Studies in History and Philosophy of Modern Physics 50 (2015) 25–42

Contents lists available at ScienceDirect

Studies in History and Philosophy of Modern Physics

journal homepage: www.elsevier.com/locate/shpsb

The quantum Hall effects: Philosophical approach

P. Lederer

Laboratoire de Physique des Solides, Université Paris-Sud et CNRS, Campus d'Orsay, 91405 Orsay Cedex, France

ARTICLE INFO

Article history:
Received 18 June 2014
Received in revised form
10 January 2015
Accepted 10 February 2015
Available online 6 March 2015

Keywords:
Physics
Quantum Hall Effects
Scientific realism
Non-Figurative Realism
Dialectical materialism

ABSTRACT

The Quantum Hall Effects offer a rich variety of theoretical and experimental advances. They provide interesting insights on such topics as gauge invariance, strong interactions in Condensed Matter physics, emergence of new paradigms. This paper focuses on some related philosophical questions. Various brands of positivism or agnosticism are confronted with the physics of the Quantum Hall Effects. Hacking's views on Scientific Realism, Chalmers' on Non-Figurative Realism are discussed. It is argued that the difficulties with those versions of realism may be resolved within a dialectical materialist approach. The latter is argued to provide a rational approach to the phenomena, theory and ontology of the Quantum Hall Effects.

When citing this paper, please use the full journal title *Studies in History and Philosophy of Modern Physics*

1. Introduction

Bachelard (1934) stresses that Philosophy must submit to the teachings of Science. As a physicist and a philosopher of science, I am inspired by this point of view. In the following, I am introducing a study of a relatively new field of physics, the Quantum Hall Effects, and trying to extract some relevant philosophical view point from that study.

The structure of the paper is as follows: the first parts of this paper (Sections 2–5) are devoted to an elementary introduction to this field.[1]

Section 2 sets the historical stage which allowed for the appearance of the Quantum Hall Effects (hereafter QHE). Section 3 explains why the QHE qualify as a scientific revolution. Section 4 specializes in the history of these effects, beginning with the classical one, and introducing some simple elements of theory for the motion of electrons in a magnetic field. Sections 4.1 and 4.2 deal, respectively, with the classical Hall effect, ancestor of the QHE, and the basic quantum theory of electron dynamics in a magnetic field. Section 4.3 describes the “normal science” prediction, published before experiments were conducted. The astonishing experimental discovery of the Integer QHE (Klitzing, Dorda, & Pepper, 1980) (hereafter IQHE), which seemed to refute qualitatively those theoretical expectations, is described in Section 4.4. Section 4.5 introduces the second revolutionary finding: the Fractional QHE (hereafter FQHE) (Tsui, Stormer, & Gossard, 1982) and briefly introduces the discoveries for which Laughlin (1981, 1983) is responsible, such as fractional statistics and fractionally charged excitations; a novel theoretical entity, Composite Fermions, is mentioned. It was introduced by Jain (1989) as a development of Laughlin's theory, to account for some experimental results which the latter did not explain. Section 5 enters in more technical detail, while remaining at a simple pedagogical level. Section 5.2 summarizes the main points of the theory for the IQHE based on Laughlin's (1981) work. Section 5.3 discusses some aspects of gauge symmetry which are relevant in the FQHE theory. Sections 5.4 and 5.5 introduce two new theoretical and experimental entities which are by-products of the QHE: the topological insulator and the Quantum Hall ferromagnet. Section 6 is devoted to the second Quantum Hall revolution: the experimental discovery (Tsui et al., 1982) and the theory of the Fractional Quantum Hall Effects (hereafter FQHE) also by Laughlin (1983); Section 6.2 explains the main idea at the basis of the Composite Fermion proposal.

In the last parts (Section 7), I will attempt to draw some philosophical inferences from the material described in the previous sections. In particular, I will discuss two versions of “Realism”. First, I will spend some time discussing “Scientific Realism”, as developed by Ian Hacking (Section 7.1), in his book “*Representing and Intervening, Introductory topics in the philosophy*

E-mail address: Pascal.lederer@u-psud.fr

[1] Some readers will find that this introductory part is not so elementary, as it requires some training in quantum mechanics… Is it conceivable to deal with the philosophy of physics nowadays without a sufficient amount of knowledge of quantum mechanics?

http://dx.doi.org/10.1016/j.shpsb.2015.02.002
1355-2198/© 2015 Elsevier Ltd. All rights reserved.

of natural science" (Hacking, 1983). Hacking's views on the importance of practice in establishing truths about the world will be stressed; this section contrasts Hacking's views with those of dialectic materialism. Section 7.2 discusses the possibility of establishing truths about the world from Hacking's point of view, in relation with the QHE. This bears also on the Non-Figurative Realism picture developed by Chalmers in his book on "*What is this Thing Called Science?*" (Chalmers, 1976) which is mentioned in Section 7.3. Scientific pluralism is discussed in Section 7.4; Section 7.5 discusses the QHE from the point of view of various other science philosophers. In Section 7.6, I discuss some of the relations this study may have with the question of the unity and struggle of opposites in nature, namely one of the theses of dialectic materialism in Nature.

The conclusion lists the main results of this work (Section 8).

The discoveries of the IQHE in 1980, and of the FQHE in 1982, deal with an apparently restricted class of quantum phenomena: the behaviour of electronic systems in a two dimensional space under strong magnetic fields perpendicular to the two dimensional sample (Das Sarma & Pinczuk, 1997). What could we possibly learn about nature or about knowledge which could be of any universal interest?

This paper aims at offering some answers to this question.

2. The result of theoretical and experimental progress

A first observation is that the developments which are the topic of this paper were made possible by progress in the physics of semi-conductors. The latter is an intimate mixture of theoretical and experimental progress, based in particular on the quantum mechanics of electrons in various pure and impure crystalline structures.

At the interface of two types of semi-conductors, experimentalists have been able to create electron populations which are confined, at low enough temperatures, to a thin spatial slice of the order of a nanometer. This is made possible by mastering the theory and experiments on the electronic band structure of the relevant semi-conductors, and of their interface: the energy for an electronic excitation to migrate to positions far from the interface can be made a few orders of magnitude larger than temperatures of order 100 K, while the energy for an electronic displacement in the interface is much smaller. Then, at low enough temperatures, electrons are restricted to a two dimensional (2D) world. This, in turn, was made possible by advances in the purity and regularity control of the crystalline arrays at the interface. The reader will notice how important is the notion of "order of magnitude": of energy compared with temperature, of distances compared to interatomic ones, etc. This notion was first highlighted in the philosophy of physics, I believe, by Bachelard (Lecourt, 1970).

Improving the mobility of electrons at the interface of specially selected semi-conducting materials was a precondition for the experimental and theoretical study of quantum particles in a two dimensional environment.[2] This sets another example of the importance of the order of magnitude of the entity under study, in comparison with orders of magnitude of other relevant entities. The concept "order of magnitude" is a relational one.

Since the discovery of the QHE, two very different experimental systems have been found to exhibit QHE. An anisotropic crystal of weakly coupled organic conducting filaments exhibits the IQHE (Poilblanc, Montambaux, Héritier, & Lederer, 1987); then the discovery of graphene (Novoselov et al., 2004) in 2004 has provided a genuinely two dimensional electronic system: a sheet of Carbon, the thickness of an atomic radius, can be sliced off a graphite crystal. Although I will not discuss those systems in this paper, it is worth mentioning that electrons in graphene have zero inertial mass, obey a relativistic Dirac equation, and move in a two-dimensional space where the "velocity of light" is the Fermi velocity, two to three orders of magnitude slower than the actual velocity of photons in the vacuum.

3. A revolution in theory

The observation of Quantum Hall Effects, and particularly that of FQHE, participated in changing significantly the theoretical outlook on electronic liquids in condensed matter physics. Indeed the collective behaviour of electrons in simple metals[3] has been described with considerable success by the Landau liquid theory (Landau & Lifshitz, 1990). Within that picture, interactions between electrons alter *adiabatically* the ground state, as compared to that for which interactions are neglected. In other words interactions in that picture are considered as perturbations which modify only quantitatively the parameters of the theory which has no interaction: no spontaneous symmetry breaking is usually expected. From a technical point of view, the main theoretical methods used in this context have been those of Feynman diagrams, and quantum field theory.

Superconductivity has been explained, in part, with the Landau liquids as starting point,[4] and the mechanism for its breakdown – together with a spontaneously broken gauge symmetry – with the BCS theory: at low temperatures, the Fermi sea becomes unstable to the formation of electron pairs, due to an effective attractive interaction mediated by the vibration quanta of the crystalline network (Bardeen, Cooper, & Schrieffer, 1957); those pairs are bosons which (to be simple) form a Bose–Einstein condensate. This theoretical framework, although responsible for some irreversible advances in the understanding of a large class of insulators, semi-conductors and conductors,[5] has met its limits with the discovery of the QHE, and of a number of other phenomena, such as Mott insulators, or the high temperature superconductivity in copper oxides in 1986 (Bednoz & Mueller, 1986).

New theoretical methods have been necessary to account for such discoveries, and in particular that of the QHE. The path followed by Laughlin (1981, 1983) led him to the Nobel prize award in 1993. What is revolutionary in the QHE is (a) the original Laughlin's method to find the almost exact ground state wave function for strongly interacting fermions (electrons) in two space dimensions, on the basis of symmetry considerations, within a particular gauge choice; (b) this opened – within the vast field of quantum mechanics – a new field of physics, with new methods, new theoretical entities, such as incompressible quantum fluid, Composite Fermions, or topological insulators. The method was a radical departure from methods that had been followed until then.

In perturbative approaches, the theorist starts from a known solution for the non-interacting problem, which is related to the single particle problem. Although this approach may seem to justify a reductionist point of view (i.e. the properties of electron liquids would be the sum of properties of single electrons), the statistical properties of electrons, due to the antisymmetry of their wave function, introduce from the start of a major correction (the exclusion principle) to a naive reductionist viewpoint.

---

[2] At the time of this writing (April 2014), the electronic mobility at the interface of the so-called GaAs/AlGaAs heterostructures is larger than $5\times10^7\ \mathrm{cm}^2/\mathrm{V\,s}$, which allows us to observe details at a much finer scale than at the time of the original discovery of the IQHE.

[3] For example elements in the 3d and 4d transition series in the periodic table of elements.

[4] The term "Fermi liquid" is also used in this context.

[5] The so-called large band electronic systems.