Introduction

> The history of the exclusion principle is already an old one, but its conclusion has not yet been written.[1]

It is now eighty years since Wolfgang Pauli introduced an 'extremely natural' prescriptive rule, while dealing with some spectroscopic anomalies that beset physicists in the heyday of the old quantum theory. The rule excluded the possibility that any two bound electrons in an atom were in the same dynamic state, identified by a set of four quantum numbers. Hence the name of *Ausschließungsregel* (exclusion rule), or Pauli's *Verbot* (Pauli's veto) as Werner Heisenberg nicknamed it. The far-reaching physical significance of this rule became clear only later.

From spectroscopy to atomic physics, from quantum field theory to high-energy physics, there is hardly another scientific principle that has more far-reaching implications than Pauli's exclusion principle. It is thanks to Pauli's principle that one obtains the electronic configurations underlying the classification of chemical elements in Mendeleev's periodic table as well as atomic spectra. To this same principle we credit the statistical behaviour of any half-integral spin particles (protons, neutrons, among many others) and the stability of matter.[2] Shifting to high-energy physics, it is the exclusion principle that fixes the crucial constraint for

[1] Pauli (1946), p. 215

[2] On this result, established by the seminal proof of Dyson and Lenard (1967, 1968) and Dyson (1967), and later by the simplified Lieb–Thirring proof (1975), see Lieb (1991). The theorem, whose original proof was valid only in the non-relativistic domain and in the absence of gravitational interactions, shows that 'if *N* charged non-relativistic point particles belonging to a finite number of distinct species interact with each other according to Coulomb's law, and if the negatively charged particles of each species satisfy the exclusion principle, then the total energy of the system cannot be less than (–*AN*) where *A* is a constant independent of *N*', Dyson (1996), p. 32. Although this constitutes a very important application of the exclusion principle, for reasons of space I have not addressed it in this book, together with many other applications, to focus instead on a historico-philosophical analysis of the principle. In

binding quarks in hadrons, which together with leptons compose our physical world.

This book advances a philosophical analysis of the enduring and far-reaching validity of Pauli's principle. It does not aim to address what a scientific principle is. It addresses instead the following epistemological question: under what conditions are we justified in regarding an empirical and contingent rule as a scientific principle? Since the exclusion principle was born as a phenomenological rule in a period of crisis for the old quantum theory, we need to explain how it could be accredited as an important scientific principle of the new quantum theory (after 1925). And only by exploring the function Pauli's rule played in the quantum mechanics framework can we shed light on its distinctive nomological feature.

A historical investigation will accompany and support the philosophical analysis. In the following chapters I reconstruct the historical evolution of the exclusion principle across three main phases: from the original spectroscopic context (1920–4, Chapter 2), to the building-up of the quantum mechanics framework within which the spin–statistics theorem was proved (1925–40, Chapter 4), to the development of quantum chromodynamics and parastatistics which opened the door to experimental tests of the principle (1960s–90s, Chapter 5). As the historical reconstruction will highlight, Pauli's rule attained the status of a scientific principle in virtue of the *regulative* function it played in the quantum mechanics framework broadly construed. Regulative function as opposed to constitutive function: this distinction has a distinguished philosophical pedigree in Kant and in the neo-Kantian tradition of Ernst Cassirer. I latch my analysis of the exclusion principle onto this tradition, of which I give an overview in Chapter 1. Accordingly, I shall propose a version of 'dynamic Kantianism' that focuses on the regulative rather than on the constitutive function of scientific principles, and as such can be seen as complementing Michael Friedman's dynamic Kantianism,[3] while owing an obvious debt to Gerd Buchdahl's reading of Kant.[4]

The reasons for this choice reside in the nature and peculiar history of the exclusion principle itself. Pauli's rule did not play any constitutive role, in Hans Reichenbach's sense of coordinating a mathematical formalism with the physical part of a scientific theory so as to provide the conditions

the end, this book is not meant to be a comprehensive physics monograph on the exclusion principle in all its physical aspects and applications, but rather a monograph on its philosophical status as a scientific principle.

[3] Friedman (2001). [4] Buchdahl (1969a), (1969b).

of possibility of the theory. In this respect, it was a *sui generis* principle as compared to others such as the light principle[5] and the equivalence principle of special and general relativity.[6] Pauli's principle was introduced as a tentative rule on mainly phenomenological grounds, within the semi-empirical discipline of spectroscopy, and in a context of revolutionary transition characterized by the waning fortunes of the old quantum theory. It was from spectroscopic phenomena, with the help of some theoretical assumptions of the old quantum theory, that Pauli's rule was originally derived. Once suitably reinterpreted in the new quantum theory framework as a prescription to antisymmetrize the wave function (Fermi–Dirac statistics), it could accomplish a Kantian regulative function: it granted 'systematic unity' to the increasing body of quantum mechanical knowledge, and in so doing it made it possible to derive new laws (e.g. the spin–statistics theorem), whose effect was to enlarge in turn the nomological[7] scope of the principle itself. Systematic unity is an open-ended regulative goal of scientific inquiry. Necessity and nomological strength accrued to Pauli's rule in virtue of the regulative function it accomplished.

Under the action of permutation invariance, the exclusion principle in its Fermi–Dirac reformulation turned out to be one among several possible quantum statistical prescriptions. The larger mathematical structure disclosed by permutation invariance paved the way for the experimental validation of the principle, thanks to the development of the rival programmes of parastatistics and quantum chromodynamics in the 1960s, both prompted by some prima facie negative evidence against the exclusion principle in the context of the quark theory. This process of validation was a two-way street. On the one side, it passed through the parastatistics prediction of Pauli-violating states or more precisely through the prediction of hypothetical particles called 'parons', which supposedly violated the principle by a small amount. This led to the first rigorous experimental tests of the principle more than sixty years after its introduction. It passed, on the other side, through the empirical support that quantum chromodynamics, based on the Pauli-obeying 'coloured' quarks, received.

[5] 'Light principle' denotes the special relativity principle that fixes the finite value for the velocity of light.
[6] For Reichenbach's notion of coordinating principles and its relation to Friedman's analysis of the constitutive role of these two principles, see Section 1.3.
[7] 'Nomological scope' denotes the scope of applicability of Pauli's principle as a scientific principle.

My version of dynamic Kantianism owes much to Ernst Cassirer, not only in the priority given to the regulative over the constitutive function, but also in the reappraisal of scientific rationality it delivers. This book is in the end an essay on why we are justified in believing in the exclusion principle and on the rationale for it. This rationale is rooted in the history of the principle. What then needs to be explained in the first place is how the exclusion principle became a live option in the period of revolutionary transition around 1924, when the old quantum theory was proving increasingly inadequate and a new framework had still to be developed. Second, what is the rationale for the enduring validity of the exclusion principle, in the face of some negative evidence. Chapters 3 and 5 are respectively dedicated to these two aspects.

In Chapter 3, following on the historical reconstruction of Chapter 2, I shall argue that the exclusion rule and the associated concept of the electron's spin became a live option for physicists around 1925 because of the piecemeal process of transformation of the old quantum theory into the new quantum theory. Against Kuhn's much celebrated incommensurability thesis, I shall defend the prospective intelligibility of the revolutionary transition around 1925. I shall focus on Kuhn's later writings, where incommensurability is redefined as untranslatability between scientific lexicons, and assess Kuhn's argument, its hidden lemmas and credentials. I shall conclude that the electron's spin and Pauli's exclusion rule were live options for physicists still working with the old quantum theory because they were derived from anomalous phenomena with the help of some theoretical assumptions of the old quantum theory itself, no matter how shaky the grounds these were on already. Newton's method of deduction from phenomena will then provide the methodological framework for defending the prospective intelligibility of this revolutionary shift.

Having reconstructed in Chapter 4 how Pauli's rule became an important principle of the new quantum theory, in Chapter 5 I shall concentrate on the rationale for retaining Pauli's principle in the face of recalcitrant evidence. Against the Duhem–Quine thesis, and more precisely against the threat of underdetermination of theory by evidence that Quine's epistemological holism seems to deliver, I shall argue for the rationale of retaining Pauli's principle in the quark theory, despite some negative evidence. This rationale resides in the regulative function of the principle within a system of knowledge where phenomena are the starting point and final point. In the end, the enduring nomological validity of the principle rests on experimental tests and on the empirical support that accrues to it through various channels.

This view retains a Kantian 'internal' element in distancing itself from traditional scientific realism as well as from antirealism. It does not involve a top-down realist approach (from theory to reality), but rather a bottom-up approach that starts from phenomena to deduce rules, which can then be accredited in virtue of their regulative function within a body of knowledge, and recursively strengthened via other phenomena and larger mathematical structures in a bootstrapping process. It is via this process that epistemic access to scientific entities is disclosed. In the Conclusion I foreshadow this complex issue, which goes far beyond the scope and purpose of this monograph, and I indicate possible lines of future research.

I have written this book not only for my fellow philosophers of science, but also for historians of science, and for physicists. This book occupies a border territory. Although the aim is to advance a philosophical analysis of the role and function of the exclusion principle, it also raises some points about Kuhnian incommensurability and the rationality of inter-framework shifts that apply to physics in a way that does not differ significantly from the way they may apply to social sciences. This book originates from talking to physicist friends and looking with never-ending philosophical curiosity at their work. I hope the book will also serve a different kind of audience, namely graduate students and advanced undergraduates both in philosophy and in physics. I have always thought that philosophy of science should give more of a role to history of science as well as to science itself: this book is an attempt to do philosophy of science with an eye towards both history and physics. Physics courses usually do not have time for the philosophical questions students may find themselves asking as they progress in learning physics. This book is written also for them.

Given the variety of interwoven themes, each audience will probably find parts of this book difficult to read. Summaries are placed at the beginning of each chapter to allow readers approaching the book from different perspectives to follow the overall line of argument without necessarily going through all sections. There is much philosophical, historical, and physical literature that this book assumes. Even so, there are important aspects that, for reasons of space, I could not address.[8] I have tried to write a book that could effectively bring together philosophy, history,

[8] For instance, I shall not address metaphysical issues concerning Pauli's principle, namely the issue of identity and individuality of indistinguishable particles obeying the exclusion principle, and the related Leibniz's principle of identity of indiscernibles, which is at the centre of an ongoing debate in philosophy of physics. See French and Redhead (1988), Redhead and Teller (1992), Massimi (2001).

and physics, without reducing interdisciplinarity to a hollow sloganeering. The reader will find some chapters eminently historical, others purely philosophical; in both cases I have endeavoured to keep the discussion at a physically informed level, without going into painstaking physical details. I sense that the final result still cannot do complete justice to the complexity of the topic in all its different aspects. It remains an attempt to venture into a borderland where different fields merge and important philosophical questions may be raised. The challenge was definitely worth taking up. And if others are attracted to venture into the same borderland to correct my mistakes, the challenge can be considered won.

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1
The exclusion principle: a philosophical overview

This chapter sets the scene for the philosophical analysis of the exclusion principle that I shall carry out in this book. What is the role and function of a scientific principle? Whence does it derive its accreditation and nomological strength? In the philosophical literature on scientific principles, different answers have been given to these questions, from Poincaré's conventionalism to Reichenbach's analysis of coordinating principles. More recently, Michael Friedman has latched onto the latter tradition to defend 'relativized a priori principles' as principles that are subject to revision during scientific revolutions, but at the same time maintain a *constitutively* a priori role within a theoretical framework. This is germane to a reinterpretation of Kant's notion of 'a priori', whose purpose is to make a Kantian approach to scientific principles compatible with scientific revolutions and modern scientific developments; whence a resultant 'dynamic Kantianism'. I shall endorse a suitable version of dynamic Kantianism to investigate the nature of the exclusion principle as playing a 'regulative' rather than a 'constitutive' function. The regulative/constitutive distinction has a distinguished philosophical pedigree in Kant and in the neo-Kantian tradition of Ernst Cassirer, as I shall spell out in Section 1.4.

1.1 Introduction

In a letter to Alfred Landé on 24 November 1924, Wolfgang Pauli announced an 'extremely natural prescriptive rule' that could shed light on some puzzling spectroscopic phenomena he had dealt with in the past three years. The foundation of the rule remained an open question.

Nevertheless, a few months later, in January 1925, Pauli announced it as if it were a commandment of nature:

> In an atom there cannot be two or more equivalent electrons for which the values of all four quantum numbers coincide. If an electron exists in an atom for which all of these numbers have definite values, then this state is occupied.[1]

The rule excluded the possibility for any two bound electrons in an atom to be in the same dynamic state, characterized by a set of four quantum numbers.[2] Hence the name *Ausschlieβungsregel*: exclusion rule. One year later, in 1926, independently of each other, Fermi and Dirac gave a more precise mathematical formulation to the rule by noticing that restriction to antisymmetric state functions implied it. The rule was accordingly reformulated as prescribing the mathematical nature of quantum states allowed for electrons: it excluded all classes of mathematically possible solutions of the wave equation for any two electrons different from the antisymmetric one. The resultant Fermi–Dirac statistics allowed a system of indistinguishable particles obeying Pauli's principle ('fermions') to be only in antisymmetric states.

When in 1940 Pauli proved the spin–statistics theorem, it became clear that not only electrons, but in fact *any* half-integral spin particle obeyed the Fermi–Dirac statistics, and hence the exclusion principle. The impact of this result for subsequent scientific developments is striking: as we shall see in Chapter 5, when quarks were introduced in the 1960s, they were taken as particles obeying the exclusion principle, given their half-integral spin and the spin–statistics connection established by Pauli's theorem. The discovery of some prima facie negative evidence against quarks obeying Pauli's principle gave rise to two rival research programmes: the parastatistics programme that revoked the strict validity of the exclusion principle for quarks; and quantum chromodynamics that on the contrary reconciled the negative evidence by introducing a further degree of freedom ('colour') for quarks. It was precisely the development of these two rival research programmes that, in different ways, strengthened the nomological validity of Pauli's principle.

1 Pauli (1925b), p. 776.
2 The four quantum numbers in the modern notation are n, l, m, s. The principal quantum number n defines the energy level of the electron; the azimuthal quantum number l measures the orbital angular momentum; the magnetic quantum number m represents the possible orientations of the electron's orbit with respect to a magnetic field; and the fourth quantum number is the spin s. Notice that these are not the quantum numbers Pauli used in his article, as we will see in detail in Chapter 2.

Why and how could Pauli's rule – tentatively introduced to deal with some puzzling spectroscopic phenomena – become a building-block of physics, whose validity sweeps across nuclear and atomic physics, from condensed matter physics to quantum chromodynamics? Only by exploring the function Pauli's rule accomplished within the quantum mechanics framework can we shed light on its distinctive nomological features. To this purpose, a historical analysis is required. I shall focus on three main phases in the history of the principle: (i) its origin in the context of spectroscopy around 1920–4 (Chapter 2); (ii) its embedding into the quantum mechanics framework, from which the spin–statistics theorem was later derived (1925–40) as I shall reconstruct in Chapter 4; and (iii) the development of quantum chromodynamics and of the rival parastatistics programme in the 1960s, which paved the way for recent experimental tests of the principle (1960s–90s), to which Chapter 5 is dedicated. Along this historical path, we will find records of now forgotten physical concepts (e.g. Sommerfeld's inner quantum number); discarded models (from the atomic core model to the semi-classical spinning electron model); and novel, undreamt-of scientific entities (coloured quarks). The history of the exclusion principle cuts across the ups-and-downs of twentieth century physics, across its great achievements as well as some of its once popular but now dismissed ideas.

Before any analysis can be undertaken, an overview of the philosophical literature on scientific principles is required. We have to go back to the beginning of last century, when the breakthroughs of relativity theory and quantum mechanics stimulated and prompted philosophical investigations. Henri Poincaré and Hans Reichenbach advanced significant analyses of scientific principles, which only the repeated attacks and the subsequent demise of conventionalism and logical positivism made philosophers forget about. Michael Friedman has very recently offered a long overdue reappraisal of this literature, whose philosophical significance is still so relevant. The bulk of this chapter is dedicated to this literature. It will provide me with a foil to clarify how my analysis of the exclusion principle latches onto a time-honoured philosophical tradition.

1.2 From Poincaré's conventionalism to Popper and Lakatos on the nature of the exclusion principle

Henry Poincaré's investigation of scientific principles was prompted by the role that the so-called Physics of the Principles played in his 'structural realist' view. Poincaré believed that the objectivity of science resides in some (almost) permanent relations among the mathematical structures of subsequent scientific theories. For instance, the structural continuity between Fresnel's ether theory – no matter how ontologically false the hypothesis of ether was – and Maxwell's electromagnetic theory was warranted by some fundamental physical principles such as the principle of conservation of energy and the principle of least action.[3] Poincaré's structural realism is hardly conceivable without the Physics of the Principles. And this urged an analysis of scientific principles as bridging the gap between subsequent theories.

The distinctive features Poincaré attributed to scientific principles were certainty and permanence through scientific developments. Poincaré explained these two features in terms of the usefulness of the principles, more precisely in terms of their being useful *conventions*:

> If these postulates possess a generality and a certainty which are lacking to the experimental verities whence they are drawn, this is because they reduce in the last analysis to a mere convention which we have the right to make, because we are certain beforehand that no experiment can ever contradict it.[4]

In contrast with the more radical conventionalist approach of LeRoy, who claimed that science consists of wholly arbitrary conventions,[5] Poincaré insisted that conventions are not at our arbitrary caprice, but are adopted because some experiments have shown that they would be useful and their contraries would not generally succeed. A convention is chosen whenever scientists deal with experimental situations that apparently defy laws of nature. Suppose, for instance,[6] that astronomers discover that stars (call them A) do not exactly obey Newton's law of gravitation (call it B). As a result, they can decide to question *either* that gravitation varies exactly as the inverse of the square of the distance *or* that gravitation is the only force acting on stars. But, Poincaré claimed, the tension between A and B is resolved by introducing an intermediary C (the very notion of gravitation)

[3] 'We know nothing as to what the ether is, how its molecules are disposed, whether they attract or repel each other; but we know that this medium transmits at the same time the optical perturbations and the electric perturbations; we know that this transmission must take place *in conformity with general principles of mechanics*, and that suffices us for the establishment of the equations of [Maxwell's] electromagnetic field', Poincaré (1905), English translation (1982) p. 301, emphasis added. See also Poincaré (1902), Chapter XII, Section 3. For the complete list of principles, see the section entitled 'The Physics of the Principles' in Poincaré (1905), English translation (1982) pp. 299–301.

[4] Poincaré (1902), English translation (1982), p. 124.

[5] For a criticism of LeRoy, see Poincaré (1902), Part III, Chapter 10.

[6] See Poincaré (1905), English translation (1982), pp. 334–5.