Realization of a continuous time crystal in a photonic metamaterial

Time crystals are a new state of matter. Conventional crystal properties are periodic in space, while the properties of a time crystal are periodic in time. A continuous quantum time crystal has recently been realized, and now, using optically driven many-body interactions in a nano-mechanical photonic metamaterial, a classical continuous time crystal has been created.

The question

Since their prediction[1] in 2012, 'time crystals' have been eagerly sought. Their properties are periodic in time, rather than in space (as conventional crystals' are). Time crystals break time-translation symmetry. Discrete time crystals do so by oscillating under the influence of a periodic external parametric force, and this type of time crystal has been demonstrated in trapped ions, atoms and spin systems. Continuous time crystals are more interesting and arguably more important: they exhibit continuous time-translation symmetry but can spontaneously enter a regime of periodic motion, induced by a vanishingly small perturbation. It is now understood that this state is only possible in an open system, and a continuous quantum-time-crystal state has recently been observed in an ultracold atomic condensate inside an optical cavity illuminated with light[2]. But can this state be realized in a classical system?

The solution

We have demonstrated a classical continuous time crystal. It is realized as a two-dimensional array of plasmonic metamolecules (each metamolecule consists of three gold nanorods arranged in a Π shape), supported on neighbouring pairs of flexible nanowires (mechanical oscillators). If the nanowires are mutually displaced, there is a strong effect on the resonant plasmonic scattering of the metamolecules. This coupling between mechanical and optical properties of the lattice makes it possible to detect the state of the lattice through changes in its optical transmittivity.

The array can be driven to a continuous time-crystal state by light: illumination with a single continuous laser beam, at a wavelength resonant with the plasmonic modes of the metamolecules and above a certain threshold of intensity, spontaneously triggers strong periodic oscillation of the optical transmissivity; the oscillations result from many-body dipole–dipole interactions between metamolecules of the array, induced by the incident light, whereby the individual thermomechanical oscillations of nanowires are replaced by coherent, superradiant-like motion of the illuminated ensemble.

The transition to the coherent oscillatory regime shows hysteresis (Fig. 1) – it is a first-order phase transition. Once achieved, the time-crystal state persists over arbitrarily long times and is robust to small perturbations (such as fluctuations in laser power). The state exhibits long-range order in space, as manifested in synchronization of the illuminated ensemble; and long-range order in time, as seen in the robust persistence of synchronous oscillations.

Future directions

The nano-mechanical metamaterial continuous time crystals are easy to engineer for specific studies and applications: they are simple to fabricate (the design of the metamolecules determines the quality factors of resonances and bandwidth), and require no cryogenics, no ultra-high vacuum and no sophisticated lasers to stimulate a transition to the synchronized state. Numerous applications can be envisaged in all-optical modulation, frequency conversion and mixing, and timing. Moreover, the phenomenon is of interest to the study of dynamic classical many-body states in the strongly correlated regime, complementing the cold atom and spin platforms where many-body quantum states are investigated.

There is a choice of two candidates for the mechanism of the light-induced phase transition to a persistent oscillatory regime, the main feature of a time crystal. According to the Kuramoto model, synchronization can result from nano-mechanical nonlinearities in the system when the interaction strength exceeds a certain threshold. Intriguingly, it can also occur in the linear regime of oscillations, if non-reciprocal, non-Hamiltonian interaction forces between metamolecules are present. Such forces can emerge from the radiation pressure of scattered fields, which constantly pumps energy into the system[3]. It will be a matter of future research to investigate how the competition between these two sources of synchronization plays out in this classical continuous time crystal.

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EXPERT OPINION

"Many-body systems can spontaneously break time-translation symmetry and begin oscillations at a random phase due to many-body interactions. This study demonstrates the existence of a phase of matter called a 'continuous time crystal' in a photonic metamaterial by illuminating a 2D array of plasmonic metamolecules that interact via dipole–dipole interactions. Utilizing many-body phase transitions in photonics is an exciting route for future applications." **An anonymous reviewer.**

FIGURE

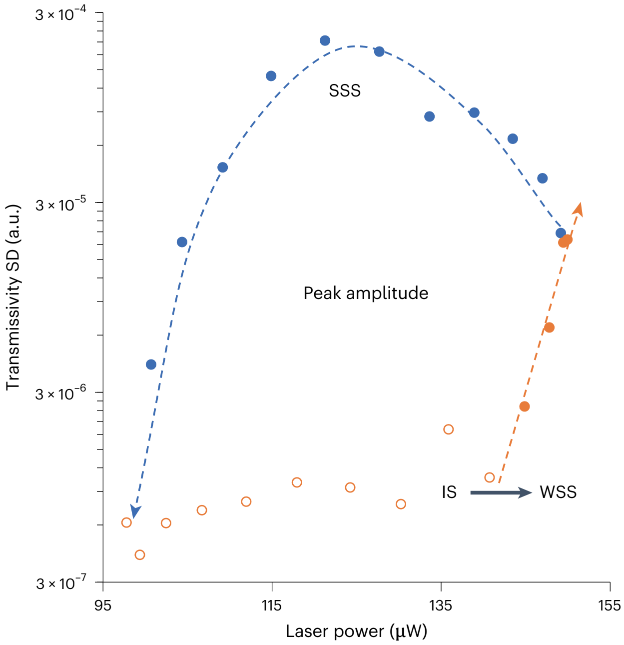

Fig. 1 | Synchronization as a first-order phase transition in a metamaterial analogue of a continuous time crystal. When an array of plasmonic metamolecules supported on an ensemble of flexible dielectric nanowires is illuminated by laser light, the wires' mutual displacement strongly affects the metamolecules' resonant optical properties. At low laser power (open orange circles), the array of nanowire oscillators is in an incoherent state (IS); with increasing laser power, a weakly synchronized state (WSS) emerges and the peak amplitude of transmittivity spectral density grows exponentially (filled orange circles). Finally, a strongly synchronized state (SSS) is reached, which persists even as the laser power is reduced (blue circles), until the oscillations become incoherent once again. This kind of hysteresis loop is characteristic of a first-order phase transition. © 2023, Liu, T. et al., CC BY 4.0.

BEHIND THE PAPER

Our research programme initially targeted the study of picometric Brownian and ballistic thermal motion dynamics[4] in nanomechanical cantilevers and beams — the building blocks of nano-opto-mechanical metamaterials and the manifestations of thermal motion in the optical properties of nanostructures[5]. In the course of this work, we realized that light-induced interaction can compete with the forces of elasticity at the nanoscale. It was logical then to look at many-body effects in optically driven ensembles of oscillators, but the ability to achieve a new state of matter — the continuous time crystal state — in a classical system came as an unexpected gift of nature. **N.I.Z.**

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FROM THE EDITOR

"The term 'time crystal' sounds quite sci-fi and has in the past created some buzz in the media. But the reality is that they have only been realized under stringent experimental conditions. This paper introduces a more accessible photonic platform for one type of time crystal." **Editorial Team, *Nature Physics*.**