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Type-II Weyl semimetal vs gravastar

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There are different scenarios of the development of the black hole in the process of evaporation by Hawking radiation. In particular, the end of the evaporation can result in a macroscopic quantum tunnelling from the black hole to the white hole, see [1] and references therein. Another scenario is the formation of compact object – the vacuum star, where event horizon can be considered as the boundary separating different phases of the quantum vacuum [2]. Such consideration was based on the condensed matter analogies, which in particular are presented by the superfluid ^{3}He [3]. Topological materials such as the Weyl and Dirac semimetals bring a new twist to this analogy. They provide new support for the scenario of the formation of a vacuum star after the end of Hawking evaporation.

The analog of the event horizon emerges on the boundary between type I and type II Weyl semimetals [4–11]. The energy spectrum of electrons in Weyl semimetals becomes relativistic in the vicinity of the Weyl point. In its simplest form the Hamiltonian near the Weyl point at $\mathbf{p}=0$ is:

$$H(\mathbf{p},\mathbf{r}) = c\boldsymbol{\sigma}\cdot\mathbf{p} + \mathbf{v}(\mathbf{r})\cdot\mathbf{p}, \qquad (1)$$

where $\boldsymbol{\sigma}$ are the Pauli matrices; $c=1$ is the analog of the speed of light; $\mathbf{v}(\mathbf{r})$ is the analog of the shift velocity in this effective metric, which for spherical horizon is:

$$ds^2 = -dt^2 + (dr - v(r)dt)^2 + r^2 d\Omega^2. \qquad (2)$$

The horizon is at the boundary between the region with $|v(r)| < 1$ (type I Weyl semimetal), and the region with the overtilted Dirac cone, $|v(r)| > 1$ (type II Weyl semimetal [12]). The overtilted Dirac cone $E(\mathbf{p}) = p_r v \pm pc$ produces Fermi surface $E(\mathbf{p})=0$ in Fig. 1.

When the type II region is formed, the Fermi surface is still not occupied by electronic quasiparticles: the negative energy states are empty, while the positive energy states are occupied, Fig. 1 (left). The initial stage of the process of equilibration is the filling of the negative energy states by the fermions occupying the positive energy states. This process corresponds to the creation of the particle-hole pairs at the horizon, which is the analog of the Hawking radiation with the Hawking temperature $T_H = v'/2\pi$, where v' is the derivative of the shift velocity at the horizon. Finally the equilibrium "vacuum" state is formed, in which all the negative energy states inside the Fermi surface become occupied, Fig. 1 (right). In this final vacuum state, there is no Hawking radiation, while the horizon still exists.

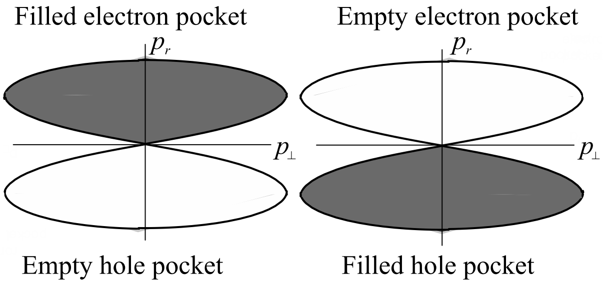

Fig. 1. Fermi surface $E(\mathbf{p})=0$ in the type II Weyl semimetal inside the horizon. Left: Nonequilibrium state in the first moment after formation of the event horizon. The positive energy states in the newly formed Fermi surface are fully occupied, while the negative energy states are empty. The relaxation of this highly nonequilibrium state is accompanied by Hawking radiation and reconstruction of the vacuum state. Right: Final equilibrium state after reconstruction. The positive energy states are empty, and the negative energy states are occupied. There is no Hawking radiation after this final state is reached

Applying this scheme to the black holes (BH), one comes to the following "circle of the life of a BH" [13]. At the beginning of its formation, the BH appears in a non-equilibrium state. This is the conventional state of a BH with the singularity at the origin. This state is quasi-equilibrium, since it is accompanied by Hawking radiation. The interior of the horizon contains the Fermi surfaces [13–16]. The filling of negative energy states will

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be accompanied not only by the Hawking radiation, but also by the back reaction of the gravitational field inside the horizon, which again will be followed by the reconstruction of spectrum. As a result, the black hole interior arrives at the equilibrium state. The analog of the homogeneous ground state in the type-II semimetal is the state with the homogeneous vacuum energy density, that is the de Sitter vacuum.

Different configurations with the de Sitter quantum vacuum in the core of the black hole have been discussed in [2], [17–19] and [20–24]. These firewall objects serve as an alternative to the conventional black holes, and they can resolve the information loss problem [25–28]. In its simplest form the shift velocity has the form:

$$v(r) = -\sqrt{\frac{r_h}{r}},\ r > r_h,\ v(r) = -\frac{r}{r_h},\ r < r_h. \tag{3}$$

Here $r_h = 1/(2M)$ is the horizon radius, and $H = -1/r_h$ is the Hubble parameter of the (collapsing) de Sitter vacuum inside the horizon (in units $\hbar = G = c = 1$).

The jump in the velocity gradient is resolved by the thin layer, which is either outside the "horizon" [17, 18] (the type I gravastar), or inside the horizon [23] (the type II gravastar). The analogy between the Weyl semimetal black hole and the real black hole is in favour of the type II gravastar. The shell inside the horizon is made of the vacuum fields. We considered the vacuum field using the q-field describing the phenomenology of the quantum vacuum [29].

In conclusion, we considered the possible scenario of the formation of the equilibrium final state of the black hole. This scenario is inspired by the consideration of the black hole analog in Weyl semimetals, where the analog of the event horizon separates two topologically different types of the Weyl materials: type I and type II. The relaxation of the initial state of the black hole analog is accompanied by the Hawking radiation and by the reconstruction of vacuum state inside the horizon. In the final equilibrium state, the event horizon separates two different vacuum states, and there is no more Hawking radiation. Such final state in Weyl semimetals is analogous to the dark energy stars discussed earlier. In such black hole there is the real event horizon. The interior of the horizon contains the de Sitter vacuum and thin shell, both made of the vacuum fields.

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