

Review



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Symmetry breaking and the deconstruction of mass

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We briefly review some of the connections between symmetry breaking in condensed matter physics and in particle physics, assisting, in particular, our current understanding of the origin of mass.

1. Introduction

It is a pleasure to thank the organizers, and in particular John Ellis and Jim Virdee for the invitation to present this contribution in such an impressive venue. We are still celebrating the recognition from the Nobel committee to the mechanism and the particle associated with the breaking of the gauge symmetry of the standard model (SM)¹ last December. Some aspects of the mechanism and its history can be found in reference [1], and a major recent presentation on Higgs physics appeared in reference [2].

Understanding the role played by symmetry in the description of the physical world is one of the major themes in twentieth-century physics. Symmetry has had applications in atomic physics, condensed matter physics, nuclear and particle physics, etc. Cross-fertilization in several areas was important in making progress. This happened in condensed matter and particle physics, in what is known today as the Brout, Englert, Higgs (BEH) [3–6] mechanism in particle physics and with the Bardeen, Cooper, Schrieffer (BCS) theory of superconductivity.² The recent discovery of the *H*-particle at CERN has profound implications in our understanding of the standard model (see footnote 1) and what could come beyond. The value of its mass is, indeed, challenging a number of concepts and ideas that have been very influential in high-energy physics in the

¹A good reference on the standard model and all its properties is the recent book by Chris Quigg, *Gauge theories of the strong, weak, and electromagnetic interactions: 2nd edn*, Princeton University Press (23 September 2013). The subject is so central in modern physics that one hardly refers to the original references any longer. They are part of general knowledge.

²An excellent book with the history of superconductivity is L. Cooper and D. Feldman, *BCS: 50 years*. World Scientific Publishing Company; (1 June 2010).

past decades. In particular, the notion of naturalness is currently under a certain tension owing to the low mass of the H -particle, and the fact that we have not found any unknown states around a TeV in mass.³

In this article, we make a number of remarks concerning the origin of mass in the standard model and its connection with the theory of superconductivity. The presentation is informal.

2. Generalities on symmetries

It is far from simple to explain spontaneous symmetry breaking (SSB) in the SM, the BEH mechanism. We are making statements about the properties of the ground state of the universe, the vacuum, a quantum state. The mechanism is fundamentally a quantum phenomenon, so often classical metaphors may be misleading. Nature offers an excellent one which has been extraordinarily fertile in the interplay between condensed matter and particle physics.

Symmetries in physics come in many varieties. Some are discrete, such as parity (mirror reflection), charge conjugation (exchange of particles and antiparticles); some are continuous. Among them, we can distinguish kinematical space–time transformations that act on space–time, such as rotations, translations and Lorentz boosts, and some are continuous but internal, acting on the internal quantum numbers describing the non-kinematic attributes of a given particle or quantum state. These include isospin of protons and neutrons, the colours of quarks, etc. We dealing with the realization of these symmetries.

At the quantum level, the dynamics of a system is described by a Hamiltonian operators $\mathcal{H}$ containing all basic interactions. In any consistent theory, there is always a lowest energy state, the vacuum $|0\rangle$ containing a large amount of information about the system. The continuous symmetries are implemented by a set of operator charges Q_a . They are symmetries when they commute with the Hamiltonian:

$$[Q_a, \mathcal{H}] = 0. \quad (2.1)$$

To see whether the spectrum of the theory falls into explicit representation of the given symmetry, we have to verify if the symmetry is implemented in the Wigner–Weyl (WW) or Nambu–Goldstone (NG) modes:

$$\text{and} \quad \left. \begin{array}{ll} Q_a|0\rangle \geq 0 & \text{WW mode} \\ Q_a|0\rangle \neq 0 & \text{NG mode.} \end{array} \right\} \quad (2.2)$$

In a relativistically invariant theory, we associate a massless particle with every global continuous broken symmetry, i.e. those symmetries that do not leave the vacuum invariant. The interplay between local (gauge) symmetries and SSB is one of the themes of this conference.

Nearly a century ago, two fundamental discoveries were made that are quite important in our current understanding of broken symmetries and on the origin of the mass. The first was made by Kamerlingh Onnes in 1911. When passing an electric current through mercury, Onnes observed that below a (critical) temperature, the electrical resistance fell to zero. The material superconducts electrical current. For details see (footnote 2), and references therein.

At about the same time, Ernest Rutherford discovered that the atom is made of a central nucleus, where most of its mass resides, and a cloud of electrons bound to it. The atom is indeed quite empty, and most of its mass, and therefore, our mass is mostly accounted by the mass of the nucleus. A very interesting question arises: Is the mass of the nucleus due to the BEH symmetry-breaking mechanism? The answer is far more subtle than one might first think.

Let us delay for the time being the study of the mass of the nucleus and continue with superconductivity. In the early 1930s, Meissner and Ochsenfeld observed that superconducting materials are perfect diamagnets. Below the critical temperature, they expel moderate magnetic fields from their interiors. This is currently exhibited in most science museums using magnetic levitation, bringing well-justified awe to many visitors.

³For a nice review on the concept of Naturalness and applications, see G. F. Giudice: *Naturalness after LHC8*. (<http://arxiv.org/abs/1307.7879>)

The road to our current understanding of superconductivity has been paved by quite a number of great scientists. Some salient contributions are listed in references [7–14], but they are by no means exhaustive. Many more details and references are provided in footnote 2. There is still plenty to be understood in the subject, in particular in the study of high-temperature superconductors.

The main idea of the BCS theory is to show that at low temperatures, the interactions of the conduction electrons with the ion lattice generates a small attraction between electrons which form what are called Cooper pairs. Cooper pairs behave now like bosons and they can condense in a charged state, the superconducting state. In an oversimplified account of the phenomenon, the condensed pairs are responsible for the supercurrent. In this picture, the ground state is a condensate of charged particles. Among other things, this implies that the gauge symmetry associated with electromagnetism breaks down spontaneously, and the photon acquires an effective mass inside a superconductor. I must apologize here for the perhaps excessive simplification. From this point of view, if we want to describe long-distance properties of the superconducting material (beyond hundreds or thousands of Angstroms, we can use an effective Hamiltonian description provided by the Ginzburg–Landau theory [7–14].

The Cooper pair density is described by a single, complex scalar field $\phi = (1/\sqrt{2})(\phi_1 + i\phi_2)$. Its modulus represents pair density, and the phase is related to charge rotations. Below the critical temperature, the potential describing the field ϕ is the celebrated Mexican hat potential:

$$V(\phi) = \frac{\lambda}{4}(|\phi|^2 - \mu^2)^2, \quad \phi = |\phi| e^{i\theta}. \quad (2.3)$$

In the ground state of this potential, the modulus of ϕ has a constant value and θ is undetermined. We have a charge condensate. It is the interaction of the photon with this condensate that gives it a mass. Its spin-zero component is represented by the variation of the phase θ . Effectively, the photon field A_μ absorbs the phase of the ϕ -field and becomes massive $A_a \rightarrow A_a + 2e\mu\partial_a\theta$ (for details see, footnote 1).

This is, in a nutshell, the beautiful metaphor provided by nature for the BEH mechanism.

3. The problem of mass in the standard model

In the electroweak theory of Glashow, Weinberg and Salam, we have four agents transmitting forces, the vector bosons W^+ , W^- , Z and the photon field γ . Their description is in terms of a gauge theory with group $SU(2) \times U(1)$, and it is not consistent to add masses by hand.

In this gauge group, we have four quantum numbers similar to electric charge: three for weak isospin (the $SU(2)$ part) and one for weak hypercharge (the $U(1)$ part). It is a remarkable fact about the weak interactions (as obtained by numerous experiments), that the left- and right-handed components of quarks and leptons couple differently to the force fields. This fact protects them from acquiring mass if we try to use the analogy with how we represent the mass of the electron in quantum electrodynamics (QED). Adding by hand a mass term in the SM again violates gauge invariance and renders the theory inconsistent.

The key to SSB in the SM is to introduce two complex scalar field that form a doublet with respect to weak isospin:

$$\begin{pmatrix} H^+ \\ H^0 \end{pmatrix} \quad |H|, \theta_1, \theta_2, \theta_3. \quad (3.1)$$

In analogy with §2, we can describe the scalar doublet in terms of a common modulus $|H|^2 \equiv |H^+|^2 + |H^0|^2$ and three angles. Three of the charges develop condensates, and only one, electric charge does not. The phases associated with the condensing charges are represented by the three angles $\theta_{1,2,3}$. The angles, as in the case of superconductivity, are absorbed by three of the vector bosons, the $W^\pm$ and the Z^0 thus acquiring masses, and the photon remains massless, because the ground state is annihilated by the electric charge generator. The potential used to achieve the condensates is the same mexican potential used in §2. By this mechanism, one gives masses to

the W, Z vector bosons explaining the short range of the weak interactions. This condensate also allows to accommodate the masses for quarks and leptons without violating the symmetries of the theory. This is achieved with interactions of the form:

$$gLHR,$$

where L, R represent respectively the left- and right-handed components of quarks and leptons.

This procedure easily accommodates the electron mass, as well as the masses of the other observed leptons, the muon and the tau particles. It also accommodates the so-called the current algebra masses of the quarks. Unfortunately, this is far from accounting for the masses of protons and neutrons that make up nuclei.

The explanation of the mass of protons and neutrons is a fascinating story that is once again related to symmetry breaking. The symmetries involved are known as chiral symmetry and scale invariance. An excellent and accessible account is provided in a recent article by Wilczek [15]. We simply outline the arguments. Those interested in the details should consult this reference.

In the absence of the BEH mechanism, the left- and right-handed components of quarks can be rotated independently. This is the chiral symmetry of quantum chromodynamics (QCD). This symmetry is broken spontaneously by the quantum properties of QCD, a gauge theory based on the colour gauge group $SU(3)$. If we consider just the pure gauge interactions associated with the $SU(3)$ -vector bosons, the gluons, the classical theory is invariant under scaling transformations. Namely, if A_μ represents the gluon fields, and A_μ is a classical solution to the equations of motion, then so is the scaled configuration: $\lambda A(\lambda x)$, for any real parameter λ . Again, the quantum structure of the vacuum of QCD breaks this symmetry. One starts with a scale invariant theory, but quantum mechanics generates a scale, known as $\Lambda_{\text{QCD}} \sim 200 \text{ MeV}$.

The proton and neutrons are each made of three quarks (uud for the proton, udd for the neutron). The mass parameters for the u, d quarks that appear in the SM as a consequence of the BEH mechanism are very small (in the few MeV range) compared with the masses of protons and neutrons, which are about 1000 MeV. Hence, the sum of two up and one down quark mass parameters hardly account for the mass of the proton. The largest contribution come, in fact, from the fact that the quarks and gluons are highly relativistic objects confined in a space of the order of a fermi. A purely quantum phenomenon owing to QCD: the confinement of colour. As mentioned before, a new scale is generated dynamically in this case. Even if the mass parameters of the up and down quarks were set to zero, we would still have protons and neutrons with masses approximately equal to those we observe. Incidentally, what makes the study of the strong interactions hard is the fact that

$$\Lambda_{\text{QCD}} \gg m_u, m_d.$$

A large fraction of the mass of protons and neutrons has its origin in this quantum phenomenon of confinement.

Finally, we should take into account that for most nuclei, their mass is obtained by summing the masses of their constituent protons and neutrons (up to a relatively small but very important binding energy). This implies that apart from identical particles effects, the protons and neutrons keep their identities inside nuclei. Hence most of the mass that makes our bodies and most of the matter that we see around us has its origin in a rather deep quantum phenomenon, confinement, and the breaking of scale invariance. It is remarkable, most of our mass is of quantum origin.

4. Parting comments

We are still far from understanding all the mass of universe. From the WMAP⁴ and Planck⁵ satellites as well as from many astronomical observations, we have learnt recently that at this moment in the history of the universe most of its mass or energy is dark. What we call standard matter only accounts for about 5% of the total, whereas dark matter accounts for

⁴For details on the WMAP collaboration, results and publications, see <http://map.gsfc.nasa.gov>.

⁵For details on the Planck collaboration, results and publications, see <http://sci.esa.int/planck/>.

nearly 22% and dark energy for about 70%. We have no idea about the origin of the two last components that currently dominate the energy budget of our universe. It is a fundamental challenge to determine their origin, and also if their ultimate explanation will have anything to do with BEH-like mechanisms. Even closer to home, although we can accommodate the masses for the known quarks and leptons using the BEH paradigm, we are in the dark as far as understanding their measured values. Let us hope that with all the experiments planned in the next decade on accelerators, satellites and underground laboratories we may learn enough clues to being answering these questions. I am sure that once we do, our view of the universe will be vastly different.

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