ISSN 0021-3640, JETP Letters. ©Pleiades Publishing, Inc., 2023 , vol. 118, iss. 7, pp. 546 – 547 © 2023 October 10

Gravity through the prism of condensed matter physics

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Submitted 24 August 2023
Resubmitted 2 September 2023
Accepted 2 September 2023

DOI: 10.31857/S1234567823190126, EDN: xskopf

In the paper "Life, the Universe, and everything – 42 fundamental questions" [1], Roland Allen and Suzy Lidström presented personal selection of the fundamental questions. Here, based on the condensed matter experience, we suggest the answers to some questions concerning the vacuum energy, black hole entropy and the origin of gravity. In condensed matter we know both the many-body phenomena emerging on the macroscopic level and the microscopic (atomic) physics, which generates this emergence. It appears that the same macroscopic phenomenon may be generated by essentially different microscopic backgrounds. This points to various possible directions in study of the deep quantum vacuum of our Universe.

There are at least 6 different scenarios of emergent gravity, which are supported by the condensed matter examples, and it is not clear which of them (if any) is preferred by Nature:

(1) In the Akama–Diakonov theory [2, 3] the gravitational tetrads emerge as the order parameter of symmetry breaking phase transition, the vacuum expectation value of fermionic operators:

$$e^a_\mu = < \hat{E}^a_\mu > \,,\; \hat{E}^a_\mu = \frac{1}{2}\left(\Psi^\dagger\gamma^a\partial_\mu\Psi - \Psi^\dagger\overleftarrow{\partial_\mu}\gamma^a\Psi\right). \quad (1)$$

This scenario is supported by the condensed matter example. The vielbein emerges as the order parameter and metric emerges as fermionic quartet in the spin-triplet p-wave superfluid ^{3}He-B [4].

(2) Tetrads emerge together with Weyl fermions and gauge fields in the vicinity of the topological Weyl points in the energy spectrum of fermionic quasiparticles [5, 6]. The expansion of the 2×2 Hamiltonian for fermionic quasiparticles near the Weyl point at $\mathbf{p}=\mathbf{p}^0$ gives

$$H \approx e^i_a\sigma^a(p_i - p^0_i). \quad (2)$$

Here σ^a are Pauli matrices; the spacetime dependent matrix e^i_a plays the role of the effective triad field; and the spacetime dependent vector $\mathbf{p}^0$ plays the role of the vector potential of the effective $U(1)$ gauge field. This scenario takes place in the Weyl superfluid ^{3}He-A and now is intensively discussed in Weyl semimetals.

(3) The gravitational tetrads may emerge as the elasticity tetrads, which describe the elasticity theory in crystals [7, 8]. In this approach, an arbitrary deformed crystal structure can be described as a system of three crystallographic surfaces, Bragg planes, of constant phase $X^a(x)=2\pi n^a$, $n^a\in\mathbb{Z}$ with $a=1,2,3$. The intersections of the surfaces

$$X^1(\mathbf{r},t)=2\pi n^1,\; X^2(\mathbf{r},t)=2\pi n^2,\; X^3(\mathbf{r},t)=2\pi n^3, \quad (3)$$

represent the lattice points of a deformed crystal. In the continuum limit, the elasticity triads are gradients of the phase functions:

$$E_i{}^a(x)=\partial_i X^a(x) \quad i=x,y,z, \quad a=1,2,3. \quad (4)$$

(4) The metric may emerge from the non-quadratic vielbein. The dimension of spin space in the vielbein matrix can be smaller or larger than the dimension of coordinate space. Example of the latter is the 4×5 vielbein with dimension 5 of the spin space, which takes place in the planar phase of superfluid ^{3}He [9]. Such scenario can be extended to the Akama–Diakonov gravity. In this scenario one may have continuous change of the signature of the metric [9]. Dynamical signature has been also discussed in Ref. [10].

(5) The broken symmetry may lead to formation of different tetrads for different fermionic species [11]. If Minkowski vacuum is degenerate with respect to discrete symmetries [12], one may have separate tetrads: i) tetrads for left fermions; ii) tetrads for right fermions; iii) tetrads for left antiparticles; and iv) tetrads for right antiparticles [13]. This serves as the multi-tetrad extension of bi-metric gravity introduced by Rosen [14].

(6) The scenario with complex tetrads takes place in the B-phase of superfluid ^{3}He [4]. The possible realization in gravity is in [15].

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In all six scenarios of emergent gravity, tetrads are the primary emergent objects, while metric is the secondary object, which is the bilinear form of tetrads. This would mean that geometry is the secondary emergent phenomenon. Whatever scenario (if any) is preferred by Nature, the gravity is not described by Einstein metric theory and requires the extended theory in terms of tetrads such as the Einstein–Cartan–Sciama–Kibble theory [16]. There are the condensed matter scenarios, in which metric emerges as primary object, such as acoustic metric in moving liquid [17, 18]. These analogs of gravity do not describe the interaction of gravity with fermions, and cannot serve as the guiding rule for constructing the quantum gravity. But they are useful for the experimental simulations of different effects related to quantum gravity [19].

Scenarios (1) and (2) suggest very different origins of quantum gravity. However, they have similar predictions for the number of fermionic degrees of freedom in quantum vacuum. In the Diakonov theory, where the original action is the product of 8 fermionic operators, the grand unification with symmetry $SO(16)$ is suggested. This fits four generations of the Standard Model with 16 Weyl fermions in one generation [3]. The Weyl point scenario is realized, in particular, in superconductors of class $O(D_2)$ [20, 21]. In this superconductor, there are 8 Weyl points in the energy spectrum, which form cube in 3D momentum space giving rise to 8 Weyl fermions. In the 4D extension [22, 23] the Weyl nodes may form the 4D cube in the momentum-frequency space, which results in 16 Weyl fermions. The numbers 2^N also follow from the topological analysis of condensed matter systems. If the vacuum of Standard Model is considered as topological Weyl semimetal, the maximal number of massless fermions in the symmetric phase is $16g$, where g is number of generations [24]. The group Z_{16} also appears in the classification of topological phases in $3+1$ dimension [25].

We also discuss the condensed matter views on the cosmological constant problem and black hole thermodynamics. In particular, the answer to the question "Why does conventional physics predict a cosmological constant that is vastly too large?" [1] is the following. The so-called conventional physics ignores the condensed matter lesson that in the full equilibrium the diverging zero-point energy of quantum fields is cancelled by the atomic (trans-Planckian) degrees of freedom. The reason for cancellation is the general laws of thermodynamics, which are the same for relativistic and non-relativistic vacua (ground states).

This work has been supported by Academy of Finland (grant 332964).

This is an excerpt of the article "Gravity through the prism of condensed matter physics". Full text of the paper is published in JETP Letters journal. DOI: 10.1134/S0021364023602683

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