Elementary particles part ways with their properties

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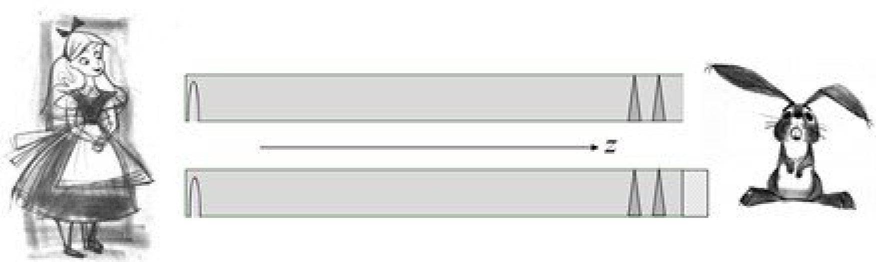

A particle separating from its properties may help explain the paradox of a mirror's impact on a particle that never comes into contact with it in counterfactual quantum communication. Credit: Physical Review Letters.

"Spooky action at a distance," Einstein's summation of quantum physics, has been a criticism of quantum mechanics since the field emerged. So far, descriptions of entangled particles to explain their apparently faster-than-light responses, and even explanations for the phase shifts induced by an electromagnetic field in regions where it is zero—the "Aharonov-Bohm" effect—have mostly addressed these concerns. However, recent theoretical and experimental demonstrations of a "counterfactual" quantum communication protocol have proved difficult to explain in terms of physical cause and effect. In this kind of quantum communication, observers on either side of a "transmission channel" exchange information without any particle passing between them—spooky indeed.

Now, Yakir Aharonov, Professor at Tel Aviv University in Israel and Chapman University in the U.S., and Daniel Rohrlich, Professor at Ben-Gurion University of the Negev in Israel, have taken a closer look at this so-called counterfactual quantum communication protocol in terms of conserved particle properties. Their analysis provides an explanation of counterfactual quantum communication that does not call upon "spooky action at a distance," but instead implies that the particle and one of its conserved properties—modular angular momentum—part ways.

The spooky quantum protocol

The counterfactual quantum communication protocol reported in 2013 arose through theoretical studies of two observers—good old Alice and Bob—liaising via particles along a transmission channel, as reported by Hatim Salih, Zheng Hong Li, Mohammad Al-Amri and Muhammad Suhail Zubairy (then at the National Center for Mathematics and Physics in Saudi Arabia and Texas A&M University in the U.S.).

"They got very interested in the fact that these massive particles, which would be signals, could be stopped and blocked," explains Rohrlich. In their analysis, Salih and co-authors showed that when there were two partially blocking barriers in the channel, Alice was able to identify whether or not Bob had closed his end of the channel with a reflecting mirror or left it open, even though the wavefunction as it evolved under the conditions set could not enter Bob's end of the channel.

"We found it extremely interesting—the possibility of communication without anything passing between the two people who communicate with each other," says Aharonov. "And we wanted to see if we can understand it better."

A conservative approach

In fact, Aharonov already has a legacy in interpretations of apparently weird quantum phenomena, dating back to his work in 1959 to explain the Aharonov-Bohm effect, sometimes referred to as the Ehrenberg-Siday-Aharonov-Bohm effect in acknowledgment of a theoretical prediction of the effect in 1949. Experimental researchers had observed a phase shift in charged particles near an electromagnetic field even though the field was zero throughout the region occupied by the particle's wave function.

"Usually, people think only about the wave function," says Aharonov, referring to common descriptions of superposition. "They think about it mathematically but they don't connect it with a conserved quantity which is the modular momentum." By analyzing quantum effects in terms of the exchange of a conserved variable—the modular momentum—Aharonov and David Bohm were able to explain the Aharonov-Bohm effect. Now, alongside Rohrlich, he set about applying the same kind of analysis to the counterfactual quantum communication protocol.

Rohrlich and Aharonov considered two parallel transmission channels—one with Bob's end closed with a mirror and one with it open. (This also equates to a single transmission channel where Bob's mirror is in a superposition of open and closed states.) They then consider an initial wave function in a superposition of the state in the open-ended channel plus the state in the closed channel.

The problem arises because, as Salih and co-authors had shown, the wave function evolves differently depending on whether Bob's end is closed or not. As a result, after a certain period of time has elapsed, the superposition will be the state of one channel minus the state of the other channel, but that equates to a different phase from the initial wavefunction. Since the modular angular momentum depends on the phase this suggests the modular angular momentum of the particle has changed even though the particle's wave function could not occupy the part of the channel where Bob has his mirror open or closed.

"The only way to explain how the angular momentum did change is that part of the angular momentum of the particle left it and went to the other side," says Aharonov. As he and Rohrlich explain it, part of the angular momentum leaves the particle, enters the region of the transmission channel that the particle's wavefunction cannot, and there, it is absorbed by the mirror so that the value of the modular angular momentum on the particle is altered. They also suggest that similar results could result through considering the spin angular momentum and other conserved properties.

Temperamental properties

Aharonov and Rohrlich liken the behavior of the particle and its modular angular momentum to the grinning Cheshire cat in "Alice's Adventures in Wonderland," which appears to move on, leaving its grin behind. "Although it's very surprising that properties can leave their particles, it is not as surprising as to say that nothing happened and there was an effect," says Aharonov, comparing their explanation with the idea of the particle with its properties encountering nothing that can change the modular angular momentum, yet that property changing anyway.

Like all new concepts, Aharonov and Rohrlich's explanation is not without its criticisms, either. Rohrlich highlights the point raised by one of the (anonymous) peer reviewers of the paper, who nonetheless gave an overall positive appraisal of the paper. "They were saying, humorously, yes we avoided one problem, but we got ourselves into another problem," says Rohrlich. Yet he adds, "If you're talking about a cat and its grin, that's very strange, but of course, all of this has to translate back to elementary particles, and if an elementary particle loses its spin because its spin goes somewhere else—maybe that's something we can get used to."

More information: Yakir Aharonov and Daniel Rohrlich What is nonlocal in counterfactual quantum communication?, *Physical Review Letters*, Accepted Manuscript. journals.aps.org/prl/accepted/ … bc9200223328b0ab042b

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