (in Kelvin) using the Monte Carlo method. It is assumed that all the particles we will consider for mapping their trajectories have velocities within the capture velocity of that atomic species in the 2D\(^+\)MOT at that particular temperature. The capture velocity is determined by the temperature of the atoms as well as the intensity, detuning and size of the cooling beams of the 2D\(^+\)MOT. After assigning an initial position and velocity to each particle, each of their trajectories is mapped out using RK4 (Runge-Kutta 4) method in the presence of radiation force due to the cooling laser beams, and the magnetic field gradient in the 2D\(^+\)MOT. While calculating the force, a simplified model of two-level atoms was assumed where the atoms are subjected to the cooling beams with frequency red-detuned to the cooling transition. The velocity-dependent force on the atoms is imparted by the four transverse cooling laser beams and a pair of longitudinal cooling beams along the line of zero magnetic field axis within the 2D\(^+\)MOT glass cell along the longitudinal Y-direction. The magneto-optical trapping happens only in the transverse directions determined by the intensity and polarization of the transverse cooling beams as well as the corresponding magnetic-field gradient in the transverse (XZ) directions.

For each axis, the total force on each atom in the 2D\(^+\)MOT glass cell is contributed from two directions denoted by ‘+’ and the ‘−’ directions of a particular axis. The detuning of the cooling laser beams plays a very important role in determining the force on the atoms. The effective detuning \( \delta_{\pm} \) of the beams are given by

\[
\delta_{\pm} = \delta \pm k_v v \mp \mu_{eg} B(r) / \hbar
\]

where \( \delta \) is the detuning of the laser beam from the atomic resonance. The total magneto-optical force on the atoms is given by

\[
F_{\pm} = \pm \frac{\hbar k_v \Gamma}{2 \left(1 + s_0 + (2\delta_{\pm}/\Gamma)^2\right)} s_0
\]

where \( k_v \) is the wave vector of the laser beams, \( \hbar \) is the Planck’s constant and \( \Gamma \) is the natural linewidth of the cooling transition, \( v \) is the velocity of the atoms, \( \mu_{eg} \) is effective magnetic moment for the cooling transition, \( B(r) \) is the magnetic field along the particular axis, \( s_0 \) is the saturation parameter given by \( s_0 = I/I_{sat} \) where \( I \) is the intensity of the cooling beams and \( I_{sat} \) is the saturation intensity of the atomic transition. Along the longitudinal Z axis, \( B(r) = 0 \) and for the transverse axes (i.e. X or Y), \( B(r) = \sqrt{B_x^2 + B_y^2} \).

The ‘+’ and the ‘−’ signs in the force equations are chosen according to the direction in which the force is calculated on the atoms with respect to the centre of the 2D\(^+\)MOT glass cell.

\[
\mu_{eg} = (g_e m_{Fe} - g_g m_{Fg}) \mu_B
\]

where \( g_e m_{Fe} \) (\( g_g m_{Fg} \)) is calculated for the excited state (ground state), and \( \mu_B \) is the Bohr magneton. The value of \( (g_e m_{Fe} - g_g m_{Fg}) \) has been obtained to be 1 for the \( D_2 \) cooling transition of both \( ^{23}\text{Na} \) and \( ^{39}\text{K} \) atoms and hence \( \mu_{eg} = \mu_B \) for both the atomic species.

**Simulation results**

In this section, we present the results obtained from the numerical simulation. The final positions of the particles at the
end of their trajectories obtained from the numerical simulation are shown in Fig. 3. The trajectories of all the particles coming out of the 2D\textsuperscript{+}MOT glass cell is shown in Fig. 4. The results of the numerical simulation for the capture rate of the 39\textsuperscript{K}-MOT and the 23\textsuperscript{Na}-MOT as a function of the corresponding 2D\textsuperscript{+}MOT cooling intensity per beam are compared with the corresponding experimental results as shown in Fig. 7. Since, we have performed the simulation considering typically 10\textsuperscript{5} atom trajectories in the cooling volume, whereas the total number of atoms in 2D\textsuperscript{+}MOT cooling volume is governed by the partial pressure, an overall scaling factor is used accordingly. Using the same numerical technique, we have also compared the 2D\textsuperscript{+}MOT flux as a function of magnetic field gradient with the experimental measurements as shown in Fig. 10.

V. EXPERIMENTAL RESULTS

For our experiment, the essential parameters which characterise the performance of the two 2D\textsuperscript{+}MOTs are the loading rates into the corresponding 3DMOT for 23\textsuperscript{Na} and 39\textsuperscript{K} atoms. We experimentally studied its dependence on several 2D\textsuperscript{+}MOT parameters, such as the vapour pressure in the 2D\textsuperscript{+}MOT glass cell, the total cooling beam intensities, 2D\textsuperscript{+}MOT magnetic field gradient, the detuning of the cooling and repumping beams, intensity ratios between the repumping and cooling beams as well as the pushing and retarding beams. The optimized values of these parameters are displayed in Tab. I. Additionally, we have also observed a significant enhancement in the performance of the 2D\textsuperscript{+}MOT for both the atomic species when we use Light Induced Atomic Desorption (LIAD)\textsuperscript{56,57} in both the 2D\textsuperscript{+}MOT vacuum manifolds.

We determine the capture rate of atoms into the 3DMOT using fluorescence measurements. We present our typical measurements from 39\textsuperscript{K} (23\textsuperscript{Na}) 3DMOT using fluorescence images recorded on a CCD camera in Fig. 5(a) (Femtowatt detector in Fig. 5(b)). The number of atoms in the 3DMOT as a function of the loading time is calculated using the expression for the scattering rate, where the experimental parameters are saturation intensity\textsuperscript{58,59} and laser detuning (calibrated using a weak probe beam to determine the exact resonance frequency). The number of atoms captured in the 39\textsuperscript{K}-MOT and 23\textsuperscript{Na}-MOT as a function of time for various detunings of the cooling beam of the corresponding 2D\textsuperscript{+} MOT is shown in Fig. 5(a) and Fig. 5(b) respectively. For optimised parameters, we observe a fast loading of 5 × 10\textsuperscript{10} atoms in 800 ms for 39\textsuperscript{K} atoms. In the case of 23\textsuperscript{Na} atoms, we observe the loading of 5 × 10\textsuperscript{8} atoms in 1.2 s limited only by the two-body collisional loss rate in the bright 23\textsuperscript{Na} 3DMOT.

Fig. 6 shows the dependence of the capture rate of the 39\textsuperscript{K}-MOT and the 23\textsuperscript{Na}-MOT on the detuning of the corresponding 2D\textsuperscript{+}MOT cooling beams. The curve has an effect on both the atomic flux 39\textsuperscript{K}-MOT and the 23\textsuperscript{Na}-MOT as a function of the cooling beam intensity of the corresponding 2D\textsuperscript{+} MOT is depicted in Fig. 7. The curve almost linearly increases with the beam power without a clear indication of saturation. The increase is due to two effects: First, the 2D\textsuperscript{+}MOT capture velocity increases with laser power due to the power broadening of the atomic spectral lines. Second, the scattering force increases, resulting in steeper transverse confinement, which facilitates the injection of the atoms into the differential pumping tube. The absence of saturation demonstrates that light-induced collisions for the used range of laser powers are negligible. As the rate for

FIG. 5. Number of atoms captured in the (a) 39\textsuperscript{K}-MOT (b) 23\textsuperscript{Na}-MOT as a function of time for various detunings of the cooling beam of the corresponding 2D\textsuperscript{+} MOT.

FIG. 6. Capture rate of (a) 39\textsuperscript{K}-MOT (b) 23\textsuperscript{Na}-MOT as a function of the detuning of the corresponding 2D\textsuperscript{+} MOT cooling beams. The 3DMOT cooling beam detuning was kept fixed at -6.8\textGamma and -1.4\textGamma for 39\textsuperscript{K} and 23\textsuperscript{Na} atoms respectively.
FIG. 7. Experimental measurements and comparison with numerical simulation of the capture rate of (a) $^{39}$K-MOT (b) $^{23}$Na-MOT as a function of the corresponding 2D$^+$ MOT cooling intensity per beam. The intensity ratios between 2D$^+$ MOT repumping and cooling beams were maintained at 0.75 and 0.18 for $^{39}$K and $^{23}$Na, respectively.

FIG. 8. Capture rate of (a) $^{39}$K-MOT (b) $^{23}$Na-MOT as a function of the intensity ratio between the corresponding 2D$^+$ MOT repumping and cooling beams. In the case of $^{39}$K atoms a relatively large repumping to cooling intensity ratio of around 0.75 is required for the optimised operation of the 2D$^+$ MOT due to the narrow spacing of the excited state hyperfine splitting. On the other hand, $^{23}$Na source works well with a relatively low repumping to cooling intensity ratio of around 0.18.

FIG. 9. Capture rate of (a) $^{39}$K-MOT (b) $^{23}$Na-MOT as a function of the intensity ratio of the pushing and retarding beams of the corresponding 2D$^+$ MOT. The optimum value of the intensity ratio is experimentally obtained at 8.1 (3.6) for $^{39}$K ($^{23}$Na) atoms. The data presented in this graph is recorded at a reduced oven temperature whereas we have experimentally checked that the optimum intensity ratio remains the same as a function of the partial vapour pressure for both $^{39}$K and $^{23}$Na atoms.

FIG. 10. Experimental results and comparison with the numerical simulation for the capture rate of (a) $^{39}$K-MOT (b) $^{23}$Na-MOT as a function of the magnetic field gradient of the corresponding 2D$^+$ MOT. At the low magnetic field gradient the experimental data matches well with the model developed with simple two-level atom approximation. However, at high field gradients, expectedly, the results deviate especially for Potassium atoms where the excited state splitting is less compared to Sodium atoms, as elaborate in the text.

| 2D$^+$ MOT parameters | $^{23}$Na | $^{39}$K |
|------------------------|----------|---------|
| $\delta_{\text{cooling}}^{2D}$ ($\Gamma$) | -1.8     | -6.5    |
| $I_{\text{cooling}}^{2D}$ per beam ($I_S$) | 7        | 10      |
| $I_{\text{repumping}}^{2D}$/$I_{\text{cooling}}^{2D}$ | 0.18     | 0.75    |
| $I_{\text{pushing}}^{2D}$/$I_{\text{cooling}}^{2D}$ | 3.6      | 8.1     |
| $\delta B$, $\delta_z B$ (G/cm) | 26       | 9       |
| $I_{\text{additional-push}}$ ($I_S$) | 7.7      | 5.38    |
| Vapour pressure (mbar) | $1.4 \times 10^{-8}$ | $2.2 \times 10^{-7}$ |
| 3DMOT capture rate (atoms/s) | $3.5 \times 10^8$ | $5 \times 10^{10}$ |

TABLE I. Optimised parameters for the 2D$^+$ MOTs

| 3DMOT parameters | $^{23}$Na | $^{39}$K |
|------------------|----------|---------|
| $\delta_{\text{cooling}}^{3D}$ ($\Gamma$) | -1.4     | -6.8    |
| Total $I_{\text{cooling}}$ ($I_S$) | 10       | 22.7    |
| 3DMOT field gradient (G/cm) | 17.6     | 18.5    |
| $I_{\text{repumping}}^{3D}$/$I_{\text{cooling}}^{3D}$ | 0.225    | 0.75    |
| Total number of atoms | $5.8 \times 10^8$ | $3 \times 10^{10}$ |

TABLE II. Optimised parameters for the 3DMOT

induced collisions depends on the atom number density in the 2D$^+$ MOT; the absence of saturation effect implies that the atomic density in the 2D$^+$ MOT is low due to the absence of three-dimensional confinement. This qualitative description given above is supported well using our numerical simulation results which agree well with the experimental observation as evident in Fig. 7. The capture rate of atoms in the 3DMOTs is limited by the available laser power in our experiment.

Fig. 8 shows the dependence of the capture rate of the $^{39}$K-MOT and the $^{23}$Na-MOT on the intensity ratio between the cooling and repumping beams of the corresponding 2D$^+$ MOT. The graph shows that the $^{39}$K-MOT and $^{23}$Na-MOT capture rate increases with increasing repumping intensity and that it saturates at high intensities of repumping beams. The dependence of the capture rate on the repump-
The optimised experimental parameters for the $^{39}$K and $^{23}$Na 2D$^{+}$MOTs are summarised in Table I and the optimised parameters for the $^{39}$K and $^{23}$Na 3D MOTs are summarised in Table II.

In order to vary the vapour pressure in the 2D$^{+}$MOT side for $^{39}$K atoms, the oven temperature was varied between 50°C to 130°C. The metal parts near the 2D$^{+}$MOT glass cell were kept mildly heated to 40°C so as to prevent coating of $^{39}$K atoms there and to facilitate $^{39}$K atomic vapour coming into the glass cell. In the case of $^{23}$Na 2D$^{+}$MOT, the oven was heated to 300°C and the metal parts near the glass cell were heated to 100°C. The region around the $^{23}$Na 2D$^{+}$MOT glass cell was kept heat-insulated using a heat-insulation blanket and two layers of aluminium foil while keeping sufficient openings for the cooling laser beams. Heating rods were inserted inside the insulated region to keep the air tempera-
ture around the 2D$^+$ MOT glass cell between 60-75°C. In the case of Na, this special arrangement is done (in contrast to 23K) because 23Na atoms have a particular tendency to stick to glass surfaces and the melting point of 23Na is also relatively high (98°C). We have avoided heating the glass cell to a higher temperature so as to prevent degrading the vacuum at the 2D$^+$ MOT side.

The total number of atoms captured in the 39K-MOT and 23Na-MOT as a function of time demonstrating the effect of switching on the LIAD (Light-induced atomic desorption) for the corresponding 2D$^+$ MOT is shown in Fig. 12. In our experiment, the LIAD plays a significant role in increasing the vapour pressure of 39K and 23Na atoms in their respective 2D$^+$ MOT glass cells increasing the atomic beam flux and thereby the capture rate of atoms in the corresponding 3DMOT. We use commercially available high-power UV Light-Emitting diodes (LED) (centre wavelength 395 nm) (Thorlabs M395L5) for the 39K side and a 100 low-power UV LED array for the 23Na side. Both 39K and 23Na atoms are efficiently desorbed from the glass surface on shining the UV light thereby increasing the partial pressure of the atoms without affecting the overall vacuum in the 2D$^+$ MOT glass cells. This results in a significant increase in the 2D$^+$ MOT flux as well as the 3DMOT capture rate as shown in Fig. 12. This is particularly useful because apart from the improved performance of the cold atom sources, the UV light also prevents the glass surface to be coated by 39K and 23Na atoms.

**VI. LIGHT-ASSISTED INTERSPECIES COLD COLLISIONS**

Finally, we report on the effect of cold collisions between 23Na and 39K atoms while they are simultaneously captured in the 3DMOT. The effects are considerable and may cause significant atom loss from the trap as evident from a typical experimental data shown in the inset of Fig 13 where we monitored only the number of 23Na trapped atoms while loading the 39K 3DMOT which overlaps with the 23Na 3DMOT in space. From a series of such data recorded with different 39K loading rate we experimentally find an interspecies loss-coefficient ($\beta_{NaK}$). We present the results as a survival probability of one species (reported for 23Na) in presence of the other species by calculating the total trap loss in the asymptotic limit (Fig 13). In this context, the survival probability is defined as the fraction of atoms remaining after interspecies light assisted collision is turned on.

It is worth noting that we observe as much as nearly 50% loss of 23Na atoms due to interspecies light assisted cold collisions. As the 39K numbers are increased in the trap by increasing the 39K 2D$^+$ MOT flux, the interspecies collisions results in further loss of 23Na atoms which saturates above a mixture ratio (the ratio of the number of 39K atoms to the 23Na atoms in the trap) beyond 5. In this high Mixture ratio 39K can be considered a bath in which 23Na atoms move as “impurities”. As the bath size is increased we reach a constant density limit for 39K cloud, and the interspecies collision also reaches a steady state value. For typical dual species overlapping 3DMOTs of 23Na and 39K, we find the interspecies loss co-efficient, $\beta_{NaK} = 2 \times 10^{-12}$ cm$^3$/sec (using the semi-classical approach described in [51]). In comparison, the intra-species light-assisted collision rates for 23Na - 23Na is, $\beta_{NaNa} = 2.1 \times 10^{-11}$ cm$^3$/sec and for 39K - 39K is, $\beta_{KK} = 3 \times 10^{-11}$ cm$^3$/sec. These measurements are performed using the typical single species loading curves in the 3DMOT using a similar measurement technique described in [62].

In order to verify the above argument physically, we varied the interspecies loss-coefficient ($\beta_{NaK}$) by varying the excited state population of the bath atoms (39K). Experimentally, this is done by controlling the repump laser power in 3DMOT which regulates the population of the 39K atoms in the $|F = 2\rangle$ state. The resulting data is presented in Fig 14. The observation indicates that as the excited state population is increased, the interspecies collision rate also increases resulting in further decrease in the number of minority species (23Na) atoms. Interestingly, beyond a certain excited state fraction of around 1.75% in 39K atoms the survival probability of the 23Na atoms actually increases again. This is because, at such high 39K excited state population, 39K-39K collisions (governed through $C_3/R^3$ potential) dominates over the 23Na-39K collisions (which is governed through $C_6/R^6$ potential [52]). Here, $R$ is the inter-atomic separation and $C_3$ and $C_6$ are the resonant and off-resonant dipole-dipole interaction co-efficients, respectively. This effect results in the decrease of the density of the majority species (39K) and hence the interspecies collision rates. This observation suggests that the interspecies collision can be tuned and significantly reduced by controlling the excited state population of the bath. This way, we could vary the $\beta_{NaK}$ in a range between 1.7 - 3.3 $\times 10^{-12}$ cm$^3$/sec.

![FIG. 13. The survival probability of 23Na atoms as a function of the “Mixture ratio” (ratio between the number of 39K and 23Na atoms). Inset: A typical data of 23Na atom number in the 3DMOT in absence and presence of 39K 3DMOT loading.](image-url)
and quantum sensing.

ACKNOWLEDGMENTS

This work was partially supported by the Ministry of Electronics and Information Technology (MeitY), Government of India, through the Center for Excellence in Quantum Technology, under Grant(4/7)/2020-ITEA. S. R acknowledges funding from the Department of Science and Technology, India, via the WOS-A project grant no. SR/WOS-A/PM-59/2019. We acknowledge Meena M. S., Md. Ibrahim, S. Barui, Sujatha S, S. Bhar, B. B. Boruah, S. Bagchi, the RRI mechanical workshop, RRI HPC facility, for the instruments and assistance with the experiments.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

1. I. Bloch, J. Dalibard, and W. Zwerger, “Many-body physics with ultracold gases,” Rev. Mod. Phys. 80, 885–964 (2008).
2. I. Bloch, J. Dalibard, and S. Nascimbène, “Quantum simulations with ultracold quantum gases,” Nature Phys. 8, 267–276 (2012).
3. C. Gross and I. Bloch, “Quantum simulations with ultracold atoms in optical lattices,” Science 357, 995–1001 (2017). https://www.science.org/doi/pdf/10.1126/science.aal3837.
4. F. Schäfer, T. Fukuhara, S. Sugawa, Y. Takasu, and Y. Takahashi, “Tools for quantum simulation with ultracold atoms in optical lattices,” Nature Reviews Physics 2, 411–429 (2020).
5. J. H. Denschlag, J. E. Simsarian, H. Häffner, C. McKenzie, A. Browaeys, D. Cho, K. Helmersson, S. L. Rolston, and W. D. Phillips, “A bose-einstein condensate in an optical lattice,” Journal of Physics B: Atomic, Molecular and Optical Physics 35, 3095–3110 (2002).
6. J. Ye, S. Blatt, M. M. Boyd, S. M. Foreman, E. R. Hudson, T. Ido, B. Lev, A. D. Ludlow, B. C. Sawyer, B. Stuhl, and T. Zelinsky, “Precision measurement and frequency metrology with ultracold atoms: measurement based on ultracold atoms and cold molecules,” International Journal of Modern Physics D 16, 2481–2494 (2007). https://doi.org/10.1142/S0218271807011826.
7. X. Zhang and J. Ye, “Precision measurement and frequency metrology with ultracold atoms,” National Science Review 3, nw013 (2016).
8. C. J. Myatt, E. A. Burt, R. W. Ghrist, E. A. Cornell, and C. E. Wieman, “Production of two overlapping bose-einstein condensates by sympathetic cooling,” Phys. Rev. Lett. 78, 586–589 (1997).
9. D. S. Hall, M. R. Matthews, J. R. Ensher, C. E. Wieman, and E. A. Cornell, “Dynamics of component separation in a binary mixture of bose-einstein condensates,” Phys. Rev. Lett. 81, 1539–1542 (1998).
10. J. Stenger, S. Inouye, D. M. Stamper-Kurn, H.-J. Miesner, A. P. Chikkatur, and W. Ketterle, “Spin domains in ground-state bose–einstein condensates,” Nature 396, 345–348 (1998).
11. G. Modugno, G. Ferrari, G. Roati, R. J. Brecha, A. Simoni, and M. Inguscio, “Bose-einstein condensation of potassium atoms by sympathetic cooling,” Science 294, 1320–1322 (2001). https://science.sciencemag.org/content/294/5555/1320.full.pdf.
12. Z. Hadzibabic, C. A. Stan, K. Dieckmann, S. Gupta, M. W. Zwierlein, A. Görlitz, and W. Ketterle, “Two-species mixture of quantum degenerate bose and fermi gases,” Phys. Rev. Lett. 88, 160401 (2002).
13. G. Modugno, M. Modugno, F. Riboli, G. Roati, and M. Inguscio, “Two atomic species superfluid,” Phys. Rev. Lett. 89, 190404 (2002).
14. C. A. Regal, M. Greiner, and D. S. Jin, “Observation of resonance condensation of fermionic atom pairs,” Phys. Rev. Lett. 92, 040403 (2004).

FIG. 14. The survival probability of $^{23}$Na atoms as a function of the excited state population of the $^{39}$K atoms.
C. Silber, S. Günther, C. Marzok, B. Deh, P. W. Courtille, and C. Zimnemmer, “Quantum-degenerate mixture of fermionic lithium and bosonic rubidium gases,” Phys. Rev. Lett. 95, 170408 (2005).

K. Günter, T. Stöferle, H. Moritz, M. Köhl, and T. Esslinger, “Bose-fermi mixtures in a three-dimensional optical lattice,” Phys. Rev. Lett. 96, 180402 (2006).

S. B. Papp, J. M. Pino, and C. E. Wieman, “Tunable miscibility in a dual-species Bose-fermi condensate,” Phys. Rev. Lett. 101, 040402 (2008).

S. Ospelkaus, C. Ospelkaus, O. Wille, M. Succo, P. Ernst, K. Sengstock, and K. Bongs, “Localization of bosonic atoms by fermionic impurities in a three-dimensional optical lattice,” Phys. Rev. Lett. 96, 180403 (2006).

J. Catani, L. De Sarlo, G. Barontini, F. Minardi, and M. Inguscio, “Degenerate Bose-Fermi mixture in a three-dimensional optical lattice,” Phys. Rev. A 77, 011603 (2008).

M. Teglbjer, A. C. Voigt, T. Aoki, T. W. Hänsch, and K. Dieckmann, “Quantum degenerate two-species fermi-fermi mixture coexisting with a Bose-Fermi condensate,” Phys. Rev. Lett. 100, 010401 (2008).

D. J. McCarron, H. W. Cho, D. L. Jenkins, M. P. Köppinger, and S. L. Chin, “Dual-species Bose-fermi condensate of 87Rb and 133Cs,” Phys. Rev. A 84, 033602 (2011).

B. Pasquieu, A. Bayerle, S. M. Tzanova, S. Stellmer, J. Szczepkowski, M. Parigger, R. Grimm, and F. Schreck, “Quantum degenerate mixtures of strontium and rubidium atoms,” Phys. Rev. A 88, 025601 (2013).

L. Ferrier-Barbut, M. Delbroux, S. Laurent, A. T. Ritter, M. Pierre, B. S. Rem, F. Chevy, and C. Salomon, “A mixture of Bose and Fermi superfluids,” Science 345, 1035–1038 (2014). https://www.science.org/doi/pdf/10.1126/science.1255380.

L. Wacker, N. B. Jørgensen, D. Birkmose, R. Horchani, W. Ertmer, C. Klempt, N. Winters, J. Sherson, and J. J. Arlt, “Tunable dual-species Bose-Fermi condensates of 40K and 87Rb,” Phys. Rev. A 92, 053602 (2015).

C. Ravensbergen, V. Corre, E. S. Soave, M. Kreyer, E. Kirilov, and R. Grimm, “Production of a degenerate Fermi-Fermi mixture of dysprosium and potassium atoms,” Phys. Rev. A 98, 063624 (2018).

P. C. M. Castilho, E. Pedrozo-Peñafiel, E. M. Gutierrez, P. L. Mazo, G. Roati, K. M. Farias, and V. S. Bagatto, “A compact experimental machine for studying tunable Bose–Fermi superfluid mixtures,” Laser Physics Letters 16, 035301 (2019).

A. P. Chikukura, A. Görlitz, D. M. Stamper-Kurn, S. Inouye, S. Gupta, and W. Ketterle, “Suppression and enhancement of impurity scattering in a Bose-Fermi condensate,” Phys. Rev. Lett. 85, 483–486 (2000).

S. Ospelkaus, C. Ospelkaus, O. Wille, M. Succo, P. Ernst, K. Sengstock, and K. Bongs, “Localization of bosonic atoms by fermionic impurities in a three-dimensional optical lattice,” Phys. Rev. Lett. 96, 180403 (2006).

M. Bruderer, A. Klein, S. Clark, and D. Jaksch, “Transport of strong-coupling polarons in optical lattices,” New Journal of Physics 10, 033015 (2007).

D. S. Petrov, “Quantum mechanical stabilization of a collapsing Bose-Fermi mixture,” Phys. Rev. Lett. 115, 155302 (2015).

C. R. Eberz, T. Liu, L. Torralbo-Campo, G. D. Bruce, G. Smirne, and D. Cassettari, “Light-induced atomic desorption for loading a sodium magneto-optical trap,” Phys. Rev. A 93, 053622 (2016).

M. Gröbner, P. Weinmann, F. Meirert, K. Lauber, E. Kirilov, and H.-C. Nagerl, “A new quantum gas apparatus for ultracold mixtures of k and es and kcs ground-state molecules,” Journal of Modern Optics 63, 1829–1839 (2016). https://doi.org/10.1080/09500340.2016.1143051.

G. Lamporesi, S. Donadello, S. Serafini, and G. Ferrari, “Compact high-flux source of cold sodium atoms,” Review of Scientific Instruments 84, 063201 (2013). https://doi.org/10.1063/1.4803735.

G. Telles, T. Ishikawa, M. Gibbs, and C. Raman, “Light-induced atomic desorption for loading a sodium magneto-optical trap,” Phys. Rev. A 73, 033415 (2006).

K. Dieckmann, R. J. C. Spreuss, M. Waidtmüller, and J. T. M. Walraven, “Two-dimensional magneto-optical trap as a source of slow atoms,” Phys. Rev. A 58, 3891–3895 (1998).

S. Ravenhall, B. Yuen, and C. Foot, “High-flux, adjustable, compact cold atom source,” Opt. Express 29, 32591–32595 (2021).
H. Metcalf, P. Van der Straten, J. Birman, J. Lynn, and H. Stanley. *Laser Cooling and Trapping*. Graduate texts in contemporary physics (Springer, 1999).

G. D. Telles, W. Garcia, L. G. Marcassa, V. S. Bagnato, D. Ciampini, M. Fuzzi, J. H. Müller, D. Wilkowski, and E. Arimondo. “Trap loss in a two-species rubidium–cesium magneto-optical trap.” *Phys. Rev. A* **63**, 033406 (2001).

T. P. Dinneen, K. R. Vogel, E. Arimondo, J. L. Hall, and A. Gallagher. “Cold collisions of Sr – Sr in a magneto-optical trap.” *Phys. Rev. A* **59**, 1216–1222 (1999).

M. S. Santos, P. Nussenzveig, A. Antunes, P. S. P. Cardona, and V. S. Bagnato, “Hyperfine-changing collision measurements in trap loss for mixed species in a magneto-optical trap.” *Phys. Rev. A* **60**, 3892–3895 (1999).

S. Chaudhuri, S. Roy, and C. S. Unnikrishnan, “Bose–Einstein condensation in optical traps and in a 1d optical lattice.” *Current Science* **95**, 1026–1034 (2008).

S. Bhar, M. Swar, U. Satpathi, S. Sinha, R. Sorkin, S. Chaudhuri, and S. Roy, “Measurements and analysis of response function of cold atoms in optical molasses.” *Opt. Continuum* **1**, 171–188 (2022).

M. Swar, D. Roy, S. Bhar, S. Roy, and S. Chaudhuri, “Detection of spin coherence in cold atoms via Faraday rotation fluctuations.” *Phys. Rev. Research* **3**, 043171 (2021).

M. Oszmaniec, R. Augusiak, C. Gogolin, J. Kolodyński, A. Acín, and M. Lewenstein, “Random bosonic states for robust quantum metrology.” *Phys. Rev. X* **6**, 041044 (2016).

I. M. Georgescu, S. Ashhab, and F. Nori, “Quantum simulation.” *Rev. Mod. Phys.* **86**, 153–185 (2014).

G. Pelegrí, J. Mompart, and V. Ahufinger, “Quantum sensing using imbalanced counter-rotating Bose–Einstein condensate modes.” *New Journal of Physics* **20**, 103001 (2018).