Observing the path less traveled boosts quantum gain

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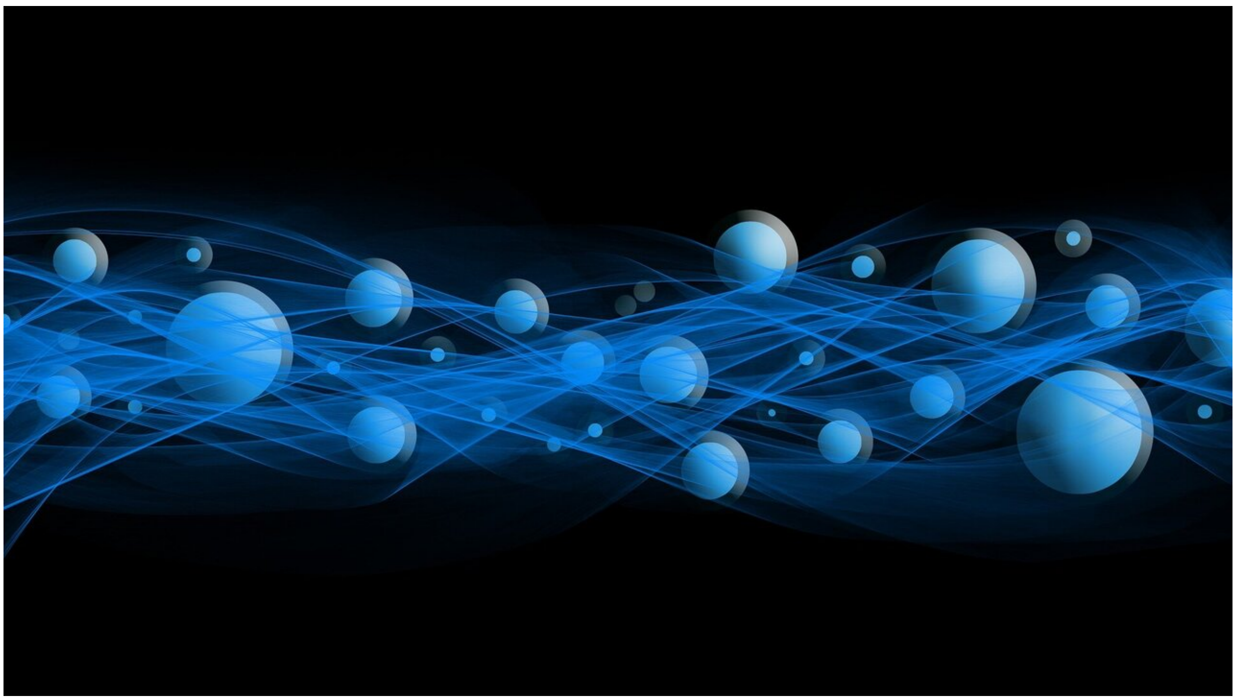

Photons set to interact weakly through an ensemble of cold atoms may still yield the outcomes of large interactions when looking for the least likely photon outcomes. Credit: Pixabay/Geralt

When probing the subtle effects of quantum mechanics, all the parameters in the system and its measurements need to be finely tuned to observe the result you are hoping for. So what happens when you gear everything towards detecting what you least expect? Researchers at MIT and Purdue University in the U.S. took just this approach and found they could amplify quantum signals by a factor of 30 while conditionally changing the relative phase of a photon from π/80 to π/2. The results could provide the missing link that nudges a number of quantum network technologies closer to practical use.

Quantum technology protocols generally aim to maximize interaction strengths, but preparing these entangled systems can be very difficult. "We asked the question, can we turn weak interactions into very strong interactions somehow?" explains Vladan Vuletic, Wolf Professor of Physics at MIT. "You can, and the price is, they don't happen often."

The effects Vuletic and colleagues observe hinge on the factors that feed into the "expectation values" of quantum experiments. Expectation values describe the average outcome of a quantum scenario and equate to the product of each possible value and its probability. Vuletic and his collaborators focused their studies on scenarios where the average is dominated by rare events, like a lottery where everyone wins a small amount on average, although in fact, just a few people win huge amounts. In quantum mechanics, light also sometimes takes the path less traveled, and as the researchers show, this really can make all the difference.

The researchers had been looking at the interactions between photons—a signal photon and an ancillary photon—following different paths through an ensemble of cold atoms in a cavity. Each photon can interact with the atoms, and that interaction bears the signature of how the other photon has interacted, giving an indirect interaction between the two photons. Interactions leave tell-tale signs in the photon, such as a phase shift, which while zero at resonance turns positive or negative away from resonance depending on which side of the system's resonance the parameters are tuned to.

Mahdi Hosseini at Purdue University explains that they noted an average phase shift as they had been studying the interaction. "I remember Vladan then did some calculation one night, and sent it to us, and we looked at it, and initially, I thought that can't work," says Hosseini. The calculation suggested surprising results for a regime where there was a high probability of an ancillary photon measurement that is associated with a low phase shift in the signal beam (as might be the case near resonance). On the rare occasions that this is not the measurement recorded for the ancillary photon, the phase shift for the signal beam must be large so that the product with the low probability still meets the expectation value.

What is more, through this phenomenon, the parameters selected to measure the ancillary photon could greatly affect the phase shift outcome for the signal photon despite weak interactions between the two, something the researchers describe as "heralded photon control." With careful manipulation of the system parameters to adjust the regime of the experiments, the researchers were able to observe the effects theory had predicted.

"We were more excited than surprised," says Hosseini. "Naively, when you look at the average, you don't expect to see any phase shift at resonance, not even a small phase shift; you expect to see none. But it turns out that by changing the measurement process, you can change this into highly interactive states, and that was surprising."

The researchers point out that protocols that also amplify signals have been demonstrated in other systems through "noiseless amplification" and "weak measurements." These protocols offer enhancements by factors between two and five, with a very small probability. "If the fidelity times the probability is much less than 50%, it's not really useful for sensing, for example," explains Hosseini. In contrast, Hosseini, Vuletic and their collaborators were able to demonstrate phase shifts up to π/2 where the average phase shift is π/80 and amplification of the photon number by a factor of around 30. While these events remain rare, the probability is more promising for practical applications.

"Before, people had thought of this noiseless amplification and any phase shift as completely disparate fields," adds Vuletic. "We have shown it is the same thing, and you can have a small change of parameters to move from phase shifts to gain."

There are many emerging quantum network technologies that face a stumbling block in the absence of a practical technology to amplify signals, such as long-distance quantum communication, or when connecting multiple quantum computers, each with a manageable number of qubits to increase the processing capability. "Losses and decoherence are always a problem," says Vuletic.

While Vuletic is now working on "superatoms" that may increase the photon coupling, Hosseini's work is broaching the messier world of solid state to replicate the phenomena in crystals with rare earth ions. These systems are not as clean because it is not possible to have such precise knowledge of the environment around the ions as for totally homogeneous ensembles of atoms. However, if the principle can be demonstrated in these systems, it may offer a more practical basis for applications and even multiplexing the effects to add the probabilities for each scenario.

More information: Yiheng Duan et al. Heralded interaction control between quantum systems Physics Review Letters (2020) Accepted Manuscript journals.aps.org/prl/accepted/ … 433120cb31b386f09378