

Single-Particle Tunneling in Strongly Driven Double-Well Potentials

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We report on the first direct observation of coherent control of single-particle tunneling in a strongly driven double-well potential. In our setup atoms propagate in a periodic arrangement of double wells allowing the full control of the driving parameters such as frequency, amplitude, and even the space-time symmetry. Our experimental findings are in quantitative agreement with the predictions of the corresponding Floquet theory and are also compared to the predictions of a simple two mode model. Our experiments reveal directly the critical dependence of coherent destruction of tunneling on the generalized parity symmetry.

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Strongly driven quantum systems are intensively studied as they appear in many different contexts in physics and chemistry [1]. Here we are interested in the situation of coherent control of tunneling due to strong driving. It has been pointed out in 1991 [2] that for a specific driving of a double-well system the tunneling dynamics can be brought to a complete standstill known as coherent destruction of tunneling (CDT).

Very recently this effect in a double-well situation has been visualized in specially designed optical wave guides [3] and a closely related effect in a periodic potential has been observed in the nonlinear dynamics of a Bose-Einstein condensate [4]. Here we report on the first demonstration of this effect for single-particle tunneling in a double-well potential. Since our system allows in a straightforward manner to manipulate the spatial as well as the temporal symmetry of the driving we can demonstrate experimentally for the first time the predicted dependence on the generalized parity symmetry $P: x \rightarrow -x, t \rightarrow t + \frac{T}{2}$ of the situation where T represents the period of the driving [5]. With the same setup also the regime of accelerated tunneling can be realized by choosing the proper driving frequency [6].

In the following we present our systematic investigations on the control of single-particle tunneling dynamics in a double-well potential. We find quantitative agreement of the observed increase as well as decrease of the tunneling rate with the theoretical prediction of a Floquet analysis [5]. The direct connection of the observed slowing down with the effect of coherent destruction of tunneling has been confirmed observing its strong dependence on the space-time symmetry of the driving force.

The qualitative behavior of the tunneling dynamics in momentum space is shown in Fig. 1. In the experiment few periodically arranged double wells are coherently populated and thus the momentum distribution is given by the corresponding diffraction pattern as shown in the insets. The tunneling dynamics directly shows up in the dynamics of the diffraction efficiencies. In Fig. 1(a) the tunneling of a

single atom in an unperturbed double-well potential is depicted and is similar to the results obtained in [7]. In Fig. 1(b) one can clearly see that the dynamics is slowed down if symmetric driving is applied. Breaking the temporal symmetry of this driving, i.e., sawtooth shape, the tunneling rate approaches the undriven tunneling rate [see Fig. 1(c)]. This is qualitatively expected from a simple

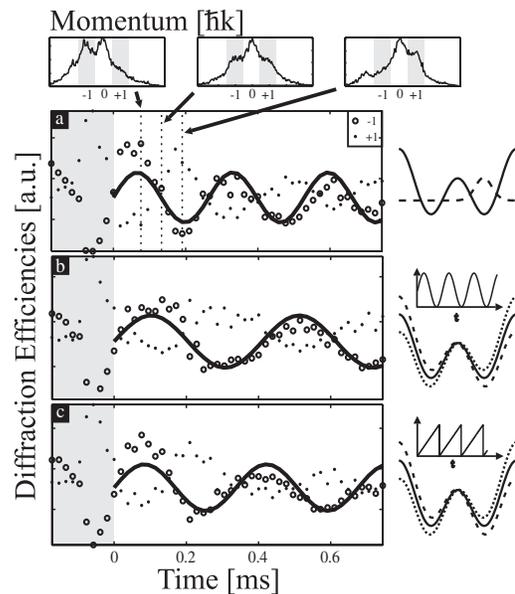


FIG. 1. Coherent control of single-particle tunneling. (a) A single atom is realized on the right side of the double-well potential and the subsequent tunneling dynamics can be directly observed in momentum space. Since a periodic arrangement of double-well potentials is used the momentum distribution is given by a diffraction pattern as shown in the insets. The gray shaded areas are evaluated to obtain the shown diffraction efficiencies. (b) Adding symmetric driving leads to the predicted slowing of the dynamics. (c) Breaking the generalized parity symmetry by applying a sawtooth driving force destroys this effect. Here the gray shaded area indicates the preparation phase. The solid lines are sinusoidal fits to the data.

symmetry argument and as we will show later it is also in quantitative agreement with theory.

Before we will discuss our systematic investigations and the corresponding Floquet description we shortly discuss the experimental setup which is schematically depicted in Fig. 2. Since we are dealing with one-dimensional physics a traditional well collimated (FWHM $< 180 \mu\text{rad}$) atomic beam is perfectly suited as a particle source and the dynamics of interest happens only in the transverse direction. We have chosen metastable argon since it allows for a spatially resolved single-particle detection using a multichannel plate. Additionally for metastable argon imaginary optical potentials [8] can be realized using resonant light at 801 nm. This transition quenches the metastable state to the ground state which is not detectable with a channel plate and thus can be employed for the preparation of a particle on one side of the barrier.

The periodic arrangement of double wells is achieved employing standard optical light shift potentials (see Fig. 2). By retroreflecting two far red-detuned light beams ($\lambda = 811.775 \text{ nm}$) realized with an acousto-optical deflector (AOD) under 0° and 60° incidence standing light waves are formed with periodicities of $\lambda/2$ and λ , respectively, in x direction. Using a gold mirror one has to take into account that the residual absorption leads to a phase shift between the two light waves of $\phi = 0.4 \text{ rad}$ for light polarized perpendicular to the plane of incidence resulting in an arrangement of asymmetric double wells. In our experiment we compensate this phase shift, i.e., asymmetry, by adjusting the reflection angle to 59.97° (by changing the AOD frequency) leading to a different spatial periodicity such that the phase is compensated at a distance of $120 \mu\text{m}$ from the mirror surface [see Fig. 2]. The imaginary potential for the preparation of the atoms in one well is implemented by retroreflection of $\lambda = 801.702 \text{ nm}$ light

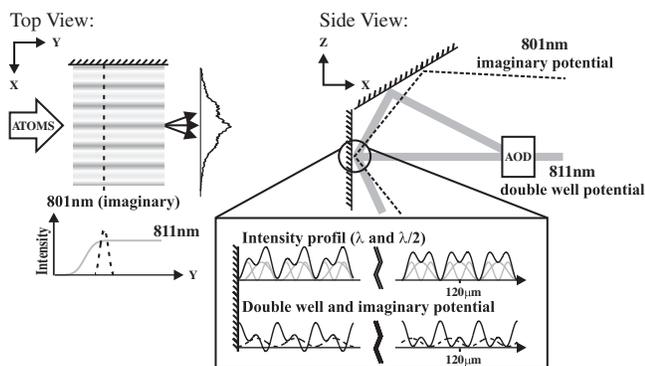


FIG. 2. Schematics of the experimental setup. The well collimated atomic beam impinges on periodic light shift potentials, which adiabatically increase along the propagation direction. The interaction time is adjusted by changing the extension of the light field in y direction. The momentum distribution is detected in the far field by a multichannel plate. The used optical setup with an acousto-optical deflector is depicted on the right-hand side. In the inset the change of symmetry due to residual phase shifts at the mirror surface is shown.

on the same mirror but under an angle such that at a distance of $120 \mu\text{m}$ the phase shift relative to the double wells is about $\pi/4$ leading to the preparation of the atom in one well.

The light intensity profile along the atomic beam is adjusted with specially designed optical gray filters such that the motion of the atoms follows adiabatically the light shift potentials. The successful preparation of the symmetric ground state for perpendicular incidence has been confirmed by observing the consequent time independent momentum distribution which is consistent with that of the lowest Bloch state. The critical alignment of being perfectly perpendicular is achieved by standard Bragg scattering. The potential heights are calibrated by either preparing nonadiabatically and observing the oscillation frequency ($\lambda/2$ periodicity) or preparing a wave packet such that it oscillates around the potential minimum (λ periodicity).

The driving is realized by tuning the relative phase between the two periodic potentials. This is experimentally implemented by periodically changing the driving frequency of the AOD, i.e., the diffraction angle. Since this is under full experimental control it offers a great freedom in choosing frequency as well as the space-time symmetry of the driving force.

In order to make a quantitative comparison of the experimental results with theoretical predictions over the whole range of experimentally accessible parameters we employ the standard Floquet formalism. Our system is described by the Hamiltonian

$$H = \frac{p^2}{2m} + V_1 \cos^2(kx) + V_2 \cos^2 \left[kx \cos \left(\frac{\pi}{3} + \epsilon f(t) \right) \right], \quad (1)$$

with $V_{1,2}$ being the amplitudes of the two potentials forming the double-well structure and $\epsilon f(t)$ the deviation from the incidence angle of 60° . In the limit of small ϵ this leads to a driving potential of the form $V_d = S \sin(k\tilde{x})f(t)$ with $\tilde{x} = 0$ at the symmetry of the double-well potential. S is the amplitude of the driving and $f(t)$ describes the time dependence of the driving force with the characteristic driving frequency $\omega_d = 2\pi/T$. As this Hamiltonian is time periodic we can introduce the Hermitian operator $\mathcal{H}(x, t) = H(x, t) - i\hbar \frac{\partial}{\partial t}$ and according to the Floquet theorem make a plane wave ansatz for the state vector $|\Psi(t)_\alpha\rangle = \exp(-i\epsilon_\alpha t/\hbar)|\Phi_\alpha(t)\rangle$ where $|\Phi_\alpha(t)\rangle = |\Phi_\alpha(t+T)\rangle$. In doing so we reduce the problem to solving the eigenvalue equation for quasienergies ϵ_α

$$\mathcal{H} \Phi_\alpha(x, t) = \epsilon_\alpha \Phi_\alpha(x, t) \quad (2)$$

which can be easily done numerically. For the time periodic function Φ_α we can make a Fourier expansion and choose the eigenstates of the unperturbed double-well potential as an orthogonal basis. For the results shown in the following we have taken into account the 15 lowest energy eigenstates.

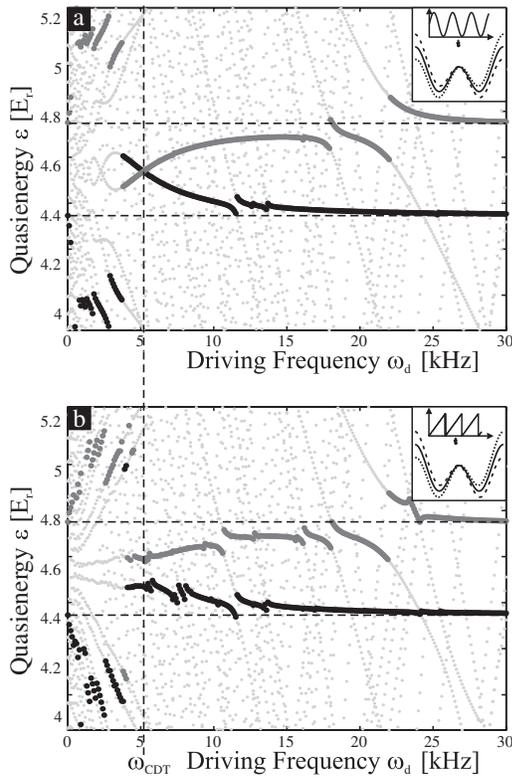


FIG. 3. The Floquet state quasienergies for the experimentally realized parameters. The initial preparation of a particle localized on one side leads to the population of mainly two Floquet states and the corresponding eigenenergies are indicated as dark-gray and black dots. The tunneling dynamics is given by the quasienergy difference. (a) In the case of symmetric driving the Floquet states cross for at ω_{CDT} leading to coherent destruction of tunneling. (b) Breaking the temporal symmetry as indicated in the inset introduces an anticrossing. Clearly for high driving frequencies independent on the driving symmetry the tunneling splitting increases and thus faster tunneling is expected.

In Fig. 3 the results for the quasienergies are shown for sinusoidal and sawtooth driving. The corresponding eigenenergies of the eigenstates which are maximally populated due to our initial condition of a particle localized on one side of the barrier are indicated with black and dark-gray points. An exact crossing of the relevant quasienergies implies that the slow dynamics comes to a complete standstill, i.e., CDT, indicated by the dashed vertical line. This happens if the eigenstates of the crossing quasienergies belong to different parity classes of the generalized parity P : $x \rightarrow -x$, $t \rightarrow t + \frac{T}{2}$. Clearly in the case of broken symmetry [Fig. 3(b)] no crossing exists. Furthermore it becomes clear that the tunneling rate will increase as the symmetry is broken. For high driving frequencies independent of the symmetry the theory predicts an acceleration of the tunneling in comparison to the undriven case. The dashed horizontal lines indicate the eigenenergies of unperturbed double well.

The results of our systematic investigations of ac control of coherent tunneling with symmetric driving are summa-

rized in Fig. 4. Plot (a) shows the tunneling splitting deduced from the observed dynamics as a function of driving frequency as solid dots ($S = 0.88E_r$ with $E_r = \hbar^2/2m\lambda^2$ for $\lambda = 811$ nm). The dashed line indicates the tunneling splitting for the unperturbed double-well potential. Since for a given driving frequency more than two quasienergy differences are relevant we have chosen a gray shading representing the weight given by the population of the corresponding eigenstates due to the initial condition, i.e., the probability to find this tunneling frequency. It has to be noted that in the theoretical prediction no free parameter is used. Thus we have very good quantitative agreement between theory and experiment. Furthermore the results show that driving allows for the full control of the tunneling dynamics, i.e., acceleration as well as suppression.

For completeness we have added the analytical prediction within the two mode approximation for the effective

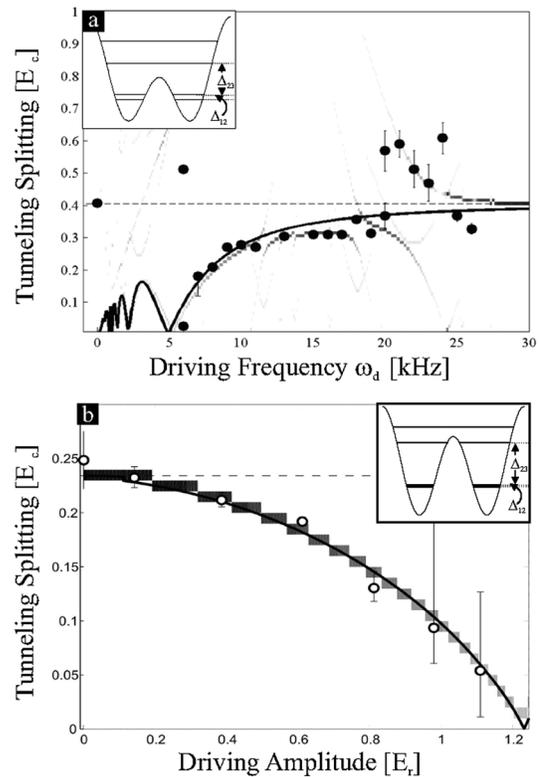


FIG. 4. Systematic study of the tunneling dynamics with symmetric driving. (a) The graph shows the driving frequency dependence of the tunneling rate. If the driving frequency is close to the resonance to the third excited state the driving leads to an acceleration of the tunneling. The experimental results (solid dots) are explained by the full Floquet analysis without free parameter over the whole range. The solid line represents the prediction within the two mode approximation. (b) In this graph we compare our experimental data obtained for fixed driving frequency but changing the driving amplitude with the theoretical predictions. For these specific experimental parameters also the two mode approximation explains quantitatively the observations.

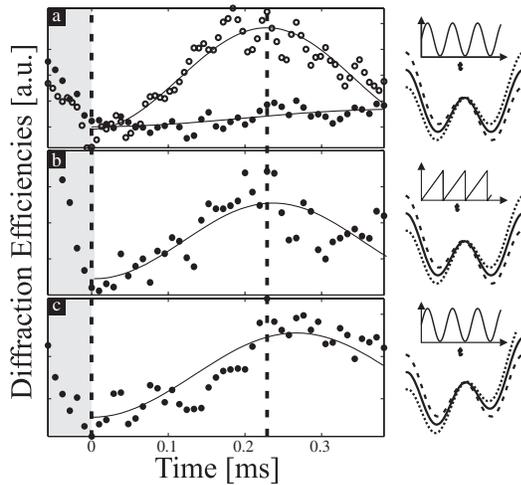


FIG. 5. Tunneling dynamics for different driving symmetries. (a) The open circles represent the tunneling dynamics in a stationary potential while the solid dots reveal the slowing down of the dynamics due to symmetric driving. (b) Applying a sawtooth temporal driving to a spatially symmetric double well leads to significant tunneling during the interaction time. (c) Breaking the spatial symmetry, i.e., asymmetric double well, but employing symmetric sinusoidal temporal driving also leads to the expected increase of the tunneling rate. Parameters: $S = 2.05 \frac{E_r}{\mu\text{m}}$, $\omega = 5.5 \text{ kHz}$, $V_1 = 5.65E_r$, $V_2 = 3.22E_r$.

tunneling splitting $\Delta_{\text{eff}} = J_0\left(\frac{Sx_{12}}{\hbar\omega}\right)\Delta_{12}$ where J_0 represents the zeroth-order Bessel function, $x_{12} = \langle\varphi_1|\sin(kx)|\varphi_2\rangle$ is the transition dipole matrix element, and Δ_{12} is the tunneling splitting of the unperturbed system [5]. It is clear that the two mode approximation captures the CDT very well. The deviation in respect to the Floquet analysis comes from the fact that we are not deep in the two mode regime as can be seen in the inset ($V_1 = 6.25E_r$, $V_2 = 5.40E_r$). The increase of tunneling rate for very high driving frequencies is due to the resonance with the second excited state in the potential well. At this resonance the tunneling dynamics follows from the interplay between three Floquet states and thus is very similar to the physics of chaos assisted tunneling [9].

The dependence of the tunneling splitting as a function of driving amplitude for fixed driving frequency $\omega_d = 6 \text{ kHz}$ is shown in Fig. 4(b). There we compare our experimental results with the Floquet and two mode theory. It is important to note that the potential parameters ($V_1 = 8.27E_r$, $V_2 = 2.68E_r$) for these experiments are deeper in the two mode regime (see inset in Fig. 4) and thus the two mode approximation fits perfectly with the Floquet theory. Clearly the splitting gets smaller, i.e., the dynamics gets slower as the amplitude is increased. Also here we get quantitative agreement between theory and experiment without free parameter.

In order to verify that CDT is indeed observed we demonstrate the critical dependence of the slowing down of the tunneling on the generalized parity symmetry of the

driving $P: x \rightarrow -x, t \rightarrow t + \frac{T}{2}$. This has been implemented experimentally in two different manners, namely, breaking the temporal symmetry for a spatially symmetric double well [see Fig. 5(b)] and breaking the spatial symmetry, i.e., asymmetric double well, with symmetric temporal driving [see Fig. 5(c)]. Clearly the tunneling dynamics is faster if the symmetry of the driving is broken.

In this Letter we have experimentally demonstrated the versatility of strong driving as a new tool to modify the coherent tunneling dynamics. In the experiment we have investigated the tunneling of a single particle in a double-well potential for different driving situations. With that we clearly demonstrate experimentally the critical dependence of coherent destruction of tunneling on the underlying symmetry of the driving. We find excellent quantitative agreement between experiment and theory. The realization of a periodic potential with perfectly controllable parameters such as symmetry of the unit cell and driving makes it a general model system for studying strongly driven systems in the quantum regime with the potential for preparation of complex quantum states in many particle systems [10] but also extendable to the regime of chaotic motion present in Hamiltonian ratchets [11].

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