# Study finds that black hole inner horizons can be charged or discharged

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Black holes are intriguing and widely studied cosmic bodies with extremely high tidal forces, from which even light is unable to escape. While many studies predicted the existence of black holes, which have also recently been detected, many questions about these cosmic bodies remain unanswered.

Researchers at University of Leipzig have recently carried out a study examining the vacuum polarization induced by a quantum-charged scalar field near the inner horizon of a charged black hole. The results of their analyses, published in *Physical Review Letters*, suggest that at a charged black hole's inner horizon, the quantum charged current could be either positive or negative.

"The theory of general relativity unites space and time into the concept of spacetime and describes gravity as a bending of that spacetime," Christiane Klein, one of the researchers who carried out the study, told Phys.org. "One of its most prominent predictions are black holes (i.e., regions of the spacetime from which even light cannot escape). If a black hole is electrically charged or rotating, its interior has an interesting feature: Inside the black hole, there is a surface with properties resembling those of the event horizon (i.e., the outer edge) of the black hole. It is therefore called the inner horizon."

Essentially, up to a black hole's inner horizon, the spacetime and everything happening within it can be theoretically predicted based on knowledge of the state of the universe at some point in the past, which physicists refer to as 'initial data." This ability to predict spacetime, known as determinism, is an important feature of physics theories.

Based on theoretical predictions, however, an observer crossing a black hole's inner horizon could bypass the central singularity of the black hole, where space and time become infinitely curved, and re-exit into a different universe. Moreover, past the inner horizon, determinism would theoretically break down, which essentially means that an observer's journey would no longer be determined by the so-called initial data.

In his work, titled "Gravitational Radiation and Gravitational Collapse," British mathematician Roger Penrose predicted that this would not happen, as there would be remnants of a black hole's collapse or other small deviations from the initial data of the black hole spacetime.

"According to Penrose, these deviations would accumulate near the inner horizon and bend the spacetime near the horizon so strongly that any observer approaching it is destroyed, turning the inner horizon into a singularity," Klein said. "This idea is called the strong cosmic censorship conjecture. In the literature, different kinds of black holes with inner horizons and different perturbations of their initial data have been studied to test this conjecture and determine the strength of the singularity at the inner horizon."

Recent studies have found that in charged black holes within an expanding universe, the singularity can be weak enough to cross. These findings (Cardoso et al. ; Dias et al. ; Cardoso et al.) ultimately inspired some of the researchers in the team to investigate what would happen if they also accounted for the quantum nature of gravitational fields and matter.

"Usually, these quantum perturbations are negligibly small," Klein said. "It turned out that close enough to the inner horizon, quantum effects dominate classical effects and are strong enough to turn the inner horizon into a strong singularity. This showed that quantum effects should not be neglected near the inner horizons of black holes and motivated us to have a closer look at other quantum effects in this region."

As an electrically charged black hole can only be formed from electrically charged matter, Klein and her colleagues decided to specifically look at electrically charged quantum matter. One of the primary observable signatures of this type of matter is the electric current it produces. Therefore, the researchers tried to determine how this current would behave in the proximity of a black hole's inner horizon.

"In previous studies it was argued that such currents are mainly due to the spontaneous creation of oppositely charged particles inside of the black hole which are then accelerated in opposite directions," Klein said. "This would have the effect of discharging the region of the black hole behind the inner horizon. One goal was to check whether this intuitive particle picture is correct."

In their recent paper, the researchers considered a spacetime describing an expanding universe with a charged black hole inside it. Subsequently, they framed quantum field theory of a charged scalar field within this hypothetical spacetime.

"For the time being, we ignored that the presence of the quantum field should alter the spacetime," Klein said.

Using their proposed framework, the team was able to study the electric current of a quantum field in the example they considered. Their numerical setup they developed was based on results they gathered in the past.

"We found that the dominant contribution to the current at the inner horizon is independent of the state (i.e., the initial conditions) of the quantum field, as long as it is physically reasonable," Klein said. "We picked a convenient state and derived a formula for the current using the techniques of quantum field theory on curved spacetimes. The formula must be evaluated numerically for a set of parameters of the spacetime (mass and charge of the black hole and a cosmological constant describing the amount of expansion of the universe) and the quantum field (mass and charge of the field)."

The key elements contained in the formula used by Klein and her colleagues are so-called 'scattering coefficients." These are numbers that describe the extent to which field perturbations are transmitted into the black hole or are reflected into space. To calculate these coefficients, Klein and her colleagues used methods they developed in one of their previous studies.

"The current should always have the same sign, but we find that the dominant contribution to the current at the inner horizon can be positive as well as negative, depending on the parameters of the spacetime and the quantum field," Klein said. "It should be noted that in the parameter region very close to the maximally allowed charge of the black hole (if the charge is increased further, there is no more event horizon and the singularity in the center becomes 'naked') the current always tends to decrease the charge of the inner horizon. This ensures that its charge cannot be increased beyond the allowed maximum."

The results of the researchers' analyses were fairly surprising, as they contradict the prediction of the particle picture. In contrast with what they expected, their results predict that under certain circumstances, the charge of a black hole inside the inner horizon can be increased by quantum effects.

"Even though our numerical results cannot cover realistic spacetime and quantum field parameters, our work demonstrates that the particle picture is insufficient to fully capture quantum effects inside black holes," Klein said.

In addition to contradicting particle picture predictions, the results gathered by Klein and her colleagues could shed further light on well-established findings related to the event horizon. In fact, their work suggests that quantum effects can behave quite differently in the proximity of a black hole's inner horizon than they do at the event horizon, where they are expected to decrease a black hole's charge. Moreover, the results could inspire new studies investigating similar quantum effects in more realistic settings.

"One expects realistic black holes to have at most a negligibly small electric charge, but significant angular momentum (i.e., rotation)," Klein said. "In fact, one could consider charged black holes as mere toy models for rotating ones: they share many features, such as the presence of an inner horizon, but charged black holes are much easier to handle mathematically. One future line of research we are currently pursuing is the extension of our results to rotating black holes. It would be interesting to test whether quantum effects can increase the rotation of the black hole near its inner horizon instead of decreasing it, as one might naively expect."

**More information:** Christiane Klein et al, Quantum (Dis)Charge of Black Hole Interiors, *Physical Review Letters* (2021). DOI: 10.1103/PhysRevLett.127.231301

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