Through the looking glass: Artificial molecules open door to ultrafast polaritonic devices

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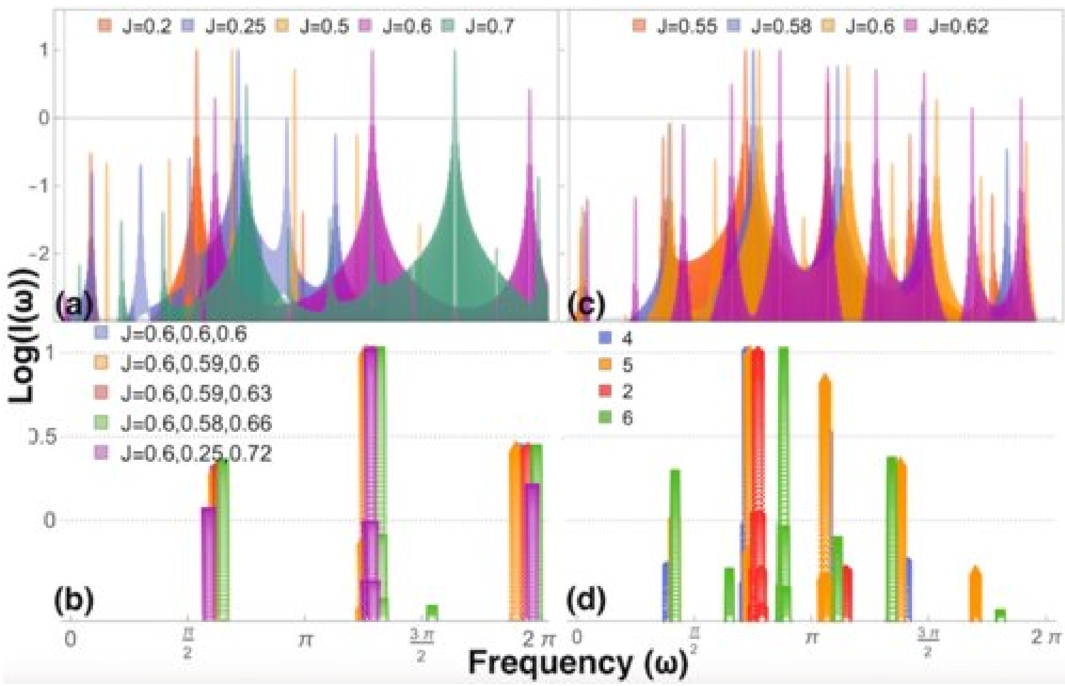

The spectral weights of oscillatory states are associated with discrete spectral lines. Their number and separation can be controlled by changing the number and geometry of condensates, reflected by the coupling strengths. Credit: *Physical Review B* (2021). DOI: 10.1103/PhysRevB.103.L060507

Researchers from Skoltech and the University of Cambridge have shown that polaritons, the quirky particles that may end up running the quantum supercomputers of the future, can form structures behaving like molecules—and these "artificial molecules" can potentially be engineered on demand. The paper outlining these results was published in the journal *Physical Review B*.

Polaritons are quantum particles that consist of a photon and an exciton, another quasiparticle, marrying light and matter in a curious union that opens up a multitude of possibilities in next-generation polaritonic devices. Alexander Johnston, Kirill Kalinin and Natalia Berloff, professor at the Skoltech Center for Photonics and Quantum Materials and University of Cambridge, have shown that geometrically coupled polariton condensates, which appear in semiconductor devices, are capable of simulating molecules with various properties.

Ordinary molecules are groups of atoms bound together with molecular bonds, and their physical properties differ from those of their constituent atoms quite drastically: consider the water molecule, H2O, and elemental hydrogen and oxygen. "In our work, we show that clusters of interacting polaritonic and photonic condensates can form a range of exotic and entirely distinct entities—"molecules"—that can be manipulated artificially. These "artificial molecules" possess new energy states, optical properties, and vibrational modes from those of the condensates comprising them," Johnston, of the University of Cambridge Department of Applied Mathematics and Theoretical Physics, explains.

When researchers were running numerical simulations of two, three, and four interacting polariton condensates, they noticed some curious asymmetric stationary states in which not all of the condensates have the same density in their ground state. "Upon further investigation, we found that such states came in a wide variety of different forms, which could be controlled by manipulating certain physical parameters of the system. This led us to propose such phenomena as "artificial polariton molecules" and to investigate their potential uses in quantum information systems," Johnston says.

In particular, the team focused on an "asymmetric dyad," which consists of two interacting condensates with unequal occupations. When two of those dyads are combined into a tetrad structure, the latter is, in some sense, analogous to a homonuclear molecule—for instance, to molecular hydrogen H2. Furthermore, artificial polariton molecules can also form more elaborate structures, which could be thought of as "artificial polariton compounds."

"There is nothing preventing more complex structures from being created. Indeed, in our work we have found that there is a wide range of exotic, asymmetric states possible in tetrad configurations. In some of these, all condensates have different densities (despite all of the couplings being of equal strength), inviting an analogy with chemical compounds," Alexander Johnston notes.

In specific tetrad structures, each asymmetric dyad can be viewed as an individual "spin," defined by the orientation of the density asymmetry. This has interesting consequences for the system's degrees of freedom (the independent physical parameters required to define states); the "spins" introduce a discrete degree of freedom, in addition to the continuous degrees of freedom given by the condensate phases.

The relative orientation of each of the dyads can be controlled by varying the coupling strength between them. Since quantum information systems can potentially have increased accuracy and efficiency if they utilize some kind of hybrid discrete-continuous system, the team therefore proposed this hybrid tetrad structure as a potential basis for such a system.

"In addition, we have discovered a plethora of exotic asymmetric states in triad and tetrad systems. It is possible to seamlessly transition between such states simply by varying the pumping strength used to form the condensates. This property suggests that such states could form the basis of a polaritonic multi-valued logic system, which could enable the development of polaritonic devices that dissipate significantly less power than traditional methods and, potentially, operate orders of magnitude faster," Professor Berloff says.

More information: Alexander Johnston et al. Artificial polariton molecules, *Physical Review B* (2021). DOI: 10.1103/PhysRevB.103.L060507

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