Game theory elucidates the collective behavior of bosons

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Credit: NIM

Quantum particles behave in strange ways and are often difficult to study experimentally. Using mathematical methods drawn from game theory, LMU physicists have shown how bosons, which like to enter the same state, can form multiple groups.

When scientists explore the mysterious behavior of quantum particles, they soon reach the limits of present-day experimental research. From there on, progress is only possible with the aid of theoretical ideas. NIM investigator Prof. Erwin Frey and his team at the Dept. of Statistical and Biological Physics (LMU Munich) have followed this route to study the behavior of bosons. Bosons are quantum particles that like to cluster together. But by applying methods from the mathematical field of game theory, the Munich physicists were able to explain why and under what conditions bosons form multiple groups.

Social bosons

There are two kinds of quantum particles in nature: fermions and bosons. Whether a particle is a fermion or a boson depends on its intrinsic angular momentum or spin. For fermions, the spin is always half-integer valued and the most prominent example is the electron. Bosons, on the other hand, always exhibit integer spins. Such is the case for photons, for example, but also whole atoms may be bosons. Bosons are social beasts that like to be on the same wavelength – or, as physicists put it, they like to be in the same quantum state. When bosons are cooled to a temperature of -273.15°C, close to absolute zero, they may even start to behave as a single "super-particle". The reason why that happens is that, at such low temperatures, all bosons want to settle into the lowest possible energy state.

This super-particle is called a Bose-Einstein condensate, where the term condensate denotes a group of particles that all behave in the same way. That it should be possible to create such a condensate was first proposed theoretically by Bose and Einstein in 1924. During the 1990s, experimentalists studying ultracold atomic gases eventually confirmed this long-standing prediction.

Group formation

Only recently have scientists come up with the theory that a collection of bosons should be capable of forming multiple condensates. In order for this to happen, however, the bosons need to be in an open system into which energy is periodically pumped from the outside – for example by a laser – and each boson may release energy into the environment. In the current issue of *Nature Communications*, Erwin Frey and his team explain why bosons group into multiple condensates in such non-equilibrium systems.

The rules of the game

The phycisists from Munich explained the formation of multiple groups by applying one of its specialties: game theory. Researchers use this mathematical theory for a diverse range of purposes. The strength of game theory lies in its ability to explain the behavior and interactions of collectives. Each member has its own strategy – whether that "agent" be a predator stalking its prey, or a participant in the children's game rock-paper-scissors who chooses to play the "rock" strategy. Owing to its simplicity, the rock-paper-scissors game serves as one of the most prominent models in game theory, but the theory also describes more serious decision-making processes and opinion formation in groups. Now Erwin Frey and his team have shown that even the behavior of bosons can be understood in the context of game theory. And this insight has led them to the physical principle underlying the condensation of bosons into multiple states.

Order emerges with time

"Our theory is based on an intuitive concept", explains Johannes Knebel, PhD student in Frey's group. "At first, all bosons do their own thing. But because energy is allowed to flow in and out of the system, the bosons eventually group into particular quantum states, whereas the other states become depleted. Similarly, when many players with different strategies compete against each other, only the successful strategies prevail. The other strategies vanish over time. In a round-table discussion, the same dynamics may be observed. At first, everybody has a different opinion, but only a few opinions will eventually be shared by most of the debaters, and these will often continue to coexist side by side." Hence, order emerges with time. The Munich physicists formulate the evolution of order in terms of the decrease of a relative measure of entropy, which guides the collective behavior of the bosons.

From theory to experiment

The scientists are now eager to learn more about the nature of quantum systems: "A direct application of our findings is not yet at hand," says Erwin Frey. "However, it is not unusual for this kind of basic research to lead to completely unexpected discoveries, opening the door to new developments. For example, research on the collective behavior of bosons has already contributed to the understanding of superfluidity and paved the path to the development of technologies like superconductivity". The exciting question now is whether the theorists' predictions will be confirmed or disproved by experimentalists. Experiments with ultracold atomic gases, such as those being conducted in the group led by NIM investigator Prof. Immanuel Bloch (LMU Munich and Max-Planck-Institute for Quantum Optics), offer promising candidates to study bosons out of equilibrium.

More information: "Evolutionary games of condensates in coupled birth–death processes." *Nature Communications* 6, Article number: 6977 DOI: 10.1038/ncomms7977

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