Monitoring and manipulating Higgs and Goldstone modes in a supersolid quantum gas

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Higgs and Goldstone modes are collective excitations of the amplitude and phase of an order parameter that is related to the breaking of a continuous symmetry. We directly studied these modes in a supersolid quantum gas created by coupling a Bose-Einstein condensate to two optical cavities, whose field amplitudes form the real and imaginary parts of a U(1)-symmetric order parameter. Monitoring the cavity fields in real time allowed us to observe the dynamics of the associated Higgs and Goldstone modes and revealed their amplitude and phase nature. We used a spectroscopic method to measure their frequencies, and we gave a tunable mass to the Goldstone mode by exploring the crossover between continuous and discrete symmetry. Our experiments link spectroscopic measurements to the theoretical concept of Higgs and Goldstone modes.

Collective excitations provide a unifying concept across different subfields of physics, from condensed matter (1) to particle physics (2) to cosmology (3). Major advances in the description of phase transitions that break continuous symmetries originated from the concept of massless and massive excitations, as introduced by Goldstone in (4, 5).

Goldstone considered the paradigmatic case of models with U(1)-symmetry breaking, where the system can be described by a complex scalar order parameter \( \alpha = \alpha_1 + i \alpha_2 = |\alpha|e^{i\phi} \), with amplitude \( |\alpha| \) and phase \( \phi \), and an effective potential that is formed by the free energy of the form \( V(\alpha) = r|\alpha|^2 + g|\alpha|^4 \), with real-valued coefficients \( r, g \) (Fig. 1, A and B) (6). In the normal (nonordered) phase with \( r, g > 0 \), the order parameter is zero because the potential is bowl-shaped with a single minimum at \( \alpha = 0 \) and the symmetry is preserved (Fig. 1A). Within the ordered phase with \( r < 0 \), the potential shape changes to resemble a sombrero with an infinite number of minima on a circle with radius \( |\alpha| > 0 \) (Fig. 1B). In this phase, fluctuations of the order parameter reveal two different excitations: a Higgs (or amplitude or massive Goldstone) mode, which stems from amplitude fluctuations at constant phase and shows a finite excitation energy owing to the radial curvature of the effective potential, and a Goldstone (or phase) mode, which stems from phase fluctuations at constant amplitude and has vanishing excitation energy. This idealized situation is often altered—for example, by a coupling between amplitude and phase excitations suppressing the Higgs mode (7) or, for charged particles, by the Anderson-Higgs mechanism suppressing the Goldstone mode (2).

Despite their conceptual relevance, it has remained a challenge to observe the Higgs and Goldstone modes directly in the same system, because this requires time-resolved access to both the amplitude and the phase of the order parameter. The modes have had to be observed using spectroscopic measurements instead. Examples include experiments on the Higgs mode in solid-state systems (8–11) and with cold atoms in two-dimensional optical lattices (12). Experiments on the Goldstone mode have been carried out, for example, in superfluid helium (13) and Bose-Einstein condensates (BECs) (14). Time-resolved studies have been limited to relaxation measurements of the amplitude of the order parameter in superconductors (15), but without access to the phase of the order parameter.

In this work, in contrast, we probed and monitored both a Higgs and a Goldstone mode in real time and directly verified their amplitude and phase character (Fig. 1C). We used two optical cavities whose modes were oriented at a 60° angle and overlapped with a BEC of \( 2.02(6) \times 10^{13} \) ⁸⁷Rb atoms. A spatial U(1)-symmetry breaking was induced by coherently driving the BEC with a standing-wave transverse pump beam at a wavelength of 785.3 nm and variable intensity. The transverse pump was far-detuned from the atomic resonance but closely tuned to the resonance frequencies of the cavity modes, which were equally coupled to the atoms (16). The transverse pump and the cavity modes induced two-photon scattering processes, transferring atoms between the BEC and excited momentum states (17). For small two-photon couplings, these processes induce fluctuations, but the system remains in the normal phase, because the kinetic energy associated with the excited momentum states cannot be overcame. As soon as the coupling strength exceeds a critical value, the kinetic energy is overcome and the system enters a self-organized phase with coherent fields in the cavity modes. In real space, the macroscopically occupied momentum states correspond to a periodic density modulation along \( z \), perpendicular to the transverse pump lattice. The global coupling of the atoms to the cavity modes results in a perfectly rigid crystal structure.

With equal coupling of the atoms set to both cavities, the photon scattering into each of them is energetically equivalent. Therefore, the mean total intracavity photon number \( n = n_1 + n_2 = c_1^2 + c_2^2 \) is constant, but the ratio of the intracavity photon numbers \( n_1 \) and \( n_2 \) can take arbitrary values. This realizes a continuous symmetry breaking of the order parameter \( \alpha = \alpha_1 + i\alpha_2 \), whose real and imaginary parts are formed by the cavity fields \( c_1 \) and \( c_2 \). By detecting the photons leaking from the cavity mirrors on single-photon detectors, we continuously monitored the order parameter along both components. Each ratio of the cavity fields corresponds to a different displacement of the density modulation along the \( z \) axis (Fig. 1C). The broken translational symmetry and the superfluidity of the cloud identify the state as a supersolid (16).

We first spectroscopically studied the collective excitations associated to the translational symmetry breaking of the quantum gas. To this end, we used cavity-enhanced Bragg spectroscopy, where probe photons are injected on-axis into one cavity and create or destroy collective excitations by photon scattering into the transverse pump or vice versa. Our technique takes advantage of two key properties of optical cavities: enhancement of Bragg scattering and realtime access to the intracavity fields. The energy scale of the excitations was determined by the corresponding atomic recoil frequency, which is \( \delta_{\text{atomic}}/2\pi = 3.7 \) kHz for a transverse pump photon (18). We prepared the system at a fixed transverse pump lattice depth and subsequently injected an on-axis probe field into either of the cavities with time-varying detuning \( \delta(t) \) relative to the transverse pump frequency. In terms of the effective potential, the probe field perturbed the order parameter along the component corresponding to the probed cavity field (Fig. 1). We scanned \( \delta \) linearly in time from negative to positive detunings and recorded the intracavity photon numbers, consisting of the probe light and the light scattered off the created excitations. Our technique is related to Bragg spectroscopy in quantum gases (19, 20) and can be regarded as a frequency-dependent extension of the method presented in (21).

We performed spectroscopic measurements at different coupling strengths below and above the critical point by varying the transverse pump lattice depth. We used three probing strategies, one in the normal phase and two in the ordered phase, to address the different expected modes (Fig. 2, A to C). In the normal phase, we applied a weak probe field on initially unpopulated cavity modes and observed symmetric resonances at positive and negative \( \delta \) (Fig. 2A). The slight difference in the amplitudes is the result of the time evolution during the probing (17). In the ordered phase, two measurement methods were used to spectroscopically detect the presence of two modes, in which the following will be identified as the Higgs and the Goldstone modes, but here are...
already labeled accordingly. For the Higgs mode, the response to a weak probe field cannot be discriminated from the noise of the finite cavity fields. Therefore, we applied the frequency ramp \( \delta(t) \) with larger probe powers, during which we observed a decay of intracavity photon numbers, which accelerated toward specific \( \delta \) (Fig. 2B). The extracted decay rate showed two resonance features at the corresponding positive and negative \( \delta \) (Fig. 2B, inset). We interpret this observation as resulting from a resonant increase in the number of excitations, which continuously decay, thereby heating the sample and decreasing the order parameter. Owing to its phase character, the Goldstone excitation is always orthogonal to the direction

**Fig. 1. Higgs and Goldstone modes for a U(1) symmetry.** In (A) and (B), effective potential in the normal and ordered phases is shown as a function of the order parameter \( \alpha = \alpha_1 + i\alpha_2 = |\alpha|e^{i\theta} \). (A) In the normal phase, two excitations, \( \delta\alpha_1 \) and \( \delta\alpha_2 \), correspond to fluctuations of the order parameter along each component. Both excitations have an amplitude character involving one component of the order parameter. (B) In the ordered phase, Higgs and Goldstone modes describe amplitude (\( \delta|\alpha| \)) and phase (\( \delta\phi \)) fluctuations around a finite expectation value of the order parameter. The squares of the components show either correlations (Higgs) or anticorrelations (Goldstone). (C) Illustration of the experiment. A Bose-Einstein condensate (blue stripes) is cut into slices by a transverse pump lattice potential along \( y \) (red stripes) and enters a supersolid state with a density modulation along \( x \) breaking translational symmetry. This state is signaled by the occupation of two cavity modes \( \alpha_1 \) (red) and \( \alpha_2 \) (yellow) with photons that can be detected when leaking from the cavity mirrors (wave-packet arrows). The emerging Higgs and Goldstone excitations correspond to fluctuations of the strength and position of the density modulation, as shown in the zoom-in for one slice. They can be excited with probe pulses on each cavity (the red arrow shows this for one cavity as an example).

**Fig. 2. Excitation spectrum across the phase transition.** Shown in (A) to (C) is the response of the intracavity photon number to a probe field, which is injected into one cavity, as illustrated in Fig. 1C (red arrow). Pink lines show the mean photon numbers for cavity 1, binned in intervals of 0.2 ms and averaged over at least 10 realizations. Red lines show fits from a theoretical model (17). (A) Response in the normal phase [transverse pump lattice depth of 16.7(4) \( \hbar a_{\text{rec}} \), where \( \hbar \) is the reduced Planck constant] with \( \alpha_1 = \alpha_2 = 0 \) to a probe field in cavity 1 with a mean photon number \( \bar{n}_1 = 3.4(2) \) whose frequency is ramped by 1 kHz/ms. (B) Response in the ordered phase [lattice depth, 35.9(8) \( \hbar a_{\text{rec}} \)] with \( \alpha_1 \neq 0 \) and \( \alpha_2 = 0 \) to a probe field in cavity 2 with \( \bar{n}_2 = 3.4(1) \) whose frequency is ramped by 1 kHz/ms. Because in this situation, the probe field is applied on top of a populated cavity mode (note the different scale for \( \bar{n}_1 \)), we determine the resonance from the decay of intracavity photons owing to heating caused by decaying excitations. The inset displays the inferred negative derivative of the photon trace, representing the response as a function of \( \delta \). The fit accounts for the resonance at negative frequency only to limit the influence from the decaying order parameter. (C) Response in the ordered phase [lattice depth, 35.9(8) \( \hbar a_{\text{rec}} \)] for \( \alpha_1 \neq 0 \) and \( \alpha_2 = 0 \) to a probe field in cavity 1 with \( \bar{n}_1 = 0.06(1) \) whose frequency is ramped by 0.2 kHz/ms. (D) Resonance frequencies for the normal phase (circles) and the ordered phase at high and low frequencies (triangles and squares, respectively) extracted from the response to probe pulses in cavity 1 (red) and 2 (yellow). The gray-shaded area shows the theoretical prediction, including experimental uncertainties (17). Error bars combine fit errors and the uncertainty of the probe frequency.
of the order parameter (Fig. 1B). Therefore, we can prepare a purely real or imaginary order parameter, corresponding to only one of the cavities being populated, and probe it orthogonally—i.e., on the empty cavity. To this end, we prepared the system with a slight imbalance in the cavity detunings, energetically favoring occupation of photons in only one cavity. This imbalance was removed before applying a weak probe field on the empty cavity and detecting the response (Fig. 2C). Depending on the coupling in a particular measurement, we adjusted the probe power to a value within the range of \( \Delta_2 = 0.06(1) - 3.4(2) \) to compensate for the increasing susceptibility of the system on approach to the critical point. The signals could be obtained by probing either of the cavities. The resonance frequencies of the excitations were extracted from the spectra in Fig. 2, A to C, by fitting the data with a theoretical model that accounts for atomic and cavity decay, as well as the time evolution, during the probe (17).

The combined result is shown in Fig. 2D. In the normal phase, we observed decreasing resonance frequencies on approach to the critical point. When entering the ordered phase, two branches appeared, one remaining at frequencies small compared with \( \omega_{\text{ac}} \) and the other showing increasing frequency values as the pump power was increased. The measurements for the two cavities agree well over the entire covered range. The excitation frequencies can be well described with a microscopic model (17), which is related to previous theoretical work on spin systems with continuous symmetries (22–24).

The separation of the excitation frequencies inside the ordered phase into a high- and a low-frequency branch suggests an interpretation in terms of a Higgs and a Goldstone mode. To carry out a direct test of the distinctive amplitude and phase character of the modes, we exploited the fact that the two cavity fields form the real and the imaginary parts of the order parameter. We studied the excitation dynamics induced by a strong probe pulse with constant detuning and a length of 1 ms, sufficiently long to keep the spectral width smaller than the frequency gap between the two excitations. After a pulse at \( \delta/2\pi = 2.5 \) kHz, we observed correlations between the intracavity photon numbers of the two cavities (Fig. 3A). When converting the real-time evolution of the intracavity photon numbers into polar coordinates, we found a periodic amplitude modulation at constant phase, the signature of the Higgs mode (Fig. 3A, inset). The evolution of the light fields showed a damping of the amplitude mode over \( \approx 15 \) ms, accompanied by a decreasing order parameter.

After applying a pulse at \( \delta/2\pi = 0.5 \) kHz, anticorrelations between the intracavity photon numbers of the two cavities were detected (Fig. 3B). The transformation into polar coordinates showed a dominant phase modulation, the signature of the Goldstone mode (Fig. 3B, inset). The persisting low-frequency Goldstone mode was overlaid by a second fast-oscillating phase mode that decayed within \( \approx 15 \) ms. The reduced lifetime of the Higgs mode compared with that of the Goldstone mode is consistent with coupling to an increased number of Bogoliubov modes that are available at the frequency of the Higgs mode. The residual noise level is dominated by shot noise from the photon detection.

Because the cavity fields and the transverse pump create a dipole potential for the atoms, the observed dynamics of the intracavity photon numbers are intimately linked to the evolution of the atomic density (Fig. 3C). The Higgs mode is an excitation of the amplitude of the atomic density modulation, because it implies fluctuations in the total number of photons in the two cavities and therefore a modulation of their lattice depths. The Goldstone mode instead is an excitation of the phase of the density modulation, which translates the lattice along the \( x \) axis at constant amplitude while redistributing photons from one cavity to the other via the pump field at constant total photon number.

The global nature of the cavity-mediated coupling suppresses Higgs and Goldstone excitations at nonzero wave numbers (25, 26), different from the theoretically expected spectrum in supersolid helium (27). Despite the density modulation being one-dimensional, the global interaction leads to a system with effectively infinite dimensions. As a consequence, the Mermin-Wagner-Hohenberg theorem does not apply, and continuous symmetry breaking is possible (6). In addition, the system exhibits a Lorentz-invariant time evolution, which is a prerequisite for the independent presence of Higgs and Goldstone modes (1):

Specifically, our system exhibits a formal invariance under the exchange of \( \alpha_1 \) and \( \alpha_2 \), analogous to the particle-hole symmetry in, for example, superconductors and optical lattices at half filling. Furthermore, finite-temperature effects are not expected to overdamp the Goldstone mode (28).

A hallmark of the Goldstone mode is its sensitivity to deviations from the continuous symmetry. Goldstone modes only show a vanishing excitation frequency for perfect symmetries in the absence of symmetry-breaking fields or further interactions. Analogous behavior is known, for example, in the context of chiral symmetry breaking, approximate symmetries, extra dimensions, and the mass hierarchy problem (29, 30). The continuous symmetry that is broken in our system is the result of balanced coupling to two
cavities, whose individual self-organization processes break parity symmetry only. We can generate an adjustable symmetry-breaking field along each component of the order parameter individually by controlling the coupling to each cavity mode through its detuning from the transverse pump frequency $\Delta$. A nonzero imbalance $\Delta$ favors photon scattering into the more strongly coupled cavity and leaves the other cavity unpopulated. The evolution of the resonance frequency of the Goldstone mode for various $\Delta$ around the balanced situation is shown in Fig. 4. It tends toward zero for vanishing $\Delta$ and increases for larger $|\Delta|$, approaching the soft mode associated with the phase coherence of the supersolid ($31$). A promising extension to our work would be to add contact interactions among the atoms ($32$, $33$) and observe the dynamics of a crystallizing strongly correlated one-dimensional system. Furthermore, our experiments provide a path to exploring the dynamics of quantum chaotic behavior and broken time-translational symmetry ($34$).

**REFERENCES AND NOTES**

17. Materials and methods are available as supplementary materials.

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**SUPPLEMENTARY MATERIALS**

www.sciencemag.org/content/358/6369/1415/suppl/DC1 Materials and Methods Figs. S1 to S4 References (35–37)

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Breaking the symmetry in a supersolid

The concept of broken symmetry has relevance across all branches of physics, including particle and condensed matter physics. In many cases, the shape of the potential energy resembles a Mexican hat, and the symmetry of the system is broken when it chooses a particular spot along the "trough" of the hat. Out of this minimum-energy state, the system can undergo collective excitations either along the trough or perpendicular to it. Léonard et al. detected these so-called Goldstone and Higgs modes in a supersolid Bose-condensed atomic gas held in two crossed optical cavities. By monitoring the dynamics of the light field in each cavity, the oscillations of the order parameter associated with both modes were observed in real time. Science, this issue p. 1415