

APPARATUS AND METHOD FOR CONTINUOUS LOADING OF NEUTRAL ATOM REGISTERS

FIELD OF INVENTION

[0001] The present disclosure relates to apparatuses, methods and computer programs for trapping and manipulating neutral atoms, particularly for continuous loading of neutral atom registers that can be used as quantum registers for quantum technologies such as quantum computing, atomic clocks, and quantum simulation.

INTRODUCTION

[0002] Ensembles of neutral atoms trapped in optical traps are a promising approach for the realization of quantum computers and other quantum technologies. Using neutral atoms for quantum computing or analog quantum simulation requires the initialization of the atomic ensemble using known quantum gas microscopy techniques: Laser-cooled atoms are loaded into a plurality of optical trapping potentials formed by either optical tweezer arrays or optical lattices or combinations thereof. Initializing the atomic ensemble into a suitable register e.g., for quantum computing requires the preparation of precisely one neutral atom per trapping site. This has been demonstrated by actively moving the atoms in their trapping potential using mobile optical tweezers. Preparing defect-free atomic ensembles in a configurable two-dimensional optical trap provides the initialization of the quantum register required for quantum computing.

[0003] Various quantum technologies, e.g., as mentioned above, benefit from the largest possible systems sizes, i.e., the largest number of neutral atoms in the register as well as from the fastest possible initialization of the system. Preparing defect-free ensembles typically requires the detection of the initially random trapping

site occupation via established imaging techniques, e.g., fluorescence imaging using a microscope objective prior to the resorting e.g., via a movable optical trap or similar device.

[0004] In this context M. Norcia et al. *Iterative assembly of 171Yb atom arrays in cavity-enhanced optical lattices*, arXiv:2401.16177v1 29 Jan 2024 discloses assembly of atomic arrays, based on a combination of optical tweezers and cavity-enhanced optical lattices, and the incremental filling of a target array from a repetitively filled reservoir. In this protocol, tweezers provide for trapping and microscopic rearrangement of atoms, while the cavity-enhanced lattices enable rapid low-loss imaging of atoms.

[0005] Further, applicant's publication R. Tao, J. Zeiher, I. Bloch et al. *High-fidelity detection of large-scale atom arrays in an optical lattice*, arXiv:2309.04717v2 of 12 Sep 2023 (in the following: Ref. [1]) discloses high-fidelity and high-survival imaging of strontium atoms using repulsive Sisyphus cooling. An optical lattice is used as a pinning potential for atoms in a large-scale tweezer array with up to 399 tweezers and allows for repeated, high-fidelity lattice-tweezer-lattice transfers. The scalability of the platform is demonstrated by directly loading more than 10000 atoms in a single plane of the optical lattice, which can be used as a locally addressable and sortable reservoir for continuous refilling of optical tweezer arrays and similar trapping arrays. To avoid redundancies, Ref. [1] is incorporated herein in its entirety by reference.

Summary

[0006] Scaling approaches as mentioned above to large system sizes requires preparation and loading of atoms into arrays of optical traps. However, preparation times increase with system size and constitute a severe bottleneck in the assembly of large, ordered arrays from typically stochastically loaded optical trap arrays. In particular, a typical experimental sequence to control neutral atoms starts with preparation of an ensemble, followed by a quantum simulation, quantum computation or metrology sequence. Afterwards, typically, a destructive measurement of the state of the system is performed that renders recycling of atoms from one experimental cycle to

the next impossible. The preparation of a fresh ensemble of atoms typically requires significantly more time than the actual experimental sequence leading to a dead time that becomes significantly longer for large arrays. Thus, there is a perpetual need for fast and large-scale preparation and/or loading of neutral atom quantum registers while overcoming at least some of the discussed limitations.

[0007] A current limitation in further scaling up atom numbers in atomic arrays is the absence of a continuous operation mode, where an atomic register is continuously operated. Continuous operation in this case means that atoms are kept in a storage register without loss, possibly in a coherent superposition of two internal states, and lost atoms can be replenished continuously from a reservoir register. In such a scheme, a problem emerges in reloading atoms into the reservoir register without unintentionally loading atoms into the storage register, or, equivalently, removing newly loaded atoms in the storage register selectively without removing the stored atoms already in place.

[0008] To address such and similar problems the present disclosure provides, in a first aspect, a method for trapping and manipulating neutral atoms, comprising loading a plurality of neutral atoms into a loading trap array (e.g., an array of optical tweezers, a part of an optical lattice or a combination thereof) that is arranged adjacent to or at least partially collocated with a storage trap array (e.g., an array of optical tweezers, a part of an optical lattice or a combination thereof). The method further comprises selectively removing neutral atoms in a first electronic state $|1\rangle$ (e.g., an electronic ground state of an Alkali-earth like atom such as ^{88}Sr or ^{171}Yb), from the storage trap array, determining a trap occupancy of neutral atoms in the storage trap array in a second electronic state $|2\rangle$ (e.g., an electronic excited state, such as the long-lived $^3\text{P}_0$ in ^{88}Sr), and of neutral atoms in the loading trap array, and moving, based on the determined trap occupancy of the neutral atoms in the storage trap array and in the loading trap array, neutral atoms from the loading trap array to one or more non-occupied trapping sites of the storage trap array (for details see Fig. 5 to Fig. 9 discussed below).

[0009] As discussed below, for example, the loading trap array may be formed by an array of optical tweezers that are collocated with a subset of trapping sites of an

optical lattice, and the storage trap array may be formed by an further array of optical tweezers, a further subset of trapping sites of the optical lattice, or a different optical lattice operated at a different wavelength than the optical lattice used for the loading trap array (see for details see Fig. 1 to Fig. 8 discussed below). For example, the storage trap array may be formed by a plurality of trapping sites of a so-called *magic* optical lattice, i.e. an optical lattice that provides essentially identical polarizabilities for the $|0\rangle$ state and the $|1\rangle$ state. Further possible implementation details of the loading trap array and the storage trap array are discussed in Ref. [1] and Ref [2].

[0010] In a typical implementation, the first electronic state $|1\rangle$ of the neutral atoms may be a state with a lower energy compared to the second electronic state $|2\rangle$. For example, the first electronic state $|1\rangle$ may be the 1S_0 state of ^{88}Sr , and the second electronic state $|2\rangle$ may be the 3P_0 state, which exhibits a natural lifetime on the order of 100 s, due to a doubly forbidden transition to the 1S_0 state. Evidently, other states may be used, e.g., the 3P_0 state may be used as the $|1\rangle$ state and the 1S_0 state may be used as the $|2\rangle$ state.

[0011] In some implementations, the loading trap array could be overlapped with the storage trap array by interleaving loading sites and storage sites (see Fig. 7 below). Using such a configuration is beneficial since it increases the available space for the storage trap array and the average required move distance from the loading trap array to the storage trap array is decreased which reduces heating and speeds up cycle time. Typically, the loading trap array can be loaded from a source region of laser-cooled neutral atoms, e.g., from a magneto-optical trap, MOT, for the neutral atoms that may be operated in the same region of space (e.g., in an ultra-high vacuum, UHV, environment) as known in the art. In some implementations, the source region of laser-cooled atoms may be spatially separated from the loading trap array. In such a configuration, the laser-cooled atoms need first to be transported to the region of the loading trap array, e.g., by a transport dipole trap, a transport lattice or similar device known in the art.

[0012] For instance, selectively removing neutral atoms in the first electronic state $|1\rangle$ from the storage trap array may ensure that that only atoms in the second

electronic state $|2\rangle$ are present when determining trap occupancy thereby allowing reliable assembly of large arrays of neutral atoms in the storage trap array. As discussed below, selectively removing neutral atoms in the $|1\rangle$ state from the storage trap array may be realized by a state- and trap-selective heating laser-pulse that essentially leaves the neutral atoms in the loading trap array and neutral atoms in the $|2\rangle$ state unaffected (see Fig. 12 below).

[0013] A further aspect of the present disclosure relates to a method for trapping and manipulating neutral atoms. The method comprises transferring a plurality of neutral atoms trapped in a storage trap array from a first electronic state $|1\rangle$ to a second electronic state $|2\rangle$, loading a plurality of laser-cooled neutral atoms into a loading trap array arranged adjacent to or at least partially collocated with the storage trap array, determining a trap occupancy of the neutral atoms in the storage trap array in the second electronic state $|2\rangle$, and of neutral atoms in the loading trap array, and moving, based on the determining a trap occupancy, neutral atoms from the loading trap array to one or more non-occupied sites of the storage trap array.

[0014] As discussed below with reference to Fig. 10, transferring the neutral atoms from the first electronic state $|1\rangle$ to the second electronic state $|2\rangle$ may be implemented coherently, e.g., via a π -pulse generated by an ultra-narrow laser system resonant to a clock transition of alkaline-earth like atoms such as ^{88}Sr , or incoherently, e.g., via optical pumping (see Fig. 12). For example, the $|2\rangle$ state may be an electronic excited state such as the $^3\text{P}_0$ clock state of ^{88}Sr that has no dipole-allowed transitions to the electronic ground state. In the following transferring the first electronic state $|1\rangle$ to the second electronic state $|2\rangle$ may also be designated as *shelving* and the second electronic state $|2\rangle$ may also be designated as a *shelving state*.

[0015] For instance, shelving atoms in the storage trap to the shelving state (e.g., the $|2\rangle$ state) may have the advantage that other atoms that are stochastically loaded into the storage trap array, e.g., when loading the loading trap array, can be identified and / or selectively removed from the storage trap array as described above and in detail below (see Fig. 12). In this manner, full control over the trap occupancy of neutral atoms in the storage trap array can be achieved which allows for reliable

initialization of neutral atom registers for quantum simulation, metrology, and quantum computing.

[0016] A further aspect of the present disclosure relates to a method for trapping and manipulating neutral atoms, comprising loading a plurality of neutral atoms into a loading trap array adjacent to or collocated with a storage trap array, wherein the loading trap array that may be formed by an optical lattice and comprises at least 1000 trapping sites, preferably at least 5000 trapping sites, and more preferably at least 10000 trapping sites overlapped with a source region for laser-cooled neutral atoms, determining a trap occupancy of neutral atoms in the storage trap array, and of neutral atoms in the loading trap array, and moving, based on the determined trap occupancy of the neutral atoms in the storage trap array and in the loading trap array, neutral atoms from the loading trap array to one or more non-occupied trapping sites of the storage trap array.

[0017] Such a *large N* loading trap array may for example be implemented by a plurality of trapping sites of a folded optical lattice as described in detail in applicant's own international patent application PCT/EP2023/074768 titled *APPARATUS AND METHOD FOR TRAPPING AND MANIPULATING LARGE NUMBERS OF INDIVIDUAL NEUTRAL ATOMS* (Ref. [2] in the following), which is incorporated herein in its entirety by reference and whose priority is claimed.

[0018] As discussed in detail in Ref. [2] a *large N* loading trap array may be formed by a plurality of trapping sites of an optical lattice, wherein a trap depth of the optical lattice is larger than 0.1 mK, preferably larger than 1.0 mK, and / or wherein a trap frequency in a z-direction that is essentially orthogonal to an x-y-plane that comprises the optical lattice is larger than $2\pi \times 1$ kHz, preferably larger than $2\pi \times 2$ kHz, more preferably larger than $2\pi \times 4$ kHz, and even more preferably larger than $2\pi \times 8$ kHz. For instance, such an optical lattice, designated as *optical trapping lattice* in Ref. [2] may be realized by an apparatus for trapping and manipulating neutral atoms, comprising: a trapping laser system, and optics for generating an optical trapping lattice at a trapping volume inside a vacuum chamber, wherein the optics for generating the optical trapping lattice are configured to generate, based on the output

of the trapping laser system, a single elliptical trapping laser beam that is retroreflected and focused, using a bow-tie configuration, to the trapping volume to generate the optical lattice (for details see Fig. 1, Fig. 2 and Fig. 3 below, and [Ref. 2]).

[0019] As explained in the following, the number of atoms N_L that can be loaded into the loading trap array during each iterative loading cycle is an important parameter that *inter alia* determines the saturated number of atoms N_S that can continuously maintained in the storage trap array for essentially arbitrarily long holding times. For instance, the saturated atom Number N_S in the storage trap array can be modeled as:

$$N_S = (1 - \alpha_r) \cdot N_L / \alpha_c \quad (\text{Eq. 1})$$

where α_c is a normalized cycle loss, and α_r a resorting infidelity associated with moving neutral atoms from the loading trap array to non-occupied sites of the storage trap array. For instance, it has been shown that shelving efficiency can reach 99.7% [e.g., see W. Tian et al. *Parallel assembly of arbitrary defect-free atom arrays with a multi-tweezer algorithm*, Physical Review Applied 19, 034048 (2023)]. Further, for a lifetime of the second state $|2\rangle$ of the order of ~ 100 s that can routinely be reached for storage trap arrays with optimized trapping parameters [S. Dörscher et al. *Lattice-induced photon scattering in an optical lattice clock*, Physical Review A 97,063419 (2018)] and a typical MOT stage duration of 100 ms, a loss of shelved atoms can be as low as 0.4% or even lower. Factoring in typical vacuum lifetimes of ~ 250 s e.g., in room-temperature UHV systems, a total cycle loss of $\alpha \approx 0.8\%$ can be achieved with current operational technologies. Further, atom loss due to resorting moves can be as low as $\alpha_r \approx 2\%$ (e.g., see A. W. Young, et al. *An atomic boson sampler*, arXiv:2307.06936. Based thereon, the achievable amplification factor $\beta = (1 - \alpha_r) / \alpha_c$ (see Eq. 1) can reach values $\beta > 100$. With such amplification, one could reach about 10000 atoms continuously maintained in a single array in the storage trap array with as few as 100 atoms loaded into the loading trap array during each loading cycle. Using a *large N* loading trap array as disclosed in Ref. [1] and Ref. [2] thus allows to increase this number even further, paving the way to near-term quantum advantage for neutral atom-based quantum technologies (e.g., see Bluvstein, D. et al. *Logical quantum processor based on reconfigurable atom arrays*. Nature 626, 58–65 (2024)).

[0020] The present disclosure also relates to a method for continuous operation of a quantum computation, simulation and / or metrology device comprising: repeating the steps of the methods as discussed above to iteratively assemble and maintain an ensemble of neutral atoms in the storage trap array, and using a subset of the ensemble of neutral atoms for executing a quantum computation sequence, a quantum simulation sequence, and / or a quantum metrology sequence. Such a method may further comprise receiving, from a remote computation device (e.g., from an interface, via a network, to a cloud-computing system or a super-computing facility or similar), instructions for executing the quantum computation sequence, the quantum simulation sequence, and / or a the quantum metrology sequence, executing, based on the received instructions, the quantum computation sequence, the quantum simulation sequence, and / or a the quantum metrology sequence; and sending (e.g., via the network) a result of the executed quantum computation sequence, the executed quantum simulation sequence, and / or the executed quantum metrology sequence to the remote computation device. Such a method allows to provide modern quantum computation sequences, quantum simulation sequences, and / or a quantum metrology sequences to various remote computing devices that can be spatially separated from the actual quantum hardware by even long distances.

[0021] The present disclosure further relates to a quantum computation, simulation and / or metrology device (for an example see Fig. 1 to Fig. 3, Ref. [1] and Ref. [2]) comprising means for executing any of the methods disclosed herein, e.g., the methods discussed above or below with reference to Fig. 8 to Fig. 10. The present disclosure further relates to a computer program comprising instructions for causing a control unit to control a quantum computation, simulation and / or metrology device to execute any of the methods disclosed herein.

[0022] In essence the present disclosure thus relates to new approach to replenish an atomic register from a reservoir without affecting the stored atoms. The approach disclosed herein relies on the combination of a number of aspects and techniques, including, for example, high-efficiency shelving of atoms in metastable states where they are hidden from fluorescence light associated with a magneto-optical

trap that serves as a reservoir as well as a combination of two atom registers: a loading register and a storage register that in some implementations may operate at different wavelengths. This operation mode allows to selectively remove atoms that are loaded in the storage register while keeping atoms in the loading register before resorting. This approach can be leveraged to assemble and maintain large-scale neutral-atom quantum registers. Thus, the present disclosure thus to assemble and store densely packed, atom arrays in storage trap arrays such as optical lattices or optical tweezer arrays. In particular, aspects of the present disclosure allow for the assembly of larger atom arrays that can be stored indefinitely and that may serve as register and /or as reservoir of neutral atoms for quantum computing, simulation and metrology. Further aspects of the methods disclosed herein are discussed below with reference to Fig. 9, Fig. 10 and Fig. 11.

[0023] Further details of the apparatuses, and methods described above, and a related computer program are discussed in the following with reference to exemplary implementations illustrated by the drawings. The foregoing broadly outlines the features and technical advantages of examples in accordance with the present disclosure in order that the detailed description that follows may be better understood. Additional features and advantages will be described hereinafter. The conception and specific examples disclosed may be readily utilized as a basis for modifying or designing other structures for carrying out the same purposes of the present disclosure. Characteristics of the concepts disclosed herein, both their organization and method of operation, together with associated advantages will be better understood from the following description when considered in connection with the accompanying figures. Each of the figures is provided for the purposes of illustration and description, and not as a definition of the limits of the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0024] **Fig. 1** illustrates an exemplary apparatus for trapping and manipulating neutral atoms that may be used in and / or may be part of possible implementation of the present disclosure;

Fig. 2 illustrates a typical setup for generating a loading trap array as well as a storage trap array that may be used in and / or may be part of possible implementations of the present disclosure;

Fig. 3 shows a side view of a part of an apparatus for trapping and manipulating neutral atoms that may be used in and / or may be part of possible implementation of the present disclosure;

Fig. 4 illustrates an exemplary experimental sequence for assembly and continuous operation of an array of neutral atoms in a storage trap array that may be used in and / or may be part of possible implementation of the present disclosure;

Fig. 5 illustrates a possible implementation of a loading trap array that is arranged adjacent to a storage trap array according to aspects of the present disclosure;

Fig. 6 illustrates transport of atoms from a loading trap array to an adjacent storage trap array with minimal heating according to aspects of the present disclosure;

Fig. 7 illustrates a possible implementation of a loading trap array that is arranged at least partially collocated with trapping sites of a storage trap array according to aspects of the present disclosure;

Fig. 8 illustrates iterative assembly and continuous operation of a $N > 1000$ neutral atom array for more than 30 minutes in an exemplary storage trap array that may be used in and / or may be part of possible implementation of the present disclosure;

Fig. 9 illustrates a method for trapping and manipulating neutral atoms according to aspects of the present disclosure, e.g., using an apparatus as described herein, in Ref. [1] and / or in Ref. [2].

Fig. 10 illustrates a method for trapping and manipulating neutral atoms according to aspects of the present disclosure, e.g., using an apparatus as described herein, in Ref. [1] and / or in Ref. [2].

Fig. 11 illustrates a method for trapping and manipulating neutral atoms according to aspects of the present disclosure, e.g., using an apparatus as described herein, in Ref. [1] and / or in Ref. [2].

Fig. 12 illustrates a possible implementation of a trap- and state-selective removal of neutral atoms from the storage trap array according to aspects of the present disclosure.

DETAILED DESCRIPTION OF EXEMPLARY EMBODIMENTS

[0025] Various aspects of the present disclosure are described in more detail hereinafter with reference to the accompanying drawings. The present disclosure may, however, be implemented in many different forms and should not be construed as limited to any specific structure or function presented herein. Rather, these aspects are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the present disclosure to those skilled in the art. Based on the teachings herein one skilled in the art should appreciate that the scope of the present disclosure is intended to cover any aspect of the present disclosure disclosed herein, whether implemented independently of or combined with any other aspect of the present disclosure. For example, an apparatus, a device or a system may be implemented, or a method may be practiced using any number of the aspects set forth herein. In addition, the scope of the present disclosure is intended to cover such a device, apparatus, system or method which is practiced using other structure, functionality, or structure and functionality in addition to or other than the various aspects of the present disclosure set forth herein. Any aspect of the present disclosure disclosed herein may be implemented by one or more elements of a claim. While specific feature combinations are described in the following with respect to certain aspects of the present disclosure, it is to be understood that not all features of the discussed examples must be present for realizing the technical advantages of the devices, apparatuses, systems, methods and computer programs disclosed herein. Disclosed aspects may be modified by combining

certain features of one aspect with one or more features of other aspects. A skilled person will understand that features, steps, components and / or functional elements of one aspect can be combined with compatible features, steps, components and / or functional elements of any other aspect of the present disclosure.

[0026] Several aspects of trapping and manipulating (e.g., imaging, gate operations, spectroscopy, heating, shelving, resorting etc.) of neutral atoms will now be presented with reference to various devices, apparatuses, systems and methods that are described in the following detailed description and illustrated in the accompanying drawings by various blocks, modules, components, circuits, steps, processes, algorithms, and/or the like (collectively referred to as “elements”). These elements may be implemented using hardware, software, or combinations thereof. Whether such elements are implemented as hardware and/or software depends upon the particular application and design constraints imposed on the overall system. Further, the apparatuses and methods disclosed herein can be part of complex quantum technology systems such as neutral atom quantum computers. The skilled person will appreciate that in the following several components of such systems, such as laser sources, experiment control and timing units etc. are not explicitly described. Further details on such quantum technology elements are provided in applicant’s own earlier European patent application 23181879.0, titled *HARDWARE-EFFICIENT NEUTRAL ATOM QUANTUM COMPUTING METHOD AND DEVICE*, which is incorporated herein by reference in its entirety.

[0027] While aspects of the present disclosure are presented in the following for the bosonic Strontium isotope ^{88}Sr , and /or a specific laser wavelength of an optical trapping lattice in the range of 1010 nm to 1100 nm it is to be understood, that any other species of neutral atom such as other alkaline-earth like atoms (e.g., ^{171}Y) with a suitable internal level structure and any other suitable trapping laser system may also be used in other implementations of the present disclosure. Further, while the internal states $^1\text{S}_0$ and $^3\text{P}_0$ are discussed as examples in the following other pairs of states may also be used, e.g. $^1\text{S}_0$ and $^3\text{P}_2$.

[0028] FIG. 1 illustrates aspects of an exemplary apparatus 100 for trapping and manipulating neutral atoms as provided by the present disclosure. The illustrated apparatus 100 may comprise a trapping laser system (not shown), and optics 110 (such as lenses, mirrors, waveplates, fiber collimators, etc.) for generating an optical lattice 120 at a trapping volume 140 inside a vacuum chamber 150. The optics 110 for generating the optical lattice 120 may be configured to generate, based on the output of the trapping laser system, a single elliptical trapping laser beam 130 that is retroreflected and focused, using a bow-tie configuration having a crossing angle θ , to the trapping volume 140 inside the vacuum chamber 150 to generate the optical lattice 120, e.g., via four-fold interference of the crossed and retroreflected beams of the bow-tie configuration. The plane of interference of the beams of the bow-tie configuration defines an x-y-plane of an x-y-z coordinate system, where the z-axis is orthogonal to the x-y-plane.

[0029] In some aspects, an aspect ratio of the elliptical trapping laser beam 130 may be configured / selected such that a trap depth of the optical lattice is larger than 0.1 mK, preferably larger than 1 mK, and / or such that a trap frequency in the z-direction that is essentially orthogonal to the plane that comprises the optical trapping lattice 120 is larger than $2\pi \times 1$ kHz, preferably larger than $2\pi \times 2$ kHz, more preferably larger than $2\pi \times 4$ kHz, and even more preferably larger than $2\pi \times 8$ kHz.

[0030] For example, in one possible implementation, the optical lattice 120 is created with a single 1040 nm laser beam 130 retroreflected in 4f configuration on the x-y-plane. The beam crossing angle θ is chosen to be $\sim 26.56^\circ$ resulting in a lattice spacing $a_x = 1186.5$ nm along the x-axis of the lattice and $a_y = 578.5$ nm along the y-axis. The foci of all four beams overlap at the center of the objective's 160 field of view with waists of ~ 20 μm (~ 100 μm) along z-axis (in the x-y plane) respectively. With the polarization of all beams aligned along z-axis, multiple-pass interference yields a trap frequency that can reach $2\pi \times 150$ kHz ($2\pi \times 300$ kHz) along the x-axis (y-axis) respectively, at a trap depth of 1.4 mK with 12W optical power. In the z-axis, the trapping frequency of the lattice is larger than $2\pi \times 4$ kHz. Increasing the laser power of the elliptical / anisotropic beam and / or the aspect ratio of the beam can yield up to $2\pi \times 10$ kHz within technological feasible parameters, e.g., using an aspect ratio of 1 / 10.

Such trapping parameters facilitates efficient loading of the optical lattice 120 from a MOT operated in the trapping volume 140 to provide a source of laser-cooled neutral atoms to be trapped and manipulated in the optical lattice 120, and, in some implementations, after transfer in a physics trap array 170 or a physics trapping lattice that may be operated at a different wavelengths and / or at a lower trap depth, e.g., to increase the lifetime of neutral atoms in the physics trap array 170 or a physics trapping lattice, e.g., via reducing off-resonant scattering events.

[0031] In some implementations, the trapping laser system may comprise an Ytterbium doped fiber amplifier with an operation wavelength λ in the range of 1010 nm to 1100 nm, where output powers of more than 10 W are readily available – in contrast to wavelengths ranges that may be required, e.g., because of a magic trapping condition where commercially available laser sources with high output power are not available. In the example of Fig. 1, the physics trap array may be implemented as a physics trap array 170 (e.g., as an array of optical tweezers), e.g., generated by a spatial light modulator or similar device and imaged to the trapping volume 140 through a high-resolution objective 160.

[0032] In the example of Fig. 1 the tweezer spacing in both axes may be chosen to be $6 a_y$ and $3 a_x$, respectively (see insert in Fig. 1). Here, using 650 mW optical power and computer-generated holograms a 2D array of $21 \times 19 = 399$ tweezers traps 170 with a trap depth of $\sim 140 \mu\text{K}$ each can be generated at a wavelength of $\sim 520 \text{ nm}$. The waist of the tweezer traps can be estimated as roughly $472(3) \text{ nm}$ from independent calibration of trap depth and trap frequency. The trap frequency at $140 \mu\text{K}$ depth is about $2\pi \times 77 \text{ kHz}$ radially and $2\pi \times 19 \text{ kHz}$ axially (i.e., in z-direction). Using ^{88}Sr atoms as reference the trap depths for the tweezers 170 can be equalized to a root-mean-square intensity variation of $\sim 2.2\%$ by minimizing variations in measured differential light-shifts on the $^1\text{S}_0 - ^3\text{P}_1$ transition of an initial tweezer pattern pre-corrected for diffraction efficiency. Further details of the apparatus of Fig. 1 are discussed in Ref. [2].

[0033] Fig. 2 illustrates a typical optical setup for generating an optical trapping lattice as well as a physics lattice, using a bow-tie configuration at a trapping

volume 140 inside a vacuum chamber 150, and, in some examples in the field of view of a high-resolution imaging objective 160. To realize such a bow-tie configuration the optics may comprise a set of three mirrors 220a to 220 c, as well as a set of focusing lenses 210a that are arranged in the x-y-plane. For realizing an optical trapping lattice as described herein a single elliptical trapping laser beam (cf. Fig. 1) may enter the bow-tie configuration via a first focusing lens 210 a that focusses the optical trapping beam to a focus point at the trapping volume 140. A second lens 210b then collimates the trapping laser beam that is then reflected via steering mirrors 220a and 220b to be focused a second time to the focus point at the trapping volume 140 via lens 210c. Lens 210d again collimates the laser beam to retroreflecting mirror 220c and focusses the laser beam a third time to the focus point at the trapping volume 140. The retroreflected laser beam is then collimated via lens 210c, steered via mirrors 220b and 220c, and focused a fourth time to the focus point at the trapping volume 140 resulting in a four-fold interference generating an optical trapping lattice as described above with reference to Fig. 1. The crossing angle θ of the bow tie configuration formed by mirrors 220 and lenses 210 can be adjusted to tune the lattice constant in the x-direction and the y-direction as discussed above. As also discussed above, using an elliptical / anisotropic laser beam as input for a bow-tie configuration as illustrated in Fig. 2 provides a strong confinement in z-direction although the optical trapping lattice merely comprises a single 2D lattice plane.

[0034] A similar bow tie configuration, e.g., using $\theta=45^\circ$ may also be used for generating a physics trapping lattice at the trapping volume 140. By adjusting the crossing angle of the optical trapping lattice and the physics trapping lattice as well as the wavelengths of the respective laser beams can be used to ensure that both lattices are essentially commensurate (see Fig. 9 of Ref. [2]). In addition, the bow-tie configuration of one or both lattices may also comprise an adjustable phase shift element (e.g., an EOM, a rotatable glass plate, etc.) that allows to tune the relative phase between the optical lattice and the physics lattice.

[0035] **Fig. 3** shows a side view of a part of the apparatus 100 of Fig. 1 in a configuration where the optical trapping laser beam 130 generates an optical trapping lattice at the trapping volume 140 and a physics trap beam 310 generates, e.g., using a

second bow-tie configuration having a different crossing angle (e.g., 45°), a physics trapping lattice at the trapping volume 140. At the trapping volume 140 a MOT may be operated to provide a reservoir of laser-cooled atoms that may be loaded into the optical trapping lattice and / or the physics trapping lattice. Further, a high-resolution objective 160 may be used for imaging a physics trap array as well as movable optical tweezers 310b onto the trapping volume 140. Using the same objective 160, fluorescence light from neutral atoms inside the optical trapping lattice and / or the physics trap can be collected and imaged to an imaging sensor 340, e.g., using a dichroic mirror 320 and a further focusing lens 320.

[0036] The exemplary apparatus discussed above may in particular be used to provide a loading trap array and an adjacent or partially collocated storage trap array as disclosed herein.

[0037] **Fig. 4** illustrates an exemplary experimental sequence that may be used to iteratively assemble and maintain large arrays of neutral atoms in a storage trap array. Implementations of the present disclosure thus may involve a combination of a storage register (also designated as storage trap array herein) with a loading register (also designated loading trap array herein). The storage register is used to hold atoms for quantum operations, while the loading register is repetitively loaded from a reservoir, e.g. a magneto-optical trap or optical dipole trap. An exemplary sequence of steps allows for continuous reloading of atoms into the storage register. In general, as discussed herein, such a sequence may comprise:

1. Shelf atoms located in a storage register in a metastable state of alkaline earth or alkaline earth like atoms.
2. Establish a magneto-optical trap to load atoms in ground internal state into loading register, which is kept at a wavelength optimized for loading and cooling of atoms.
3. Perform a parity projection pulse that only affects atoms in state two in the loading register, and removes double occupancy of sites in that register without

affecting atoms in the storage register in state one.

4. Remove atoms in the ground state that are accidentally loaded in the storage register using a specifically tuned laser on a transition that selectively removes atoms in the ground state from the storage register, but keeps atoms in the ground state in the loading register as well as atoms shelved into the meta-stable excited state in the storage register unaffected. For this crucial step, the wavelengths of the storage and loading registers typically should carefully be selected.
5. Move atoms from the loading register to the storage register.
6. Unshelve atoms from the storage register, i.e. transfer them from the shelving state to the ground state.
7. Image all atoms and, conditioned on the image obtained, rearrange atoms to new locations in the storage register to free the loading register.
8. Continue with step 1 to close the loop.

For instance, for the loading register, an array of optical traps may be used that is generated with, e.g. a spatial light modulator or an acousto-optic deflector. For the storage register, an array of optical traps as formed by an optical lattice or a spatial light modulator may be used. For an array-specific heating pulse, a repulsive Sisyphus cooling technique may be used that addresses a transition heating atoms in the storage register in internal state two, while keeping atoms in the storage register in state one and in the loading register in state two unaffected.

[0038] **Fig. 5** illustrates a possible implementation of a loading trap array that is arranged adjacent to a storage trap array according to aspects of the present disclosure. Specifically, a 1040 nm stationary bow-tie optical lattice similar to the one as discussed above may serve as physics array 510 (a grid with $a_x = 579$ nm and $a_y = 1187$ nm). The accessible area may be subdivided into a loading zone 520 and a storage zone 530. The trapping sites of the optical lattice in the loading zone 520 may be overlapped with a stationary array of optical tweezers 525, e.g. at a wavelength of 520

nm to form a loading trap array. As discussed in detail below, neutral atoms can be moved / transported with an acousto-optic deflector that steers a single optical tweezer beam 540 in the lattice plane from the loading zone 520 to the storage zone 530. The trapping sites of the optical lattice in the storage zone 530 form a storage trap array where large arrays of neutral atoms can iteratively be assembled with single atom control and maintained essentially indefinitely as shown in Fig. 8.

[0039] **Fig. 6** illustrates typical movement trajectories of neutral atoms from the loading trap array to the storage array. The top graph of panel **a)** shows an energy landscape of the optical lattice. The bottom graph of panel **a)** shows a reduction of the trap depth modulation experienced by an atom travelling in between lattice sites (line 610 the top graph), as compared to through the lattice sites (line 620 in the top graph).

Panel **b)** shows an exemplary resorting sequence, using the AOD controlled travelling resorting tweezer favoring horizontal moves along corridors in between the lattice sites to keep heating as low as possible.

Panel **c)** shows atom loss probability as a function of the distance between an occupied lattice site and the travelling resorting tweezer. Disturbance leading to atom loss are observed below 1 μm of distance.

Panel **d)** shows an atom move success probability as a function of the travelling distance, when the moves are performed through the lattice sites (trace 630) and when they are performed in between the lattice sites (trace 640). The atom move success probability may for example be defined as the probability of not losing the atom during the entire move operation.

[0040] **Fig. 7** illustrates a possible implementation of a loading trap array that is arranged at least partially collocated with the storage trap array. For example, in Fig. 7 the grid 710 illustrates the optical lattice where the vortices 715 illustrate a plurality of trapping sites of the optical lattice in the loading zone. The black dots 720 indicate the positions of a collocated optical tweezer array. In such a configuration, the combined trapping potentials of the optical lattice and the optical tweezers form the loading trap

array and the adjacent trapping sites of the optical lattice form the storage trap array. As mentioned above such a configuration reduces complexity of moving atoms from the loading array to the storage array.

[0041] **Fig. 8** shows the atom number of the continuously operated array in the storage zone (trace 810) and the atom number in the loading zone (trace 820). The inset in Fig. 8 shows the atom number during the initial assembly phase from 0 to ~2.0 mins. As can be seen in Fig. 8 an array exceeding 1000 neutral atoms on average can be iteratively assembled and maintained essentially indefinitely using the methods and apparatuses disclosed herein. The insets I, II and III show exemplary fluorescence images taken during three different points in time of neutral atoms in the storage trap array.

[0042] The various apparatuses for trapping and manipulating neutral atoms as disclosed herein can be employed as part of a quantum computing device comprising an apparatus as discussed above, and a qubit gate laser system for performing local single-qubit and local two-qubit gate operations on neutral atoms in the physics trap array or the physics trapping lattice. Similarly, an atomic clock device may comprise an apparatus as discussed above and a clock laser system for performing a clock spectroscopy sequence on the neutral atoms in the physics trapping lattice or the physics trap array. Similarly, a quantum simulation device may comprise an apparatus as discussed above, wherein the physics trap array or the physics trapping lattice can be operated such that the neutral atoms can tunnel within the physics trap array or the physics trapping lattice, and optionally a many-body evolution laser system for performing a many-body evolution on the neutral atoms in the physics trap array or the physics trapping lattice.

[0043] **Fig. 9** illustrates a method 900 for trapping and manipulating a plurality of neutral atoms, e.g., using an apparatus as described above and / or in Ref. 1, and Ref. [2]. Step 910 comprises loading a plurality of neutral atoms into a loading trap array arranged adjacent to (see Fig. 5) or at least partially collocated with a storage trap array (see Fig. 7). In step 920 neutral atoms in a first electronic state $|1\rangle$ are selectively removed from the storage trap array. In step 930, the trap occupancy of neutral atoms

in the storage trap array in a second electronic state $|2\rangle$ (i.e. indirectly by repumping atoms in state $|2\rangle$ to state $|1\rangle$ and then imaging state $|1\rangle$) and of neutral atoms in the loading trap array is determined. The method 900 further comprises the step 940 of moving, based on the determined trap occupancy of neutral atoms in the storage trap array and in the loading trap array, neutral atoms from the loading trap array to one or more non-occupied trapping sites of the storage trap, e.g., as illustrate in Fig. 6 above. Typically, during detection, atoms in state $|2\rangle$ will rapidly be repumped to state $|1\rangle$.

[0044] In some implementations, a trap depth of the loading trap array for the neutral atoms is different from a trap depth of the storage trap array for the neutral atoms. Preferably, the trap depth of the loading trap is larger than the trap depth of the storage trap. For example, the trap depth of the loading trap array may be at least 10%, preferably at least 30%, and more preferably at least 30% larger or smaller than the trap depth of the storage trap array. Using such loading and storage trap arrays allows to implement state- and trap-selective atom removal such as the state- and trap-selective heating pulse discussed with reference to Fig. 12 below.

[0045] In general, step 820 of selectively removing the neutral atoms in the first electronic state $|1\rangle$ from the storage trap array may comprise a selective heating of neutral atoms in the first electronic state $|1\rangle$ in the storage trap array. Alternatively, or in addition, step 830 may comprise a selective ionizing of neutral atoms in the first electronic state $|1\rangle$ in the storage trap array. Alternatively, or in addition, step 830 may comprise a selective modifying a trapping potential for the neutral atoms in the first electronic state $|1\rangle$ in the storage trap and/or a selective modifying a trapping potential for the neutral atoms in the loading trap array. Specifically, the selective heating of neutral atoms in the first electronic state $|1\rangle$ in the storage trap array may comprise application of a trap- and state-selective heating laser pulse to the loading trap array and the storage trap array. Preferably, the trap- and state-selective heating pulse may be a trap- and state selective Sisyphus-heating pulse (see Fig. 12 below). In some embodiments, application of the trap- and state-selective heating laser pulse may comprise application of a sideband heating laser pulse at a frequency detuning corresponding to a blue sideband for the neutral atoms in the loading trap array.

[0046] In general, the determination of the trap occupancy of the neutral atoms in the storage trap array and in the loading trap array may comprise fluorescence imaging of the neutral atoms, while laser-cooling the neutral atoms. For example, laser-cooling of neutral atoms may use Sideband-cooling, Raman sideband cooling, optical molasses cooling, or Sisyphus-cooling and a combination thereof.

[0047] Step 840 of moving the neutral atoms from the loading trap array to the one or more non-occupied trapping sites of the storage trap array may comprise a determination of one or more movement trajectories for one or more neutral atoms in the loading trap, based on the determined trap occupancy of the neutral atoms in the storage trap and in the loading trap. Step 840 may further comprise controlling a beam steering unit of one or more optical tweezers to execute the determined movement trajectories for the one or more neutral atoms. For example, the beam steering unit may comprise a single or multi-axis acousto-optic-deflector or a digital mirror device. As discussed with reference to Fig. 6, determining the one or more movement trajectories may further comprise determining a movement trajectory that follows a minimal energy surface in a trapping potential of a folded, single-plane bow-tie lattice as disclosed above, in Ref. [1] and in Ref. [2].

[0048] In general, method 900 may further comprise generating the laser-cooled neutral atoms by operating a magneto-optical trap (MOT) for the neutral atoms in a region of space that comprises at least a part of the loading trap array and at least a part of the storage trap array. Specifically, the MOT for the neutral atoms may be operated without using laser light that is resonant with an optical transition of the neutral atoms involving the second electronic state $|2\rangle$. Further, the neutral atoms may be alkali-earth-like atoms exhibiting a dipole-forbidden transition, coupling the first electronic state $|1\rangle$ and the second electronic state $|2\rangle$. For example, the neutral atoms may be Strontium atoms, or Ytterbium atoms or similar elements. For example, the Strontium atoms may be ^{88}Sr -atoms and the first electronic state $|1\rangle$ may be a $^1\text{S}_0$ state and the second electronic state $|2\rangle$ may be a long-lived $^3\text{P}_0$ state or a long-lived $^3\text{P}_2$ state. Similar states are also available for ^{171}Yb atoms.

[0049] In general, the loading trap array may comprise an array of optical tweezers which may be overlapped with a first subset of trapping sites of an optical lattice (see Fig. 5 and Fig. 7). For example, the optical lattice may be a folded optical lattice in a bow-tie configuration as discussed above and in Ref. [1] and Ref [2]. Further, a second subset of the trapping sites of the optical lattice may form the storage trap array. Specifically, the loading of the plurality of neutral atoms into the loading trap array may comprise increasing, preferably while operating the MOT for the neutral atoms, a laser intensity of the array of optical tweezers. In addition, the optical lattice may be operated to maintain the storage trap array for the neutral atoms in the second electronic state $|2\rangle$. In some embodiments, the determination of the trap occupancy of the neutral atoms in the loading trap array may comprise transferring neutral atoms from the loading trap array into trapping sites of the first subset of trapping sites of the optical lattice. Optionally, the determination of the trap occupancy may further comprise fluorescence imaging the neutral atoms in the first subset of trapping sites of the optical lattice while laser-cooling the neutral atoms in the optical lattice, e.g., as described in Ref. [1] and Ref. [2]. In general, the method 900 may further comprise transferring neutral atoms in the storage trap from the first electronic state $|1\rangle$ to the second electronic state $|2\rangle$ as discussed in more detail with reference to Fig. 10.

[0050] Fig. 10 illustrates a further method 1000 for trapping and manipulating neutral atoms. The method 1000 comprises a step 1010 of transferring a plurality of neutral atoms trapped in a storage trap from a first electronic state $|1\rangle$ to a second electronic state $|2\rangle$ (e.g., shelving the atoms in a long-lived, meta-stable shelving state such as 3P_0 of ^{88}Sr). In step 1020, a plurality of laser-cooled neutral atoms is loaded into a loading trap array arranged adjacent to or at least partially collocated with the storage trap array. In step 1030, a trap occupancy of the neutral atoms in the storage trap and in the loading trap array in the second electronic state $|2\rangle$ and of neutral atoms in the loading trap array is determined. In step 1040, neutral atoms are moved from the loading trap array to one or more non-occupied sites of the storage trap array, based on the determination of a trap occupancy as discussed in more detail above.

[0051] Specifically, method 1000 may further comprise selective removing neutral atoms in the first electronic state $|1\rangle$ from the storage trap array (as discussed

above and with reference to Fig. 12) after transferring the plurality of neutral atoms trapped in the storage trap array from the first electronic state $|1\rangle$ to the second electronic state $|2\rangle$. In this manner shelved atoms are not removed from the storage trap array.

[0052] In some embodiments, a loading duration of the plurality of laser-cooled neutral atoms into a loading trap array may be smaller than a lifetime of the second electronic state $|2\rangle$. For example, the loading duration may be at least 2 times smaller, preferably 4 times smaller, more preferably 10 times smaller and even more preferably 100 times smaller than the lifetime of the second electronic state $|2\rangle$. In general, the loading of the plurality of laser-cooled neutral atoms into a loading array may comprise a generation of the laser-cooled neutral atoms by operating a MOT for the neutral atoms. Preferably, the MOT is operated in a region of space that comprises at least a part of the loading trap array and, optionally, at least a part of the storage trap array. Generally, transferring the plurality of neutral atoms trapped in the storage trap array from the first electronic state $|1\rangle$ to the second electronic state $|2\rangle$ may comprise coherently transferring the plurality of neutral atoms from the first electronic state $|1\rangle$ to the second electronic state $|2\rangle$. Alternatively, or in addition, transferring the plurality of neutral atoms may comprise incoherently transferring the plurality of neutral atoms from the first electronic state $|1\rangle$ to the second electronic state $|2\rangle$ using one or more re-pump lasers.

[0053] **Fig. 11** illustrates a method for trapping and manipulating neutral atoms. The method comprises the step 1110 of loading a plurality of neutral atoms into a loading trap array adjacent to or at least collocated with a storage trap array. The loading trap array is configured to comprise at least 1000 trapping sites, preferably at least 5000 trapping sites and more preferably at least 10000 trapping sites overlapped with a source region for laser-cooled neutral atoms. For example, the loading trap array may be formed by a plurality of trapping sites of an optical lattice, wherein, for example, a trap depth of the optical lattice may be larger than 0.1 mK, preferably larger than 1.0 mK. Alternatively, or in addition, a trap frequency in a z-direction that is essentially orthogonal to an x-y-plane that comprises the optical lattice may be larger

than $2\pi \times 1$ kHz, preferably larger than $2\pi \times 2$ kHz, more preferably larger than $2\pi \times 4$ kHz, and even more preferably larger than $2\pi \times 8$ kHz.

[0054] The method 1100 further comprises a step 1120 of determining a trap occupancy of neutral atoms in the storage trap array, and of neutral atoms in the loading trap array. In step 1130 neutral atoms are moved from the loading trap array to one or more non-occupied trapping sites of the storage trap array, based on the determined trap occupancy of the neutral atoms in the storage trap array and in the loading trap array as discussed in more detail above.

[0055] Further aspects of the present disclosure relate to a method for continuous operation of a quantum computation, simulation and/or metrology device. The method comprises the step of repeating the method for trapping and manipulating neutral atoms according to one of the above-described embodiments to iteratively assemble and maintain an ensemble of neutral atoms in the storage trap array. The method further comprises the step of using a subset of the ensemble of neutral atoms for executing a quantum computation sequence, a quantum simulation sequence and/or a quantum metrology sequence. Specifically, the method may further comprise the step of receiving, from a remote computation device, instructions for executing the quantum computation sequence, the quantum simulation sequence and/or the quantum metrology sequence. Further the method may comprise executing, based on the received instructions, the quantum computation sequence, the quantum simulation sequence and/or the quantum metrology sequence. In addition, the method may comprise the step of sending a result of the executed quantum computation sequence, the executed quantum simulation sequence and/or the executed quantum metrology sequence to the remote computation device.

[0056] A further aspect is directed to a quantum computation, simulation and/or metrology device comprising means for executing the method for trapping and manipulating neutral atoms according to one of the above-described embodiments and the method for continuous operation of a quantum computation, simulation and/or metrology device according to one of the above-described embodiments.

[0057] A further aspect relates to a computer program for controlling a quantum computation, simulation and/or metrology device to execute the method for trapping and manipulating neutral atoms according to one of the above-described embodiments and the method for continuous operation of a quantum computation, simulation and/or metrology device according to one of the above-described embodiments.

[0058] **Fig. 12** illustrates a possible implementation of a trap- and state-selective removal of neutral atoms from the storage trap array according to aspects of the present disclosure.

Panel a) shows relevant states and energy levels of ^{88}Sr .

Panel b) shows resulting trap filling after a trap-selective 689 nm Sisyphus-heating laser-pulse applied to atoms trapped in the storage trap array (trace 1210) and in the loading trap array (trace 1220) as a function of the applied laser frequency detuning in MHz. The traces are normalised to the loading fraction without heating pulse for the lattice and normalised to the number of optical tweezer number for the combined potential of the loading trap array. An extinction of 5×10^{-4} for ground state ($|1\rangle$ state) atoms in the storage trap array (only lattice potential) is achieved when choosing a frequency detuning of 1.28 MHz (dotted line) while the atoms in the combined tweezers-lattice potential remain almost unaffected.

Panel c) shows round-trip shelving infidelity as a function of shelving duration, reaching 3% after 10 ms (dotted line).

Panel d) shows shelving lifetime in the storage trap array at a trap depth of $\sim 200 \mu\text{K}$, reaching a $1/e$ lifetime of 13 seconds. The dotted line indicates an exponential fit of the last fit of the last four data points. The inset shows a Zoom-in of the hold time region below one second.

[0059] The foregoing disclosure provides illustration and description but is not intended to be exhaustive or to limit the aspects to the precise form disclosed.

Modifications and variations may be made in light of the above disclosure or may be acquired from practice of the aspects. As used herein, the term component is intended to be broadly construed as hardware, firmware, or a combination of hardware and software. As used herein, a processor is implemented in hardware, firmware, or a combination of hardware and software.

[0060] It will be apparent that systems and/or methods described herein may be implemented in different forms of hardware, firmware, or a combination of hardware and software. The actual specialized control hardware or software code used to implement these systems and/or methods is not limiting of the aspects. Thus, the operation and behavior of the systems and/or methods were described herein without reference to specific software code—it being understood that software and hardware can be designed to implement the systems and/or methods based on the description herein.

[0061] Even though particular combinations of features are recited in the claims and/or disclosed in the specification, these combinations are not intended to limit the disclosure of various aspects. In fact, many of these features may be combined in ways not specifically recited in the claims and/or disclosed in the specification. Although each dependent claim listed below may directly depend on only one claim, the disclosure of various aspects includes each dependent claim in combination with every other claim in the claim set. A phrase referring to “at least one of” a list of items refers to any combination of those items, including single members. As an example, “at least one of: a, b, or c” is intended to cover a, b, c, a-b, a-c, b-c, and a-b-c, as well as any combination with multiples of the same element (e.g., a-a, a-a-a, a-a-b, a-a-c, a-b-b, a-c-c, b-b, b-b-b, b-b-c, c-c, and c-c-c or any other ordering of a, b, and c).

[0062] No element, act, or instruction used herein should be construed as critical or essential unless explicitly described as such. Also, as used herein, the articles “a” and “an” are intended to include one or more items, and may be used interchangeably with “one or more.” Furthermore, as used herein, the terms “set” and “group” are intended to include one or more items (e.g., related items, unrelated items, a combination of related and unrelated items, and/or the like), and may be used

interchange-ably with “one or more.” Where only one item is intended, the phrase “only one” or similar language is used. Also, as used herein, the terms “has,” “have,” “having,” and/or the like are intended to be open-ended terms.

[0063] As used herein, the phrase “based on” shall not be construed as a reference to a closed set of information, one or more conditions, one or more factors, or the like. In other words, the phrase “based on A” (where “A” may be information, a condition, a factor, or the like) shall be construed as “based at least on A” unless specifically recited differently.

[0064] As used herein, the term “or” is an inclusive “or” unless limiting language is used relative to the alternatives listed. For example, reference to “X being based on A or B” shall be construed as including within its scope X being based on A, X being based on B, and X being based on A and B. In this regard, reference to “X being based on A or B” refers to “at least one of A or B” or “one or more of A or B” due to “or” being inclusive. Similarly, reference to “X being based on A, B, or C” shall be construed as including within its scope X being based on A, X being based on B, X being based on C, X being based on A and B, X being based on A and C, X being based on B and C, and X being based on A, B, and C. In this regard, reference to “X being based on A, B, or C” refers to “at least one of A, B, or C” or “one or more of A, B, or C” due to “or” being inclusive. As an example of limiting language, reference to “X being based on only one of A or B” shall be construed as including within its scope X being based on A as well as X being based on B, but not X being based on A and B.

[0065] Further, process diagrams such as Fig. 9, Fig. 10 and Fig. 11 do not necessarily indicate a particular order or sequence of steps. For example, steps may also be performed in a different order or, if hardware capabilities allow it, simultaneously, without deviating from the scope of the present disclosure.

ASSOCIATED ORIGINAL RESEARCH

[0066] To illustrate further concepts, advantages, and exemplary implementation details of the present disclosure are further described in the attached

original research paper titled *Continuous operation of large-scale atom arrays in optical lattices*, which is incorporated herein in its entirety and thus forms an integral part of the present disclosure. It is to be understood that due to their special legal function in the context of a patent application, terms such as “consists”, “consisting”, etc. used in the original research paper are to be replaced by the appropriate terms “comprises” and “comprising” or similar.

Continuous operation of large-scale atom arrays in optical lattices

Flavien Gyger,^{1,2} Maximilian Ammenwerth,^{1,2} Renhao Tao,^{1,2,3} Hendrik Timme,^{1,2} Stepan Snigirev,⁴
Immanuel Bloch,^{1,2,3} and Johannes Zeiher^{1,2,3,*}

¹*Max-Planck-Institut für Quantenoptik, 85748 Garching, Germany*

²*Munich Center for Quantum Science and Technology (MCQST), 80799 Munich, Germany*

³*Fakultät für Physik, Ludwig-Maximilians-Universität, 80799 Munich, Germany*

⁴*PlanQC GmbH, 85748 Garching, Germany*

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Scaling the size of assembled neutral-atom arrays trapped in optical lattices or optical tweezers is essential for a number of applications ranging from quantum simulations to quantum metrology. However, preparation times increase with system size and constitute a severe bottleneck in the bottom-up assembly of large ordered arrays from stochastically loaded optical traps. Here, we demonstrate a novel method to circumvent this bottleneck by recycling atoms from one experimental run to the next, while continuously reloading and adding atoms to the array. Using this approach, we achieve densely-packed arrays with more than 1000 atoms stored in an optical lattice, continuously refilled with a net 2.5 seconds cycle time and about 200 atoms reloaded during each cycle. Furthermore, we show that we can continuously maintain such large arrays by simply reloading atoms that are lost from one cycle to the next. Our approach unlocks the path towards quantum science with large ordered atomic arrays containing thousands of atoms in continuous operation.

I. INTRODUCTION

Atom arrays stored in optical lattices or optical tweezers are a promising platform for quantum simulation, quantum computation, and quantum metrology [1–6]. A usual experimental sequence to control atoms in optical lattices or optical tweezers starts with the preparation of an ensemble, followed by the simulation, calculation or metrology sequence. Finally, a destructive measurement of the state of the system is performed that typically renders a recycling of atoms from one cycle to the next impossible. The subsequent preparation of a fresh ensemble of atoms requires significantly more time than the actual experimental sequence, leading to a dead time that becomes significantly longer for large arrays. This naturally calls for a different mode of operation in which only the lost atoms are prepared and replaced in each cycle. While recently demonstrated in a seminal work in bulk gases [7], a re-use of atoms and cyclic operation with microscopic control are challenging and require non-destructive detection in combination with resorting to replenish lost atoms [8, 9]. High-fidelity and low-loss detection of single atoms is now routinely achieved for several species in optical lattice and optical tweezers [10–15]. Although first steps towards extended operation of atom arrays have recently been demonstrated in small-scale systems with finite reservoirs [16, 17], truly continuous operation requires schemes for reloading new atoms that do not affect the atomic array already present in the system. Effective strategies to “hide” stored atoms during the reloading of new atoms have recently been demonstrated in dual-element arrays of two alkali-atom species [18, 19], where atoms of one species are only minimally affected by

forming a magneto-optical trap (MOT) of the other element, thereby enabling continuous operation with arrays of each element prepared in alternation. An alternative route is offered by utilising the more complex level structure available in alkaline earth(-like) atoms such as strontium or ytterbium. Here, two separate optical series with different total spin and metastable states exist, which has proven useful for a variety of applications in combination with microscopic control [17, 20–30]. In particular, the metastable states can also be used to effectively hide stored atoms while forming a MOT for the ground-state atoms. Although this level structure has been shown to be well adapted for the preparation of one-dimensional atomic arrays with near-unity filling based on dark-state enhanced loading combined with site control using two crossed acousto-optic deflectors (AODs) [29], continuous loading has so far remained an elusive goal.

Here, we show a novel scheme that combines several of the foregoing aspects to realize continuously operated large-scale atom arrays with atom numbers continuously exceeding 1000 atoms and reaching up to 1247 atoms. Our scheme relies on a continuously operated storage zone in an optical lattice, which is periodically replenished from a loading zone and a MOT. Using a bichromatic combination of loading and storage arrays, we achieve excellent spatial control over the loading zone, strongly suppressing loading of sites in the storage register. Loading about 200 new atoms for each cycle, we grow and then continuously maintain an array of atoms in an optical lattice with more than 1000 atoms, which is five times larger than the number of atoms loaded during each cycle. Our results mark a paradigm shift in the operation of quantum simulators and quantum computers based on neutral atoms to iteratively assembled and continuously operated arrays.

* johannes.zeiher@mpq.mpg.de

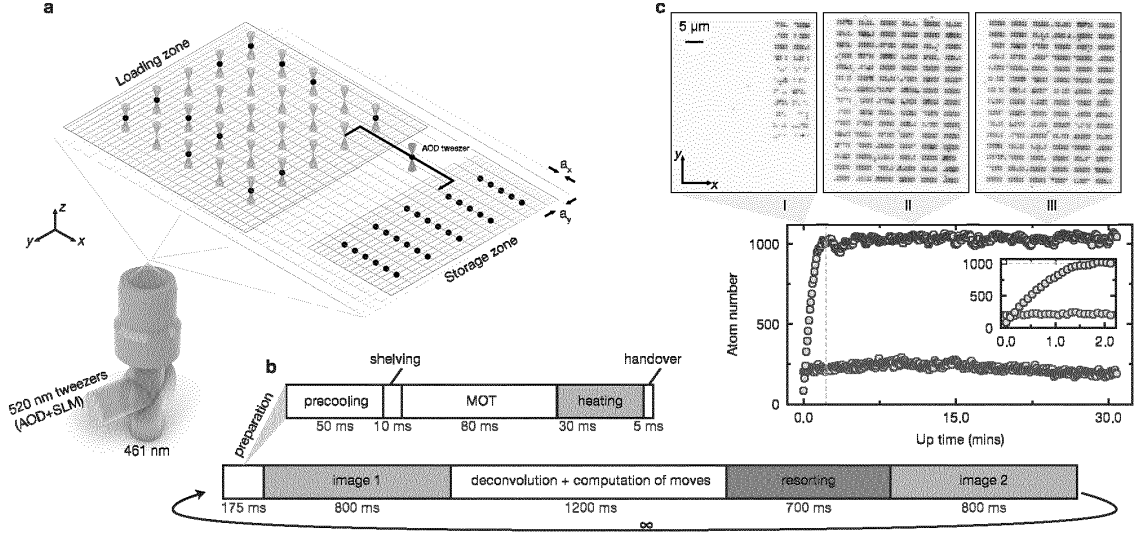


FIG. 1. **Concept and demonstration of continuous operation.** **a** Main features of our experimental machine. We use a 1040 nm stationary bow-tie optical lattice as our physics array (grey grid with $a_x = 579$ nm and $a_y = 1187$ nm). We subdivide the accessible area into a loading zone and a storage zone. The loading zone is overlapped with a stationary array of tweezers at 520 nm. Atoms are transported with AODs that steer a single beam in the lattice plane from the loading zone to the storage zone. **b** Experimental sequence of our continuous loading scheme. **c** Exemplary single shots at various instances in time of an iteratively assembled array exceeding 1000 atoms on average. Bottom graph: Atom number of the continuously operated array (blue) and atom number in the loading area (red). Inset: Zoom-in of the atom number in the build-up phase.

II. ASSEMBLY OF LARGE ARRAYS

The architecture of our apparatus [13] for continuous operation is shown in Fig. 1. We operate the experiment in one region spanning about $130 \mu\text{m} \times 130 \mu\text{m}$, corresponding to the area that the AODs can currently address. This region is centered above our objective lens and contains about 24000 trapping sites in a bow-tie lattice. We divide this lattice region into two sub-regions: a loading zone and a storage zone, see Fig. 1a. The loading zone of the lattice is replenished from a reservoir of 342 tweezers, which are overlapped in three dimensions with the lattice sites. These tweezers are themselves loaded with ^{88}Sr atoms from a dual-stage MOT, on the broad $^1\text{S}_0$ - $^1\text{P}_1$ transition at 461 nm and on the narrow-line $^1\text{S}_0$ - $^3\text{P}_1$ transition at 689 nm [31]. For high-fidelity detection, we transfer the atoms from the tweezer array into the optical lattice [13] and perform fluorescence imaging therein. Our cyclic sequence is presented in Fig. 1b and has a cycle time of 2.5 seconds, excluding data processing.

In the first iteration, we load in average N_L atoms from the MOT into the tweezers. Then, we transfer the atoms in the lattice and perform a high-fidelity and low-loss imaging to detect the position of loaded atoms in the loading zone [13]. Detected atoms are subsequently displaced on demand from the loading zone to the storage zone by a moving tweezer controlled by crossed

AODs. After resorting, we shelve the atoms in the storage zone to the long-lived metastable $^3\text{P}_0$ -state and subsequently refill the tweezers in the loading zone from a MOT created at the location of our lattice. Shelving in the magnetically-insensitive clock state protects the stored atoms from loss occurring during the MOT. A subsequent fluorescence image of both the storage and the loading zone depumps the atoms in $^3\text{P}_0$ back to the ground state $^1\text{S}_0$, revealing unoccupied sites in the storage zone that need to be refilled. The possibility of reusing atoms across experimental runs results in an important scaling advantage for the achievable array sizes. The largest array size is reached when the number of atoms lost during the previous cycle is precisely balanced by the number of atoms replenished in the current cycle. This condition limits the maximally reachable atom number to $N_\infty = \beta N_L$, where the amplification factor

$$\beta = \frac{1 - \alpha_r}{\alpha_c} \quad (1)$$

is proportional to the transport success probability $1 - \alpha_r$, and inversely proportional to the cycle loss α_c , which quantifies the fraction of atoms lost from one cycle to the next. The effective number of atoms that can be added to the array in each cycle is $N_{L,\text{eff}} = N_L \cdot (1 - \alpha_r)$ which is smaller than the loaded atom number due to atom loss during the transport. For typically achieved cycle losses in this work ($\alpha_c \approx 10\%$), the saturated atom numbers

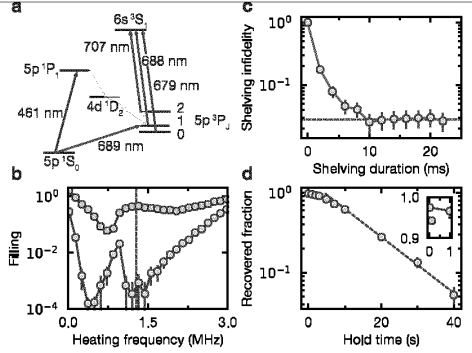


FIG. 2. **Atomic state preparation.** **a** Energy level of ^{88}Sr . **b** Resulting filling after a trap-selective 689 nm Sisyphus-heating pulse applied to atoms trapped in the lattice (blue) and in the combined tweezers+lattice potential (red) as a function of the applied frequency detuning. The trace is normalised to the loading fraction without heating pulse for the lattice and normalised to our tweezer number (342) for the combined potential. An extinction of 5×10^{-4} for ground state lattice atoms is achieved when choosing a frequency detuning of 1.28 MHz (green dotted line) while the atoms in the combined tweezers-lattice potential remain almost unaffected. **c** Round-trip shelving infidelity as a function of shelving duration, reaching 3% (green dotted line) after 10 ms. **d** Shelving lifetime in our lattice at $200 \mu\text{K}$, reaching 13 seconds. Dotted line, exponential fit of the last four data points. Inset: Zoom-in of the hold time region below one second. The red dot indicates our actual recovered fraction when a MOT is created within the hold time.

already significantly exceed the number of loaded atoms per cycle, see Fig. 1d. We note that, in principle, the loading zone could be fully overlapped with the storage zone by interleaving loading sites and storage sites. Such a configuration would be beneficial, since it increases the available space for the storage area and shortens the move distance between the loading and storage zone. However, in our configuration, the tweezer light at 520 nm induces considerable loss of atoms stored in the $^3\text{P}_0$ states and prevents us from overlapping the two zones. We find evidence that photoionization of the $^3\text{P}_0$ state is responsible for this loss, see Appendix A [26], which could be mitigated in the future at alternative tweezer wavelengths, such as 813 nm. In the following, we perform a detailed characterization of all steps involved in the continuous operation of our arrays.

III. RELOADING THE RESERVOIR

An important step in the cyclic operation of the array concerns the transfer of atoms from $^1\text{S}_0$ to $^3\text{P}_0$ before reloading the reservoir. Population shelving is currently implemented via a combination of light at 689 nm and 688 nm driving $^1\text{S}_0 \rightarrow ^3\text{P}_1 \rightarrow ^3\text{S}_1$. An additional

repumper beam at 707 nm renders the $^3\text{P}_0$ -state the only dark state, see Fig. 2a. The fraction of shelved atoms reaches 97% after 10 ms of pumping, as shown in Fig. 2c. We note that a higher shelving fraction could be achieved by a combination of coherent shelving and incoherent pumping, which would directly reduce our cycle loss [32]. At our lattice trap depth of $200 \mu\text{K}$, the lifetime of atoms in $^3\text{P}_0$ state is 13 s, see Fig. 2d. The lifetime significantly exceeds the total duration during which the shelved atoms stay in $^3\text{P}_0$ of 115 ms in our sequence, such that holding of shelved atoms by itself induces an insignificant loss. However, we observe a small increase of the shelved atom loss induced by the presence of the MOT, resulting in a total of 6% shelving loss during the $^3\text{P}_0$ preparation and atom reloading steps, see Fig. 2d inset. Importantly, we make our MOT without a repumper at 679 nm, which would otherwise deplete the shelved atoms in $^3\text{P}_0$. This considerably reduces the number of loaded atoms.

However, with optimized parameters, we obtain a filling fraction as high as 45% atom loading probability in the loading tweezers+lattice register sites after parity projection. An additional consequence of the absence of a $^3\text{P}_0$ repumper is the decay of a small fraction of atoms into $^3\text{P}_0$ via $^1\text{D}_2 \rightarrow ^3\text{P}_2 \rightarrow ^3\text{S}_1$, where they become indistinguishable from the shelved atoms in the stored array. To counteract this effect, the $^1\text{D}_2$ state could be repumped to higher-lying $^1\text{P}_1$ states on transitions either at 716 nm or 448 nm [33], which would increase the MOT loading fraction and remove defects originating from accidentally shelved atoms in $^3\text{P}_0$ during the MOT stage. Importantly, the MOT loads the entire lattice, including the loading zone and the storage zone. To remove ground state atoms from the lattice everywhere except from the sites overlapped with tweezers in the loading zone, we subsequently apply an essential trap-selective heating pulse. This heating pulse is optimized to remove ground-state atoms in the lattice, while leaving both ground-state atoms in tweezers and $^3\text{P}_0$ atoms in the lattice intact, see Fig. 2b. To realise this selective removal of atoms, we use a beam at 689 nm tuned to a repulsive Sisyphus heating regime. This heating feature is unique to transitions narrow enough to spatially resolve the differential trap depth between the $^1\text{S}_0$ state and the $^3\text{P}_1$ state. For the chosen detuning, a net kinetic energy gain is realized between subsequent excitation-decay cycles, and thus leads to a fast, highly parallel, and well-controllable heating mechanism of ground-state atoms in the lattice. Importantly, the atoms in the loading zone, which experience a combined bichromatic lattice-tweezer potential, are shielded from the heating resonance and thus remain trapped, see Fig. 2b. Consequently, our selective heating pulse effectively removes all atoms in $^1\text{S}_0$ that only experience the lattice potential with an extinction of more than 5×10^{-4} . This prevents uncontrolled storage of atoms directly loaded from the MOT in the storage zone. Alternatively, site-selective parallel addressing can also be used to hide already loaded sites from

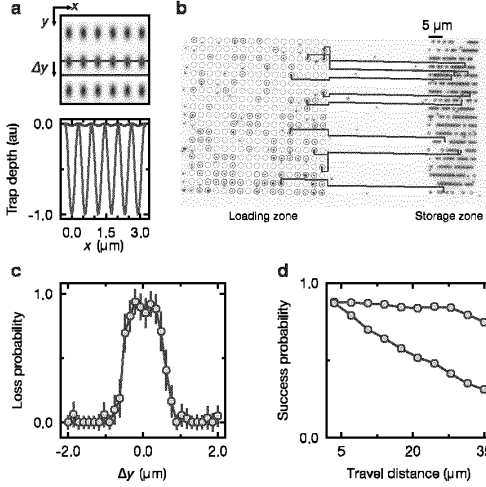


FIG. 3. **Atom rearrangement.** **a** Upper graph: Energy landscape of our folded lattice. Lower graph: Reduction of the trap depth modulation experienced by an atom travelling in between the lattice sites (red line in the top graph), as compared to through the lattice sites (blue line in the top graph). **b** Resorting algorithm favouring horizontal moves along corridors in between the lattice sites. **c** Atom loss probability as a function of the distance between an occupied lattice site and the travelling resorting tweezer. Disturbance leading to atom loss are observed below $1 \mu\text{m}$ of distance. **d** Atom move success probability as a function of the travelling distance, when the moves are performed through the lattice sites (red points) and when they are performed in between the lattice sites (blue points). The atom move success probability is defined as the probability of not losing the atom during the entire move operation.

being further loaded, as effectively shown in 1d [29], with direct extensions using state-selective parallel addressing in higher dimensions [34].

IV. RESORTING IN AN OPTICAL LATTICE

The next important step in our cyclic sequence is the rearrangement of newly loaded atoms to vacancies in the target of the sorted array. We perform such moves using a pair of AODs similar to previous work [14, 35, 36]. In contrast to the case of optical tweezer arrays, atoms moving through lattice sites experience a large periodic trap depth modulation, potentially leading to strong heating. In the special case of a bow-tie lattice, this modulation can be strongly reduced by moving atoms in between the lattice sites, thereby ameliorating any heating effects, see Fig. 3a. In line with this expectation, we directly observe that long moves in between the lattice sites exhibit a significantly higher success probability than moves through lattice sites, see Fig. 3d. In this measurement and dur-

ing the continuous loading operation, all moves are performed with a peak velocity of $54 \mu\text{m/ms}$. In particular, for the long moves considered in this work, movement between sites is crucial. Our lattice has spacings between sites of $a_x = 579 \text{ nm}$ and $a_y = 1187 \text{ nm}$ along the x - and y -axis respectively, and is therefore particularly suited for horizontal moves, see Fig. 3a. To optimally leverage the favourable geometry of our lattice, our resorting procedure has been designed to predominantly move between lattice sites with a five-stroke move pattern, see Fig. 3b. The first stroke removes the atom out of its lattice site and brings it in between lattice sites. The second stroke displaces the atom outside of the loading area. The third and fourth strokes adjust the vertical (y -axis) and horizontal (x -axis) positions respectively to almost match that of its final destination, and finally the last stroke inserts the atom in its final location, see Fig. 3b. Each move consists of (i) a slow ramp-up of the moving tweezer potential depth to about ten times the lattice depth to extract the target atom out of the lattice, (ii) a sequence of parameterized frequency chirps encoding velocity profiles and turns, and (iii) a final ramp-down of the tweezer depth to release the atom in the desired target lattice site in the storage zone. The initial and final intensity ramp durations are $400 \mu\text{s}$ each, to ensure adiabaticity [37]. The imperfect resorting process affects continuous loading in two ways: First, it reduces the effective atom number $N_{L,\text{eff}}$ that can be maximally added to the storage array in each cycle when atoms are lost during transfer. Second, by travelling at a close distance to an already stored atom, the unintended perturbation of the trapping site can result in a loss of the stored atom and thus directly increases the cycle loss. We observe a corresponding limit for the minimum distance between a stored atom and the trajectory of the moving tweezer, which is approximately equal to $1 \mu\text{m}$, see Fig. 3c. This minimum distance sets a limit for the minimal achievable spacing between atoms in the storage register. The total resorting duration for each cycle is about 700 ms . This duration could be drastically reduced by implementing a more complex parallel resorting scheme [8, 14, 38, 39].

V. CONTINUOUS OPERATION

Finally, combining all steps, we demonstrate the ability to build and maintain a large-scale, densely packed tweezer array for more than an hour, see Fig. 4. After the initial loading stage, the array remained above 1000 atoms for 97% of the time and we recorded a maximum number of 1247 atoms in the array. From the atom loss within and across different cycles, we can extract both the normalized cycle loss α_c , as well as the resorting infidelity α_r , that enter in a simple model for the build-up and saturation of the stored atom number N_i at each

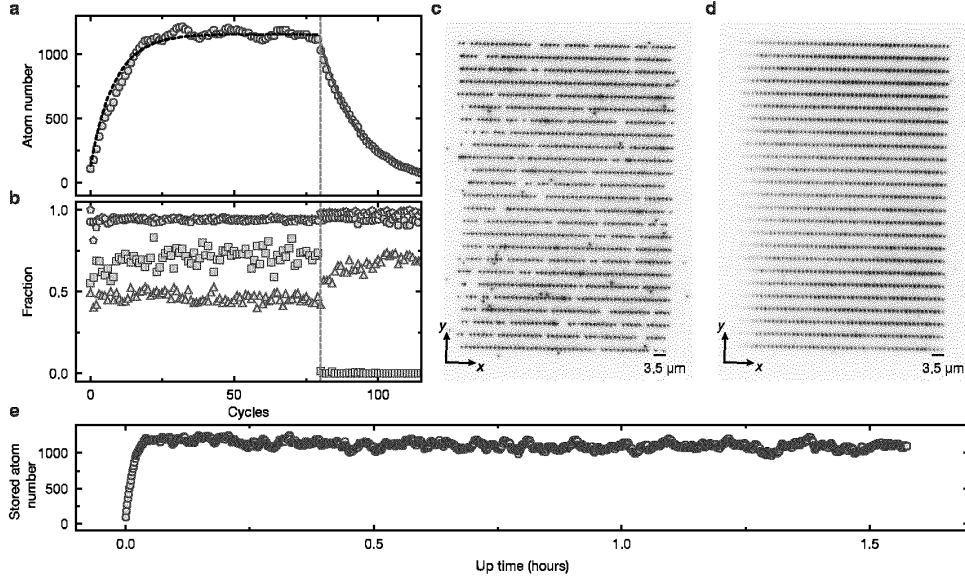


FIG. 4. **Continuous operation.** **a** Number of atoms in the storage area as a function of cycles. After 80 cycles, we disable the resorting and let the array naturally decay. The black dotted line is our model from Eqs. 2 with measured average parameters, while the red line is an exponential fit that enables us to measure the cycle loss α_c (neglecting the influence of resorting in this case). **b** Evolution of the loading fraction (orange triangles), resorting move success probability (red squares), shelved survival fraction (blue circles) and resorting stored survival fraction (green pentagons) as a function of cycles. **c** Single-shot image of the storage array containing 1230 atoms. **d** Average image of the storage array. **e** Continuous operation of the array for more than 1.5 hour.

cycle i ,

$$N_{i+1} = (1 - \alpha_c) \cdot N_i + (1 - \alpha_r) \cdot N_L, \quad i = 0, 1, \dots$$

$$N_\infty = \frac{(1 - \alpha_r) \cdot N_L}{\alpha_c}. \quad (2)$$

The dotted line in Fig. 4a is computed from these equations using time-average values of the measured cycle loss and resorting loss, and is in excellent agreement with the measured atom number. Four parameters of interest are extracted from the occupation matrices and plotted in Fig. 4b: (i) The loading fraction, defined as the number of loaded atoms in the loading zone normalized to total number of tweezer sites (342), (ii) the resorting move success probability, defined as the fraction of loaded atoms that are moved in the storage zone after resorting, (iii) the shelving survival fraction, defined as the fractional number of atoms which survive the shelving, holding and repumping operation between two cycles and (iv) the resorting stored survival fraction, defined as the fractional number of atoms in the stored array that survive through the resorting without being themselves not moved). After 80 cycles, we disable the resorting operation and let the stored array naturally decay. From this moment, we can observe that (i) the loading curve raises, since the loaded atoms are no longer moved out and accumulate

in the loading zone, and (ii) the stored atoms survival fraction raises, since no resorting operation disturbs the stored array.

A more detailed correlation analysis relating the measured final atom numbers to the synchronistically extracted cycle loss, the resorting infidelity and the reloaded atom number, directly reveals that the fluctuations of the final atom number are most strongly correlated with the cycle loss, see Appendix B. Such a behavior is expected from the inverse scaling of steady-state atom number with cycle loss, and highlights the large potential gains in a further optimized sequence.

VI. CONCLUSION AND OUTLOOK

To conclude, we have presented a first realization of densely packed, continuously loaded atom arrays stored in an optical lattice. Prospectively, we expect that our technique could allow for the assembly of significantly larger atom arrays than what we have demonstrated. In previous work, the efficiency of shelving atoms in 3P_0 has been shown to reach 99.7% [32]. For a clock-state lifetime of the order of 100 s with a reduced lattice potential [40] and a typical MOT stage of 100 ms duration, the shelved atoms loss during the MOT stage could be

reduced to 0.1%, leading to a total shelving loss as low as 0.4%. Assuming our measured vacuum lifetime of 273 s, the typical vacuum-limited loss for a 1-second cycle time experiment is roughly also equal to 0.4%, leading to a total cycle loss of about $\alpha_c \approx 0.8\%$. Together with an achieved atom loss due to resorting moves as low as $\alpha_r \approx 2\%$ [14], Eq. (1) predicts the achievable amplification factor to reach $\beta > 100$. With such a large amplification, one could reach about 10000 atoms in a single array with 100 loaded atoms at each cycle, provided that a sufficient area for storage and high-fidelity detection is available [13]. Deterministically loaded arrays [21, 41], or directly loaded lattices [13] as loading zones could further boost the achievable steady-state atom numbers potentially by orders of magnitude. We want to emphasise that, compared to directly assembling such a large number of atoms in a single experimental cycle, continuous loading has the benefit of only moving the newly loaded atoms for each cycle, thus reducing both move-induced losses as well as the resorting time overhead by the amplification factor β . Moreover, maintaining coherence during the reload stage, for example for atoms placed in a specially shielded physics array, would open up exciting new perspectives for quantum metrology or quantum information tasks [17, 19]. Such large, continuously maintained atom arrays combined with the recently demonstrated fast, high-fidelity quantum gates [42] and elementary logical quantum circuits [35] make neutral atoms a promising platform for quantum computing and quantum simulation at scale.

Note added: During the preparation of the manuscript, we became aware of related work, where similar results have been reported using arrays of ^{171}Yb [43].

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Appendix A: $^3\text{P}_0$ ionisation in 520 nm tweezers

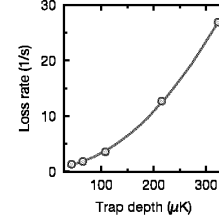


FIG. 5. $^3\text{P}_0$ ionisation from 520 nm tweezers. Measured and parabolic fit of $^3\text{P}_0$ lifetime as a function of the tweezers trap depth. The extracted quadratic contribution to the loss rate is $250 \text{ s}^{-1} (\text{mK})^{-2}$.

In our experiments, we find the $^3\text{P}_0$ lifetime of atoms in 520 nm tweezers to be limited to 40 ms for tweezers at a trap depth of $300 \mu\text{K}$, and to depend quadratically on the trap depth, as shown in Fig. 5. This suggests that light at 520 nm could ionize atoms stored in $^3\text{P}_0$ in a two-photon excitation. In our continuous loading experiment, we observed that the shelving lifetime was considerably decreased for atoms in the loading zone, even when atoms were trapped in a lattice site not overlapping with a tweezer. As a consequence of this observation, we spatially separated our loading and storage zone to mitigate this extra tweezer-induced cycle loss. We anticipate that using another wavelength for the tweezers (e.g. 813 nm) would sidestep this issue and increase the available space for both the loading and storage zones.

Appendix B: Correlation analysis on the atom number fluctuation in the stored array

To understand the origin of the atom number fluctuation in continuous operation of the stored array, we study the correlations between the fluctuations and a set of parameters based on the atom occupation during various stages of the sequence. In this analysis, we only consider atoms placed at sites of the stored array defined by a custom target; all atoms which are not in a site of the stored array, even if they are placed in the storage zone (defects), are ignored. We define the survival fraction s_{mn} where $0 \leq s_{mn} \leq 1$ as the sum over all stored array sites that are both filled in image m and image n , normalised to the occupation of image n . Therefore, s_{mn} quantifies the atoms in the stored array that survived from image m to image n . Similarly, we define the gain a_{mn} as the sum over all stored array sites that are empty in image m but filled in image n , normalised to the occupation of image m . Therefore, a_{mn} where $1 \geq a_{mn} \geq 0$ quantifies the atoms that have appeared in the stored array from image m to image n . For the survival fraction s_{mn} and

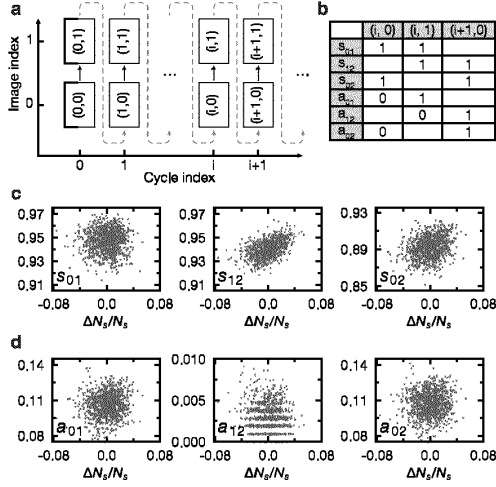


FIG. 6. **Correlations analysis on atom number fluctuation.** **a** Image labeling during continuous operation of the array. Each image can be identified by the cycle index $i \in [0, 1, \dots, \infty]$ and image index $j \in [0, 1]$. **b** Truth table illustrating the Boolean operations carried out on occupations between selected pairs of images in order to compute s_{mn} and a_{mn} . A one means occupied site, while a zero means unoccupied site. For example, s_{01} returns the number of lattice sites in the storage zone that are occupied both in image $(i, 0)$ and in $(i, 1)$, normalized to the number of loaded sites in image $(i, 1)$. Similarly, a_{02} returns the number of target lattice sites in the storage zone that are occupied in image $(i + 1, 0)$ but not in $(i, 0)$, normalized to the number of loaded sites in image $(i, 0)$. **c** Survival fraction of atoms from one image to another, as a function of atom number fluctuation. s_{12} correlates the strongest to the atom number fluctuation in the storage zone. **d** Gain of atoms from one image to another, as a function of atom number fluctuation.

gain a_{mn} , we label the images using an augmented image index $m, n = 0, 1, 2$, where the index 0 and 1 refer respectively to the first and second image of a cycle i , and index 2 refers to the first image of the next cycle $i + 1$, see Fig. 6b. The fluctuations are quantified by the quantity $\Delta N_s / N_s$, where N_s is the number of filled sites in our stored array while ΔN_s is defined as the difference of the number of filled sites in the stored array between the two images in consideration.

The correlations of the atom fluctuations $\Delta N_s / N_s$ with s_{mn} and a_{mn} are summarised in Fig 6c,d. It follows that $\Delta N_s / N_s$ correlate the strongest to s_{12} (Pearson coefficient 0.5) and next strongest to s_{02} (Pearson coefficient 0.3). The Pearson coefficients of the other correlations are below 0.15 in absolute value. This suggests the atom number fluctuation is most sensitive to the shelving fidelity in our parameter regime. We expect a_{12} to be identically 0 since no atom is intentionally added to the array between the second image of the cycle i and the first image of the cycle $i + 1$. However, we observe that some atoms are added at each cycle. Since both imperfect heating pulse and defects induced by $^3\text{P}_0$ shelved atoms during the MOT give a too small contribution, we attribute it to misclassification of our deconvolution algorithm.

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Claims

1. Method for trapping and manipulating neutral atoms, comprising:
loading a plurality of neutral atoms into a loading trap array arranged adjacent to or at least partially collocated with a storage trap array;
selectively removing neutral atoms in a first electronic state $|1\rangle$ from the storage trap array;
determining a trap occupancy of neutral atoms in the storage trap array in a second electronic state $|2\rangle$, and of neutral atoms in the loading trap array, and
moving, based on the determined trap occupancy of the neutral atoms in the storage trap array and in the loading trap array, neutral atoms from the loading trap array to one or more non-occupied trapping sites of the storage trap array.
2. The method of claim 1,
wherein a trap depth of the loading trap array for the neutral atoms is different from, preferably larger than, a trap depth of the storage trap array for the neutral atoms by at least 10%, preferably by at least 30%, and more preferably by at least 75%.
3. The method of claim 1 or 2, wherein selectively removing the neutral atoms in the first electronic state $|1\rangle$ from the storage trap array comprises one or more of:
selectively heating neutral atoms in the first electronic state $|1\rangle$ in the storage trap array;
selectively ionizing neutral atoms in the first electronic state $|1\rangle$ in the storage trap array;
selectively modifying a trapping potential for the neutral atoms in the first electronic state $|1\rangle$ in the storage trap array; and
selectively modifying a trapping potential for the neutral atoms in the loading trap array.

4. Method of claim 3, wherein selectively heating neutral atoms in the first electronic state $|1\rangle$ in the storage trap array comprises:
 - applying a trap-selective heating laser pulse to the loading trap array and the storage trap array, preferably a trap-selective Sisyphus-heating laser pulse.
5. Method of claim 4, wherein applying the trap-selective heating laser pulse comprises applying a sideband heating laser pulse at a frequency detuning corresponding to a blue sideband for the neutral atoms in the loading trap array.
6. The method of any of claims 1 to 5, wherein determining the trap occupancy of the neutral atoms in the storage trap array and the neutral atoms in the loading trap array comprises:
 - fluorescence imaging of the neutral atoms in the storage trap array and in the loading trap array or in trapping sites of an optical lattice collocated with the loading trap array, while laser-cooling the neutral atoms, preferably using Sideband-cooling, Raman sideband cooling, optical molasses cooling, or Sisyphus cooling and a combination thereof.
7. The method of any of claims 1 to 6, wherein moving the neutral atoms from the loading trap array to the one or more non-occupied trapping sites of the storage trap array comprises:
 - determining one or more movement trajectories for one or more neutral atoms in the loading trap array, based on the determined trap occupancy of the neutral atoms in the storage trap array and in the loading trap array; and
 - controlling a beam steering unit, preferably comprising a single or a multi-axis acousto-optic-deflector or a digital mirror device, of one or more optical tweezers to execute the determined movement trajectories for the one or more neutral atoms.
8. Method of any of claims 1 to 7, further comprising
 - generating the laser-cooled neutral atoms by operating a magneto optical trap, MOT, for the neutral atoms in a region of space that comprises at least a part of the loading trap array and at least a part of the storage trap array.

9. The method of claim 8, wherein the MOT for the neutral atoms is operated without using laser light that is resonant with an optical transition of the neutral atoms involving the second electronic state $|2\rangle$.

10. The method of any of the preceding claims, wherein the neutral atoms are alkali-earth-like atoms exhibiting a dipole-forbidden transition coupling the first electronic state $|1\rangle$ and the second electronic state $|2\rangle$.

11. The method of claim 10, wherein the neutral atoms are Strontium atoms, Preferably ^{88}Sr -atoms, and/or wherein the first electronic state is an $^1\text{S}_0$ state and the second electronic state is a $^3\text{P}_0$ state.

12. The method of any of claims 1 to 11,
wherein the loading trap array comprises an array of optical tweezers which are overlapped with a first subset of trapping sites of an optical lattice, preferably a folded optical lattice in a bow-tie configuration; and
wherein, a second subset of the trapping sites of the optical lattice forms the storage trap array.

13. The method of claim 12,
wherein loading the plurality of neutral atoms into the loading trap array comprises increasing, preferably while operating the MOT for the neutral atoms, a laser intensity of the array of optical tweezers; and
operating the optical lattice to maintain the storage trap array for neutral atoms in the second electronic state $|2\rangle$.

14. The method of any of claims 12 or 13,
wherein determining the trap occupancy of the neutral atoms in the loading trap array comprises:
transferring neutral atoms from the loading trap array into trapping sites of the first subset of trapping sites of the optical lattice; and optionally,
fluorescence imaging the neutral atoms in the first subset of trapping sites of the optical lattice while laser-cooling the neutral atoms in the optical lattice.

15. Method of any of claims 1 to 14, further comprising:
transferring neutral atoms in the storage trap array from the first electronic state $|1\rangle$ to the second electronic state $|2\rangle$.
16. Method for continuous operation of a quantum computation, simulation and / or metrology device comprising:
repeating the method of any of claims 1 to 15 to iteratively assemble and maintain an ensemble of neutral atoms in the storage trap array;
using a subset of the ensemble of neutral atoms for executing a quantum computation sequence, a quantum simulation sequence, and / or a quantum metrology sequence.
17. Method of claim 16, further comprising:
receiving, from a remote computation device, instructions for executing the quantum computation sequence, the quantum simulation sequence, and / or a the quantum metrology sequence;
executing, based on the received instructions, the quantum computation sequence, the quantum simulation sequence, and / or a the quantum metrology sequence; and
sending a result of the executed quantum computation sequence, the executed quantum simulation sequence, and / or the executed quantum metrology sequence to the remote computation device.
18. Quantum computation, simulation and / or metrology device comprising means for executing the method of any of claims 1 to 17.
19. Computer program for controlling a quantum computation, simulation and / or metrology device to execute the method of any of claims 1 to 17.
20. Method for trapping and manipulating neutral atoms, comprising:
transferring a plurality of neutral atoms trapped in a storage trap array from a first electronic state $|1\rangle$ to a second electronic state $|2\rangle$;

loading a plurality of laser-cooled neutral atoms into a loading trap array arranged adjacent to or at least partially collocated with the storage trap array;
determining a trap occupancy of the neutral atoms in the storage trap array, and of neutral atoms in the loading trap array, and
moving, based on the determining a trap occupancy, neutral atoms from the loading trap array to one or more non-occupied sites of the storage trap array.

21. Method of claim 20, further comprising:

selectively removing neutral atoms in the first electronic state $|1\rangle$ from the storage trap array after transferring the plurality of neutral atoms trapped in the storage trap array from the first electronic state $|1\rangle$ to the second electronic state $|2\rangle$.

22. Method of any of claims 20 or 21,

wherein a loading duration of the plurality of laser-cooled neutral atoms into a loading trap array is at least 2 times smaller, preferably 4 times smaller, more preferably 10 times smaller, and even more preferably 100 times smaller, than a lifetime of the second electronic state $|2\rangle$.

23. The method of any of claims 20 to 22, wherein loading the plurality of laser-cooled neutral atoms into a loading trap array comprises:

generating the laser-cooled neutral atoms by operating a MOT for the neutral atoms, in a region of space that comprises at least a part of the loading trap array and at least a part of the storage trap array, or in a region that is spatially separated from the region of space that comprises at least a part of the loading trap array.

24. The method of any of claims 20 to 23, wherein transferring the plurality of neutral atoms trapped in the storage trap array from the first electronic state $|1\rangle$ to the second electronic state $|2\rangle$ comprises:

coherently transferring the plurality of neutral atoms from the first electronic state $|1\rangle$ to the second electronic state $|2\rangle$; and / or

incoherently transferring the plurality of neutral atoms from the first electronic state $|1\rangle$ to the second electronic state $|2\rangle$ using one or more re-pump lasers.

25. Method for continuous operation of a quantum computation, simulation and / or metrology device comprising:

repeating the method of any of claims 20 to 24 to iteratively assemble and maintain an ensemble of neutral atoms in the storage trap array;

using a subset of the ensemble of neutral atoms for executing a quantum computation sequence, a quantum simulation sequence, and / or a quantum metrology sequence.

26. Method of claim 25, further comprising:

receiving, from a remote computation device, instructions for executing the quantum computation sequence, the quantum simulation sequence, and / or a the quantum metrology sequence;

executing, based on the received instructions, the quantum computation sequence, the quantum simulation sequence, and / or a the quantum metrology sequence; and

sending a result of the executed quantum computation sequence, the executed quantum simulation sequence, and / or the executed quantum metrology sequence to the remote computation device.

27. Quantum computation, simulation and / or metrology device comprising means for executing the method of any of claims 20 to 26.

28. Computer program for controlling a quantum computation, simulation and / or metrology device to execute the method of any of claims 20 to 26.

29. Method for trapping and manipulating neutral atoms, comprising:

loading a plurality of neutral atoms into a loading trap array adjacent to or collocated with a storage trap array, wherein the loading trap array comprises at least 1000 trapping sites, preferably at least 5000 trapping sites, and more preferably at least 10000 trapping sites overlapped with a source region for laser-cooled neutral atoms, wherein the loading trap array is formed by a plurality of trapping sites of an optical lattice,

determining a trap occupancy of neutral atoms in the storage trap array, and of neutral atoms in the loading trap array, and

moving, based on the determined trap occupancy of the neutral atoms in the storage trap array and in the loading trap array, neutral atoms from the loading trap array to one or more non-occupied trapping sites of the storage trap array.

30. Method of claim 29,

wherein a trap depth of the optical lattice is larger than 0.1 mK, preferably larger than 1.0 mK, and / or

wherein a trap frequency in a z-direction that is essentially orthogonal to an x-y-plane that comprises the optical lattice is larger than $2\pi \times 1$ kHz, preferably larger than $2\pi \times 2$ kHz, more preferably larger than $2\pi \times 4$ kHz, and even more preferably larger than $2\pi \times 8$ kHz.

31. Method of claim 29 or 30,

wherein a trap depth of the loading trap array is at least 2 times larger, preferably 10 times larger than a trap depth of the storage trap array; and/or

wherein a lifetime of the neutral atoms in the storage trap array is at least 2 times larger, preferably 10 times larger than a lifetime of the neutral atoms in the loading trap array.

32. Method of any of claims 29 to 31, wherein the neutral atoms are alkaline-earth like atoms of the same atomic species; and

wherein the storage trap array is operated at a magic wavelength for an electronic ground state and a long-lived metastable electronic excited state of the neutral atoms.

33. Method for continuous operation of a quantum computation, simulation and / or metrology device comprising:

repeating the method of any of claims 1 to 15 to iteratively assemble and maintain an ensemble of neutral atoms in the storage trap array;

using a subset of the ensemble of neutral atoms for executing a quantum computation sequence, a quantum simulation sequence, and / or a quantum metrology sequence.

34. Method of claim 33, further comprising:
- receiving, from a remote computation device, instructions for executing the quantum computation sequence, the quantum simulation sequence, and / or a the quantum metrology sequence;
 - executing, based on the received instructions, the quantum computation sequence, the quantum simulation sequence, and / or a the quantum metrology sequence; and
 - sending a result of the executed quantum computation sequence, the executed quantum simulation sequence, and / or the executed quantum metrology sequence to the remote computation device.
35. Quantum computation, simulation and / or metrology device comprising means for executing the method of any of claims 29 to 34.
36. Computer program for controlling a quantum computation, simulation and / or metrology device to execute the method of any of claims 29 to 34.