Observation of a Dynamical Sliding Phase Superfluid with *P*-Band Bosons

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Sliding phases have been long sought after in the context of coupled *XY* models, as they are of relevance to various many-body systems such as layered superconductors, freestanding liquid-crystal films, and cationic lipid-DNA complexes. Here we report an observation of a dynamical sliding phase superfluid that emerges in a nonequilibrium setting from the quantum dynamics of a three-dimensional ultracold atomic gas loaded into the *P* band of a one-dimensional optical lattice. A shortcut loading method is used to transfer atoms into the *P* band at zero quasimomentum within a very short time duration. The system can be viewed as a series of "pancake"-shaped atomic samples. For this far-out-of-equilibrium system, we find an intermediate time window with a lifetime around tens of milliseconds, where the atomic ensemble exhibits robust superfluid phase coherence in the pancake directions, but no coherence in the lattice direction, which implies a dynamical sliding phase superfluid. The emergence of the sliding phase is attributed to a mechanism of cross-dimensional energy transfer in our proposed phenomenological theory, which is consistent with experimental measurements. This experiment potentially opens up a novel venue to search for exotic dynamical phases by creating high-band excitations in optical lattices.

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A sliding phase [1] mechanism has been proposed in the study of weakly coupled stacks of *XY* models [2,3], which was introduced to characterize intricate phase transitions in a broad range of many-body systems such as layered superconductors [4,5], freestanding liquid-crystal films [6,7], and even biological molecules [8,9]. In the sliding phase, the system behaves like a stack of decoupled superfluid layers in spite of the physical interlayer Josephson coupling being finite. With field theory analysis, it has been shown that the sliding phase typically appears under extreme conditions for thermal equilibrium systems [1] or quantum ground states [10–15], causing a grievous challenge in experimental implementation.

Recent experimental progress in synthetic quantum systems has achieved unprecedented approaches to investigate fascinating collective phenomena in controllable quantum dynamics, such as light-induced nonequilibrium superconductivity [16,17], time crystals in trapped ions [18], correlated quantum kinematics in reduced-dimensional systems [19–21], and many-body localization with cold atoms in artificial light crystals [22–27]. While a complete theoretical framework to describe nonequilibrium phase transition is still lacking, a formal analogy between temperature and time by comparing partition function in the thermal ensemble and unitary evolution operator in quantum dynamics allows such concepts in statistical physics as many-body phases and condensation, to generalize to the time domain [28,29].

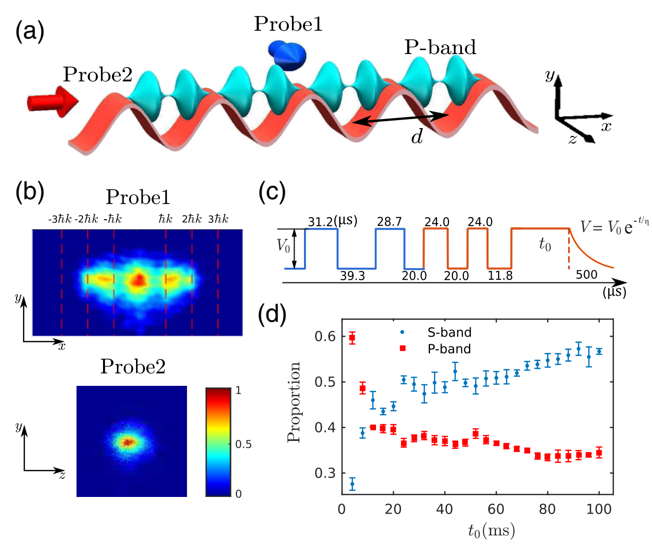

FIG. 1. (a) Experimental configuration for a 1D *P*-orbital lattice, where atoms form discrete pancakes. (b) The system is probed in two ways. Probe 1: probe with a laser beam along the $\hat{z}$ direction after the band mapping. Probe 2: with the probe beam along the $\hat{x}$ direction, the image is taken by switching off the potential abruptly within 30 ns. Atoms are loaded to the zero quasimomentum state of the *P* band through a designed pulse sequence, with an example shown in (c) for lattice depth $V_0 = 5E_r$ (E_r is one-photon recoil energy). We then hold atoms for time t_0, and the absorption images after time of flight (TOF) are taken in two directions. (d) The atom proportion in *S* and *P* band. Error bars are given by the standard deviation of five experiments.

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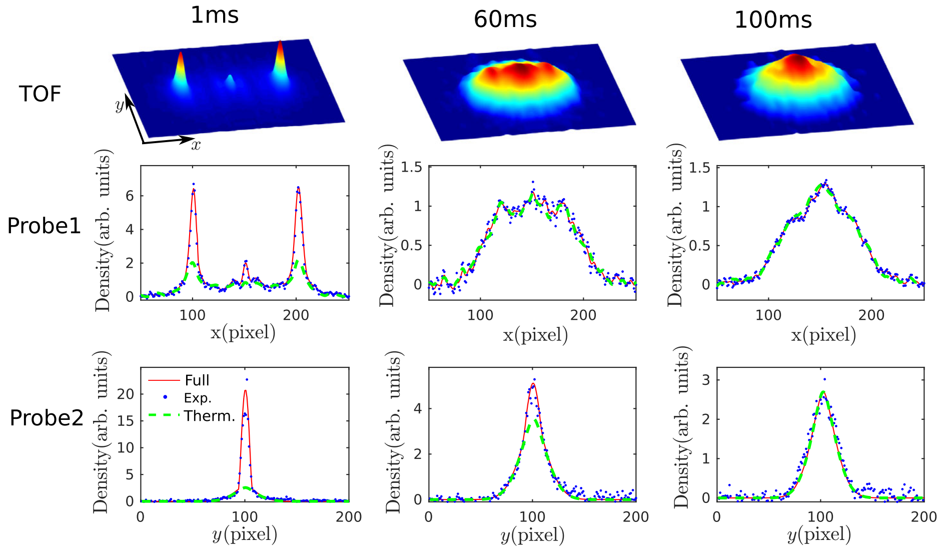

FIG. 2. Momentum distributions measured at three different holding times $t_0 = 1, 60, 100$ ms, along different directions. The images shown in the first row represent experimental TOF measurements in the xy plane by probe 1 (see main text), and the corresponding momentum distribution in the central line along the $\hat{x}$ direction is given in the second row with blue dots. The red solid line gives a full fitting line, while the green dashed line gives the distribution of the thermal component. Atomic distribution in the S band (P band) is revealed in the first (second) Brillouin zone. The third row shows the atomic distribution along the central line in the $\hat{y}$ direction for the experimental images in the yz plane measured by probe 2. Experimental results shown here are taken at temperature 120 nK and lattice depth $V_0 = 5E_r$.

Here, we report on an observation of a sliding phase superfluid in a dynamical system of ultracold atoms loaded into the P band of an optical lattice. Our Letter goes beyond previous studies in P-band optical lattices focused on static phases [30–32], by considering nonequilibrium aspects. We have a three-dimensional quantum gas confined with a one-dimensional lattice, sliced into "pancakes" (Fig. 1). Using an adiabatic short passage [33,34] to load atoms into the zero quasimomentum state in the P band, the system is driven far out of equilibrium. The loading method has been used in our previous experiments to study atomic interference between different energy bands [35] and longtime evolution [36]. As in previous works, the coherent fraction is extracted from the interference pattern to explore phase coherence [37–39]. During the rethermalization process, a metastable region is observed, where the atomic sample shows strong phase coherence in the pancake directions, but no coherence in the lattice direction. These observations imply the first experimental discovery of the sliding phase superfluid in the time domain, which is extremely challenging to reach in equilibrium according to the field theoretical analysis [1,40]. This Letter may also shed light on the high-T_c mechanism in light-probed cuprates [16,17].

Experimental procedure.—The experiment is performed with a Bose-Einstein-Condensate (BEC) of ^{87}Rb prepared in a hybrid trap with the harmonic trapping frequencies $(\omega_x, \omega_y, \omega_z) = 2\pi \times (28, 55, 60\,\mathrm{Hz})$ [34]. A one-dimensional optical lattice is produced by a standing wave with the lattice constant $d = \pi/k = 426$ nm along the x axis with k as the wave number. As shown in Fig. 1(a), atoms are confined in more than 50 discrete pancakes in the yz plane, and the sizes of the condensate in the $\hat{y}$ and $\hat{z}$ directions are about $L_y = 15.6$ and $L_z = 14.9$ μm, respectively. The number of atoms in the trap is about 10^5.

A shortcut method with the designed pulse sequences is applied to load atoms into the P band of the optical lattice (see Fig. 1 and Supplemental Material [41]). The loading pulse sequence consists of two sets of pulses whose nodes are shifted in the $\hat{x}$ axis by half of the lattice constant [33]. We stress here that, after loading to the zero quasimomentum state of the P band, the quantum system is driven to a far-out-of-equilibrium but at the same time phase-coherent state. The short-time collisional dynamics of P-band bosons has previously been observed [42]. We hold the condensate in the P band for a certain amount of time t_0 and let the system evolve, then the TOF images are taken after 28 ms of free flight in two probe directions—probe 1 and probe 2, to be described below.

For the probe from the $\hat{z}$ direction (probe 1), the lattice potential is switched off adiabatically, this band mapping procedure enables measurements of the atomic population in each band. From such images at different times t_0, we can quantitatively determine the time-dependent proportion of atoms between the S and P bands, as shown in Fig. 1(d). We investigate the dynamical phase during the decay process from the excited P band to the S band. The probe from the $\hat{x}$ direction is performed by an abrupt nonadiabatic switch off of the lattice, as shown in Fig. 1, which is referred to as probe 2. The distribution is analyzed via a bimodal fitting, with a parabola superimposed on a

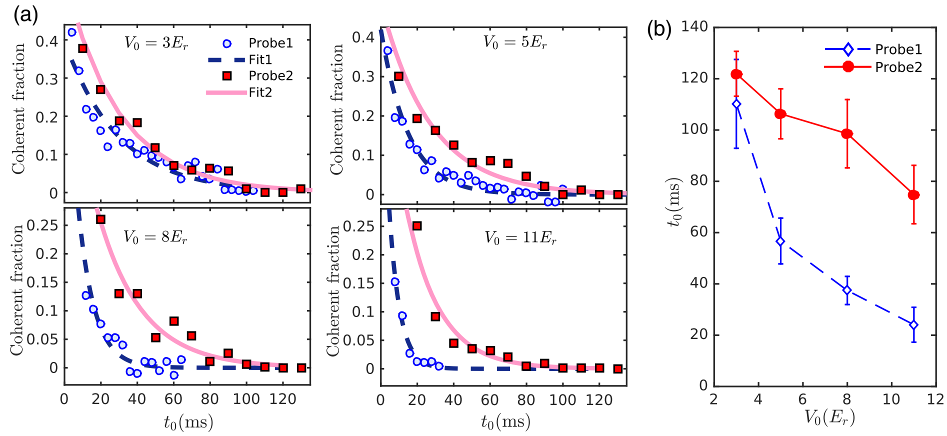

FIG. 3. (a) The coherent fraction measured by probes 1 and 2 with the different holding times for $V_0 = 3E_r$, $5E_r$, $8E_r$, and $11E_r$, respectively. (b) The time t_0 for the atoms to lose coherence in lattice and pancake directions with different optical-lattice depths. The blue "diamonds" are for the $\hat{x}$ direction (lattice) by probe 1 and the "dotted" points are for the $\hat{y}$ direction (pancake). Error bars are given by the 95% confidence interval of fitting result. We find the time dependence of the coherent fractions fits to a form of $Ae^{-t/\tau}$ with A as the amplitude and τ as the characteristic time. The starting (ending) point of the sliding phase superfluid is defined by the time t_0 when the coherent fraction in the lattice (pancake) direction vanishes. With a relatively shallow lattice, say lattice depth $V_0 = 3E_r$, there is essentially no difference in the time dependence of the coherent fractions in lattice and pancake directions, which means a shallow lattice does not support the intermediate sliding phase superfluid. With a deeper lattice, we find a significant difference in coherent fractions for lattice and pancake directions, leading to two dynamical timescales and an intermediate time window supporting the sliding phase superfluid. The sliding phase lifetime can be systematically improved upon, increasing lattice depth. Experimental results shown here are taken at a temperature of 120 nK.

Gaussian function [43,44]. From the bimodal fitting, we extract the coherent fraction so that the phase coherence of the dynamical many-body state can be inferred (see Supplemental Material [41] for more details).

Observation of the sliding phase superfluid.—In order to characterize the real-time dynamics after the P band gets occupied, we measure momentum distributions in the lattice (probe 1) and pancake (probe 2) directions at the different holding times (Fig. 2). Since the system is approximately rotation symmetric in the yz plane, the momentum distribution in the $\hat{z}$ direction is equivalent to that in the $\hat{y}$ direction and is thus not shown here. From the time evolution, we identify three distinct dynamical regions. At early time—the first stage—the system has superfluid phase coherence in all three directions, which is clearly demonstrated through the sharp peaks observed in the momentum distribution shown in Fig. 2 at $t_0 = 1$ ms. A bimodal fitting shows the system is coherent in all directions. At late time—the final stage after about 100 ms—the quantum gas has rethermalized with a complete loss of phase coherence. The bimodal fitting (see Fig. 2) shows all atoms are thermal in the complete absence of any condensed component. There is yet an intermediate time region with significant time duration where the phase coherence of the quantum system survives partially. The bimodal fitting in Fig. 2 at 60 ms shows that there is a finite condensed component in the pancake directions, but no such component in the lattice direction. In this intermediate region, the phase coherence in the lattice direction already disappears, whereas the coherence in the pancake directions still persists, as revealed by momentum distributions.

The evolution of phase coherence in the three stages is described by a time-dependent correlation function,

$$\langle \hat{\phi}^\dagger(\mathbf{r}, t)\hat{\phi}(\mathbf{r}', t)\rangle \propto \exp(-|\mathbf{r}_x - \mathbf{r}'_x|/\xi_x - |\mathbf{r}_y - \mathbf{r}'_y|/\xi_y - |\mathbf{r}_z - \mathbf{r}'_z|/\xi_z), \qquad (1)$$

where $\hat{\phi}(\mathbf{r}, t)$ is the bosonic field operator with spatial coordinate $\mathbf{r}$, and $\xi_{x,y,z}$ is the superfluid correlation length in the three directions. At the first stage, the three correlation lengths diverge or, equivalently, are comparable with the system size, whereas at the final stage, the correlation lengths are all finite. In the intermediate time region, we have divergent correlation lengths in the yz plane, i.e., $\xi_{y,z} \sim L$ with L the system size, but finite correlation length in the x direction, i.e., $\xi_x/L \to 0$. The peculiar dynamical phase in the intermediate time region represents the long-sought-after sliding phase superfluid—each pancake is phase coherent, but the relative phase across different pancakes is sliding. We find that the sliding phase phenomenon is mainly supported by atoms in the P band (see Supplemental Material [41]).

Phase lifetime.—To test the robustness of the dynamical sliding phase superfluid, we measure its lifetime in dynamics. In the experiment, the lifetime is defined from time-dependent phase-coherent fractions in pancake and lattice directions, which are extracted from the momentum distributions (see Supplemental Material [41]). Experimental

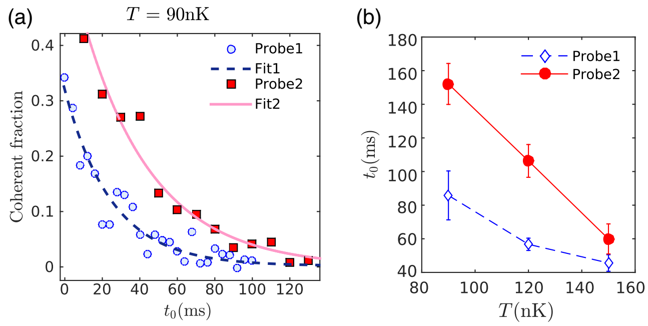

FIG. 4. (a) The coherent fraction with different holding times for a lower atomic temperature $T = 90$ nK at $V_0 = 5E_r$. (b) The time (t_0) for atoms to lose coherence in lattice and pancake directions at different temperatures, which is extracted from an exponential fit of the coherent fraction (see Supplemental Material [41]). By increasing the temperature, we find the intermediate time window supporting the sliding phase gets smaller with larger thermal fluctuations. The temperature dependence indicates the sliding phase lifetime can be further improved by cooling down to a lower temperature. Error bars are given by the 95% confidence interval of fitting result.

results are shown in Fig. 3. We find that, with the total atom number fixed in the experiment, there appears a critical lattice depth ($V_0 = 3E_r$ in our experiment) beyond which the sliding phase superfluid starts to emerge. We expect the phase coherence starts to form from the pancakes in the trap center, as those ones have relatively larger density and consequently larger superfluid stiffness. It is worth emphasizing that at $V_0 = 3E_r$ the P-band tunneling is still significant (around $0.5E_r$ [30]). As we increase the optical lattice depth further, the sliding phase superfluid becomes more robust in dynamics. For both lattice and pancake directions, a deeper lattice causes an overall decrease in the decay time of the coherence, owing to the increase of the interaction, which accelerates the condensate depletion. But the coherence decay time for the lattice direction is affected more compared to the pancake directions, leading to a widening time window that supports the intermediate sliding phase superfluid.

For completeness, we also examine finite temperature effects on the dynamical sliding phase. We note here that the temperature in the following refers to that of the atomic gas before loading into the lattice. Comparing the results at temperature $T = 90$ nK [Fig. 4(a)] with $T = 120$ nK [Fig. 3(a)], the phase coherence gets more robust against decay at lower temperature, as expected. The lifetime of the sliding phase superfluid depends on the relative coherence robustness in lattice and pancake directions. In the experiment, we find the coherence decay time in the pancake direction is more prone to temperature effects compared to the lattice direction and increases more upon temperature decrease. This leads to a systematic increase in the lifetime of the intermediate sliding phase superfluid [see Fig. 4(b)] as the system is cooled down to a lower temperature.

Phenomenological theory for the sliding phase.—The emergence of the sliding phase in the time domain can be qualitatively captured by a P-band model [30],

$$H = \int d^2\mathbf{r}\Big\{\sum_j p_j^\dagger(\mathbf{r})\Big[-\frac{\hbar^2}{2M}\vec{\nabla}^2 - \mu - V_{\mathrm{trap}}(\mathbf{r})\Big]p_j(\mathbf{r}) + J_p\sum_{\langle j,j'\rangle} p_j^\dagger(\mathbf{r})p_{j'}(\mathbf{r}) + g\sum_j p_j^\dagger p_j^\dagger p_j p_j\Big\}, \quad (2)$$

where p_j ($p_j^\dagger$) is the annihilation (creation) field operator, $\langle j, j'\rangle$ represents nearest neighboring lattice sites, V_{trap} is the harmonic trap potential, J_p is the tunneling in the lattice direction, and g represents the interaction strength. Atoms are initially prepared at the P-band maximum, so the system is dynamically unstable [45–47]. The coherence in the lattice direction is then quickly lost, during which the kinetic energy in the lattice direction can be converted into kinetic energy in the pancake directions. This cross-dimensional energy transfer is expected to be the order of tunneling J_p. Since the gas is continuous in each pancake, the in plane (yz plane) degrees of freedom would quickly relax and acquire an effective temperature description. The effective temperature of each pancake is estimated from energy conservation to be

$$k_B T_{\mathrm{eff}} \sim [N(\hbar\omega)^2 J_p/L_x]^{1/3}, \quad (3)$$

which is obtained at the weak interaction limit (see Supplemental Material [41]). Here k_B is the Boltzmann constant, ω is the trap frequency in the yz plane, N is the total particle number, and L_x is the number of lattice sites in the x direction. The number of thermal atoms is to the order of

$$N_{\mathrm{therm}} \sim N[(J_p/\hbar\omega)^2 L_x/N]^{1/3}. \quad (4)$$

The excessive atoms then remain condensed, giving rise to the phase coherence in each pancake. With particle number being fixed, we have a critical value of J_p, and consequently a critical lattice depth, for the sliding phase to emerge, which is qualitatively consistent with experimental observations. In creating the sliding phase superfluid, the role of the P band is to enable an efficient preparation of the BEC in a dynamically unstable region using an adiabatic shortcut method developed in our experiments [33]. Considering higher bands with odd parity is expected to support the dynamical sliding phase in a similar fashion.

On a microscopic level, modeling the sliding phase phenomena demands theoretical treatment of correlated dynamics in weakly coupled XY models beyond Gross-Pitaevskii treatment to carefully take into account thermal excitations. A quantitative description is expected to be nontrivial, for example, whether thermal atoms could act as effective disorder, previously proposed to stabilize the sliding phase [48], is worth consideration.

Conclusion.—To conclude, through quantum dynamics of ultracold atoms loaded in the excited band, our measurements unveil a sliding phase superfluid. This sliding phase appears due to thermalization timescale separation for discrete and continuous degrees of freedom. The robustness of the dynamical phase has been tested by increasing lattice depth and temperature. This potentially opens up a novel route to search for metastable correlated phases with ultracold atoms driven far out of equilibrium. The intricate exotic phases challenging to achieve in thermal equilibrium or the quantum ground state might find their natural realization in nonequilibrium settings. This Letter is also expected to shed light on understanding the high-T_c mystery in the nonequilibrium layered cuprates.

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