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Black Hole and Hawking Radiation by Type-II Weyl Fermions

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The elementary particles of Standard Model (quarks and leptons) are originally the fermions obeying the Weyl equation. In condensed matter the Weyl fermions live in the vicinity of the Weyl points in chiral superfluid ^{3}He-A [1] and in topological semimetals [2–5]. Recently the so-called type-II Weyl points attracted attention in condensed matter [6]. In relativistic theories the type-II Weyl fermions also appear. They emerge in particular in the vacuum of the real (Majorana) fermions [7], and also behind the event horizon [1, 8]. In general relativity the stationary metric, which is valid both outside and inside the black hole horizon, is provided in particular by the Painlevé–Gullstrand spacetime [9]. The line element of the Painlevé–Gullstrand metric is equivalent to the so-called acoustic metric [10, 11]:

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu = -c^2 dt^2 + (d\mathbf{r} - \mathbf{v}dt)^2. \quad (1)$$

This is stationary but not static metric, which is expressed in terms of the velocity field $\mathbf{v}(\mathbf{r})$ describing the frame dragging in the gravitational field. For the spherical black hole the velocity field is radial:

$$\mathbf{v}(\mathbf{r}) = -\hat{\mathbf{r}} c \sqrt{\frac{r_h}{r}},\ r_h = \frac{2MG}{c^2}. \quad (2)$$

Here M is the mass of the black hole; r_h is the radius of the horizon; G is the Newton gravitational constant. The corresponding tetrad fields are $e^j_k = c\delta^j_k$ and $e^j_0 = v^j$ [12]. Behind the black hole horizon the drag velocity exceeds the speed of light, $\mathbf{v}^2(\mathbf{r}) > c^2$.

The energy spectrum of the relativistic fermions living in the Painlevé–Gullstrand spacetime is given by the contravariant metric tensor, $g^{\mu\nu} p_\mu p_\nu = 0$. The corresponding Hamiltonian for the fundamental Weyl fermions interacting with the tetrad field corresponding to the Painlevé–Gullstrand metric has the form [8]:

$$H = \pm c \boldsymbol{\sigma} \cdot \mathbf{p} - p_r v(r) + \frac{c^2 p^2}{E_{\rm UV}},\ v(r) = c\sqrt{\frac{r_h}{r}}. \quad (3)$$

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Here p_r is the radial momentum of fermions; the second term in the right hand side of (3) is the Doppler shift; the third term is the added nonlinear dispersion. In the heat bath reference frame the negative energy states of the originally positive branch

$$E_+ = (c - v(r)) p_r + \frac{c^2 p^2}{E_{\rm UV}}, \quad (4)$$

form the Fermi surface. Together with the Fermi surface of holes (antiparticles) one has the pair of the Fermi surfaces attached to the Weyl point.

The behavior of the energy spectrum behind the event horizon has one to one correspondence with the energy spectrum of the type-II Weyl fermions [6]. This allows us to construct the analog of the black hole horizon starting with the fermionic spectrum of Weyl semimetals. The Hamiltonian (3) determines the effective tetrad field, which in turn gives rise to the effective contravariant metric, $g^{\mu\nu} = e^\mu_a e^\nu_b \eta^{ab}$. The latter describes the conical spectrum of Weyl quasiparticles, $g^{\mu\nu} p_\mu p_\nu = 0$. The corresponding covariant metric $g_{\mu\nu}$ determines the effective space-time, in which the quasiparticles live, and describes the behavior of the effective "light cone".

Let us now consider the inhomogeneous semimetal, where the transition between the type-I and type-II Weyl points takes place at some surface. Let us discuss, for example, a spherical surface of radius r_h, with type-II Weyl fermions inside the sphere, see Fig. 1 (bottom). Then the Hamiltonian has the form of Eq. (3) with $v(r_h) = c$, and the effective space-time is determined by covariant metric $g_{\mu\nu}$ in Eqs. (1), (2). At $r < r_h$ the effective light cone is overtilted, which simulates the interior of the black hole in the Painlevé–Gullstrand space-time in Fig. 1 (top). This mechanism of formation of the artificial event horizon differs from the traditional dynamic mechanism based on the supercritical flow behind the horizon [1, 10, 13, 14]. The formed black hole horizon is fully stationary in equilibrium, when all the negative

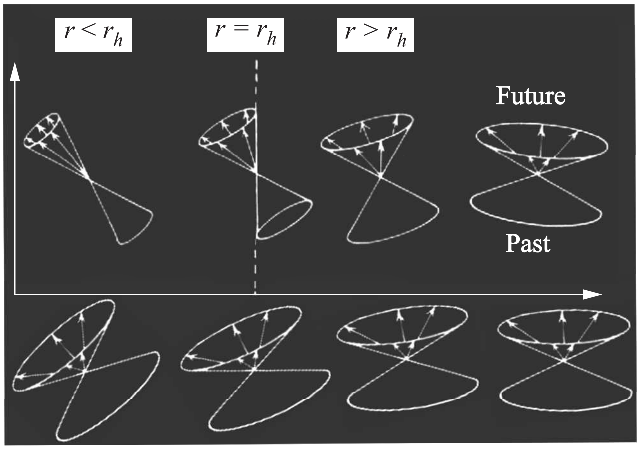

Fig. 1. Illustration of the black hole horizon at $r = r_h$ and of the artificial event horizon at the interface between the type-I ($r > r_h$) and type-II ($0 \leq r < r_h$) Weyl semimetals. Top: The light cone for relativistic Weyl and Dirac fermions, $g_{\mu\nu}x^\mu x^\nu = 0$, outside and inside the black hole in the Painlevé–Gullstrand space-time. At $r < r_h$ the light cone is overtilted and relativistic fermions with linear spectrum are locked inside the horizon. Bottom: The corresponding Dirac cone in the energy spectrum of relativistic Weyl fermions is described by the contravariant metric tensor, $g^{\mu\nu}p_\mu p_\nu = 0$. At $r = r_h$ the cone touches the zero energy level. At $r < r_h$ the cone is overtilted and two Fermi surfaces are formed. In Weyl semimetals, the Dirac cone in the energy-momentum space, $g^{\mu\nu}p_\mu p_\nu = 0$, is the primary quantity, where $\mathbf{p}$ is counted from the position of the Weyl point. The corresponding covariant metric tensor, $g_{\mu\nu}x^\mu x^\nu = 0$, describes the effective space-time for Weyl fermions. This metric experiences the event horizon at the boundary between the type-I ($r > r_h$) and type-II ($0 \leq r < r_h$) Weyl semimetals

energy states in the Fermi surfaces inside the horizon are occupied. Such equilibrium black hole is not radiating, as is probably distinct from the black hole in the fundamental Einstein theory of gravity. However, at the first moment of creation of the black hole analog, the system is not in the equilibrium state: the negative energy states of the former positive branch E_+ are empty, while the positive energy states of the former negative branch E_- are occupied. The initial stage of equilibration – the filling of the negative energy states by the fermions occupying the positive energy states – corresponds to creation of the particle-hole pairs at the horizon and thus simulates the Hawking radiation. The corresponding Hawking temperature is determined by effective gravitational field at the horizon:

$$T_{\mathrm{H}} = \frac{\hbar}{2\pi}\left(\frac{dv}{dr}\right)_{r=r_h}. \tag{5}$$

For the sufficiently small black hole regions the gradient of the system parameter v can be large, and T_{H} may reach the room temperature.

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