An Ideal Mean-Field Transition in a Modulated Cold Atom System

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We show that an atomic system in a periodically modulated optical trap displays an ideal mean-field symmetry-breaking transition. The symmetry is broken with respect to time translation by the modulation period. The transition is due to the interplay of the long-range interatomic interaction and nonequilibrium fluctuations. The observed critical dynamics, including anomalous fluctuations in the symmetry broken phase, are fully described by the proposed microscopic theory.

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The mean-field approach has been instrumental for developing an insight into symmetry breaking transitions in thermal equilibrium systems [1]. It has been broadly applied also to nonequilibrium systems, the studies of pattern formation being an example [2]. However, close to the phase transition point the mean field approximation usually breaks down. This happens even in finite-size systems provided they are sufficiently large.

In this paper we study a nonequilibrium system of $\sim 10^7$ particles which, as we show, displays an ideal mean-field symmetry breaking transition. It is accompanied by anomalous fluctuations, which are also described by a mean-field theory. The system is formed by moderately cold atoms in a magneto-optical trap (MOT) [3, 4]. The atoms are periodically modulated in time [5]. Periodically modulated systems form one of the most important classes of nonequilibrium systems, both conceptually and in terms of applications. They have discrete time-translation symmetry: they are invariant with respect to time translation by modulation period τ_F. Nevertheless, they may have stable vibrational states with periods that are multiples of τ_F, in particular $2\tau_F$. Period doubling is well-known from parametric resonance, where a system has two identical vibrational states shifted in phase by π. It is broadly used in classical and quantum optics and has attracted significant attention recently in the context of nano- and micro-mechanical resonators [6–9].

In a many-body system, dynamical period doubling in itself does not break the time translation symmetry. This is a consequence of fluctuations. Even though each vibrational state has a lower symmetry, fluctuations make the states equally populated and the system as a whole remains symmetric. However, if as a result of the interaction the state populations become different, the symmetry is broken. It is reminiscent of the Ising transition where the interaction leads to preferred occupation of one of the two equivalent spin orientations, except that the symmetry is broken in time. For atoms in a parametrically modulated MOT spontaneous breaking of the discrete time-translation symmetry was observed experimentally by Kim *et al.* [10].

Here we show that the time-translation symmetry breaking in a modulated MOT results from the cooperation and competition between the inter-particle interaction and the fluctuations that lead to atom switching between the vibrational states. The interaction is weak. On its own, it cannot change the state populations. However, it may become strong enough to change the rates of fluctuation induced switching, which in turn will cause the population change. We provide a quantitative theory of the phenomenon. We measure the critical exponents and the frequency dispersion of the susceptibility. The observations are consistent with the mean-field behavior and are in good agreement with the theory.

In the experiment, ^{85}Rb atoms in a MOT were cooled down to $\approx$0.4 mK. Full three-dimensional confinement was achieved with three pairs of counter-propagating laser beams. The intensity of the beams along the MOT axis z was 0.19 mW/cm^2, the transverse beam intensities were 5 to 10 times larger. The magnetic field gradient at the trap center was 10 G/cm. The transverse beams were detuned from the atomic transition by $\delta \approx -2.3\Gamma_p$, the longitudinal beams were further detuned by 5 MHz (the atomic decay rate is $\Gamma_p/2\pi \approx 5.9$ MHz). The atomic cloud motion was essentially one-dimensional, along z-axis, with frequency $\omega_0/2\pi \approx 45$ Hz and the damping rate $\Gamma \approx 36\ \mathrm{s}^{-1}$. The total number of trapped atoms $N_{\rm tot}$ was varied by changing the hyperfine-repumping laser intensity at a decrease rate of 0.5% per second. For the order parameter and the variance measurements very close to criticality, the decrease rate was reduced to 0.03%.

The beam intensities were modulated at frequency $\omega_F = 2\omega_0$ by acousto-optic modulators. When the modulation amplitude exceeded a threshold value, after a transient, the atomic cloud split into two clouds [5], which were vibrating in counter-phase with frequency $\omega_F/2$, see Fig. 1a. We took snapshots at the maximum separation of the clouds at the frame rate of 1-50 Hz to obtain the

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