The experimental observation of a dissipative time crystal in a Rydberg gas

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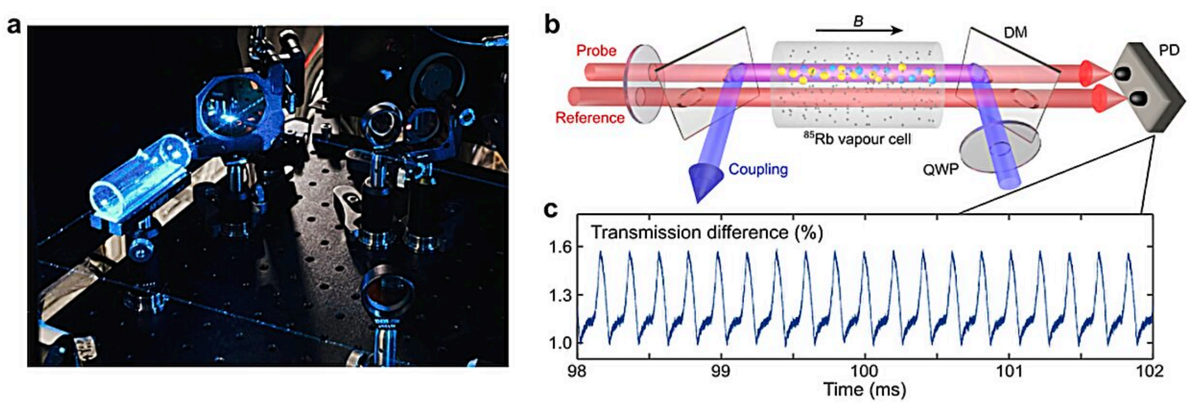


a. Photo of the team's experimental setup, with the luminated vapor cell at room temperature without cooling or heating. b. Schematic of the experimental setup, where a probe beam overlaps with a counterpropagating coupling beam in a room-temperature 85Rb-vapor cell and establish EIT. c. A typical oscillating time crystal signal. Credit: Dr. Xiaoling Wu

A dissipative time crystal is a phase of matter characterized by periodic oscillations over time, while a system is dissipating energy. In contrast with conventional time crystals, which can also occur in closed systems with no energy loss, dissipative time crystals are observed in open systems with energy freely flowing in and out of them.

Researchers at Tsinghua University recently observed a dissipative time crystal in a strongly interacting Rydberg gas at room temperature. Their paper, published in *Nature Physics*, opens new possibilities for the study of this fascinating state of matter.

"The results we achieved were totally unplanned," Dr. Li You, supervising researcher for the study, told Phys.org. "During the corona pandemic three years ago, the lead author Dr. Xiaoling Wu, then a Ph.D. student, was determined to continue working in the lab when only a few students were allowed in. At that time, our primary objective was to experiment with Rydberg excitation in an ultra-cold atomic gas."

While pursuing his Ph.D. at Tsinghua University, Dr. Xiaoling experimentally observed noise-like oscillations in the transmission of a probe light passing through the thermal vapor cell used to lock lasers to atomic transitions. At the time, neither he nor his colleagues understood what this surprising phenomenon was, as it had not yet been predicted or theoretically described.

"Xiaoling Wu, together with Zhuqing Wang, and Dr. Fan Yang (the three co-first authors of our paper), joined by Dr. Xiangliang Li from Beijing Academy of Quantum Information Science, began their exciting explorations of the physics associated with this newly found phenomenon both from the experimental and theoretical sides, which eventually led to the reported work," You said. "Xiaoling's instinct and persistence as well as the cooperation of all people in our team are crucial for this unexpected discovery that has since been reported by many groups."

The researchers were also joined by Dr. Thomas Pohl, who contributed to the theoretical aspects of the study. Pohl worked in close collaboration with Yang, who was working as a post-doc with him at the time.

"There have been several earlier experiments studying laser interaction with atomic Rydberg gases and none of them had reported the type of oscillating behavior seen in the present experiment," Pohl said. "So, the experimental observation was a wonderful puzzle that had to be solved in order to understand its origin and convince ourselves that the oscillations were indeed emerging purely from interactions between atoms and light."

A time crystal is essentially a state of matter in which temporal oscillations spontaneously emerge. These observations somewhat resemble those observed in normal crystals, in which the mutual interactions between atoms cause them to spontaneously arrange following specific spatial patterns.

"There are two types of time crystals: a discrete time crystal that forms under a periodic driving force and a continuous time crystal that emerges spontaneously under otherwise time independent conditions," Yang explained. "The latter was observed in our work."

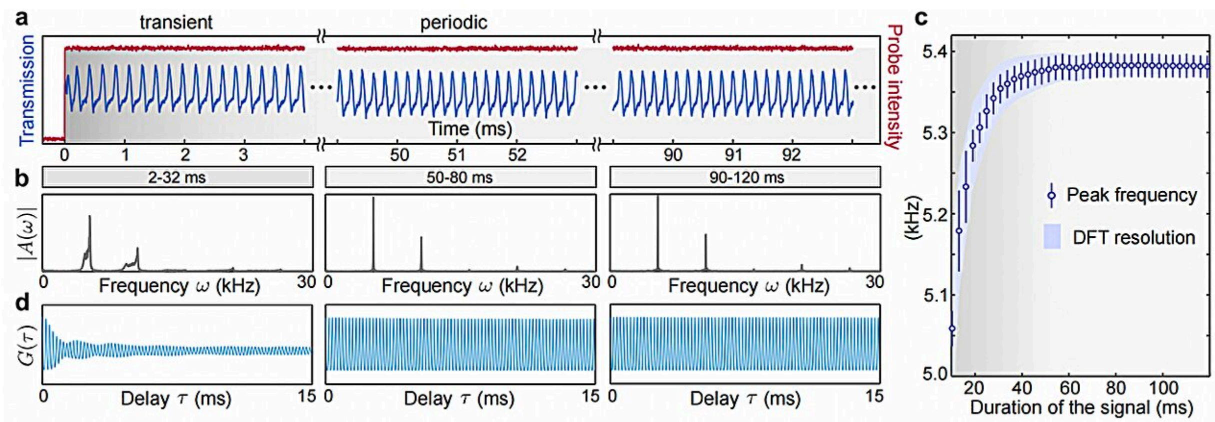
Electromagnetically induced transparency (EIT) is a quantum optical phenomenon in which, due to destructive interference, two strongly coupled quantum states establish a window of transparency for the probe light onto a near resonant third state. Notably, the shapes of the light's transmission lines through this window are altered in the presence of strong dipole–dipole interactions between Rydberg atoms.

"In our experiments, we adopted a three-state ladder configuration, with a top Rydberg state coupled to an intermediate excited state, which is probed from the ground state," You explained. "Such a simple setup enables studying non-equilibrium physics for a plethora of topics such as epidemic dynamics, forest fires, and self-organized criticality, in a cold or hot atomic gas.

"Our experiments are carried out in a vapor cell of ^{85}Rb atoms, with the

780 nm probe light near resonant to the transition $|g\rangle = |5S_{1/2}\rangle$ to $|e\rangle = |5P_{3/2}\rangle$, which is further coupled by a 480 nm coupling light to the Rydberg manifolds $|nD_J\rangle$."

In their experiments, You, Pohl and their colleagues illuminated a gas of atoms at room temperature, using a laser light. The applied laser fields excited some of the atoms in the gas into so-called Rydberg states, which strengthened the interactions between the atoms.



Establishment of the long-range temporal order. a. Single quenching dynamic of a time crystal b. Fourier transform of the oscillations for different time windows. c. The peak frequency of oscillation gradually stabilizes to a constant over time. d. The autocorrelation function (ACF) of time crystals for different time windows. Credit: Dr. Xiaoling Wu

The resulting strong interaction affects the process of exciting atoms into a Rydberg state, which in turn affects the atomic interactions, creating a "virtuous cycle" marked by increasingly stronger interactions between atoms. Interestingly, the researchers found that under some specific conditions, this feedback loop can result in spontaneous oscillations in the number of Rydberg atoms.

"It turned out that one needs special conditions under which the applied laser field excited two distinct types of Rydberg atoms, such that their mutual interaction can cause oscillations that can be observed directly as oscillations of the laser-light intensity transmitted through the atomic gas," Pohl said. "However, once these conditions are met, the resulting continuous time crystal is remarkably robust and displays self-sustained oscillations for a practically indefinite time."

A key difference between the researchers' experiment and similar ones performed in the past is that they tuned the polarization of the coupling light, which drove |e⟩ to distinct Rydberg states. The interactions and competition between the multiple Rydberg components in the team's setup significantly enrich their system's phase diagram, allowing the dissipative time crystal phase to emerge.

"Signatures of a dissipative time crystal have recently been observed in two other systems, where it emerges from the coupling of atoms to a single mode of photons in an optical resonator or due to the coupling of a single electron spin to the nuclear spins in a solid-state material," Yang said.

"Our work reports the observation of a continuous time crystal that emerges from the mutual interactions between particles in a many-body system. In this sense, the discovery provides a promising platform for deepening our understanding of the time crystal phenomenon that comes closer to the original idea of a time crystal proposed by Frank Wilczek in 2012."

The recent study by this team of researchers sheds light on the conditions required to observe time crystal behavior in Rydberg atom gases. Their work has already inspired additional experiments within their laboratories, some of which were aimed at controlling the properties of the self-sustained oscillations they observed.

"In this way, the time crystal phase could be exploited to enhance the performance of high-precision electric-field sensors, for which giant Rydberg atoms have already found technological applications," Pohl explained.

You, Pohl and their colleagues introduced a highly promising platform to study dissipative time crystals. Their work has already paved the way for experiments at other labs worldwide, aimed at further studying the dissipative time crystal and controlling the properties of the oscillations.

In the future, these works could contribute to the development of new technological devices. For instance, they could allow engineers to design better performing and high-precision sensors based on Rydberg atoms.

"In the immediate future, we shall concentrate on delineating the differences between limit cycle and continuous time translation symmetry breaking time crystal," You said. "The latter of which, or TC, is often referenced to a macroscopy quantum system with rigidity and many-body entanglements."

In their next studies, You and his colleagues hope to directly observe salient features associated with macroscopic quantum correlations. Their efforts could gather new evidence confirming that these features are indeed beyond the mean-field theory description employed in their paper.

You and his colleagues also plan to investigate the possible applications of the time crystal they observed. For instance, they will try to determine if it could be used to develop more advanced devices for electromagnetic field sensing and metrology.

"In the future, it will be important to better understand the detailed microscopic processes that lead to spontaneous oscillations in a room-temperature gas of atoms," Pohl added. "Our findings may also help to identify the basic mechanisms that are generally required for the emergence of continuous time crystals in systems of many interacting particles.

"It will be particularly important to understand the significance and the role of quantum entanglement between the particles, which may become uniquely possible in our system."

More information: Xiaoling Wu et al, Dissipative time crystal in a strongly interacting Rydberg gas, *Nature Physics* (2024). DOI: 10.1038/s41567-024-02542-9