Generation and detection of atomic spin entanglement in optical lattices

Han-Ning Dai\textsuperscript{1,2,3}, Bing Yang\textsuperscript{1,2,3}, Andreas Reingruber\textsuperscript{1,4}, Xiao-Fan Xu\textsuperscript{1}, Xiao Jiang\textsuperscript{2,3}, Yu-Ao Chen\textsuperscript{2,3*}, Zhen-Sheng Yuan\textsuperscript{1,2,3*} and Jian-Wei Pan\textsuperscript{1,2,3*}

Ultracold atoms in optical lattices hold promise for the creation of entangled states for quantum technologies. Here we report on the generation, manipulation and detection of atomic spin entanglement in an optical superlattice. Using a spin-dependent superlattice, atomic spins in the left or right sites can be individually addressed and coherently manipulated with near-unity fidelity by microwave pulses. The spin entanglement of the two atoms in the double wells of the superlattice is generated via the dynamical evolution governed by spin superexchange. By monitoring the collisional atom loss with \textit{in situ} absorption imaging we measure the spin correlations of the atoms inside the double wells and obtain a lower bound on the entanglement fidelity of 0.79 ± 0.06, and a violation of a Bell’s inequality $S = 2.21 ± 0.08$.

During recent decades, quantum entanglement, the key resource for quantum information processing\textsuperscript{5}, has been created in a wide range of systems, such as photons\textsuperscript{6}, ions\textsuperscript{7}, superconducting circuits\textsuperscript{8}, and solid-state qubits\textsuperscript{9}. They have been widely used for studying quantum computation\textsuperscript{10} and quantum simulation\textsuperscript{11}. At present, a significant requirement in the quest to develop scalable quantum information processing is to efficiently construct multipartite entangled states. Because ultracold atoms in an optical lattice\textsuperscript{12} have excellent coherence properties and can be manipulated in parallel, an attractive protocol\textsuperscript{13} was proposed to create resilient entangled states for measurement-based quantum computation\textsuperscript{14,15} with optical superlattices. In this protocol, maximally entangled Bell-type states are first prepared in double-well arrays (DWs) of a superlattice, then these Bell pairs are connected to each other to create cluster states by using Ising-type superexchange interactions\textsuperscript{16}, and finally a computational algorithm is implemented by performing single-particle measurements together with unitary operations\textsuperscript{17}.

Following this line of research, atomic spin exchange\textsuperscript{18} and superexchange\textsuperscript{19} in optical lattices have been studied. Entangled spin pairs were created during the dynamical evolution of spin pairs driven by exchange interactions. However, it was not possible to directly verify the entanglement by measuring the spin correlations. More sophisticated techniques, such as single-atom imaging and addressing\textsuperscript{20,21}, have been developed to detect and manipulate atomic spins in optical lattices in recent years. Nevertheless, it has remained a challenge to verify the spin entanglement in optical superlattices, which is an essential task towards scalable quantum computation with such systems\textsuperscript{22}.

In this work, we developed a new superlattice configuration featuring spin dependence\textsuperscript{23,24}, which allows us to individually address and manipulate the spins in the left or right sites of the DWs with microwave (MW) pulses. Relying on this configuration, high-fidelity initialization of the DWs from $| \downarrow, \downarrow \rangle$ to $| \uparrow, \downarrow \rangle$ is achieved ($| \uparrow \rangle$ and $| \downarrow \rangle$ denote the two spin states, with the comma separating the left and right occupations). The entangled state, $(| \uparrow, \downarrow \rangle + | \downarrow, \uparrow \rangle)/\sqrt{2}$, is generated by means of a \textit{SWAP} operation\textsuperscript{25} in every double well of the superlattices. Afterwards, an effective short-range gradient magnetic field is induced to manipulate the phase of the entangled state and transfer it to the Bell state $(| \uparrow, \downarrow \rangle + | \downarrow, \uparrow \rangle)/\sqrt{2}$. Developing a new detection routine with two-stage filtering and imaging, we break the bottleneck of measuring spin correlations $\langle S_x \otimes S_x \rangle$ and $\langle S_y \otimes S_y \rangle$ of the two atoms by observing the atom loss arising from hyperfine changing collisions\textsuperscript{26,27}. For the first time, the entanglement of spin pairs in optical superlattices is measured by deriving the lower boundary of entanglement fidelity from the spin correlations, and further verified by violating the Clauser–Horne–Shimony–Holt (CHSH) Bell’s inequality\textsuperscript{28}.

Scheme for generating spin entanglement in superlattices

The system under consideration is a series of isolated double-well arrays created by an optical superlattice—a system which can be described well with a Bose–Hubbard model characterized by a nearest-neighbour tunnelling $J$, an on-site interaction energy $U$ and an imbalance offset $\Delta$ in the DWs (ref. 12). All these parameters can be well controlled by the intensities and frequencies of the lattice lasers. In the following we focus on the condition of balanced DWs ($\Delta = 0$) and deep lattices, where the interaction dominates $U \gg J$. With the initial states in the subspace of singly filled states of $| \uparrow, \downarrow \rangle$ and $| \downarrow, \uparrow \rangle$, double occupation at each site is allowed only virtually. Then the Bose–Hubbard model can be described as a Heisenberg spin model $\mathbf{H} = -J_n \mathbf{S}_n \cdot \mathbf{S}_n$, where $J_n = 4J/U$ denotes the superexchange coupling between the two sites in a DW, and the corresponding operators are $\mathbf{S}_n = (\mathbf{S}_n^x, \mathbf{S}_n^y, \mathbf{S}_n^z)$, $\mathbf{S}_n^x = (| \uparrow \rangle\langle \downarrow | + | \downarrow \rangle\langle \uparrow |)/2$, $\mathbf{S}_n^y = (| \uparrow \rangle\langle \downarrow | - | \downarrow \rangle\langle \uparrow |)/2i$, and $\mathbf{S}_n^z = (\mathbf{n}_x - \mathbf{n}_y)/2$, with $n_x$, the number operators for spin $\sigma = \uparrow, \downarrow$ on lattice site $j = L, R$. By initializing the DW to $| \uparrow, \downarrow \rangle$ and using appropriate potentials, one can observe the superexchange-driven evolution from $| \uparrow, \downarrow \rangle$ to $| \downarrow, \uparrow \rangle$, and vice versa\textsuperscript{29}. The SU(2) symmetry is
applied to generate the entangled state $|\psi\rangle = (|\uparrow\downarrow\rangle + i|\downarrow\uparrow\rangle)/\sqrt{2}$ by halting the superexchange-driven evolution at $t_1 = h/(4\epsilon)$, with $\hbar$ being Planck's constant. However, we intend to prepare the Bell state $|\psi\rangle = (|\uparrow\downarrow\rangle + i|\downarrow\uparrow\rangle)/\sqrt{2}$ (the spin triplet), which is taken as the starting point for creating cluster states for measurement-based quantum computation. To achieve $|\psi\rangle$ from $|\psi\rangle$, an additional phase between the two components $|\uparrow\rangle$ and $|\downarrow\rangle$ has to be introduced. We first induce an effective gradient magnetic field inside the double well by creating a spin-dependent superlattice. This breaks the degeneracy between the two components with an energy split of $\delta$. By holding the atoms in this lattice for a period $t_2$, an additional phase of $\delta t_2$ is accumulated. Therefore the phase of the entangled state can be modulated and the spin triplet $|\psi\rangle$ is obtained by controlling $t_2$.

**Superexchange-driven dynamics**

We first prepare a Mott insulator and load the DWs with each site occupied by one $|\uparrow\rangle$ atom (see Fig. 1 and Methods). Then all the DWs are initialized to $|\uparrow, \downarrow\rangle$ by flipping the atomic spins in every left site inside the spin-dependent superlattice by means of a MW pulse. In short, tuning the voltage applied to the electro-optical modulator (EOM), an angle of $\theta$ between the polarizations of the incident and the retro-reflected beams of the short lattice is created, and hence a spin-dependent superlattice is built up (see Supplementary Information). In the condition $V_{f} = 56.3(4) E_r$, $V_{c} = 150(1) E_r$, and $\theta = 46^\circ$, the resonant microwave frequency for coupling $|\uparrow\rangle$ in the left site is shifted $31.8(1)$ kHz away from the resonance $|\downarrow\rangle$ in the right site, as shown in Fig. 2a. A high addressing fidelity is achieved by using a MW pulse with a Rabi frequency of $\Omega = 2\pi \times 8.1$ kHz, during which the magnetic field $B_r = 95 \mu$T along the X direction is actively stabilized and the noise is suppressed to less than 16 nT.

After state initialization, the spin dependence is switched off by ramping up the short lattice to $10.0(1) E_r$, and afterwards ramping down the short lattice to the final value $V_{\text{ex}}$ in 500 $\mu$s. After letting the system evolve for a time $t_1$, we halt the superexchange by ramping up the short lattice to $60.0(4) E_r$, in 500 $\mu$s. The spin configuration is then frozen until the state detection.

To detect the spin state inside the DWs, the quantization axis is aligned to the X direction, then the spin dependence is switched on for addressing the left sites. Flipping the spins in the left sites, the two spin configurations will end up along two different channels: $|\uparrow, \downarrow\rangle \Rightarrow |\downarrow, \downarrow\rangle$ and $|\downarrow, \uparrow\rangle \Rightarrow |\downarrow, \uparrow\rangle$, as shown in Fig. 2a. Only the $|\uparrow\rangle$ state can absorb the imaging light (cycling transition $|\uparrow\rangle \leftrightarrow |\downarrow\rangle$, $F = 2 \leftrightarrow 3$). Therefore, the superexchange-driven oscillation between $|\uparrow, \downarrow\rangle$ and $|\downarrow, \uparrow\rangle$ can then be observed with the imaging by comparing the population of atoms in spin up $N_{\uparrow}$ with the total atom number $N_0$ in the region of interest (ROI). Two typical oscillations measured at different DW potentials are shown in Fig. 2b. For a lower barrier height ($f/U = 0.37$), the dynamics can be directly described with the Bose–Hubbard model, in which the fast oscillations correspond to the first-order tunnelings. The simulation matches well with the experiment, as shown in Fig. 2b. For larger barrier heights ($f/U < 1$), the oscillation is then mainly driven by the superexchange interaction. In the experimental condition $V_{f} = 10.0(1) E_r$, $V_{\text{ex}} = 20.0(1) E_r$, ($f/U = 0.04$), an oscillation frequency $10.0(5)$ Hz and a decay constant of $280(20)$ ms is obtained.

**Generation of Bell states in the superlattice**

The $\sqrt{\text{SWAP}}$ operation is realized by halting the superexchange-driven evolution ($V_{f} = 10.0(1) E_r$, $V_{\text{ex}} = 20.0(1) E_r$) at $t_2 = 25.1$ ms, and the DWs are then prepared in the entangled state $|\psi\rangle$. To control the phase between the two components in this entangled state, we induce an effective short-range gradient magnetic field inside the DW by switching on the spin dependence with $V_{\text{ex}} = 5.60(4) E_r$, $V_{\text{ex}} = 60.0(4) E_r$, and $\theta = 7.5^\circ$. This gradient creates a non-degeneracy of $\delta = 2\pi \times 427$ Hz between the two components and initiates an oscillation between the spin singlet state $|s\rangle = (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}$ and the triplet state $|t\rangle$. After a single–triplet oscillation (STO) time $t_2$, we switch off the spin dependence and ramp down the long lattice to 0. By measuring in the rotated basis $|\pm\rangle = (|\uparrow\rangle \pm |\downarrow\rangle)/\sqrt{2}$, that is, applying a $\pi/2$-pulse on both DW sites, the triplet and the singlet state can be discriminated: $|t\rangle \rightarrow (|\uparrow\rangle + |\downarrow\rangle)/\sqrt{2}$ and $|s\rangle \rightarrow |s\rangle$. 

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**Figure 1 | The experimental apparatus.** a, Three retro-reflected optical lattices create the double-well arrays: a short lattice $V_{\text{ex}}$, a long lattice $V_{f}$ along the X direction, and lattice $V_{c}$ along the Y direction. The imaging beam is along the Z direction. b, The laser beams around the atom cloud. The 2D gas is loaded into a single layer of a pancake-shaped trap, which is a series of layers separated by a distance of 4 $\mu$m, created by interfering two beams, c. The density distribution of the MI derived from an average over ten samples by in situ absorption imaging. The central part of the atom cloud with a diameter of 16 pixels (0.93 $\mu$m per pixel) is used as the region of interest (ROI) for later studying spin dynamics and entanglement. The averaged filling in the ROI is approximately 0.8 atoms per site. The geometries of the lattices are shown in the X and Y directions. (See details in the Methods.)
Counts: 0, 1, 1, 0

N↑′/Nt

Figure 2 | Observation of spin dynamics driven by the superexchange interaction. a, Initialization, evolution and detection of spin states in the spin-dependent superlattice. The lattice potentials for ↓ and ↑ are different, and the coupling frequency of ↓ ↔ ↑ in the left site is shifted 31.8 kHz away from that in the right site. The spins in left sites can be individually addressed with a MW pulse, and the DW can be initialized from ↓↓ to ↑↑. Then the spin state is evolved to a superposition state by superexchange-driven evolution. By flipping the spin in every left site before the imaging pulse, the DW states of ↑↑ and ↓↑ are transferred to ↓↑ and ↑↑, respectively, for detection. Only the ↑↑ can be coupled with the imaging pulse. With this detection method, the superexchange-driven evolution is observed by recording the population of ↑↑ in two experimental conditions. b, Vxs = 120(1)Er, Vsd = 100(1)Ee, J/U = 0.37, a numerical simulation based on the Bose–Hubbard model agrees well with the experimental data. c, Vxs = 200(1)Er, Vsd = 100(1)Ee, J/U = 0.04, a damped sine fit shows a superexchange frequency of 10.0(5) Hz with a 1/e lifetime of 280(20) ms. Error bars represent statistical errors, which are ±1 s.d.

Figure 3 | Measurement of the entanglement phase. a, Two-stage filtering and imaging routine for detecting the phase of entanglement: (i) the complete spin correlated basis in the DW; (ii) remaining ↑↑ atoms after recording the number of ↑↑ atoms and the MW rapid adiabatic passage; (iii) merging the DWs and holding the atoms for 500 ms in a deep lattice to remove the double occupancies; (iv) counting the number of remaining atoms N↓. The four different initial pair states will contribute differently to the final atom count; thus, by projecting the entangled state to ↓↑ basis, one can resolve the singlet and triplet state. b, Time evolution of the remaining atom number for different STO time after the two-stage filtering and imaging process. A period of 2.34(2) ms is derived from a sine fit. Error bars represent statistical errors, which are 1 s.d.

Then a two-stage filtering and imaging routine is employed to determine the entanglement phase, as shown in Fig. 3a. We assume the complete spin correlated basis in the DW, {↓↓, ↑↑, ↓↑, ↑↓}. First, an imaging pulse is used to count all the spin-up atoms N↑ and remove them from the lattices by heating. Afterwards, a rapid MW adiabatic passage is applied to flip all the remaining atoms to ↑↑ = 5S1/2(F = 2, mF = -1). Then, the atoms are transferred to the long lattice of 35.0(2)Er in 2 ms, by ramping down the short lattice. Meanwhile the lattice depth along the Y direction is increased to 60.0(4)Er to enhance the on-site interactions. With this condition, the double occupancies will be removed from the lattice after a holding time of 500 ms as a result of hyperfine changing collisions, whereas the single fillings will survive. Then, in situ imaging is performed to count the remaining
number of atoms, \(N\). By using this method, the triplet state does not contribute any count to the final number of atoms, whereas one atom of the singlet will be counted. As shown in Fig. 3b, an oscillation curve with a period of 2.34(2) ms is obtained by counting the number of atoms in the ROI at different STO times with this detection routine. According to the STO curve, the phase of the entangled state can be well controlled and the Bell state \(|\Psi\rangle\) can be prepared after a STO time \(t_0 = 0.3\) ms.

**Detecting spin entanglement in the superlattice**

Spin correlations in different correlated bases should be measured to determine the entanglement\(^2\). We verify the spin entanglement in the DWs by comparing the sum of the two images \((N_1 + N_2)\) with the total number of atoms \(N\) in the ROI. The number of atoms in the correlated basis of \(|\downarrow\downarrow\rangle, |\uparrow\uparrow\rangle\) is then derived as \(N_{1,2} = N - (N_1 + N_2)\). By addressing and flipping the spins on the left site, right site or both sites before the detection process, we can project the states \(|\downarrow\downarrow\rangle, |\uparrow\uparrow\rangle\) or \(|\downarrow\uparrow\rangle, |\uparrow\downarrow\rangle\) to the measurement state \(|\uparrow\downarrow\rangle, |\downarrow\uparrow\rangle\) and derive the number of atoms for \(N_{1,1}, N_{1,2}\), or \(N_{2,1}\), respectively. From these measured spin fractions, we can get coincidence-like probabilities \(P_{a,b} = N_{a,b}/\sum_{a,b} N_{a,b}\) \((a, b = \uparrow, \downarrow\rangle\) and the spin correlation of \((\hat{S}_x \otimes \hat{S}_y)\) is \(E_{xy} = P_{\downarrow\uparrow} - P_{\downarrow\downarrow} - P_{\uparrow\downarrow} + P_{\uparrow\uparrow}\).

This technique for measuring spin correlations is similar to the measurement of polarization correlations in photonic entanglement\(^2\). Similarly, the spin fractions in the \(|\downarrow\rangle, |\uparrow\rangle\) basis can be measured by applying a \(\pi/2\)-pulse to both sites before these measurements, and the probabilities \(P_{+,-}\) \((c, d = +, -\rangle\) are derived. The spin correlation of \((\hat{S}_x \otimes \hat{S}_y)\) is \(E_{yx} = E_{xy}\), \(E_{xy} = E_{yx}\), and \(E_{xy} = E_{yx}\). From these measurements, as shown in Fig. 4a,b, we obtain the lower boundary of the entanglement fidelity\(^2\) \(F \geq (E_{xx} + E_{yy})/2 = 0.79 \pm 0.06\), higher than the classical limit of 0.5 by 5 standard deviations.

Furthermore, we demonstrate the existence of spin entanglement by violating the CHSH-type Bell inequality. The spin-correlation curves are measured by first assigning the left site an additional rotation \(\beta = \alpha \pi/4\) \((\alpha = 1, 2, 3, \ldots, 8)\), and then repeating the above measurements for the spin correlations of \(E_{xy}^x(x)\) and \(E_{yx}^y(y)\), as shown in Fig. 4c. Choosing the rotation of \(\alpha \pi/4\) for the left site causes minimum response to the atoms in the right site. From fitting the two spin-correlation curves, the quantity \(S = |E(\theta_1, \theta_2) + E(\theta_1, \theta_2') - E(\theta_1, \theta_2) + E(\theta_1, \theta_2')|\), with \((\theta_1, \theta_1', \theta_2, \theta_2') = (0, \pi/2, 3\pi/4, 5\pi/4)\), is derived as \(S = 2.21 \pm 0.08\), which violates the CHSH inequality by 2.7 standard deviations.

The observed entanglement fidelity is limited by several experimental imperfections. First, owing to the coupling with the environment, the spin states experience decoherence during the period of superexchange operation, which causes a degradation of the fidelity by 8.5%. Increasing the speed of superexchange will decrease the degradation to a negligibly small value. This can be implemented by lowering the superlattice barrier while increasing the on-site interaction with higher transversal trapping frequencies or Feshbach resonances\(^2\) to suppress the single-atom tunnelling process. Second, another holding time of 26 ms to stabilize the magnetic field before further microwave operations also reduces the fidelity by 8.3%. This period can be greatly shortened by improving the response speed of the stabilizing circuit for the magnetic field. Finally, imperfections in microwave operations decrease the fidelity by about 3%, but should be effectively suppressed by optimizing the temporal shape of the microwave pulses. Using clock states as storage qubits and magnetically sensitive states as working states would prolong the quantum coherence\(^2\). Furthermore, decoherence-free subspace-encoded qubits will be insensitive to both uniform and gradient magnetic fluctuations, and therefore sustain a long coherence time\(^2\). These improvements will reduce the operation time and are expected to substantially increase the fidelity. Although the generation of spin entanglement in double wells is deterministic, extending to longer chains of spin entanglement suffers from lattice defects as a result of the finite temperature. Further cooling\(^2\) the atom cloud will be helpful in suppressing vacant sites and achieving unit filling in the lattices.

**Summary and outlook**

In summary, we have demonstrated the generation, manipulation and detection of atomic spin entanglement in an optical superlattice, the first step towards measurement-based quantum computation. The spin dependence built into the superlattice gives great flexibility in addressing the single spins in the double-well arrays, which leads to high-fidelity state initialization and detection. Both the longitudinal and transversal inhomogeneities are suppressed well by confining the ultracold atoms in a two-dimensional (2D) plane and employing in situ imaging. Therefore, a long coherence time of the entangled state is achieved. The routine...
of two-stage filtering and imaging makes it possible to measure the spin correlations, from which we can derive the lower boundary of the entanglement fidelity as 0.79 ± 0.06 and the violation of the Bell’s inequality with $S = 2.21 ± 0.08$. As multipartite entanglement in optical lattices can be detected by measuring pairwise correlations of two identical copies of the quantum state\(^3\), the present detection method is well suited for this requirement of pairwise measurement and will be adapted in characterizing large entangled states.

The optical lattice system has a distinct advantage in generating large-scale entangled state thanks to its parallel control over massive atoms. As identical entangled spin pairs have been prepared in parallel within a single superexchange operation, with just two more (independent of the number of particles) connecting operations, a second and a third superexchange operation, all the atoms will be prepared to a two-dimensional entangled state\(^1,12,13\), a basic resource for universal quantum computing. This parallelism greatly relaxes the requirement on the speed of superexchange. Individual measurements required by measurement-based quantum computation\(^11,12\) can be implemented by integrating the present method with the single-spin addressing technique\(^3\). Owning to the site-resolved spin addressability in the spin-dependent superlattice, a wide range of physics of many-body systems can be studied with the present set-up. The set-up provides an ideal tool for studying the quantum magnetism of spinor Bose gases in optical lattices\(^11,12\).

During preparation of the manuscript, we became aware of a recent related work by T. Fukuhara et al.\(^3\) detecting a spin-entanglement wave in a Bose–Hubbard chain.

**Methods**

Methods and any associated references are available in the online version of the paper.

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**Author contributions**

Y.-A.C., Z.-S.Y. and J.-W.P. initiated and designed this research project. H.-N.D., B.Y., A.E., F.-X. and Z.-S.Y. set up the experiment. X.J. built the electronic circuits for the locking lasers. H.-N.D. B.Y. and A.R. performed the measurement and analysed the data. All authors contributed in writing the manuscript. Z.-S.Y. and J.-W.P. supervised the whole project.

**Additional information**

Supplementary information is available in the online version of the paper. Reprints and permission information is available online at www.nature.com/reprints.

Correspondence and requests for materials should be addressed to Y.-A.C., Z.-S.Y. or J.-W.P.

**Competing financial interests**

The authors declare no competing financial interests.
Methods
Experimental set-up. Our experiment starts with the preparation of a two-dimensional (2D) quantum gas by loading a nearly pure $^{87}$Rb Bose–Einstein condensate (BEC) into a single layer of a pancake-shaped trap, which is created by interfering two laser beams with a wavelength of $\lambda = 767$ nm and an intersection angle of $11^\circ$, as shown in Fig. 1a,b. The confinement of this trap is highly anisotropic, with trap frequencies $\omega_{x,y,z} \approx 2\pi \times (16, 14, 7.000)$ Hz, leading to an aspect ratio of 467:1. This 2D sample contains approximately $1.2 \times 10^4$ atoms spin-polarized in $|\pm i\rangle$ and reaches temperatures as low as $T_{2D} = 23$ nK. We use the hyperfine levels $|\downarrow\rangle = 5S_1/2, F = 1, m_F = -1\rangle$ and $|\uparrow\rangle = 5S_1/2, F = 2, m_F = -2\rangle$ to represent the pseudo spin-1/2 system. The ratio $N_h/\omega_{z,T_{2D}} \approx 14.6$, with $k_B$ being the Boltzmann constant, indicates that the sample is deep in the 2D regime.

The atoms are then adiabatically loaded into a square lattice, which is composed of two retro-reflected lattices $V_x$ (short lattice) and $V_y$ (Y lattice) along the X and Y directions with wavelength $\lambda = 767$ nm, as shown in Fig. 1a,b. The system enters the Mott insulator (MI) regime, where most sites are filled with single atoms when the lattices are ramped to $V_x = V_y = 25.0(2)E_r$, with $E_r = h^2/2m\lambda^2$ being the recoil energy and $m$ the mass of the atom. Afterwards, the two lattices are increased further to $V_x = 60.0(4)E_r$ and $V_y = 40.0(3)E_r$ to freeze out the atom tunnelling. The density distribution of the sample is obtained by in situ absorption imaging along the Z direction with a microscope objective (N.A. = 0.48) and a low-noise charge-coupled device (CCD) camera, as shown in Fig. 1c. An average filling number of 0.80 atoms per site in the centre part of the atom cloud is obtained. Measuring the atom loss of hyperfine changing collisions in the lattices reveals that 76% of the lattice sites are filled with one atom, approximately 2% are filled with two atoms, and the rest are vacant sites (see Supplementary Information). A great advantage of using in situ imaging is that one can select an appropriate area in the sample with optimal filling properties and the least transversal inhomogeneity.

Next, the MI atoms are transferred into the DWs of a superlattice along the X direction. By superimposing another retro-reflected lattice $V_x$ (long lattice, wavelength $\lambda_x = 1,534$ nm) with the short lattice, a superlattice $V_x(x) = V_x \cos^2(k_x x) - V_x \cos^2(k_x x/2 + \psi)$ is formed, where $k_x = 2\pi/\lambda_x$ is the wavevector and $\psi$ is the superlattice phase. By controlling the relative frequency between the long and short lattices, the superlattice phase is tuned to 0, such that balanced DWs with spin state $|\downarrow\downarrow\rangle$ are prepared.