**////Title: Viewing Quantum Phases with ‘Time Order’**

**////Standfirst:**

Discovering new phases of matter and classifying such phases are among the most important goals in physics. In a new study, Dr Tie-Cheng Guo and Professor Li You at Tsinghua University in Beijing present a new methodology to discover new *quantum* phases of matter, using the concept of ‘time order’. Through identifying and defining quantum phases from this perspective, time order could become a new paradigm in physics, helping researchers to gain more insight into quantum many-body systems.

**////Main text:**

Discovering new phases of matter is one of the most important goals in physics. Since the very beginning of human history, people have been searching for various kinds of materials and exotic phases.

In quantum many-body physics – a field that explores complex systems of many interacting quantum particles – many scientists are also interested in discovering various intriguing ‘quantum’ phases of matter and classifying them. Novel quantum phases could be used to illustrate and understand interesting quantum properties, which could be harnessed for exciting new technologies.

Time crystals are an exotic phase of matter, first proposed two decades ago by Frank Wilczek. Perhaps the most exciting outcome is that time crystals can break the principle of ‘time translation symmetry’ – which states that the states of matter must remain unchanged for a ‘time translation symmetric’ system, regardless of when in time they are measured.

While the atoms in a regular crystal form a repeating arrangement in space, the atoms that make up a time crystal are arranged periodically in both space *and* time. In other words, a time crystal’s constituent atoms are never static, but exhibit repetitive motions over time. This means that on larger scales, these systems never come to rest, or lose energy to their surrounding environment. Over recent years, researchers have proposed many kinds of time crystals.

Time crystals provide us with a deeper understanding about time in quantum many-body physics. Time crystals also encourage researchers to concentrate on understanding time itself.

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In a recent study, Dr Tie-Cheng Guo and Professor Li You introduce a new concept, which could provide a new perspective for ongoing efforts to identify and categorise quantum many-body systems. Named ‘time order’, their concept presents a new way to view such quantum systems, by considering how the system behaves over the time dimension.

To demonstrate the validity of their concept, they illustrate a concrete procedure for ‘symmetry-based time order’. Several model systems presented in the paper show intriguing time order, especially time-crystalline order and time-functional order. These model systems show the usefulness and power of the team’s proposed new concept.

The time order presented in the team’s paper is a new concept, although it is associated with the continuous time crystal definition proposed by Watanabe and Oshikawa, because the concrete procedure here for ‘symmetry-based time order’ also uses the two-time correlation function.

Time order and time crystals are totally different. Time order is a methodology which uses the time perspective to classify and discover quantum many-body phases. Time crystals are a type of novel quantum many-body phases that break time translation symmetry spontaneously.

Dr Guo and Professor You gain a deeper understanding of the characteristic periods and amplitudes of a continuous time crystal’s oscillations, by introducing a so-called ‘twisted vector’. Many-body phases with generalised time-crystalline order can be also called a generalised continuous time crystal.

The team’s work gives a more complete understanding of a continuous time crystal that fits Watanabe and Oshikawa’s definition. Moreover, they give two concrete examples of the generalised continuous time crystal with generalised time-crystalline order.

An intriguing outcome of the team’s study is the quantum phases with generalised time-crystalline order. When we look at one small part of a continuous time crystal with generalised time-crystalline order, we will find nothing that changes over time, as the time-crystalline properties only appear when looking at the whole entity.

To understand this phenomenon, Dr Guo asks us to imagine a sea of spinning quantum particles. If the overall state of the quantum system is a generalised continuous time crystal, the observer will notice that the spin of each individual particle is frozen in time. However, when looking at the system as a whole, the sea of spinning quantum particles oscillates over time. In Dr Guo’s own words: ‘What a surprise the quantum world brings to us!’

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Using this ‘time order’ approach to describe many-body quantum systems offers a fresh and powerful new tool. Using time order, we can view and classify quantum many-body phases. Dr Guo is very excited about time order, because it offers a completely new methodology to identify and understand quantum phases of matter.

He gives an example to illustrate time order. In the example, there is one lemon and one banana on a desk, and a child asks which one is the lemon. How would you answer? If you say ‘The round one is the lemon,’ this description represents the symmetry of the system. To make an analogy with time order, Dr Guo explains that you might say, ‘If you were to take a bite, you would cry due to its very sour taste.’

By drawing from their initial proposal of time order, Dr Guo and Professor You hope that researchers in future studies could uncover even deeper insights into quantum many-body physics and connect the static and dynamic behaviours of quantum many-body states. With time order, physicists could be far better equipped to explore and classify new quantum many-body phases of matter, as well as their associated transitions.

The team believes that time order will hopefully become a new paradigm for quantum many-body physics. As Dr Guo concludes: ‘Time is all you need, even when you are viewing static quantum phases.’

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This SciPod is a summary of the paper ‘Quantum Phases of Time Order in Many-Body Ground States’, from Frontiers in Physics. <https://doi.org/10.3389/fphy.2022.847409>

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