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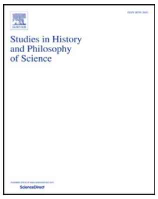

The making of an intrinsic property: “Symmetry heuristics” in early particle physics

Arianna Borrelli

Technische Universität Berlin, Institut für Philosophie, Literatur-, Wissenschafts- und Technikgeschichte, Germany

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ABSTRACT

Mathematical invariances, usually referred to as “symmetries”, are today often regarded as providing a privileged heuristic guideline for understanding natural phenomena, especially those of micro-physics. The rise of symmetries in particle physics has often been portrayed by physicists and philosophers as the “application” of mathematical invariances to the ordering of particle phenomena, but no historical studies exist on whether and how mathematical invariances actually played a heuristic role in shaping microphysics. Moreover, speaking of an “application” of invariances conflates the formation of concepts of new intrinsic degrees of freedom of elementary particles with the formulation of models containing invariances with respect to those degrees of freedom. I shall present here a case study from early particle physics (ca. 1930–1954) focussed on the formation of one of the earliest concepts of a new degree of freedom, baryon number, and on the emergence of the invariance today associated to it. The results of the analysis show how concept formation and “application” of mathematical invariances were distinct components of a complex historical constellation in which, beside symmetries, two further elements were essential: the idea of physically conserved quantities and that of selection rules. I shall refer to the collection of different heuristic strategies involving selection rules, invariances and conserved quantities as the “SIC-triangle” and show how different authors made use of them to interpret the wealth of new experimental data. It was only *a posteriori* that the successes of this hybrid “symmetry heuristics” came to be attributed exclusively to mathematical invariances and group theory, forgetting the role of selection rules and of the notion of physically conserved quantity in the emergence of new degrees of freedom and new invariances. The results of the present investigation clearly indicate that opinions on the role of symmetries in fundamental physics need to be critically reviewed in the spirit of integrated history and philosophy of science.

1. Introduction

Mathematical invariances and group-theoretical structures, which are usually referred to collectively as “symmetries”, have special prominence in today’s theoretical physics. In the last decades they have also increasingly often attracted the attention of philosophers of science who see them as providing a privileged guideline for knowledge construction and possibly also for ontological reflection (Brading & Castellani, 2003; Debs & Redhead, 2007; van Fraassen, 1989; French, 1999, 2000; Lyre, 2012). The present study focuses on the alleged function of symmetries in the construction of physical knowledge, a function which I follow previous authors in characterizing as “heuristic”. I address the issue in the spirit of integrated history and philosophy of science by means of a case study from early particle physics.

While there is a general agreement that symmetries have become particularly significant in the context of twentieth century science, and especially particle physics (Michel, 1989, 377. Schweber, 2003, 386), so far no historical study has reconstructed how they came to play such a prominent role and whether that development was really linked to their special heuristic power, as

E-mail addresses: borrelli@tu-berlin.de, aborrelli@weatherglass.de.

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often claimed *a posteriori*. Using the term "symmetry heuristics" to indicate the complex of heuristic strategies which led to the rise of mathematical invariances in particle physics, I will try to assess how those strategies actually looked like by analyzing the emergence of the concept of "baryon number" as a conserved, intrinsic property of particles and of the invariance today associated to it. I will argue that in this process mathematical invariances were only one aspect of a heuristic constellation in which two further elements were essential: the ideas of physically conserved quantities and of selection rules. It was only *a posteriori* that the successes of this hybrid symmetry heuristics came to be attributed exclusively to mathematical invariances. After a brief discussion of the research questions and of the thesis of the paper (Sections 2 and 3) and an introduction to the history of invariance and conservation (Section 4) and to baryon number (Section 5), I shall expound in detail the case study (Sections 6–10), summarizing and tentatively generalizing the results of the analysis in some concluding remarks (Section 11).

2. The "heuristic power of symmetry" in accounts of physicists and philosophers

When discussing the heuristic power of symmetry, philosophers often state that "symmetry principles" played a role not only in modern science, but also in pre-modern natural philosophy, thus linking mathematical invariances to qualitative and aesthetic notions of "symmetry" and suggesting that no clear-cut distinction between the two obtains (Brading & Castellani, 2003, 3–11, 13; Debs & Redhead, 2007, 53–55 and 67–68; Lyre, 2012, 368–370; van Fraassen, 1989 233–289). Giora Hon and Bernard Goldstein (2008) have criticized such general claims and convincingly argued that a notion of symmetry linked to mathematical invariance only emerged at the end of the 18th century and that it is anachronistic to interpret the earlier works as "implicit" applications of the modern symmetry concept (Hon & Goldstein, 2008, 27–48). Accordingly, my discussion shall consider the heuristic role of mathematical invariances, and not of general aesthetic considerations. No historian has so far explored the role of mathematical invariances in early particle physics, but many physicists have reminisced about it. Steven Weinberg, for example, wrote:

> "When I first started doing research in the late 1950s, physics seemed to me to be in a dismal state. […] Nature, like an enemy, seemed intent on concealing from us its master plan. At the same time, we did have a valuable key to nature's secrets. The laws of nature evidently obeyed certain principles of symmetry, whose consequences we could work out and compare with observation, even without a detailed theory of particles and forces. There were symmetries that dictated that certain distinct processes all go at the same rate, and that also dictated the existence of families of distinct particles that all have the same mass. Once we observed such equalities of rates and masses, we could infer the existence of a symmetry, and this we thought would give us a clearer idea of the further observations that should be made, and of the sort of underlying theories that might or might not be possible. It was like having a spy in the enemy's high command" (Weinberg, 2011).

Weinberg, like many other physicists, regards the alleged effectiveness of symmetry consideration as following from the fact that the laws of nature "evidently" obey symmetry principles. However, his statements on how these principles actually guide research have an ambiguous character which is shared by most physicists' recollections of the same events: on the one side, experimental data on particles are presented as chaotic and puzzling, with nature "intent to conceal to us its master plan", while on the other hand scientists could somehow conceive "evident" symmetry principles and then find in observations the "equalities of rates and masses" predicted by them. In the end it remains unclear how the symmetries became evident in the first place, since those same recollections underscore how complex and long the path from chaos to order was (e.g. Michel, 1989; Ne'eman, 1987).

Which heuristic strategies were actually used to go from chaos to order and how did invariances fit in them? Steven French has extensively discussed the heuristic function of mathematical invariances and group theory in the development of micro-physics (French, 1999, 2000). Working within the philosophical framework of structural realism, French focusses on historical actors who explicitly employed invariances and/or group theory to extend already existing mathematical models, and leaves aside the issue of the emergence of such models. Although admitting that "theories and models do not spring up, inductively, from the humus of observation and experiment, nor do they simply 'pop' into existence out of the head of scientists", French searches for the "heuristic power of symmetry" only in intra-theoretical developments (French, 1999, 103–105). While this heuristic function of invariances is indisputable, it only covers a limited amount of the process of knowledge construction in quantum physics, although French seems to suggest that it may have been a main motor for the development of the discipline (French, 2000, 113).

Debs & Redhead (2007, 53–55), too, only discuss the "heuristic power" of symmetries for extending models. Brading and Castellani (2003) have a more differentiated approach to "status and significance" of symmetry in the modern physical sciences and distinguish four possible functions (classificatory, normative, unifying and explanatory), all of which are regarded as evidence that symmetries, i.e. mathematical invariances, have "an important heuristic function" and a "strong methodological status" (Brading & Castellani, 2003, 11–13, quote p. 13). Claiming that "the history of the application of symmetry principles in quantum mechanics and then quantum field theory coincides with the history of the development of twentieth-century theoretical physics" they quote four "salient aspects" of this history: the introduction of "local gauge symmetries" (i.e. space-time dependent phase transformations) in general relativity; their application to the "internal" degrees of freedom of elementary particles; the increasing importance of discrete symmetries like parity and the emergence of the notion of spontaneous symmetry breaking (Brading & Castellani, 2003, 8). In these examples the heuristic power of symmetry is once again equated to the employment of group-theoretical methods in extending mathematical models, without asking how the models emerged in the first place. One issue is here of particular relevance: In today's theories, mathematical transformations are applied not only to the four space-time coordinates, but also to the so-called "internal" degrees of freedom of elementary particles, such as "flavor" or "color". These degrees of freedom have no correspondence in the macroscopic world, but are today regarded as intrinsic physical properties of particles (Haywood, 2011; Itzykson & Zuber, 1980). How did these new particle properties come to be? Brading and Castellani deal with their origin only in a footnote:

> "The starting point for the idea of internal symmetries was the interpretation of the presence of particles with (approximately) the same value of mass as the components (*states*) of a single physical system, connected to each other by the transformation of an underlying symmetry group. This idea […] was in fact due to Heisenberg […] who in a 1932 paper introduced the SU(2) symmetry connecting the proton and the neutron (interpreted as two states of a single system)" (Brading & Castellani, 2003, 7, note 9).

Once again, an "equality of mass" is allegedly observed and from there a symmetry is inferred—but did the historical process really