

APPARATUS AND METHOD FOR TRAPPING AND MANIPULATING LARGE NUMBERS OF INDIVIDUAL NEUTRAL ATOMS

INTRODUCTION

[0001] The present disclosure relates to apparatuses, methods, and a computer program for trapping, manipulating, and imaging large numbers of individual neutral atoms in optical trapping potentials with high-fidelity and low losses that can be used for quantum technologies such as quantum computing, atomic clocks, and quantum simulation.

[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. 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 via the movable optical trap.

[0004] In this technological context US 11,293,851 B2 relates to an apparatus for individually trapping atoms, individually imaging the atoms, and individually cooling the atoms to prevent loss of the atoms from the trap caused by the imaging.

WO 2022177599 A1 relates to a trap for quantum particles, e.g., cesium atoms, that is formed using electromagnetic radiation of different wavelengths. Red and blue detuned radiation are used together to form deeper traps that can be used to detect vacant atom sites. Other combinations of trap wavelengths can also be used.

US 2021/0279628 A1 relates to transport-based qubit-array loading. When an atom is lost from a site of a qubit array, the site can be identified as a target site. A target site can be reloaded by transporting an atom from a reservoir at least two millimeters to the target site. Alternatively, in response to the identifying, an atom that has been transferred from the reservoir to a qubit-array region including the qubit array can be transferred to the target site.

WO 2022/251435 A1 relates to a method comprising providing a first optical trap and a second optical trap, trapping an atom in the first optical trap, identifying a presence of the atom in the first optical trap, and transferring the atom from the first optical trap to the second optical trap. Qubit states may be manipulated through interaction with optical, radiofrequency, or other electromagnetic radiation, thereby performing quantum computations.

Young A.W. et al: *Tweezer-programmable 2D quantum walks in a Hubbard-regime lattice*. arXiv:2202.01204v1 [quant-ph] 2 Feb 2022 describes an optical lattice operated at the clock-magic wavelength 813nm for ⁸⁸Sr that is used in an analog quantum simulator. The lattice is generated by folding the lattice beams to increase the trap depth at fixed optical power.

Young, A.W., Eckner, W.J., Milner, W.R. et al. *Half-minute-scale atomic coherence and high relative stability in a tweezer clock*. Nature 588, 408–413 (2020) describes auxiliary traps that can be used to load and image atoms before handing them over to a clock-magic physics trap.

EP 4 120 145 A1 relates to a system for performing quantum operations comprising an optical superlattice and a plurality of optical tweezers, wherein the optical superlattice

comprises a plurality of main sites. Each main site comprises a storage site and an auxiliary site, each configured to hold an atom. The optical superlattice is configured to merge the storage site and the auxiliary site of each main site, and the plurality of optical tweezers is configured to move atoms provided in the plurality of main site from one main site to another main site.

SUMMARY

[0005] Scaling the approach mentioned above to large system sizes requires high fidelity and low-loss imaging at fast repetition rates which is currently limited by several technical limitations. For instance, the available laser power for generating the optical trap array or lattice limits the number of usable trapping sites, e.g., because low-loss imaging of individual neutral atoms in a quantum register requires large trap depths, and accordingly high laser intensities. This is particularly relevant for applications that require an optical trap array or lattice operated at a so-called magic-wavelength – i.e., a wavelength that, for a given type of neutral atom, induces an equal light shift for a pair of internal states that are used as qubits states, clock states, etc. For several atomic species, e.g., ⁸⁸Sr high power laser sources are not available for the magic wavelengths. Further limitations are the homogeneity of the optical trap arrangement, e.g., due to optical aberrations, slow loading times of the trap arrangement as well as stability of the trap arrangement, e.g., due to thermal or mechanical instabilities. Thus, there is a perpetual need for fast and large-scale preparation of neutral atom quantum registers while overcoming at least some of the discussed limitations.

[0006] To address such and similar shortcomings of state-of-the-art technology the present disclosure provides 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 trapping lattice. Combining an elliptical trapping laser beam with a bow-tie configuration (i.e., a folded and retroreflected optical path; see Fig. 2) for generating the optical trapping lattice results in a 2D array of periodic trapping potentials that

comprise a pronounced laser intensity distribution in the z-direction perpendicular to the x-y-plane that comprises the 2D array (see Fig. 1). As a result, the trap frequency in the z-direction and the trap depth of the optical trapping lattice can be made large enough – using commercially available laser sources, such as Ytterbium-doped fiber amplifiers – to localize neutral atoms trapped in the optical trapping lattice essentially in a single plane at the trapping volume. In essence, the optical trapping lattice that is generated from a single elliptical laser beam thus provides a strong confinement in the vertical z-direction and, simultaneously a large area in the horizontal x-y-plane. The strong confinement in the vertical direction is required for the imaging using a high-resolution microscopy and the larger extent in the horizontal direction allows for large system sizes. The apparatus disclosed herein enables directly loading of more than 10.000 neutral atoms in a single plane of the optical trapping lattice (see Fig. 16), which can be used as a locally addressable and sortable reservoir for continuous refilling of various physics traps such as an optical tweezer array used for implementing a quantum computing register.

[0007] Further, the lattice beams of the optical trapping lattice interfere – at a specific wavelength – under specific angles to create a lattice potential with anisotropic spacing in the x- and y-direction in the horizontal plane. The increased lattice spacing in one direction facilitates tweezer-based resorting in the optical trapping lattice. In this sense, the optical trapping lattice may serve a preparation and initialization lattice as well as a reservoir for the quantum register in the physics trap. A suitable choice of wavelength and interference angles allows to match the lattice spacing in the short direction with the lattice spacing of a so called “clock-magic” lattice potential or an optical trap array. This allows for efficient transfer of atoms from the preparation trap into the physics trap. As discussed in more detail below, optics for generating the optical trapping lattice and optics for generating the physics trap may be mounted to a common monolithic mounting structure, e.g., a mounting cube, and may thereby be referenced to a microscope objective etc. This allows for high mechanical stability. In addition, magnetic field coils that may be used to generate time-varying magnetic fields are mechanically separated from the mounting structure e.g., to suppress vibrations that otherwise occur during the switching or ramping of magnetic fields (see Fig. 10 and Fig. 11).

[0008] For instance, an aspect ratio of the elliptical / anisotropic trapping laser beam can be selected such that a trap frequency in the z-direction is larger than $2\pi \times 1$ kHz, larger than $2\pi \times 4$ kHz, or larger than $2\pi \times 8$ kHz, and / or such that a trap depth of the optical trapping lattice is larger than 0.1 mK, larger than 0.5 mK, or larger than 1.0 mK, e.g., for ~ 10 W output power of the trapping laser system. For example, an aspect ratio of the elliptical / anisotropic trapping laser beam may be larger than 2, larger than 4, or larger than 10 to realize large enough trap depths and trapping frequencies for the neutral atoms in the z-direction allowing for efficient transfer to the physics trap without causing substantial heating of the atoms.

[0009] Due to the fact, that the optical trapping lattice only comprises a single lattice plane, and at the same time a strong confinement in the z-direction and large trap depth the apparatus disclosed herein allows for (i) fast loading of many laser-cooled atoms directly from a magneto-optical trap (MOT) in particular in comparison to conventionally used arrangements of optical tweezer arrays. In addition, the optical trapping lattice can be used to speed up the loading of tweezer arrays even from small magneto-optical traps. Such lattice-enhanced loading can be used in some cases to significantly reduce the experimental sequence overhead/duration, e.g., for the loading of isotopes with low natural abundance such as ^{40}K , ^{84}Sr , etc. Using a folded and retro-reflected optical path allows to generate the lattice potential using only a single beam. The use of a single beam for this purpose also drastically simplifies the optical setup. A further advantage is, that the single 2D plane of trapping potentials interferes less with MOT operation, e.g., when compared to a 3D optical lattice.

[0010] In addition, decoupling, via the optical trapping lattice, the optical power demanding atom loading sequence from a MOT from a physics trap (e.g., an optical tweezer array, optical lattice at a different wavelength, etc.), where high-power laser sources are not always available improves the scalability of neutral atom based quantum registers towards a larger number of traps and correspondingly a larger number of neutral atoms that can be used as qubits, for quantum simulation applications, or for atomic clock spectroscopy sequences.

[0011] A further advantage provided by the apparatus described above is that the optical trapping lattice allows for low-loss and high signal-to-noise imaging of neutral atoms, e.g., prior to transferring the trapped atoms to a physics trap or after being transferred from the physics trap to the optical trapping lattice.

[0012] Thus, according to the present disclosure, both, the laser power demanding initialization, and low-loss imaging of trapped neutral atoms are decoupled from a physics trap using a high-power optical trapping lattice operated at the same trapping volume as the physics trap. The optical trapping lattice can be loaded in short time and be employed for high-fidelity, low-loss detection of neutral atoms. As discussed below, both, the optics generating the physics trap and the optics generating the optical trapping lattice can be mounted to the same monolithic mounting structure which also supports the objective for high-resolution imaging and addressing, thereby ensuring high mechanical stability and common mode vibrations. Further aspects of the apparatus disclosed herein are discussed below with reference to the provided drawings.

[0013] The present disclosure also provides an apparatus for trapping and manipulating neutral atoms, wherein a part of optics for generating an optical trapping lattice via a bow-tie configuration is mounted to a monolithic (e.g., a single unit) mounting structure, and wherein a part of optics used for generating a physics trapping lattice and / or a physics trap array is mounted to the same monolithic mounting structure. The mechanical stability of such an apparatus ensures that the relative position between the optical trapping lattice and the physics trapping lattice and / or the physics trap array is less affected by mechanical vibrations and thermal expansion of mounting equipment. For instance, mechanical vibrations that are affecting the monolithic mounting structure mostly result in common mode displacements of the physics trapping lattice and / or the physics trap array and the optical trapping lattice. Such an apparatus may also be combined with aspects of the apparatus discussed above.

[0014] In some embodiments, the apparatuses discussed above may also comprise a set of magnetic field coils that generate a magnetic field at the trapping volume, wherein the magnetic field coils are mounted to a second mounting structure that is essentially vibrationally decoupled from the monolithic mounting structure. In

some embodiments, the second mounting structure may be made from a material with an electric conductivity σ in the range of 10^{-4} S/m to 10^{-1} S/m.

[0015] Comparing the time constant $\tau = \epsilon_0 \epsilon_r / \sigma$, where ϵ_r is the relative permittivity of the material for exponential dissipation of accumulated charges to ground with the typical time constant for decay of Eddy currents which increases linearly with σ shows that such a material reduces formation of patch charges while at the same time substantially suppresses Eddy currents induced in the second mounting structure, e.g., when the magnetic field coils are switched or ramped at high speed. For example, using the commercially available material TECAFORM AH ELS black with $\sigma \sim 6 \times 10^{-3}$ S/m results in a decay of patch charges with $\tau_c \sim 2$ ns and Eddy current decay with $\tau_E \sim 100$ ns. This allows to reduce stray electric and magnetic fields fast thereby improving experimental repeatability and accuracy, e.g., qubit gate fidelity. More generally, for charges to decay on a time scale smaller than 10 ns, the conductivity needs to be larger than 10^{-4} S/m and for Eddy currents to decrease on a sub microsecond time scale, the conductivity needs to be smaller than 10^{-1} S/m.

[0016] Recent advances in quantum simulation based on neutral atoms have largely benefited from high-resolution local and single-atom sensitive imaging techniques. A variety of approaches have been developed to achieve such local detection of atoms in optical lattices or optical tweezers. For alkaline earth and alkaline earth-like atoms such as ^{88}Sr , the presence of narrow cooling transitions opens the possibility of performing novel types of Sisyphus cooling, where the cooling mechanism originates from the possibility to spatially resolve differential optical level shifts for the states of the narrow cooling transition in an optical trapping potential. Up to now, it has been an open question whether high-fidelity imaging could be achieved in a repulsive Sisyphus configuration, where the trap depth of the ground state exceeds that of the excited state involved in cooling.

[0017] In this context, the present disclosure further provides an apparatus for trapping and manipulating neutral atoms, comprising a trapping laser system, and optics for generating, based on an output of the trapping laser system, an optical trapping lattice at a trapping volume inside a vacuum chamber as well as a cooling laser system and optics for generating, at the trapping volume and based on an output of the cooling laser system, cooling laser light for cooling the neutral atoms inside the optical

trapping lattice wherein the cooling laser light for cooling the neutral atoms inside the optical trapping lattice has a first wavelength component that drives a repulsive Sisyphus cooling mechanism, for the neutral atoms in the optical trapping lattice. The cooling laser light may further comprise a second wavelength component that optically pumps atoms from a first internal state that does not couple to the first wavelength component to a second internal state that couples to the first wavelength component, and, optionally, a third wavelength component that optically pumps atoms from a third internal state that does not couple to the first wavelength component to an internal state that couples to the first wavelength component. The apparatus may further comprise an imaging laser system and optics for generating, at the trapping volume and based on an output of the imaging laser system, imaging laser light for driving a dipole-allowed transition of the neutral atoms, and optics for collecting fluorescence of the dipole-allowed transition from the neutral atoms on an imaging sensor.

[0018] While conventionally, repulsive Sisyphus cooling during imaging is accompanied by a rather large atom loss probability (cf. A. Cooper, J. P. Covey, I. S. Madjarov, S. G. Porsev, M. S. Safronova, and M. Endres, Alkaline-earth atoms in optical tweezers, *Physical Review X* **8**, 041055 (2018).), the apparatus and method disclosed herein allow for high-fidelity imaging in a repulsive Sisyphus configuration, where the trap depth of the ground state exceeds that of the excited state involved in cooling. For instance, using ^{88}Sr atoms, high-fidelity (99.9995(3) %) and high-survival (99.80(5) %) imaging of ^{88}Sr using repulsive Sisyphus cooling can be achieved (see Fig. 14 below).

[0019] In this context, the present disclosure further provides an apparatus for trapping and imaging neutral alkaline-earth or alkaline earth-like atoms, comprising: an optical trapping lattice for the neutral atoms operating in a wavelength range between 1010 nm to 1100 nm at a trapping volume inside a vacuum chamber, a cooling laser system, and optics for generating, at the trapping volume, cooling laser light for cooling the neutral atoms inside the optical trapping lattice, wherein the cooling laser light for cooling the neutral atoms inside the optical trapping lattice has a first wavelength component that drives a repulsive Sisyphus cooling mechanism using a narrow inter-combination transition of the neutral atoms in the optical trapping lattice. For instance, the first wavelength component may be blue detuned with respect to a bare inter-combination resonance frequency by an amount that is less than a tensor

light shift of the narrow inter-combination transition in the optical lattice (i.e., red-detuned with respect to the light-shifted resonance). In some embodiments, the optical trapping lattice may be generated by an apparatus as described above.

[0020] In some embodiments, such an apparatus may further comprise an imaging laser system, optics for generating, at the trapping volume, imaging laser light for driving a dipole-allowed transition of the neutral atoms, and optics for collecting fluorescence of the dipole-allowed transition from the neutral atoms on an imaging sensor. Optionally, the cooling laser light for cooling the neutral atoms inside the optical trapping lattice may comprise a second wavelength component that optically pumps atoms from a first internal state that does not couple to the first wavelength component to an internal state that couples to the first wavelength component and / or a third wavelength component that optically pumps atoms from a second internal state that does not couple to the first wavelength component to an internal state that couples to the first wavelength component.

[0021] The present disclosure also provides a method for trapping and manipulating (e.g., imaging) neutral atoms, comprising: loading the neutral atoms into an optical trapping lattice comprising a single trapping lattice plane at a trapping volume inside a vacuum chamber; and imaging the neutral atoms in the optical trapping lattice, while, optionally, laser cooling the neutral atoms in the optical trapping lattice (e.g., via Sisyphus cooling as discussed above), and transferring the imaged neutral atoms into a physics lattice or into a physics trap array. As discussed above, in this manner, the power demanding loading and imaging steps can be performed in an optimized manner inside the optical trapping lattice while the neutral atoms can be manipulated, again in an optimized manner inside the decoupled physics lattice or inside a physics trap array.

[0022] For instance, certain neutral atom quantum technologies, such as quantum computing, optical lattice clocks, etc. require a physics lattice or into a physics trap array that operates at a magic wavelength where only low-power laser sources are available, conventionally leading to a trade-off between system size and loading as well as imaging efficiency. The disclosed method allows to avoid such a trade-off because loading and imaging can be done in a non-magic optical trapping lattice that is optimized for large system size and deep trap depth. In some embodiments, laser

cooling inside the optical trapping lattice prior to transferring the neutral atoms into the physics lattice or into the physics trap array allows to use much larger physics lattice or physics trapping array because, due to the lower temperature of the neutral atoms in the optical trapping lattice, the laser power available for the physics lattice or the physics trapping array can be distributed to more trapping sites. Combining imaging and laser cooling in the trapping lattice enables low loss imaging of large atomic ensembles providing a well characterized reservoir of ultra-low temperature atoms that can be used to generate a quantum register with unity filling in the physics trap. Further aspects of the methods disclosed herein are discussed below with reference to Fig. 12.

[0023] The present disclosure also provides a method for aligning an optical trapping lattice with respect to a physics trap array or a physics trapping lattice, comprising determining a relative displacement between the physics trap array or the physics trapping lattice and the optical trapping lattice; and adjusting the optical trapping lattice, the physics trap array and / or the physics trapping lattice to reduce the relative displacement. In this manner it can consistently be ensured, e.g., via a (continuously operated) feed-back loop that the optical trapping lattice and the physics trap (e.g., tweezer array or lattice) are properly aligned for high-efficiency and low-temperature transfer of neutral atoms between the optical trapping lattice and the physics trap. Further aspects of the trap alignment methods disclosed herein are discussed below with reference to Fig. 13.

[0024] 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

[0025] So that the above-recited features of the present disclosure can be understood in detail, a more particular description, briefly summarized above, may be had by reference to aspects, some of which are illustrated in the appended drawings. It is to be noted, however, that the appended drawings illustrate only some typical aspects of this disclosure and are therefore not to be considered limiting of its scope, for the description may admit to other equally effective aspects. The same reference numbers in different drawings may identify the same or similar elements.

[0026] **Fig. 1** illustrates an exemplary apparatus for trapping and manipulating neutral atoms according to a possible implementation of the present disclosure.

Fig. 2 illustrates a typical optical setup for generating an optical trapping lattice as well as a physics lattice, using a bow-tie configuration according to a possible implementation of the present disclosure.

Fig. 3 shows a side view of a part of an apparatus for trapping and manipulating neutral atoms according to a possible implementation of the present disclosure.

Fig. 4 illustrates a vertical shallow angle lattice that may be used in an apparatus for trapping and manipulating neutral atoms according to a possible implementation of the present disclosure.

Fig. 5 illustrates part of the internal level configuration of ^{88}Sr that may be used as neutral atom species for various aspects disclosed herein.

Fig. 6 illustrates a typical trapping and manipulation sequence for neutral atoms using an apparatus as disclosed herein.

Fig. 7 illustrates a further possible sequence, e.g., using an apparatus as described herein where neutral atoms are directly loaded into the optical trapping lattice from a magneto optical trap.

Fig. 8 illustrates a further possible sequence, e.g., using an apparatus as described herein where neutral atoms are loaded into a physics trap using the optical trapping lattice to enhance loading efficiency.

Fig. 9 illustrates how a crossing angle, and a laser wavelength can be adjusted to ensure that an optical trapping lattice is essentially commensurate with a physics trapping lattice.

Fig. 10 illustrates a further apparatus as disclosed herein that comprises a monolithic mounting structure for mounting optics generating the optical trapping lattice and optics for generating a physics trap array / lattice.

Fig. 11 illustrates further details of the apparatus of Fig. 10, e.g. a second mounting structure for magnetic field coils that is vibrationally decoupled from the monolithic mounting structure shown in Fig. 10.

Fig. 12 illustrates a method for trapping and manipulating neutral atoms, e.g., using an apparatus as described above.

Fig. 13 illustrates an example method for aligning an optical trapping lattice with respect to a physics trap array or a physics trapping lattice.

Fig. 14 illustrates the performance of repulsive Sisyphus cooling and imaging of ^{88}Sr using an exemplary apparatus and method as disclosed herein.

Fig. 15 illustrates transfer performance between an optical trapping lattice and a physics trap array using an exemplary apparatus and method as disclosed herein.

Fig. 16. shows a typical single-shot fluorescence image of more than 10000 neutral atoms directly loaded into the optical trapping lattice from a magneto-optical trap using an exemplary apparatus and method as disclosed herein.

DETAILED DESCRIPTION OF EXEMPLARY EMBODIMENTS

[0027] 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.

[0028] Several aspects of trapping and manipulating (e.g., imaging, gate operations, spectroscopy, 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 applicants 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.

[0029] While aspects of the present disclosure are presented in the following for the bosonic Strontium isotope ^{88}Sr , and /or a laser wavelength of the optical trapping lattice in the range of 1010 nm to 1100 nm it is to be understood, that any other species of neutral atom with a suitable internal level structure and any other suitable trapping laser system may also be used in other implementations of the present disclosure.

[0030] **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 trapping lattice 120 at a trapping volume 140 inside a vacuum chamber 150. The optics 110 for generating the optical trapping 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 trapping 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.

[0031] 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 trapping 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.

[0032] For example, in one possible implementation, the optical trapping 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 trapping 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 trapping lattice 120, and, after transfer in a physics trap array 170 or a physics trapping lattice.

[0033] 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.

[0034] In the example of Fig. 1, the physics trap is implemented as a physics trap array 170 (e.g., as an array of optical tweezers), e.g., generated by a spatial light

modulator (SLM) or similar device and imaged to the trapping volume 140 through a high-resolution objective 160.

[0035] 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.

[0036] The tweezer array 170 can be aligned with the optical trapping lattice 120 by aligning their foci in all three dimensions x, y and z. The global tweezer array position on the x-y-plane can then be adjusted actively by feedback to a grating phase on the spatial light modulator to maintain optimal overlap with the slowly drifting lattice potential (for details see **Fig. 13** below).

[0037] In some implementations, the tweezer array 170 can be loaded from a narrow-line MOT, e.g., operated on a dipole-forbidden inter-combination transition. As discussed elsewhere herein, loading of the physics trap 170 can be aided by the optical trapping lattice 120 (cf. Figs. 6 to 8), to efficiently load tweezers 170 even at a shallow tweezer trap depths such as $140 \mu\text{K}$, thereby greatly increasing the ultimate size of the quantum register, which is conventionally limited by a poor parity projection (e.g., via light assisted collisions) at lower trap depths. Here and in the following it is understood that a parity projection leaves either one or zero atoms per trapping site.

[0038] For instance, when using ^{88}Sr as neutral atom species, inducing light-assisted collisions to perform the parity projection detuned to the red of the free space resonance on the 689 nm cooling transition (cf. Fig. 5), singly occupied tweezers can be

prepared with about 45% filling fraction, serving as a starting point for further manipulations of the neutral atoms, such as clock spectroscopy and / or quantum gates.

[0039] In some implementations, the tweezer array 170 can be generated holographically using a phase-only SLM, e.g., using a variant of the Gerchberg–Saxton algorithm where the phases of tweezers at the focal plane are kept stationary. In an example setup, a collimated beam with a waist of 4.2 mm is incident on the SLM chip of 12.8 mm×15.9 mm in size. A telescope consisting of a 300 mm and 750 mm achromatic lens relays the imprinted phase pattern to the back focal plane of the high-resolution objective 160. The objective 160 then transforms the phase pattern into an array of tightly focused tweezers 170 in the x-y-plane at the trapping volume 140.

[0040] In some implementations, the crossing angle θ of the bow-tie configuration 110 used for generating the optical trapping lattice 120 is selected / adjusted such, that a lattice spacing ratio in the x-y-plane is two-to-one within 10%, accuracy, preferably, within 5% accuracy, and more preferably within 1% accuracy. For instance, the crossing angle θ may be adjusted to be 26.56° and the operation wavelength λ of the optical trapping laser beam 130 may be 1028.3 nm within 10%, accuracy, preferably within 5% accuracy, and more preferably within 1% accuracy resulting in a long lattice spacing of 1149.9 nm along the x-direction and a short lattice spacing of 574.8 nm along the y-direction of the x-y-plane. Such an apparatus may be used to generate an optical trapping lattice 120 that is essentially commensurate with a magic wavelength physics lattice for ^{88}Sr atoms (see Fig. 9 below). Here it should be noted that due to its internal level structure and bosonic character ^{88}Sr is a prime candidate for important quantum technologies such as quantum computers and optical lattice clocks.

[0041] More specifically, the wavelength range of the physics trap may be predetermined by the atomic species and / or the desired application. For example, optical lattice clocks working with ^{88}Sr atoms typically requires a physics lattice 170 for clock spectroscopy that is operated at a magic wavelength for a pair of clock states, e.g., at $\lambda = 813$ nm, where high-power lasers are not available. By contrast, the optical trapping lattice 120 can be operated in the wavelength range of Ytterbium-doped fiber amplifier with an operation wavelength λ in the range of 1010 nm to 1100 nm. Thus, in

some embodiments, the trapping laser system comprises such an Ytterbium doped fiber amplifier. Importantly, the apparatus described herein allows to make the optical trapping lattice 120 commensurate with a physics trapping lattice 170 or a physics trap array 170. For instance, the crossing angle θ of the bow-tie configuration 110 can be selected such, that a lattice spacing ratio of the optical trapping lattice is two-to-one as discussed above. Generally, a short lattice spacing a_y of the optical trapping lattice 120 may be typically given by $a_y = \lambda / (2 \cos(\theta))$, and a long lattice spacing a_x of the optical trapping lattice 120 may be given by $a_x = \lambda / (2 \sin(\theta))$. Setting $\theta \sim 26.56^\circ$ yields a lattice spacing ratio of the optical trapping lattice 120 that is essentially two-to-one. Similarly, setting θ to 45° yields a lattice spacing ratio of the optical trapping lattice 120 that is essentially one-to-one. In such a configuration, the wavelength λ of the trapping laser beam 130 may be selected such that the optical trapping lattice 120 is essentially commensurate with a physics trapping lattice (see Fig. 9 below).

[0042] In some aspects, the apparatus disclosed herein may further comprising a physics trap laser system, and optics 160 for generating, based on the output of the physics trap laser system, a physics trapping lattice and / or a physics trap array 170 for the neutral atoms at the trapping volume 140 in the vacuum chamber 150, where a lattice spacing of the physics trapping lattice and / or the physics trap array 170 may be essentially commensurate with a lattice spacing of the optical trapping lattice 120. Optionally, the physics trap laser system may operate at a magic wavelength for a pair of internal states of the neutral atoms that experience the same light shift from the physics trap laser light at the magic wavelength.

[0043] Further, in some aspects, the optics for generating the physics trapping lattice 170 may comprise a second bow-tie configuration, optionally comprising a crossing angle η that is equal to 45° within 10%, accuracy, preferably, within 5% accuracy, and more preferably within 1% accuracy such that a lattice spacing ratio in the x-y-plane is one-to-one within 10%, accuracy, preferably, within 5% accuracy, and more preferably within 1% accuracy. By adjusting the wavelengths of the optical trapping laser beams of the physics lattice laser beam a one-to-one physics lattice 170 may be made commensurate with a two-to-one optical trapping lattice 120 (see Fig. 9).

[0044] In addition, such an apparatus 100 may further comprise a cooling laser system, and optics for generating, at the trapping volume 140, cooling laser light for cooling the neutral atoms inside the optical trapping lattice 120, the physics trapping lattice, and / or the physics trap array 170. For example, the cooling laser light for cooling the neutral atoms inside the optical trapping lattice 120 may have a first wavelength component that drives a Sisyphus cooling mechanism, preferably repulsive Sisyphus cooling, for the neutral atoms in the optical trapping lattice, and, optionally, a second wavelength component that optically pumps atoms from a first internal state that does not couple to the first wavelength component to a second internal state that couples to the first wavelength component, and, optionally, a third wavelength component that optically pumps atoms from a third internal state that does not couple to the first wavelength component to an internal state that couples to the first wavelength component (for details for ^{88}Sr atoms see Fig. 5 below).

[0045] To ensure efficient laser cooling inside the optical trapping lattice 120, the first wavelength component may be blue-detuned from a bare atomic resonance used for Sisyphus cooling and red-detuned from the (tensor) light shifted atomic resonance in the optical trapping lattice 120.

[0046] Further, the apparatus 100 may also comprise an imaging laser system, and optics for generating, at the trapping volume 140, imaging laser light for driving a dipole-allowed transition of the neutral atoms (cf. Fig. 5 for ^{88}Sr), and optics for collecting fluorescence of the dipole-allowed transition from the neutral atoms on an imaging sensor. For example, the optical setup may comprise a dichroic mirror for separating the fluorescence light (e.g., at 461 nm) from the physics trap laser (e.g., at 520 nm or 813 nm). As illustrated in Fig. 10 and Fig. 11, to enhance mechanical stability, a part of the optics 110 for generating the optical trapping lattice 120 that may be used for implementing the bow-tie configuration may be mounted to a monolithic mounting structure, and a part of the optics 160 used for generating the physics trapping lattice and / or the physics trap array 170 may be mounted to the same monolithic mounting structure.

[0047] In some examples, the apparatus described herein may also comprise a set of magnetic field coils that generate a magnetic field at the trapping volume 140,

wherein the magnetic field coils may be mounted to a second mounting structure that is essentially vibrationally decoupled from the monolithic mounting structure.

Additionally, the second mounting structure may be made from a material (such as TECAFORM AH ELS black) with an electric conductivity in the range of 10^{-4} S/m to 10^{-1} S/m, e.g., to avoid accumulation of patch charges and to suppress Eddy currents, which are typical sources of systematic errors in high-precision quantum technologies.

[0048] As mentioned above, the optics for generating the physics trap array may comprise a spatial light modulator with an adjustable grating as well as a large numerical aperture objective 160 for focusing the physics trap array 170 to the trapping volume 140. Additionally, or alternatively, the optics for generating the physics trapping lattice may comprises a set of mirrors and focusing lenses (cf. Fig. 2 for an illustration), and one or more adjustable phase shifting elements such as EOMs for generating an adjustable differential phase difference for two or more interfering beams generating the physics trapping lattice 170.

[0049] As discussed in above the present disclosure also provides an apparatus 100 for trapping and manipulating neutral atoms, comprising, a trapping laser system, and optics 110 for generating, based on an output of the trapping laser system, an optical trapping lattice 120 at a trapping volume 140 inside a vacuum chamber 150 as well as a cooling laser system, and optics (not shown) for generating, at the trapping volume 140 and based on an output of the cooling laser system, cooling laser light for cooling the neutral atoms inside the optical trapping lattice 120. The cooling laser light for cooling the neutral atoms inside the optical trapping lattice 120 may comprise a first wavelength component that drives a repulsive Sisyphus cooling mechanism, for the neutral atoms in the optical trapping lattice 120. The cooling laser light may further comprise (e.g., for imaging in the optical trapping lattice while laser cooling) a second wavelength component that optically pumps atoms from a first internal state that does not couple to the first wavelength component to a second internal state that couples to the first wavelength component; and, optionally, a third wavelength component that optically pumps atoms from a third internal state that does not couple to the first wavelength component to an internal state that couples to the first wavelength component (for an example see Fig. 5). Such a setup may further comprise an imaging laser system, as well as optics for generating, at the trapping volume 140 and based on

an output of the imaging laser system, imaging laser light for driving a dipole-allowed transition of the neutral atoms, and optics 160 for collecting fluorescence of the dipole-allowed transition from the neutral atoms on an imaging sensor.

[0050] **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.

[0051] 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.

[0052] 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 (cf. Fig. 9). 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 trapping lattice and the physics lattice.

[0053] **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.

[0054] 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.

[0055] **Fig. 4** illustrates how for applications that require stronger vertical confinement the optical trapping lattice 130 is compatible with a vertical shallow angle lattice 410 that can also be directly connected to the mechanical structure described above for enhanced stability.

[0056] **Fig. 5** illustrates part of the internal level configuration of ^{88}Sr that may be used as neutral atom species in the devices and procedures disclosed herein. The electronic ground state of ^{88}Sr can be coupled via a strong dipole-allowed transition (461 nm) to the $5p\ ^1P_1$ excited state, e.g., for initial laser cooling in a Zeeman slower and / or a first stage MOT as well as for fluorescence imaging in an optical trapping lattice and / or a physics trap as disclosed herein. The 1S_0 ground state of ^{88}Sr may also be coupled via narrow, dipole-forbidden, inter-combination transitions to the $5p\ ^3P_J$ manifold, where the angular momentum quantum number J can be 0, 1 or 2. The 698nm clock transition from 1S_0 to 3P_0 can be used – inter alia – for clock spectroscopy, and single-qubit gates, and the 689 nm cooling transition from 1S_0 to 3P_1 for low-

temperature laser cooling, e.g., in a second stage MOT or for laser cooling in an optical trapping lattice and / or a physics trap.

[0057] To implement high efficiency and low-loss imaging in a non-magic optical trapping lattice (e.g., operated in the Ytterbium amplifier wavelength range between 1010 nm and 1100 nm) laser cooling using the 689nm transition needs to be performed while the 461 nm transition is used to generated fluorescence from the trapped neutral atoms. For example, as discussed above, in such an optical trapping lattice repulsive Sisyphus cooling needs to be used for ^{88}Sr . Since the $5p\ ^1P_1$ state can decay via the $4d\ ^1D_2$ state to three different J (angular momentum) states of the $5p\ ^3P_J$ manifold that do not couple to the 689 nm cooling transition, repump lasers on the 679 nm and the 707 nm transition to the $6s\ ^3S_1$ state can substantially enhance laser cooling efficiency in the optical trapping lattice.

[0058] **Fig. 6** illustrates a typical trapping and manipulation sequence for neutral atoms using an apparatus as disclosed herein. Neutral atoms are first laser cooled in a two-stage MOT wherein “Blue” may refer to a 461 nm MOT for ^{88}Sr atoms and “Red” may refer to a 689 nm MOT. Due to the low temperature attainable via the Red MOT, laser cooled atoms can be directly loaded into a tweezer array and then transferred for imaging, as discussed above, into the optical trapping lattice (Lattice image 1). After the positions of the neutral atoms are determined, a quantum register (e.g., comprising unity filling) may be formed, e.g., using movable optical tweezers. The quantum register may then be transferred into a combined trap formed by a shallow optical trapping lattice and the optical tweezers where laser cooling can be applied to transfer the neutral atoms to low lying motional states in the tweezer array. After laser cooling in the combined optical trap, the optical trapping lattice may be switched off, and the quantum register may be used for quantum physics protocols (quantum gates, clock spectroscopy, quantum simulation) in the optical tweezer array. For detection of the state of the quantum register the neutral atoms may than be transferred back to the optical trapping lattice where high efficiency and low loss imaging can be performed.

[0059] **Fig. 7** illustrates a further possible sequence, e.g., using the apparatus described above, where the neutral atoms are directly loaded into the optical trapping lattice from a two stage MOT and imaged to determine which lattice sites are occupied.

Due to the strong confinement in z-direction, a single lattice plane can be loaded with more than 10000 neutral atoms (see Fig. 16), that may then cooled and rearranged to realize large and homogenous quantum registers that may then be transferred into a physics trap that, due to the laser cooling in the optical trapping lattice can be operated at much lower trap depths, thereby facilitating large quantum registers even in absence of high power laser sources for generating the physics trap.

[0060] **Fig. 8** illustrates a further possible sequence, e.g., using the apparatus described above, where the neutral atoms are loaded from the MOT into the physics trap (e.g., a clock-magic tweezer array / lattice) using the optical trapping lattice to enhance loading efficiency from the MOT.

[0061] **Fig. 9** illustrates conceptionally, how the crossing angle and laser wavelength of the bow tie configuration used for generating the optical trapping lattice can be adjusted to ensure that the optical trapping lattice is essentially commensurate with a clock magic physics lattice. For instance, the physics trapping lattice may be operated at 813nm using a second bow-tie configuration with a crossing angle $\eta = 45^\circ$ resulting in a square lattice (circles). Using a crossing angle $\theta = 25.56^\circ$ and a wavelength of 1028.3 nm for the optical trapping lattice (squares) results in a lattice spacing ratio of essentially 2-to-1 that is essentially commensurate with the 813 nm physics lattice. For example, quantum information processors based on neutral strontium atoms typically rely on the clock-magic wavelength at 813 nm for the physics trap. In this wavelength regime high-power laser sources are not available which limits the system size of the processor or the achievable trap depth. Interfering 813nm light in a power-efficient folded configuration at a crossing angle of 45° creates lattice spacings of $\sim 0.57 \mu\text{m}$. Such a trap can be overlapped with a suitable preparation trap / optical trapping lattice (in folded configuration) by choosing angles of $\sim 26.56^\circ$ at a wavelength of 1028.3 nm (where high-power laser sources are available). The angle of 26.56° yields an asymmetric lattice spacing with an aspect ratio of 2-to-1. This facilitates the site-resolved addressing in the preparation trap which is required for the rearrangement of atom to form a quantum register. This scheme reduces significantly the technical complexity for neutral-atom based quantum computing/simulation experiments, since the physics trap can be exchanged without affecting the resorting steps in the preparation trap.

[0062] The initialization of the register requires precisely one atom per trapping site. Using high-fidelity and low-loss imaging as discussed herein in the preparation trap / optical trapping lattice the initially random distribution of atoms can be detected. Using the known occupation of the trapping sites an algorithm computes the required moves to rearrange the ensemble into a configurable pattern. A mobile optical tweezers controlled with an acousto-optic deflector (AOD) provides an additional potential to carry out the moves. By pointing the AOD at selected atoms and smoothly displacing the tweezer potential, atoms are moved within the potential of the preparation trap. Atoms are rearranged until the desired pattern is generated. The fidelity of the preparation depends on many experimental parameters and typically needs to be optimized only once for the preparation trap. After resorting atoms in the preparation trap, they are transferred to the physics trap where no further resorting is required. Thus, the optical trapping lattice can be used to efficiently prepare large-scale quantum registers either in optical tweezer arrays or other physics traps. Using the optical trapping lattice for imaging and resorting prior to loading into the physics traps decouples the initialization from the underlying physics trap.

[0063] **Fig. 10** illustrates a further apparatus as disclosed herein that – inter alia – comprises a monolithic mounting structure 910 for mounting the optics 210, 220 generating the optical trapping lattice and the optics 160 for generating the physics trap array. As illustrated the mirrors 220 and lenses 210 for generating the optical trapping lattice inside the vacuum chamber 150 are mounted to the metal frame of the monolithic mounting structure 910 that also provides support for the high-resolution objectives 160. Thus, the present disclosure also provides an apparatus for trapping and manipulating neutral atoms, comprising a trapping laser system, and optics 210, 220 for generating, based on an output of the trapping laser system, an optical trapping lattice at a trapping volume inside a vacuum chamber 150, as well as a physics trap laser system, and optics 160 for generating, based on the output of the physics trap laser system, a physics trapping lattice and / or a physics trap array for the neutral atoms at the trapping volume in the vacuum chamber 150. A part of the optics for generating the optical trapping lattice, preferably using a first bow-tie configuration as discussed above, is mounted to a monolithic mounting structure 910, and a part of the optics used for generating the physics trapping lattice, preferably using a second bow-tie configuration, and / or a part of the optics used for generating the physics trap array

is mounted to the same monolithic mounting structure 910. Such an apparatus improves the relative positional stability of the optical trapping lattice and the physics trap array / lattice e.g., because the monolithic mounting structure ensures that mechanical vibrations and / or thermal expansion are to a large extent common mode.

[0064] As shown in **Fig. 11** such an apparatus may further comprise a set of magnetic field coils 920 that generate a magnetic field at the trapping volume wherein the set of magnetic field coils 920 is mounted to a second mounting structure 930 that is essentially vibrationally decoupled from the monolithic mounting structure 910. To reduce stray EM-fields during high-precision quantum physics procedures, the second mounting structure 930 is preferably made from a material with an electric conductivity in the range of 10^{-4} S/m to 10^{-1} S/m. Choosing such a material (e.g., TECAFORM AH ELS black) ensures that charge accumulation in the material as well as Eddy currents can be reduced effectively on experimentally relevant time scales at the same time.

[0065] 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.

[0066] **Fig. 12** illustrates a method for trapping and manipulating a plurality of neutral atoms, e.g., using an apparatus as described above. Step 1210 comprises loading the neutral atoms into an optical trapping lattice that comprises a single trapping lattice plane at a trapping volume inside a vacuum chamber. In step 1230 the neutral

atoms are imaged in the optical trapping lattice. The method optionally includes a step 1220 of laser cooling the neutral atoms in the optical trapping lattice e.g., prior or during (e.g., simultaneously, or intermittently) the imaging step 1230. In step 1240, the imaged neutral atoms are transferred into a physics trapping lattice (e.g., a clock magic physics lattice) or into a physics trap array (e.g., an optical tweezer array) as described above.

[0067] In some implementations, loading the neutral atoms into the optical trapping lattice may comprise laser cooling the neutral atoms in a magneto optical trap at the trapping volume and transferring the laser cooled neutral atoms into the optical trapping lattice. Loading the neutral atoms into the optical trapping lattice may also comprise transferring the neutral atoms from the physics trapping lattice or the physics trap array into the optical trapping lattice (e.g., for state detection after a quantum physics sequence performed in the physics trap).

[0068] The method disclosed herein may further comprise laser cooling the neutral atoms in a magneto optical trap at the trapping volume, and transferring the laser cooled neutral atoms into the physics trapping lattice or the physics trap array, wherein, in some examples, transferring the laser cooled neutral atoms into the physics trapping lattice or the physics trap array may comprise operating the optical trapping lattice during transferring the laser cooled neutral atoms at an intermediate trap depth to enhance the transferring of the laser cooled neutral atoms into the physics trapping lattice or into the physics trap array (see Fig. 6 and Fig. 8).

[0069] In some examples, the method may further comprise laser cooling of the neutral atoms in the physics trap array; and / or inducing light-assisted collisions between multiple atoms at individual traps of the optical trapping lattice, the physics trap array, and / or the physics trapping lattice, e.g., to perform a parity projection prior to sorting the remaining atoms into a quantum register. The method may further comprise, performing a single-qubit and / or a two-qubit gate operation on the neutral atoms in the physics trap array or in the physics trapping lattice (e.g., for realizing a quantum computation sequence), or performing atomic clock spectroscopy on the neutral atoms in the physics trapping lattice / trap array (e.g., for operating an atomic

clock); or performing a many-body evolution sequence for the neutral atoms in the physics trapping lattice or the physics trap array (e.g., for quantum simulation).

[0070] In some examples, a distance between neighboring traps of the physics trap array is more than twice as large, or more than four times as large as a lattice spacing of the optical trapping lattice in a first direction, e.g., to implement a reservoir of trapped atoms that may be used for sorting a quantum register of unity filling. Further, transferring the neutral atoms from the physics trap array or the physics trapping lattice into the optical trapping lattice may comprise, ramping up the trap depth of the optical trapping lattice and ramping down the trap depth of physics trap array or the physics trapping lattice such that the trap depth of the optical trapping lattice is larger than the trap depth of the physics trap array or the physics trapping lattice during ramping down of the trap depth of the physics trap array or the physics trapping lattice.

[0071] Additionally or alternatively, transferring the neutral atoms from the optical trapping lattice to the physics trap array or to the physics trapping lattice may comprise ramping down the trap depth of the optical trapping lattice and ramping up the trap depth of the physics trap array or the physics trapping lattice such that the trap depth of the optical trapping lattice is larger than the trap depth of the physics trap array or the physics trapping lattice during ramping up the trap depth of the physics trap array or the physics trapping lattice, and, optionally, laser cooling the neutral atoms in a combined trapping potential generated by the ramped-up physics trap array or the ramped-up physics trapping lattice and the partially ramped-down optical trapping lattice at a trap depth that is lower than the trap depth of the physics trap array or the physics trapping lattice. In this manner efficient loading and transfer of neutral atoms at low temperature can be ensured.

[0072] In some implementations, imaging the neutral atoms in the optical trapping lattice may comprise illuminating the neutral atoms in the optical trapping lattice with an imaging laser resonant to a first optical transition of the neutral atoms, laser cooling the neutral atoms in the optical trapping lattice using a second optical transition, preferably using repulsive Sisyphus cooling (e.g., as discussed above); and collecting fluorescence from the neutral atoms using a high-resolution imaging system

and an imaging sensor as well as, optionally illuminating the neutral atoms with a repumping laser resonant to a third optical transition and / or a fourth optical transition of the neutral atoms to transfer atoms that are no longer being laser-cooled back to a state that can be laser-cooled (for an example of this general imaging scheme applied to ^{88}Sr atoms in an repulsive Sisyphus configuration, see Fig. 5).

[0073] In some aspects, the method discussed herein may further comprise (e.g., for resorting trapped atoms to form a quantum register) determining a first position in the optical trapping lattice that does not contain a neutral atom and that overlaps with an optical trap of a subset of the physics trap array or the physics trapping lattice (e.g., a subset that should form a quantum register), determining a second position in the optical trapping lattice that contains a neutral atom and that does not overlap with an optical trap of the subset of the physics trap array or the physics trapping lattice (e.g., a reservoir site of the optical trapping lattice), and moving, using a movable optical trap, the neutral atom from the second position to the first position in the optical trapping lattice, in the physics trap array or in the physics trapping lattice, e.g., to repair a defect in the quantum register. In some implementations, some or all steps of the method discussed herein may be carried out using an apparatus as discussed above.

[0074] **Fig. 13** illustrates an example method for aligning an optical trapping lattice with respect to a physics trap array or a physics trapping lattice, comprising determining (step 1310) a relative displacement between the physics trap array or the physics trapping lattice and the optical trapping lattice, and adjusting (1320) the optical trapping lattice, the physics trap array and / or the physics trapping lattice to reduce the relative displacement. For example, determining the relative displacement may comprise imaging neutral atoms in the physics trap array or in the physics trapping lattice, and comparing positions of the imaged neutral atoms to positions in one or more images of the neutral atoms obtained in the optical trapping lattice (e.g., during state detection of the neutral atoms in the optical trapping lattice). In this manner, few calibration images of the physics trap array or the physics trapping lattice can be sufficient to ensure long-term positional stability without much experimental overhead.

[0075] In some aspects, the method may further comprise imaging the neutral atoms in the optical trapping lattice while, optionally, laser-cooling (e.g., via repulsive

Sisyphus cooling) the neutral atoms in the optical trapping lattice (as discussed above). Alternatively or additionally, adjusting the physics trap array may comprise adjusting a diffraction grating of a spatial light modulator generating the physics trap array, and / or adjusting the physics trapping lattice may comprises adjusting a phase shift element (e.g. an EOM) generating a relative phase difference between two interfering beams generating the physics trapping lattice. Similarly, adjusting the optical trapping lattice may comprises adjusting a phase shift element generating a relative phase difference between two interfering beams generating the optical trapping lattice. Such a method may be employed as part of a feed-back loop ensuring long-term stability of the relative position between the optical trapping lattice and the physics trap.

[0076] The present disclosure also provides a computer program comprising instructions for causing a processor (e.g., of a real-time capable experiment control computer) to generate control signals to control a neutral atom trapping and manipulation apparatus as disclosed herein to perform the steps of a method as described above. For example, the apparatus disclosed herein may be controlled by a control signal unit and, a laser system rack may obtain instructions of a quantum computing protocol (e.g., from a digital computer or via an interface to a cloud-computing system) and, in response, control operation of the various laser systems discussed herein to perform the trapping and manipulation steps discussed herein.

[0077] **Fig. 14** illustrates the performance of repulsive Sisyphus cooling and imaging of ^{88}Sr using an exemplary apparatus and method as disclosed herein. Panel a of Fig. 14 illustrates repulsive Sisyphus cooling dynamics for the $^1\text{S}_0$ and $^3\text{P}_1$ states in the optical trapping lattice. Panel b is a schematic of an experimental sequence characterizing imaging in the optical trapping lattice. Two images (I & II) in the optical trapping lattice are taken after the neutral atoms are prepared in an optical tweezer array and transferred into the optical trapping lattice (see Figs. 6 to 8). Loss probability is calculated by comparing occupations between image I and II. Panel c shows exemplary consecutive fluorescence images of individual atoms in the optical trapping lattice using an imaging procedure as disclosed herein. Panel d shows the array-averaged atom loss probability as function of the 689 nm cooling laser detuning Δ from the bare $^1\text{S}_0$ - $^3\text{P}_1$ resonance in free space for an imaging exposure time of 300 ms (see Fig. 5 for the relevant level scheme).

[0078] The cooling features at frequencies (dashed lines) close to 2.2 MHz and 9.8 MHz detuning are attributed to cooling on $^1S_0 - ^3P_1$, $m_J = \pm 1$ and $^1S_0 - ^3P_1$, $m_J = 0$, respectively that are non-degenerate due to tensor light shift in the optical trapping lattice. For optimal cooling frequency detuning close to 2.2 MHz, imaging loss reduces to 2×10^{-3} . Panel e shows an array-averaged histogram of photon counts taken with an imaging exposure time of 300 ms, showing a well-resolved background and a one-atom fluorescence peak. The classification threshold can be set to 80 photons (dashed line) which give a typical detection fidelity of 99.9995(3) %. Panel f shows imaging loss at constant scattered photon number for reconstruction infidelity of 10^{-4} vs. exposure time. The lower dashed gray line indicates atom loss probability attributed to an estimated vacuum lifetime of 273(3) s, which can be reached by imaging the neutral atoms in the optical trapping lattice in the limit of long exposure time and low illumination power.

[0079] **Fig. 15** illustrates transfer performance between an optical trapping lattice and a physics trap array using an exemplary apparatus and method as disclosed herein. Panel a is a schematic of a typical experimental sequence for tweezer-lattice-tweezer transfers. Neutral atoms are initially prepared and imaged twice (I & II) in the optical trapping lattice, in the same way as they are in imaging benchmarking sequence illustrated in Fig. 14. After a variable number of handovers of atoms between the physics trap array and the optical trapping lattice, two more images (III & IV) are taken in the optical trapping lattice while simultaneously laser cooling the atoms as discussed above. Loss probability is calculated by comparing the occupation between image II and III. During the handover from lattice to tweezer array, the lattice is first ramped to an intermediate trap depth before being turned off completely to release atoms in tweezers (in-set). Panel b shows the cumulative loss probability p_n (circles) of atoms versus the number of lattice-tweezers-lattice round-trips n . The average single round-trip atom loss probability p_1 (triangles) decreases as n increases. The atom loss probability p_n shows a pronounced spatial dependence pre-dominantly at the boundary of the lattice, as apparent from a measurement of the site-resolved atom loss probability after $n = 80$ round-trips (inset).

[0080] Panel c shows typical single-round-trip atom loss probability p as function of the trap depth of the physics trap array after transfer. The inset shows a close-up and

confirms tweezer averaged single-round-trip losses close to 1%. Panels d and e show single round-trip atom loss probability vs. relative position between lattice and tweezer potentials along x-axis (d) and y-axis (e). A sinusoidal fit reflects the expected lattice potential with a lattice constant $a_x = 579(2)$ nm and $a_y = 1187(18)$ nm for the optical trapping lattice. The atom loss probability due to imaging alone is indicated by shaded gray lines. Inset: Sketch of the tweezer traps (circles) and the lattice potential (dots).

[0081] The feasibility of high-fidelity, low-loss imaging in the lattice offers the perspective of decoupling the power-intensive imaging step from cooling and physics per-formed in optical tweezers or other physics traps such a clock magic physics lattice. For instance, such a capability allows for the use of advantageous features of tweezers at 520 nm, e.g. for trapping of Rydberg states via the ionic core polarizability, while avoiding lossy detection at the same wavelength. Efficient and fast transfer between the lattice and the tweezers is a prerequisite to the scalability of such an architecture.

[0082] **Fig. 16.** shows a typical single-shot fluorescence image of more than 10000 neutral atoms directly loaded into the optical trapping lattice from a magneto-optical trap. The elliptical ring delimits the region in the lattice where heating dominates for repulsive Sisyphus conditions, directly showing the coolable spatial region. The large, dashed box denotes the spatial extent of a typical physics trap array imaged to the lattice plane via a high-resolution objective (see Figs. 1 to 4). The smaller dashed box is a zoom-in which illustrates that single atoms can be well resolved in the optical trapping lattice.

[0083] The apparatuses and methods disclosed herein allow for unprecedented low-loss and high-fidelity imaging under repulsive Sisyphus cooling conditions on the narrow-linewidth transition of strontium and similar atomic species used in modern quantum technologies. The possibility of performing high-fidelity and low-loss imaging in a wavelength regime accessible by high-power ytterbium amplifiers is particularly interesting regarding scalability of neutral-atom systems for a variety of applications that benefit from large quantum registers such as quantum computing and atomic clocks. Furthermore, the capability of low-loss transfer as well as the near perfect reinitialization of the initial atom temperature after transfer offer the perspective to operate tweezer arrays at arbitrary wavelengths by decoupling the power-intensive

imaging step from preparation and physics in optical tweezer arrays, with perspectives in quantum simulation of solid-state models, lattice gauge theories, quantum chemistry, or quantum-enhanced metrology in scalable ensembles. Finally, the possibility of directly loading the optical lattice from a magneto-optical trap in combination with high-fidelity imaging, followed by resorting and laser-cooling into the motional ground state, offers a new bottom-up approach of assembling large-scale quantum registers.

[0084] 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.

[0085] 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.

[0086] 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).

[0087] 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 interchangeably 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.

[0088] 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.

[0089] 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.

[0090] Further, process diagrams such as FIG. 12 and FIG. 13 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.

Claims

1. 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 trapping lattice.
2. Apparatus of claim 1, wherein an aspect ratio of the elliptical trapping laser beam is configured such that a trap depth of the optical trapping lattice is larger than 0.1 mK, preferably larger than 1.0 mK, and / or such that a trap frequency in a z-direction that is essentially orthogonal to an x-y-plane that comprises the optical trapping lattice is larger than 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 .
3. Apparatus of any of the preceding claims 1 or 2, wherein the trapping laser system comprises an Ytterbium doped fiber amplifier with an operation wavelength λ in the range of 1010 nm to 1100 nm.
4. Apparatus of any of the preceding claims,
wherein a crossing angle θ of the bow-tie configuration used for generating the optical trapping lattice is selected such, that a lattice spacing ratio in the x-y-plane is two-to-one within 10%, accuracy, preferably, within 5% accuracy, and more preferably within 1% accuracy; and / or,
wherein the crossing angle θ is 26.56° and the operation wavelength λ is 1028.3 nm within 10%, accuracy, preferably within 5% accuracy, and more preferably within

1% accuracy resulting in a long lattice spacing of 1149.9 nm along the x-direction and a short lattice spacing of 574.8 nm along the y-direction of the x-y-plane.

5. Apparatus of any of the preceding claims, further comprising
a physics trap laser system; and
optics for generating, based on the output of the physics trap laser system, a physics trapping lattice for the neutral atoms at the trapping volume in the vacuum chamber; and / or
optics for generating, based on the output of the physics trap laser system, a physics trap array for the neutral atoms at the trapping volume in the vacuum chamber,
wherein a lattice spacing of the physics trapping lattice and / or the physics trap array is essentially commensurate with a lattice spacing of the optical trapping lattice;
and, optionally,
wherein the physics trap laser system operates at a magic wavelength for a pair of internal states of the neutral atoms that experience the same energy shift from the physics trap laser light at the magic wavelength.

6. Apparatus of claim 5, wherein the optics for generating the physics trapping lattice comprise a second bow-tie configuration, optionally comprising a crossing angle η that is equal to 45° within 10%, accuracy, preferably, within 5% accuracy, and more preferably within 1% accuracy such that a lattice spacing ratio in the x-y-plane is one-to-one within 10%, accuracy, preferably, within 5% accuracy, and more preferably within 1% accuracy.

7. Apparatus of claim 5 or 6, wherein the neutral atoms comprise ^{88}Sr atoms and wherein the physics trap laser system operates at a magic wavelength for a pair of clock states of ^{88}Sr .

8. Apparatus of any of the preceding claims, further comprising
a cooling laser system; and
optics for generating, at the trapping volume, cooling laser light for cooling the neutral atoms inside the optical trapping lattice, the physics trapping lattice, and / or the physics trap array.

9. Apparatus of claim 8,
wherein the cooling laser light for cooling the neutral atoms inside the optical trapping lattice has a first wavelength component that drives a Sisyphus cooling mechanism, preferably repulsive Sisyphus cooling, for the neutral atoms in the optical trapping lattice; and, optionally,
a second wavelength component that optically pumps atoms from a first internal state that does not couple to the first wavelength component to a second internal state that couples to the first wavelength component; and, optionally,
a third wavelength component that optically pumps atoms from a third internal state that does not couple to the first wavelength component to an internal state that couples to the first wavelength component.
10. Apparatus of claim 9, wherein the first wavelength component is blue-detuned from a bare atomic resonance used for Sisyphus cooling and red-detuned from the light shifted atomic resonance in the optical trapping lattice.
11. Apparatus of any of the preceding claims, further comprising
an imaging laser system;
optics for generating, at the trapping volume, imaging laser light for driving a dipole-allowed transition of the neutral atoms; and
optics for collecting fluorescence of the dipole-allowed transition from the neutral atoms on an imaging sensor.
12. Apparatus of any of the preceding claims,
wherein a part of the optics for generating the optical trapping lattice that is used for implementing the bow-tie configuration is mounted to a monolithic mounting structure; and
wherein a part of the optics used for generating the physics trapping lattice and / or the physics trap array is mounted to the monolithic mounting structure.
13. Apparatus of any of the preceding claims, further comprising:
a set of magnetic field coils that generate a magnetic field at the trapping volume,

wherein the magnetic field coils are mounted to a second mounting structure that is essentially vibrationally decoupled from the monolithic mounting structure; and, optionally,

wherein the second mounting structure is made from a material with an electric conductivity in the range of 10^{-4} S/m to 10^{-1} S/m.

14. Apparatus of any of the preceding claims 5 to 13, wherein the optics for generating the physics trap array comprise:

a spatial light modulator with an adjustable grating; and

a large numerical aperture objective for focusing the physics trap array to the trapping volume; and / or wherein the optics for generating the physics trapping lattice comprises a set of mirrors and focusing lenses; and

one or more adjustable phase shifting elements for generating a adjustable differential phase difference for two or more interfering beams generating the physics trapping lattice.

15. Apparatus for trapping and manipulating neutral atoms, comprising:

a trapping laser system; and

optics for generating, based on an output of the trapping laser system, an optical trapping lattice at a trapping volume inside a vacuum chamber;

a cooling laser system; and

optics for generating, at the trapping volume and based on an output of the cooling laser system, cooling laser light for cooling the neutral atoms inside the optical trapping lattice wherein the cooling laser light for cooling the neutral atoms inside the optical trapping lattice has a first wavelength component that drives a repulsive Sisyphus cooling mechanism, for the neutral atoms in the optical trapping lattice.

16. Apparatus of claim 15, wherein the cooling laser light further comprises:

a second wavelength component that optically pumps atoms from a first internal state that does not couple to the first wavelength component to a second internal state that couples to the first wavelength component; and, optionally,

a third wavelength component that optically pumps atoms from a third internal state that does not couple to the first wavelength component to an internal state that couples to the first wavelength component.

17. Apparatus of any of the preceding claims 15 or 16, further comprising
an imaging laser system;
optics for generating, at the trapping volume and based on an output of the imaging laser system, imaging laser light for driving a dipole-allowed transition of the neutral atoms; and
optics for collecting fluorescence of the dipole-allowed transition from the neutral atoms on an imaging sensor.
18. Apparatus for trapping and manipulating neutral atoms, comprising
a trapping laser system;
optics for generating, based on an output of the trapping laser system, an optical trapping lattice at a trapping volume inside a vacuum chamber;
a physics trap laser system; and
optics for generating, based on the output of the physics trap laser system, a physics trapping lattice and / or a physics trap array for the neutral atoms at the trapping volume in the vacuum chamber,
wherein a part of the optics for generating the optical trapping lattice, preferably using a first bow-tie configuration, is mounted to a monolithic mounting structure; and
wherein a part of the optics used for generating the physics trapping lattice, preferably using a second bow-tie configuration, and / or a part of the optics used for generating the physics trap array is mounted to the monolithic mounting structure.
19. Apparatus of claim 18, further comprising:
a set of magnetic field coils that generate a magnetic field at the trapping volume,
wherein the set of magnetic field coils is mounted to a second mounting structure that is essentially vibrationally decoupled from the monolithic mounting structure; and, optionally,
wherein the second mounting structure is made from a material with an electric conductivity in the range of 10^{-4} S/m to 10^{-1} S/m.
20. Method for trapping and manipulating neutral atoms, comprising:

loading the neutral atoms into an optical trapping lattice comprising a single plane of periodic trapping potentials at a trapping volume inside a vacuum chamber;
and
imaging the neutral atoms in the optical trapping lattice,
while, optionally, laser cooling the neutral atoms in the optical trapping lattice;
and
transferring the imaged neutral atoms into a physics trapping lattice or into a physics trap array.

21. Method of claim 20, wherein loading the neutral atoms into the optical trapping lattice comprises:

laser cooling the neutral atoms in a magneto optical trap at the trapping volume; and
transferring the laser cooled neutral atoms into the optical trapping lattice.

22. Method of claim 20, wherein loading the neutral atoms into the optical trapping lattice comprises:

transferring the neutral atoms from the physics trapping lattice or the physics trap array into the optical trapping lattice.

23. Method of claim 22, further comprising

laser cooling the neutral atoms in a magneto optical trap at the trapping volume; and
transferring the laser cooled neutral atoms into the physics trapping lattice or the physics trap array.

24. Method of claim 23, wherein transferring the laser cooled neutral atoms into the physics trapping lattice or the physics trap array comprises:

operating the optical trapping lattice during transferring the laser cooled neutral atoms at an intermediate trap depth to enhance the transferring of the laser cooled neutral atoms into the physics trapping lattice or into the physics trap array.

25. Method of any of claims 20 to 24, further comprising:

laser cooling of the neutral atoms in the physics trap array; and / or

inducing light-assisted collisions between multiple atoms at individual traps of the optical trapping lattice, the physics trap array, and / or the physics trapping lattice.

26. Method of any of claims 20 to 25, further comprising:

performing a single-qubit and / or a two-qubit gate operation on the neutral atoms in the physics trap array or in the physics trapping lattice; or

performing atomic clock spectroscopy on the neutral atoms in the physics trapping lattice; or

performing a many-body evolution sequence for the neutral atoms in the physics trapping lattice or the physics trap array.

27. Method of any of the preceding claims 20 to 26, wherein a distance between neighboring traps of the physics trap array is more than twice as large, or more than four times as large as a lattice spacing of the optical trapping lattice in a first direction.

28. Method of any of the preceding claims 20 to 27,

wherein transferring the neutral atoms from the physics trap array or the physics trapping lattice into the optical trapping lattice comprises:

ramping up the trap depth of the optical trapping lattice and ramping down the trap depth of physics trap array or the physics trapping lattice such that the trap depth of the optical trapping lattice is larger than the trap depth of the physics trap array or the physics trapping lattice during ramping down of the trap depth of the physics trap array or the physics trapping lattice; and / or

wherein transferring the neutral atoms from the optical trapping lattice to the physics trap array or the physics trapping lattice comprises:

ramping down the trap depth of the optical trapping lattice and ramping up the trap depth of the physics trap array or the physics trapping lattice such that the trap depth of the optical trapping lattice is larger than the trap depth of the physics trap array or the physics trapping lattice during ramping up the trap depth of the physics trap array or the physics trapping lattice; and, optionally,

laser cooling the neutral atoms in a combined trapping potential generated by the ramped-up physics trap array or the ramped-up physics trapping lattice and the partially ramped-down optical trapping lattice at a trap depth that is lower than the trap depth of the physics trap array or the physics trapping lattice.

29. Method of any of the preceding claims 20 to 28, wherein imaging the neutral atoms in the optical trapping lattice comprises

illuminating the neutral atoms in the optical trapping lattice with an imaging laser resonant to a first optical transition of the neutral atoms;

laser cooling the neutral atoms in the optical trapping lattice using a second optical transition, preferably using repulsive Sisyphus cooling; and

collecting fluorescence from the neutral atoms using a high-resolution imaging system and an imaging sensor; and, optionally,

illuminating the neutral atoms with a repumping laser resonant to a third optical transition of the neutral atoms to transfer atoms that are no longer being laser-cooled back to a state that can be laser-cooled.

30. Method of any of the preceding claims 20 to 29, further comprising:

determining a first position in the optical trapping lattice that does not contain a neutral atom and that overlaps with an optical trap of a subset of the physics trap array or the physics trapping lattice;

determining a second position in the optical trapping lattice that contains a neutral atom and that does not overlap with an optical trap of the subset of the physics trap array or the physics trapping lattice; and

moving, using a movable optical trap, the neutral atom from the second position to the first position in the optical trapping lattice, in the physics trap array or in the physics trapping lattice.

31. Method of any of the preceding claims 20 to 30, wherein some or all of the method steps for trapping and manipulating the neutral atoms are performed using the apparatus of any of claims 1 to 19.

32. Method for aligning an optical trapping lattice with respect to a physics trap array or a physics trapping lattice, comprising:

determining a relative displacement between the physics trap array or the physics trapping lattice and the optical trapping lattice; and

adjusting the optical trapping lattice, the physics trap array and / or the physics trapping lattice to reduce the relative displacement.

33. Method of claim 32, wherein determining the relative displacement comprises imaging neutral atoms in the physics trap array or in the physics trapping lattice; and
comparing positions of the imaged neutral atoms to positions in one or more images of the neutral atoms obtained in the optical trapping lattice.
34. Method of claim 32 or 33, further comprising:
imaging the neutral atoms in the optical trapping lattice while, optionally, laser-cooling the neutral atoms in the optical trapping lattice; and / or
wherein adjusting the physics trap array comprises adjusting a diffraction grating of a spatial light modulator generating the physics trap array; and / or
wherein adjusting the physics trapping lattice comprises adjusting a phase shift element generating a relative phase difference between two interfering beams generating the physics trapping lattice; and / or
wherein adjusting the optical trapping lattice comprises adjusting a phase shift element generating a relative phase difference between two interfering beams generating the optical trapping lattice.
35. Quantum computing device comprising:
the apparatus of any of claims 1 to 19; 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.
36. Atomic clock device comprising:
the apparatus of any of claims 1 to 19; 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.
37. Quantum simulation device comprising:
the apparatus of any of claims 1 to 19, 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.

38. Computer program comprising instructions for causing a processor to generate control signals to control a neutral atom trapping and manipulation apparatus to perform the steps of the method of any of claims 20 to 34.