Floquet approach to $\mathbb{Z}_2$ lattice gauge theories with ultracold atoms in optical lattices

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Quantum simulation has the potential to investigate gauge theories in strongly interacting regimes, which are currently inaccessible through conventional numerical techniques. Here, we take a first step in this direction by implementing a Floquet-based method for studying $\mathbb{Z}_2$ lattice gauge theories using two-component ultracold atoms in a double-well potential. For resonant periodic driving at the on-site interaction strength and an appropriate choice of the modulation parameters, the effective Floquet Hamiltonian exhibits $\mathbb{Z}_2$ symmetry. We study the dynamics of the system for different initial states and critically contrast the observed evolution with a theoretical analysis of the full time-dependent Hamiltonian of the periodically driven lattice model. We reveal challenges that arise due to symmetry-breaking terms and outline potential pathways to overcome these limitations. Our results provide important insights for future studies of lattice gauge theories based on Floquet techniques.

Lattice gauge theories (LGTs) are fundamental for our understanding of quantum many-body physics across different disciplines ranging from condensed matter to high-energy physics. However, theoretical studies of LGTs can be extremely challenging—particularly in strongly interacting regimes, where conventional computational methods are limited. To overcome these limitations, alternative numerical tools have been developed, which enable out-of-equilibrium and finite-density computations. In parallel, the rapid progress in the field of quantum simulation has the potential to investigate gauge theories in strongly interacting regimes, which are currently inaccessible through conventional numerical techniques. Here, we take a first step in this direction by implementing a Floquet-based method for studying $\mathbb{Z}_2$ lattice gauge theories using two-component ultracold atoms in a double-well potential. For resonant periodic driving at the on-site interaction strength and an appropriate choice of the modulation parameters, the effective Floquet Hamiltonian exhibits $\mathbb{Z}_2$ symmetry. We study the dynamics of the system for different initial states and critically contrast the observed evolution with a theoretical analysis of the full time-dependent Hamiltonian of the periodically driven lattice model. We reveal challenges that arise due to symmetry-breaking terms and outline potential pathways to overcome these limitations. Our results provide important insights for future studies of lattice gauge theories based on Floquet techniques.

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Here, we explore the dynamics of a minimal model for $\mathbb{Z}_2$ LGTs coupled to matter with ultracold atoms in periodically driven double-well potentials. An alternative technique was recently proposed for digital quantum simulation of $\mathbb{Z}_2$ LGTs are of high interest in condensed matter physics and topological quantum computations. Our scheme is based on density-dependent laser-assisted tunnelling techniques and a digital quantum computer composed of four trapped ions. The challenge for analogue quantum simulators mainly lies in the complexity to engineer gauge-invariant interactions between matter and gauge fields.

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are implemented using two different species denoted $a$ and $f$ particles, which are realized by two Zeeman levels of the hyperfine ground-state manifold of $^{87}$Rb, $|a\rangle \equiv |F=1, m_f=-1\rangle$ and $|f\rangle \equiv |F=1, m_f=+1\rangle$. We prepare one $a$ and one $f$ particle in each two-site system. The matter field is associated with the $a$ particle. The $Z_2$ gauge field is the number imbalance $\tilde{\nu}_j^{(j+1)} = n_j^f - n_j^a$ of the $f$ particle and the $Z_2$ electric field corresponds to tunnelling of the $f$ particle,

$\tilde{\nu}_j^{(j+1)} = \tilde{f}_j^{(j+1)} + \tilde{f}_j^{(j+1)},$ where $\tilde{f}_j^{(j+1)}$ is the creation operator of an $f$ particle on site $j$ and $\tilde{n}_j^f = \tilde{f}_j^{(j)} \tilde{f}_j^{(j)}$ is the corresponding number-occupation operator. An extension of our scheme to realize extended 1D LTGs is presented in the Supplementary Information. It requires exactly one $f$ particle per link, while the density of $a$ particles (fermions or hard-core bosons) can take arbitrary values.

The driving scheme is based on a species-dependent double-well potential with tunnel coupling $J$ between neighbouring sites and an energy offset $\Delta$, only seen by the $f$ particle. Experimentally, it is realized with a magnetic-field gradient, making use of the opposite magnetic moments of the two states $|a\rangle$ and $|f\rangle$ (Supplementary Information). In the limit of strong on-site interactions $U\gg J$ (where $U$ is the on-site Hubbard interaction), first-order tunnelling processes are suppressed but can be restored resonantly with a periodic modulation at the resonance frequency $\hbar \omega = \sqrt{U^2 + 4J^2} \approx U$. The full time-dependent Hamiltonian can be expressed as

$$
\hat{H}(t) = -J \left( \hat{a}_1^a \hat{a}_1^a + \hat{f}_1^f \hat{f}_1^f \right) + U \sum_{j=2}^\infty \hat{n}_j^f \hat{n}_j^f + \Delta \hat{n}_1^f + A \cos(\omega t + \phi) (\hat{n}_1^f + \hat{n}_1^a) 
$$

where $A$ is the modulation amplitude and $\phi$ is the modulation phase. For resonant modulation $\hbar \omega \approx U$ and in the high-frequency limit $\omega \gg J$, the lowest order of the effective Floquet Hamiltonian contains renormalized tunnelling matrix elements for both $a$ and $f$ particles. For general modulation parameters, the amplitudes and phases are operator-valued and explicitly depend on the site occupations. For certain values of the modulation phase ($\phi=0$ or $\pi$), however, these expressions simplify and realize the $Z_2$ model.

The driving scheme can be understood by considering the individual photon-assisted tunnelling processes of $a$ and $f$ particles in situations, where one of the two particles is localized on a particular site of the double well. This generates an occupation-dependent energy offset for the other particle, which is equal to $U$ (Fig. 2a). For all configurations, tunnelling is resonantly restored for energy differences $\pm \hbar \omega$ between neighbouring sites with renormalized tunnelling $J\mathcal{J}_\nu(\chi) e^{i \phi}$; here $\nu$ is an integer, $\mathcal{J}_\nu$ is the $\nu$-th-order Bessel function of the first kind and $\chi = A/(\hbar \omega)$ the dimensionless driving parameter.

For $\phi=0$, we find that the strength of a $f$ particle tunnelling is density-independent $J_0 = J \mathcal{J}_1(\chi)$, however, depending on the position of the $f$ particle, the on-site energy difference between neighbouring sites is either $+U$ or $-U$ (Fig. 2a). This results in a sign-dependence of the renormalized tunnelling $J_0 \mathcal{J}_1(\chi)$, which stems from the property of odd Bessel functions $\mathcal{J}_\nu(-x) = (-1)^\nu \mathcal{J}_\nu(x)$ (Supplementary Information) and is central to our implementation of the $Z_2$ symmetry. It allows us to write the renormalized hopping of $a$ particles as $J_0 \tilde{\nu}_j^{(j+1)}$. Note that we drop the link index from now on to simplify notations, $\tilde{\nu} \equiv \tilde{\nu}_j^{(j+1)}.

Tunnelling of $f$ particles becomes real-valued, with an amplitude that only weakly depends on the position of the $a$ particle. Due to the species-dependent tilt $\Delta = U$, the on-site energy difference between neighbouring sites is either $\Delta = U=0$ or $\Delta = U=2U$ (Fig. 2a). Therefore, tunnelling is renormalized via zero- and two-photon processes, resulting in the real-valued tunnelling matrix

**Fig. 1** 1D $Z_2$ lattice gauge theory coupled to matter. Circles indicate lattice sites, which are empty (grey) or occupied by a matter particle (blue). Red circles and the thickness of red links illustrate the expectation value of the link operators, $\tau^x$ and $\tau^z$. a, Elementary ingredients: $Z_2$ charge $\hat{Q}_i = e^{i\pi \hat{n}_i}$, $Z_2$ gauge field $\hat{A}_i^{(j)}$, $Z_2$ electric field $\hat{E}_i^{(j)}$, and local symmetry operator $\hat{G}_i$ with conserved quantities $g_i$. Here $\hat{Q}_i^{(j)}$ denotes all lattice sites $i$ connected to site $j$ via a nearest-neighbour link, denoted as $(i,j)$. Matter and gauge fields are implemented using two different species, denoted as $a$ (blue) and $f$ (red). Matter–gauge coupling occurs with strength $J_a$. b, Dynamics of the 1D model (equation (1)) for different values of $J_a/J_f$ calculated with exact diagonalization of a system with 13 sites based on equation (1). The initial state is a single matter particle located on site $j=0$ and the gauge field is in an eigenstate of the electric field.
Fig. 2 | Driving scheme for $\mathbb{Z}_2$ LGTs on a double well. a, Effective tunnelling processes for the matter-field (blue, $\phi$) and gauge-field (red, $f$) particle. For $\phi = 0$, hopping of $\phi$ particles occurs for resonant one-photon processes at $\hbar \nu = U$ with an effective amplitude $J\mathcal{F}(\chi)$, where $U$ is the interspecies on-site interaction. Depending on the position of the $\phi$ particle, the $\phi$ particle acquires a phase shift of $\pi$, which realizes the matter–gauge coupling. Tunnelling of the $f$ particle is renormalized by zero- or induced via two-photon processes, with amplitudes $\mathcal{J}_0(\chi)$ and $\mathcal{J}_2(\chi)$ depending on the $f$ particle’s position. b, Experimental results for the renormalization of the tunnel couplings $\mathcal{J}_0(\chi)$ for single-particle $\nu$-photon processes $\nu = (0, 1, 2)$, with $\omega = 2\pi \times 4,122 \text{ Hz}$ and $J/\hbar \approx 0.5$ kHz. The solid lines are the Bessel functions, where $\chi$ was calibrated by fitting the zeroth-order Bessel function to the dark red data points (Supplementary Information). The time traces of the imbalance $I$ fitted with sinusoidal functions taking into account an inhomogeneous tilt distribution (solid black line) and shown for exemplary traces at $\chi = 1.28$ (dashed vertical line, left panel) and $\chi = 1.84$ (dashed vertical line, right panel). The solid grey vertical line marks the value $\chi_0$, where $\mathcal{J}_0(\chi_0) = \mathcal{J}_2(\chi_0)$. The error bars and the grey shading are the 1σ confidence interval obtained from a bootstrap analysis of 1,000 repetitions (Supplementary Information).

The experimental set-up consists of a 3D optical lattice generated at wavelength $\lambda = 767$ nm. Along the $x$ axis an additional standing wave with wavelength $2\lambda = 1,534$ nm is superimposed to create a superlattice potential. For deep transverse lattices and suitable superlattice parameters, an array of isolated double-well potentials is realized, where all dynamics is restricted to the two double-well sites (Supplementary Information). The periodic drive is generated by modulating the amplitude of an additional lattice with wavelength $2\lambda$, whose potential maxima are aligned relative to the double-well potential to modulate only one of the two sites. This enables the control of the modulation phase, which is set to $\phi = 0$ or $\pi$.

We first study the renormalization of the tunnelling matrix elements for the relevant $\nu$-photon processes\(^\text{53–54}\) with a single atom on each double well (Fig. 2b). For every measurement, the atom is initially localized on the lower-energy site with a potential energy difference $\Delta \approx \hbar \nu_0$ to the higher-energy site, where $\nu \in \{0, 1, 2\}$. Then, the resonant modulation is switched on rapidly at frequency $\omega$ and we evaluate the imbalance $I = n_s - n_f$ as a function of the evolution time, where $n_s$ is the density on site $j$. These densities were determined using site-resolved detection methods\(^\text{35}\). Note, this technique provides an average of this observable over the entire 3D array of double-well potentials. Hence, an overall harmonic confinement and imperfect alignment of the lattice laser beams introduces an inhomogeneous tilt distribution $\Delta(x, y, z)$, which leads to dephasing of the averaged dynamics. The renormalized tunnelling amplitude is obtained from the oscillation frequency of the imbalance and by numerically taking into account the tilt distribution $\Delta(x, y, z)$ (Fig. 2b). We find that our data agree well with the expected Bessel-type behaviour for the $\nu$-photon processes (Supplementary Information). Moreover, these measurements enable us to directly determine the value of the modulation amplitude, for which $\mathcal{J}_0(\chi_0) = \mathcal{J}_2(\chi_0)$, as indicated by the vertical line in Fig. 2b.

To study the dynamics of the $\mathbb{Z}_2$ double-well model (equation (4)), we prepare two different kinds of initial states, where the gauge field particle is either prepared in an eigenstate of the electric field $\hat{z}$ (Fig. 3) or the gauge field operator $\hat{z}$ (Fig. 4a). In both cases the matter particle is initially localized on site $j = 1$.

First, we consider the state $|\psi_0^\nu\rangle = |a, 0\rangle \otimes (|f, 0\rangle + |0, f\rangle)/\sqrt{2}$ (Fig. 3a), where the gauge-field particle is in a symmetric superposition of the two sites. This state is an eigenstate of $\hat{G}_0$ defined in equation (2). The corresponding eigenvalues are $g_j = -1$ and $g_j = +1$. After initiating the dynamics by suddenly turning on the resonant modulation, we expect that the matter particle starts to tunnel to the neighbouring site ($j = 2$) according to the matter–gauge coupling. Depending on the energy of the electric field $\hat{I}$, this process can be energetically detuned and the matter particle does not fully tunnel to the other site. Solving the dynamics according to Hamiltonian (equation (4)) analytically, gives:

$$\langle \hat{Q}_1(t) \rangle = -\frac{J_1^2 + J_2^2 \cos(2t \sqrt{J_1^2 + J_2^2})}{J_1^2 + J_2^2}$$

The maximum value of $\langle \hat{Q}_1 \rangle$ is limited to $(J_1^2 - J_2^2)/(J_1^2 + J_2^2)$. The experimental configuration is well suited to explore the regime $J_2/J_1 = \mathcal{J}_0(\chi_0)/\mathcal{J}_1(\chi_0) \approx 0.54$, which corresponds to an intermediate regime between the two limiting cases discussed in Fig. 1c. These cases can also be understood at the level of the two-site model. In the weak electric field regime ($J_2/J_1 \ll 1$) the matter particle tunnels freely between the two sites, while in the limit of a strong electric field ($J_2/J_1 \gg 1$) the matter particle remains localized.

In the experiment we can directly access the value of the charge operator $\hat{Q}_1 = e^{a(\hat{z})}$ and the link operator $\hat{z} = n_2^\phi - n_1^\phi$ via site- and
state-resolved detection techniques. They provide direct access to the state-resolved density on each site of the double well $n^G_j$ and $n^a_j$, averaged over the entire 3D array of double-well realizations. The experimental results are shown in Fig. 3b for $U/J = 6.6$ and $\phi = 0$. As expected, we find that the charge oscillates, while the dynamics of the $f$ particle is strongly suppressed. We observe a larger characteristic oscillation frequency for the $a$ particle compared to the prediction of equation (6) (grey line, Fig. 3b). This is predominantly caused by an inhomogeneous tilt distribution $\Delta(x, y, z)$ present in our system. Taking the inhomogeneity into account, the numerical analysis of the full time-dependence according to equation (3) (solid blue line, Fig. 3b) shows good agreement with the experimental results. The fast oscillations both in the data and the numerics are due to the micromotion at non-stroboscopic times.

The $f$ particle is initially prepared in an eigenstate of the electric field operator $\hat{f}^2$, which corresponds to an equal superposition of the particle on both sites of the double-well potential, that is, $\langle \hat{f}(t=0) \rangle = 0$. The $\mathbb{Z}_2$ electric field follows the oscillation of the matter particle in a correlated manner to conserve the local quantities $g_j$. At the same time the expectation value of the gauge field $\langle \hat{g}_j(t) \rangle$ is expected to remain zero at all times. This is a non-trivial result, which is a direct consequence of the $\mathbb{Z}_2$-symmetry constraints. In contrast, a resonantly driven double-well system with $\Delta_a = 0$, which does not exhibit $\mathbb{Z}_2$ symmetry, would show dynamics with equal oscillation amplitudes for the $a$ and $f$ particles. In the experiment we clearly observe suppressed dynamics for the $f$ particle, which is a signature of the experimental realization of the $\mathbb{Z}_2$ symmetry (Fig. 3b). Deviations between the time-dependent numerical analysis and the experimental results are most likely to be due to an imperfect initial state, residual energy offsets and finite ramp times.

In a second set of experiments we study the dynamics where the gauge field particle is initialized in an eigenstate of the gauge field operator $\hat{f}^2$, while the matter particle is again localized on site $j=1$, $|\psi^a_0\rangle = |a_0, 0, 0, f\rangle$ (Fig. 4a). Here, the system is in a coherent superposition of the two subsectors with $g_1 = g_2 = 0$ and the expectation value of the locally conserved operators are $\langle \hat{g}_1 \rangle = \langle \hat{g}_2 \rangle = 0$. Note that there is no coupling between different subsectors according to Hamiltonian (4). The basic dynamics can be understood in the two limiting cases of the model. For $J_1 \ll J_a$, the electric field vanishes and the system is dominated by the gauge field $\hat{f}^2$. In this limit, a system prepared in an eigenstate of $\hat{f}^2$ will remain in this eigenstate because $\hat{f}^2$ commutes with Hamiltonian (4) for $J_1 = 0$. In the opposite regime ($J > J_a$), where the electric field dominates, $\langle \hat{f}^2(t) \rangle$ oscillates between the two eigenvalues. The dynamics of the $\mathbb{Z}_2$ charge on the other hand is still determined...
finite-frequency corrections. In experiments this could be achieved using Feshbach resonances to increase the inter-species scattering length. This, however, comes at the cost of enhanced correlated tunnelling processes, which in turn can be suppressed by increasing the lattice depth (Supplementary Information). Numerical studies further indicate that certain experimental observables are robust to gauge-variant imperfections\cite{14,15}, which may facilitate future experimental implementations. We anticipate that the double-well model demonstrated in this work will serve as a stepping stone for experimental studies of $\mathbb{Z}_2$ LGTs coupled to matter in extended 1D and 2D systems, which can be realized by coupling many double-well links along a 1D chain (Supplementary Information) or in a ladder configuration\cite{11}. Finally, the use of state-dependent optical lattices could further enable an independent tunability of the matter- and gauge-particle tunnelling terms.

**Data availability**

The data that support the plots within this paper and other findings of this study are available from the corresponding author on reasonable request.

**Code availability**

The code that supports the plots within this paper is available from the corresponding author on reasonable request.

**Online content**

Any methods, additional references, Nature Research reporting summaries, source data, statements of code and data availability and associated accession codes are available at https://doi.org/10.1038/s41567-019-0649-7.

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**Fig. 5** | Finite-frequency corrections to the effective Floquet Hamiltonian (equation (4)). Stroboscopic dynamics of the expectation value of the local $\mathbb{Z}_2$-symmetry operator $\langle \hat{G}_i \rangle$ for $|\psi_0^G\rangle$, with $g_i = -1$, based on Hamiltonian (equation (3)) for different driving frequencies $\omega$. The panels on the right show examples of the time traces for $\omega \approx 1.03U$ (top) and $\omega \approx 1.01U$ (bottom).

**Code availability**

The code that supports the plots within this paper is available from the corresponding author on reasonable request.

**Online content**

Any methods, additional references, Nature Research reporting summaries, source data, statements of code and data availability and associated accession codes are available at https://doi.org/10.1038/s41567-019-0649-7.

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**Author contributions**

C.S., F.G., N.G. and M.A. planned the experiment and performed theoretical calculations. C.S. and M.B. performed the experiment and analysed the data with M.A. All authors discussed the results and contributed to the writing of the paper.

**Competing interests**

The authors declare no competing interests.

**Additional information**

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