PTEP

Prog. Theor. Exp. Phys. **2024** 08C001 (2 pages)
DOI: 10.1093/ptep/ptae121

Editorial

The Implications of Majorana Fermions for High-Energy and Condensed Matter Physics

Masatoshi Sato[1] and C. S. Lim[2,*]

[1] *Center for Gravitational Physics and Quantum Information, Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan*
[2] *Professor Emeritus, Kobe University, Kobe 657-8501, Japan*
*Email: lim@lab.twcu.ac.jp

Received August 1, 2024; Accepted August 2, 2024; Published August 5, 2024

Majorana fermions, proposed by E. Majorana in 1937, do not have a distinction between particle and antiparticle. Although in the bosonic sector, there exist particles such as photons and π^0 whose antiparticles are themselves, as of this date, no Majorana fermions have been discovered, at least as elementary particles.

Since the additive quantum numbers of an antiparticle are opposite in sign to those of a particle, Majorana fermions, if they ever exist as elementary particles, should be electrically neutral as the result of the well-established charge conservation law, just as in the case of photons or π^0. This argument also implies that the mass term of Majorana fermions inevitably leads to the nonconservation of the fermion number as one of the additive quantum numbers.

From such points of view, Majorana fermions may seem to be some special sort of fermions. On the other hand, however, e.g. a complex scalar field can be written as the linear combination of two real scalar fields (with identical masses), and Majorana fermions may be regarded as more fundamental fermions than the well-known Dirac fermions from such a viewpoint. This is one of the reasons why the notion of the Majorana fermion has attracted the theoretical interest of researchers.

As a matter of fact, Majorana fermions have been playing some critical central roles in the field of high-energy physics. To pick up a few of them, the extremely tiny neutrino masses, compared to those of charged leptons, are argued to have their origin in the Majorana nature of neutrinos, which, of course, are electrically neutral particles. Also, in the supersymmetric theory, a popular representative scenario of the physics beyond the standard model of elementary particles, “photino,” the supersymmetric partner of the photon, e.g. is regarded as a Majorana fermion.

Great efforts are also being made to prove the existence of the Majorana fermion experimentally. A well-known example is the search for the neutrino-less double beta decay realized by the lepton number nonconservation due to the Majorana neutrino mass term, by, e.g. the KamLAND-Zen experiment.

As mentioned above, Majorana fermions have been paid much attention in high-energy physics for a relatively long time. The fascinating and somewhat surprising fact is that nowadays, it has become widely recognized that the Majorana fermions also play essential roles in various topics of condensed matter physics, which is governed by the electromagnetic interactions of electrons, which, as a charged fermion, seems to have nothing to do with Majorana fermions at first glance. Recently, remarkable progress in these topics has been made, as reported in the series of papers included in this special section.

First of all, a group of materials called topological insulators/superconductors has been discovered, which has an excitation following the Dirac equation, similar to that for elementary particles. Especially in the case of topological superconductors, the existence of excitation has been made clear, which does not have a distinction between particle and antiparticle and, therefore, behaves as if it were a Majorana fermion. Furthermore, it has become apparent that some spin models formulated on a honeycomb lattice have an excitation behaving as a Majorana fermion.

Though the existence of these Majorana fermions was originally anticipated only theoretically, recent experimental results showing their existence have been reported successively and have attracted the attention of physicists.

It also has turned out that the zero mode of the Majorana fermion is not of ordinary type but behaves as an anyon with fractional statistics. In quantum field theories, a state is described by creation and annihilation operators. In the case of the Majorana fermion, however, there stems some contradiction if we attempt to describe the zero mode by use of the creation operator, since for a Majorana fermion, its antiparticle being itself, the creation and annihilation operators become identical. Hence, to form a pair of zero mode states, described by creation and annihilation operators located not necessarily in the same place, is needed. This is why the zero mode Majorana fermion has different statistics than the original fermion. This anyon state is widely expected to have important applications for a stable quantum bit, and various ways of its realization have been discussed.

A novel method to solve spin models by rewriting the system in terms of a Majorana fermion has also been developed. By utilizing this method, the aforementioned spin model on the honeycomb lattice's excitation behaving as a Majorana fermion was revealed for the first time.

It should be noticed that the Majorana fermion as an elementary particle and the Majorana fermion appearing in condensed matter physics are essentially different in some respects, though they have various similarities. In particular, they are entirely different in their responses to the electric or magnetic field. This is because relativistic quantum field theory describes the Majorana fermion as the elementary particle. Therefore, its property is constrained by the CPT theorem, whereas the Majorana fermion appearing in condensed matter physics is free from such constraint. Especially the electromagnetic response of the Majorana fermion in the topological superconductor is determined by the symmetry possessed by the superconducting Cooper pair, which is a property not shared by the Majorana fermion as an elementary particle.

In this special section, comprehensive topics concerning the Majorana fermion, as already mentioned above, ranging from high-energy physics to condensed matter physics, are introduced and discussed by the leading scientists in each field, paying special attention to their recent progress.

The editors would like to express their sincere gratitude to all of the authors for their valuable and indispensable contributions to this special section.