High-fidelity ground state preparation of single neutral atom in an optical tweezer

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Arrays of neutral-atom qubits in optical tweezers are a promising platform for quantum computation. Despite experimental progress, a major roadblock for realizing neutral atom quantum computation is the qubit initialization. Here we propose that supersymmetry—a theoretical framework developed in particle physics—can be used for ultra-high fidelity initialization of neutral-atom qubits. We show that a single atom can be deterministically prepared in the vibrational ground state of an optical tweezer by adiabatically extracting all excited atoms to a supersymmetric auxiliary tweezer with the post-selection measurement of its atomic number. The scheme works for both bosonic and fermionic atom qubits trapped in realistic Gaussian optical tweezers and may pave the way for realizing large scale quantum computation, simulation and information processing with neutral atoms.

Introduction.—Neutral atoms trapped in optical tweezer arrays [1] have emerged as a promising candidate for quantum computation and simulation [2–5] due to their attractive features such as identical qubits, large scalability through atom-by-atom assemblers [6–12], and high precision control and measurement. For neutral atom qubits, high-fidelity single qubit gates have been realized using microwave or two-photon Raman transitions [13–19]. Two-qubit gates have been realized using short-range collision or long-range Rydberg interactions [20–27], with significantly improved gate fidelity in recent years.

Experimental progress has been made on high-fidelity neutral atom qubit initialization that requires deterministic preparation of a single atom on the vibrational ground state of an optical tweezer, but major obstacles still exist. For bosonic atoms, interaction blockade and single-atom rapid imaging allow the deterministic preparation of a single atom in an optical tweezer, and defect-free atom arrays with up to tens of single atoms have been demonstrated by rearranging the occupied tweezers [7–11]. However, atoms in the tweezers are subject to imaging heating and the experimental ground-state cooling is far from perfect due to photon recoil in sideband cooling [28–30]. For fermionic atoms, high-fidelity preparation of a few atoms is possible through the method of trap deformation [31, 32]. However, to obtain a single fermion ground state, the trap need be tilted and ramped down to an extremely low depth to spill the excess atoms, making the process very sensitive to external potential noises and requiring a long trap-deforming time to avoid heating. For both bosons and fermions, the fidelity to prepare a single atom in the ground state of a tweezer is ~90% for realistic experiments [28, 30, 32].

Supersymmetry theory was first proposed within the context of particle physics and became one possible solution to many important problems in high-energy physics [33]. Though supersymmetry in particle physics remains to be observed, it has found applications in areas including condensed matter physics, cold atoms as well as optics [34–40].

In this Letter, we propose a scheme to achieve ultra-high fidelity single atom ground state preparation in an optical tweezer based on adiabatically extracting excited atoms to its supersymmetric partner, an auxiliary tweezer. For bosons, we can prepare a single atom [7] and transfer its excited components to the supersymmetric auxiliary trap, followed by postselecting the measurement result with an empty auxiliary tweezer (i.e., the single atom stays on the ground state of the original tweezer). For fermions, we start from a multi-atom occupation state [32] and transfer all excited atoms to the supersymmetric auxiliary tweezer. We consider realistic Gaussian optical tweezers and show that ultra-high fidelity ground state preparation can be achieved in a short time interval for both bosons and fermions.

Supersymmetry.—In quantum mechanics, supersymmetry theory involves a pair of partner Hamiltonians such that for every eigenstate (except the zero energy ground state) of one Hamiltonian $H_1$, its partner Hamiltonian $H_2$ has a corresponding eigenstate with the same energy [34]. The supersymmetric isospectrality can be established by factorizing the Hamiltonian in terms of two operators $A$ and $A^\dagger$

$$H_1 = A^\dagger A, \ H_2 = AA^\dagger. \quad (1)$$

Assume $|\varphi_{i,n}\rangle$ is an eigenstate of $H_1$ with eigenvalue $E_{i,n}$, i.e., $H_1|\varphi_{i,n}\rangle = E_{i,n}|\varphi_{i,n}\rangle$, then $H_2[A|\varphi_{i,n}\rangle] = A[A^\dagger A|\varphi_{i,n}\rangle] = E_{i,n}[A|\varphi_{i,n}\rangle]$. Hence, $|\varphi_{2,n}\rangle = A|\varphi_{1,n}\rangle$ with eigenvalue $E_{2,n} = E_{1,n}$, and two Hamiltonians are isospectral with their eigenstates (non-normalized) pairwise related to one another through $|\varphi_{2,n}\rangle = A|\varphi_{1,n}\rangle$ and $|\varphi_{1,n}\rangle = A^\dagger|\varphi_{2,n}\rangle$. If the ground state (with eigenvalue $E_0 = 0$) of $H_1$ is annihilated by $A$, i.e., $A|\varphi_{1,0}\rangle = 0$, then it does not have a corresponding state in $H_2$. In this case, all eigenvalues of $H_1$ and $H_2$ are exactly matched except for the zero-energy ground state of $H_1$, which means the
supersymmetry is unbroken. Otherwise, the supersymmetry is broken if the ground eigenvalue of $H_1$ has a counterpart in $H_2$, as illustrated in Fig. 1.

For the nonrelativistic Schrödinger problems, one can always identify two supersymmetric potentials, $V_1(x)$ and the superpartner $V_2(x)$, that are entirely isospectral except for the ground state of $V_1(x)$. Here we are interested in neutral atoms trapped in optical tweezers, and only low energy bound states are relevant. We consider a deep optical tweezer with $N_0$ bound states that are filled with $N_a$ non-interacting neutral atoms ($N_a$ is much smaller than $N_0$). Only the first $N$ bound states (with $N \ll N_0$) are relevant if the system is pre-cooled to a low temperature (one has $N \gtrsim N_a$ for spin-polarized fermions).

Here we still call $V_2(x)$ the superpartner tweezer of $V_1(x)$ if the first $N$ bound-state energies of $V_1(x)$ (except for the ground state) are exactly matched by the first $N - 1$ bound-state energies of $V_2(x)$.

Adiabatic extraction.— Although our scheme can be applied to any dimension, we will first limit our analysis to one spatial dimension to simplify the calculation. We assume significantly strong trapping along transverse directions, where only the ground transverse state is occupied. We consider a main optical tweezer $V_1(x)$ with non-interacting atoms populating only the first $N$ bound states (i.e., the populations on higher energy states are negligible), and introduce an auxiliary empty tweezer $V_2(x)$ that is the superpartner of $V_1(x)$. Within the subspace spanned by the first $N$ bound states, the Hamiltonians read $H_0^A = \sum_{n=0}^{N} E^0_{1,n}|\varphi_{1,n}\rangle\langle\varphi_{1,n}|$, $H_0^B = \sum_{n=1}^{N} E^0_{2,n}|\varphi_{2,n}\rangle\langle\varphi_{2,n}|$ with $E^0_{1,n} = E^0_{2,n}$ for $n \geq 1$.

The adiabatic atom extraction is performed as follows: (i) The auxiliary tweezer $V_2(x)$ is deformed such that its eigenenergies are increased by $\Delta$. (ii) $V_2(x)$ is transported toward the main tweezer $V_1(x)$ adiabatically, and the bound state $|\varphi_{1,n}\rangle$ is coupled with its counterpart $|\varphi_{2,n}\rangle$ for $n \geq 1$. (iii) $V_2(x)$ is adiabatically deformed to decrease its eigenenergies by $-2\Delta$ and then transported away from the main tweezer $V_1(x)$. After such an adiabatic process, all atoms in the excited states of the main tweezer are transported to the auxiliary tweezer, while atoms in the ground state $|\varphi_{1,0}\rangle$ are unaffected, as illustrated in Fig. 2. As a result, the remaining atoms in the main tweezer is prepared in the vibrational ground state.

The time-dependent effective Hamiltonian can be written as $H_{\text{tot}}(t) = H_0^A + H_0^B + H_{\text{int}}(t)$ with

$$H_{\text{int}}(t) = \sum_{n=1}^{N} \Delta_n(t)|\varphi_{2,n}\rangle\langle\varphi_{2,n}| + |J_n(t)|\varphi_{1,n}\rangle\langle\varphi_{1,n}| + h.c.,$$

where we have neglected the far-off-resonance couplings which do not affect the adiabatic extraction. In fact, the adiabatic process is robust against perturbations, and the deformation and transport of the auxiliary tweezer are very flexible. The only requirement is $|\Delta_n|, |J_n|$ are much smaller than the energy level splitting $|E^0_{1,n} - E^0_{2,n}|$ during the adiabatic process. Furthermore, even if $V_2(x)$ is not initialized as the exact superpartner of $V_1(x)$ (i.e., $E^0_{1,n} \neq E^0_{2,n}$), we can still extract all excited atoms as long as $|E^0_{1,n} - E^0_{2,n}| \ll |\Delta_n|, |J_n| < |E^0_{1,n} - E^0_{2,n}|$.

Physical realization.— Although our proposal does not rely on the specific shape of the tweezer, here we consider a realistic Gaussian trap function $V_1(x) = \alpha_1 e^{-2x^2/w_0^2}$ (see Fig. 3a), where $w_0$ is the width and $\alpha_1$ is the trap depth. As an example, we choose a typical width $w_0 = 1 \mu m$ [7] and the trapping wavelength $\lambda = 810 nm$ [7], and use the recoil momentum $k_R = \frac{2\pi}{\lambda}$ and energy $E_R = \frac{\hbar^2 k_R^2}{2m}$ as the units (with $m$ the atom mass). For a deep Gaussian trap, the low energy dynamics is approximately characterized by a harmonic oscillator with equal energy splitting. The superpartner of a harmonic trap can be easily obtained by a constant shift of the trapping potential that equals to the trapping frequency. Therefore, we consider an auxiliary superpartner trap $V_2(x,t) = [\alpha_2 + \delta \alpha(t)] e^{-2|x-x_c(t)|^2/w_0^2}$. With proper choice of $\alpha_1$ and $\delta \alpha(t)$, we are able to transport all excited atoms away from the main tweezer $V_1(x)$ adiabatically.
\(\alpha_2\) (e.g., \(\alpha_1 = -12E_R\) and \(\alpha_2 = -10.8E_R\)), the energy levels (we consider \(N = 5\) here) of two optical tweezers are matched except for the ground state of \(V_1\). The extraction is realized by adiabatically tuning the depth \(\delta\alpha(t)\) and center \(x_c(t)\) of \(V_2\), as shown in Fig. 3b. The creation and manipulation of controlled optical tweezers can be accomplished with an electro-optic deflector which toggles between two voltages on a sufficiently-fast time scale so that the atoms experience a time-averaged effective potential [41, 42]. Merging and separating the supersymmetric tweezer pairs could be done by a programmed sequence of voltages that are applied to an electro-optic deflector.

In Fig. 3c, we plot the spectrum of the system during the adiabatic process along the path in Fig. 3b, which is obtained by solving the real-space Schrödinger equation

\[
\left[ -\frac{\hbar^2}{2m} \frac{\partial^2}{\partial x^2} + V_1(x,t) + V_2(x,t) \right] |\varphi\rangle = E |\varphi\rangle.
\]

We see the spectrum is gapped all the time, while the eigenstates in the two tweezers exchange except for the ground state of \(V_1\). In principle, the extraction fidelity can achieve 100% for sufficient long adiabatic interval \(\tau\). Assuming an atom stays in state \(|\varphi_{1,n}\rangle\) at time \(t = 0\), we define the fidelity \(F_n\) as the probability to find the atom at time \(t = \tau\) on the ground state \(|\varphi_{1,0}\rangle\) of the main tweezer for \(n = 0\) or in the auxiliary tweezer for \(n > 0\). In Fig. 3d, we show the fidelities as functions of \(\tau\) obtained from numerical simulating the time-dependent real-space Schrödinger equation. The extraction process is a multistate Landau–Zener problem, and there are couplings between different eigenstates when \(\tau\) is small, yielding fidelities that are far below 1. The fidelity \(F_n\) can be close to 1 at a larger \(\tau\).

For a realistic shallow trap \(\alpha_1 = -12E_R\), the fidelity can be up to \(F_n \gtrsim 1 - 10^{-5}\), and an adiabatic interval \(\tau \gtrsim 7\) ms (\(\tau \gtrsim 70\) ms) for Li (Rb) atoms, which can be improved further by optimizing the adiabatic loop or using deeper tweezers.

We now consider the tweezer realized by a single strong and tightly focused Gaussian beam without additional transverse trapping (i.e., 3D). The trap is given by \(V_1(\mathbf{r}) = \alpha_1 \frac{w_z^2}{\lambda} \exp[-2(x^2 + y^2)/w_z^2]\) with the spot size \(w_z = w_0 \sqrt{1 + \frac{z^2}{\lambda^2}}\) and Rayleigh range \(z_R = \frac{\pi w_0^2}{\lambda}\). In this case, the tight transverse trapping, realized by the Gaussian tweezer itself, is much stronger than the longitudinal trapping. Therefore, atoms would stay in the transverse ground state with high-probability after sideband cooling (laser culling) for bosons (fermions) [28, 29, 32], and the overall fidelity is mainly limited by the residual excitations in the longitudinal direction. We may i) slowly bring the auxiliary tweezer to the main tweezer with their beam waists largely separated by \(z_c\) along the longitudinal direction (see Fig. 4a); ii) tune \(z_c\) and \(\delta\alpha\) along the adiabatic path (see the inset of Fig. 4b); iii) slowly move the auxiliary tweezer away from the main tweezer. Steps i) and iii) can be done with high fidelity due to large separation of the two tweezers. Here we focus on step ii) and solve the 3D Schrödinger equation numerically. We find that the extract fidelity can be up to \(F_n \sim 1 - 10^{-4}\) with proper choice of parameters, as shown in Fig. 4b. A longer extraction time is needed to achieve higher fidelity.

**Boson qubit initialization.**—We assume an initial low-temperature Fock state with \(N_a = 1\) atom. This is because, more than one atom may be left on the ground state after the extraction for \(N_a > 1\) non-interacting bosons, and the energy level coupling with the auxil-
ary tweezer would be strongly modified for interacting bosons. Fortunately, deterministic preparation of a single atom (i.e., \( N_a = 1 \)) in an optical tweezer has been realized through single atom imaging and the atom can be further sideband cooled with ground state population \( \sim 90\% \) \([7, 28, 30]\). Assuming a thermal population distribution, the total probability to find the atom on \( n > N \) states is \( < 10^{-5} \) for \( N = 5 \). After the adiabatic extraction process, all excited components of the atom are transferred to the auxiliary tweezer, in which the atom number is measured. If one (zero) atom is detected in the auxiliary tweezer, we discard (keep) the atom qubit in the main tweezer. Such postselection measurement leads to deterministic ground-state preparation of the main tweezer with a total fidelity \( \geq P_0 + \sum_{n>0} P_n F_n \geq 1 - 10^{-5} \) (\( P_n \) is the \( n \)-th state occupation probability). The detection of the auxiliary tweezer can be done by single-atom-resolved fluorescence imaging technique \([2, 15, 43]\), where a practical issue is that the resulting scattered resonant light may be absorbed by other qubits, degrading their fidelity (note that fermions do not need resonant detection during preparation, which is an advantage, see below). The resonant scattering light could be avoided by first transferring the auxiliary-tweezer atom to another hyperfine state (e.g., \( F = 2 \) state of \(^{87}\text{Rb}\)) with \( \sim \text{GHz} \) energy splitting \([14]\), where the imaging laser (focused on the auxiliary tweezer) is far-off-resonance with the main-tweezer atoms in other qubits, thus would not disturb their states.

**Fermion qubit initialization.**—For fermions, we consider that the spins are polarized by a large magnetic field. First we prepare a Fock state with \( N_a \) atoms. One can load atoms from a reservoir of degenerate fermion gas to the tweezer and spill excess highly excited atoms by varying the depth of the tweezer and the strength of a magnetic field gradient \([31]\), as realized in experiment \([32]\). Based on previous method, the trap needs to be tilted and ramped down to an extremely low depth in order to prepare a single fermion \( N_a = 1 \) to the ground state, which not only makes the process very sensitive to potential noises (induced by fluctuations in laser intensity and magnetic field), but also requires a long trap-deforming time to avoid heating \([31, 32]\). These factors limit the overall preparation fidelity in a realistic experiment. Here, we consider a larger \( N_a \) (e.g., \( N_a = 4 \)) so that the depth of the trap remains much higher than the ground state energy during the spilling process. As a result, the ground-state atom is hardly affected. Moreover, the perturbations of the magnetic field and the dipole trap, which may change \( N_a \) by \( \pm 1 \) or \( \pm 2 \), do not affect our high-fidelity extraction as long as the ground state is occupied with a high probability. The total fidelity for fermions is \( \geq P_0 \prod_{n=0}^{N_a-1} F_n \). For a reservoir with typical temperature \( T/T_F = 0.5 \) and a tweezer with depth \( 5k_B T_F \), we obtain \( P_0 \geq 1 - 10^{-5} \) \([44]\). The total fidelity can be up to \( \sim 1 - 10^{-5} \).

**Discussion.**—Combined with the capability of rearranging tweezers, our method can initialize a large array of neutral atom (bosonic or fermionic) qubits to the vibrational ground state. In addition to quantum computation, such ground state single-atom tweezers can be used as building blocks for generating entangled states such as Dicke and NOON states \([45]\) that are useful for high precision quantum metrology beyond the standard quantum limit \( 1/\sqrt{N} \).

The Dicke state is a symmetrized spin state with total spin \( J \) and \( z \)-component \( m_z \), corresponding to a two-mode Fock state with \( J + m_z \) atoms in spin up and down. Such Dicke state can be realized by merging \( 2J \) single-atom optical tweezers, with \( J + m_z \) tweezers containing spin-up and down atoms (see Fig. 5). The repulsive interaction is turned on to ensure \( 2J \) atoms remaining on the ground state \([46]\) during the adiabatic evolution. Here the many-body energy gap during the adiabatic merging is roughly given by the smaller one of two energy scales: the interaction energy \( E_{\text{int}} \) (interaction between two atoms in one tweezer) and excited state energy \( E_e \) (when the barriers between neighboring tweezers vanish). For typical tweezers and atom scattering lengths, \( E_{\text{int}} \) can be up to several tens Hz, and \( E_e \sim \frac{E_0}{T_F} \) is around a hundred Hz for \( J = 10 \) (i.e., \( 20 \) atoms), leading to the adiabatic merging time \( \sim 10\text{ms} \).

With \( 2J \) atoms on the ground state of one tweezer, we can slowly switch the repulsive interaction to attractive, then split the tweezer into two identical tweezers (see Fig. 5), generating a NOON state (i.e., a coherent superposition of all particles in the left or right tweezer) \([46]\). If the interaction energy is smaller than the single tweezer trapping frequency, even a sudden switching of the interaction would not excite the system \([46]\), which is still satisfied with \( 20 \) atoms in one tweezer. During this splitting, the many-body gap is enhanced by \( J \) times comparing to the merging process, thus can be done much faster. Both Dicke and NOON states can yield measurement precision scaling as the Heisenberg limit \( \sim 1/N \) \([45]\).

Finally, the ability of generating a few-atom Fock state in the tweezer provides a new platform for studying few-body physics with the fixed atom number. For instance, by tuning the interaction through Feshbach resonance, it is possible to study the universality of Efimov trimer and other multi-body bound states \([47–50]\).
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Quantum sensors can also be used to generate nonclassical quantum states which may find applications in other fields such as high precision measurement and quantum sensors.

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1. N. Schlosser, G. Reymond, I. Protsenko, and P. Grangier, Sub-Poissonian loading of single atoms in a microscopic dipole trap, Nature (London) 411, 1024 (2001).
2. M. Saffman, T. G. Walker, and K. Mölmer, Quantum information with Rydberg atoms, Rev. Mod. Phys. 82, 2313 (2010).
3. I. M. Georgescu, S. Ashhab, and F. Nori, Quantum simulation, Rev. Mod. Phys. 86, 153 (2014).
4. D. S. Weiss and M. Saffman, Quantum computing with neutral atoms, Phys. Today 70, 44 (2017).
5. C. Gross and I. Bloch, Quantum simulations with ultracold atoms in optical lattices, Science 357, 955 (2017).
6. D. S. Weiss, J. Vala, A. V. Thapiyal, S. Myrgren, U. Vazirani, and K. B. Whaley, Another way to approach zero entropy for a finite system of atoms, Phys. Rev. A 70, 040302R (2004).
7. M. Endres, H. Bernien, A. Keesling, H. Levine, E. R. Anschuetz, A. Krajenbrink, C. Senko, V. Vuletic, M. Greiner, and M. D. Lukin, Atom-by-atom assembly of defect-free one-dimensional cold atom arrays, Science 354, 1024 (2016).
8. H. Kim, W. Lee, H. Lee, H. Jo, Y. Song, and J. Ahn, In situ single-atom array synthesis using dynamic holographic optical tweezers, Nat. Commun. 7, 13317 (2016).
9. D. Barredo, S. de Léséleuc, V. Lienhard, T. Lahaye, and A. Browaeys, An atom-by-atom assembler of defect-free arbitrary two-dimensional atomic arrays, Science 354, 1021 (2017).
10. W. Lee, H. Kim, and J. Ahn, Three-dimensional rearrangement of single atoms using actively controlled optical microtraps, Opt. Express 24, 9816 (2016).
11. D. Barredo, V. Lienhard, S. de Léséleuc, T. Lahaye, and A. Browaeys, Synthetic three-dimensional atomic structures assembled by atom, Nature (London) 561, 79 (2018).
12. D. O. de Mello, D. Schöffner, J. Werkmann, T. Preuschoff, L. Kohlfahl, M. Schlosser, and G. Birkl, Defect-Free Assembly of 2D Clusters of More Than 100 Single-Atom Quantum Systems, Phys. Rev. Lett. 122, 203601 (2019).
13. D. D. Yavuz, P. B. Kulatunga, E. Urban, T. A. Johnson, N. Proîte, T. Henage, T. G. Walker, and M. Saffman, Fast Ground State Manipulation of Neutral Atoms in Microscopic Optical Traps, Phys. Rev. Lett. 96, 063001 (2006).
14. C. Zhang, S. L. Rolston, and S. Das Sarma, Manipulation of single neutral atoms in optical lattices, Phys. Rev. A 74, 042316 (2006).
15. C. Weitenberg, M. Endres, J. F. Sherson, M. Cheneau, P. Schauß, T. Fukuhara, I. Bloch, and S. Kuhr, Single-spin addressing in an atomic Mott insulator, Nature 471, 319 (2011).
16. D. Schrader, I. Dotsenko, M. Khudaverdyan, Y. Miroshnychenko, A. Rauschenbeutel, and D. Meschede, Neutral Atom Quantum Register, Phys. Rev. Lett. 93, 150501 (2004).
17. T. R. Beals, J. Vala, and K. B. Whaley, Scalability of quantum computation with addressable optical lattices, Phys. Rev. A 77, 052309 (2008).
18. Y. Wang, A. Kumar, T.-Y. Wu, and D. S. Weiss, Single-qubit gates based on targeted phase shifts in a 3D neutral atom array, Science 352, 1562 (2016).
19. C. Sheng, X. He, P. Xu, R. Guo, K. Wang, Z. Xiong, M. Liu, J. Wang, and M. Zhan, High-Fidelity Single-Qubit Gates on Neutral Atoms in a Two-Dimensional Magic-Intensity Optical Dipole Trap Array, Phys. Rev. Lett. 121, 240501 (2018).
20. A. M. Kaufman, B. J. Lester, M. Foss-Feig, M. L. Wall, A. M. Rey, and C. A. Regal, Entangling two transportable neutral atoms via local spin exchange, Nature (London) 527, 208 (2015).
21. D. Jaksch, J. I. Cirac, P. Zoller, S. L. Rolston, R. Côté, and M. D. Lukin, Fast Quantum Gates for Neutral Atoms, Phys. Rev. Lett. 85, 2208 (2000).
22. L. Isenhower, E. Urban, X. L. Zhang, A. T. Gill, T. Henage, T. A. Johnson, T. G. Walker, and M. Saffman, Demonstration of a Neutral Atom Controlled-NOT Quantum Gate, Phys. Rev. Lett. 104, 010503 (2010).
23. T. Wilk, A. Gaëtan, C. Evellin, J. Wolters, Y. Miroshnychenko, P. Grangier, and A. Browaeys, Entanglement of Two Individual Neutral Atoms Using Rydberg Blockade, Phys. Rev. Lett. 104, 010502 (2010).
24. Y. Y. Jau, A. M. Hankin, T. Keating, I. H. Deutsch, and G. W. Biedermann, Entangling atomic spins with a Rydberg-dressed spin-flip blockade, Nat. Phys. 12, 71 (2016).
25. H. Bernien, S. Schwartz, A. Keesling, H. Levine, A. Omran, H. Pichler, S. Choi, A. S. Zibrov, M. Endres, M. Greiner, V. Vuletic, and M. D. Lukin, Probing many-body dynamics on a 51-atom quantum simulator, Nature 551, 579 (2017).
26. H. Levine, A. Keesling, A. Omran, H. Bernien, S. Schwartz, A. S. Zibrov, M. Endres, M. Greiner, V. Vuletić, and M. D. Lukin, High-Fidelity Control and Entanglement of Rydberg-Atom Qubits, Phys. Rev. Lett. 121, 123603 (2018).
27. V. Lienhard, S. de Léséleuc, D. Barredo, T. Lahaye, A. Browaeys, M. Schuler, L.-P. Henry, and A. M. Läuchli, Observing the Space- and Time-Dependent Growth of...
Correlations in Dynamically Tuned Synthetic Ising Models with Antiferromagnetic Interactions, Phys. Rev. X 8, 021070 (2019).
[28] A. M. Kaufman, B. J. Lester, C. A. Regal, Cooling a single atom in an optical tweezer to its quantum ground state, Phys. Rev. X 2, 041014 (2012).
[29] J. D. Thompson, T. G. Tiecke, A. S. Zibrov, V. Vuletić, and M. D. Lukin, Coherence and Raman Sideband Cooling of a Single Atom in an Optical tweezer, Phys. Rev. Lett. 110, 133001 (2013).
[30] Y. Yu, N. R. Hutzler, J. T. Zhang, L. R. Liu, J. D. Hood, T. Rosenband, and K.-K. Ni, Motional-ground-state cooling outside the Lamb-Dicke regime, Phys. Rev. A 97, 063423 (2018).
[31] M. G. Raizen, S.-P. Wan, C. Zhang, and Q. Niu, Ultrahigh-fidelity qubits for quantum computing, Phys. Rev. A 80, 030302 (2009).
[32] F. Serwane, G. Zürn, T. Lompe, T. B. Ottenstein, A. N. Wenz, and S. Jochim, Deterministic Preparation of a Tunable Few-Fermion System, Science, 332, 336 (2011).
[33] M. Dine, Supersymmetry and string theory: Beyond the standard model (Cambridge University Press, 2015).
[34] F. Cooper, A. Khare, and U. Sukhatme, Supersymmetry and quantum mechanics, Phys. Rep. 251, 267 (1995).
[35] Y. Yu and K. Yang, Supersymmetry and the Goldstino-Like Mode in Bose-Fermi Mixtures, Phys. Rev. Lett. 100, 090404 (2008).
[36] M.-A. Miri, M. Heinrich, R. El-Ganainy, and D. N. Christodoulides, Supersymmetric Optical Structures, Phys. Rev. Lett. 110, 233902 (2013).
[37] M. Heinrich, M.-A. Miri, S. Stützer, R. El-Ganainy, S. Nolte, A. Szameit, and D. N. Christodoulides, Supersymmetric mode converters, Nat. Commun. 5, 3698 (2014).
[38] B. Midya, W. Walasik, N. M. Litchinitser, and L. Feng, Supercharge optical arrays, Opt. Lett. 43, 4927 (2018).
[39] B. Midya, H. Zhao, X. Qiao, P. Mino, W. Walasik, Z. Zhang, N. M. Litchinitser, and L. Feng, Supersymmetric microring laser arrays, Photonics Research 7, 363 (2019).
[40] M. P. Hokmabadi, N. S. Nye, R. El-Ganainy, D. N. Christodoulides, and M. Khajavikhan, Supersymmetric laser arrays, Science, 363, 623 (2019).
[41] V. Milner, J. L. Hanssen, W. C. Campbell, and M. G. Raizen, Optical Billiards for Atoms, Phys. Rev. Lett. 86, 1514 (2001).
[42] N. Friedman, A. Kaplan, D. Carasso, and N. Davidson, Observation of Chaotic and Regular Dynamics in Atom-Optics Billiards, Phys. Rev. Lett. 86, 1518 (2001).
[43] J. F. Sherson, C. Weitenberg, M. Endres, M. Cheneau, I. Bloch, and S. Kuhr, Single-atom-resolved fluorescence imaging of an atomic Mott insulator, Nature 467, 68 (2010).
[44] L. Viverit, S. Giorgini, L. P. Pitaevskii, and S. Stringari, Adiabatic compression of a trapped Fermi gas, Phys. Rev. A 63, 033603 (2001).
[45] L. Pezzè, A. Smerzi, M. K. Oberthaler, R. Schmied, and P. Treutlein, Quantum metrology with nonclassical states of atomic ensembles, Rev. Mod. Phys. 90, 035005 (2018).
[46] A. M. Dudarev, R. B. Diener, B. Wu, M. G. Raizen, and Q. Niu, Entanglement Generation and Multiparticle Interferometry with Neutral Atoms, Phys. Rev. Lett. 91, 010402 (2003).
[47] S. E. Pollack, D. Dries, and R. G. Hulet, Universality in Three- and Four-Body Bound States of Ultracold Atoms, Science 326, 1683 (2009).
[48] D. Blume, Few-body physics with ultracold atomic and molecular systems in traps, Rep. Prog. Phys. 75, 046401 (2012).
[49] P. Naidon, S. Endo, Efimov Physics: a review, Rep. Prog. Phys. 80, 056001 (2017).
[50] C. H. Greene, P. Giannakeas, and J. Pérez-Ríos, Universal few-body physics and cluster formation, Rev. Mod. Phys. 89, 035006 (2017).