Faculté de philosophie, arts et lettres
Commission doctorale du domaine philosophie
Institut supérieur de philosophie – Centre de philosophie des sciences et sociétés

Direct Empirical Status of Theoretical Symmetries in Physics

Thèse réalisée par
Valeriya CHASOVA

en vue de l'obtention du grade de
Docteur en philosophie

Membres du jury :

Alexandre GUAY (UCLouvain), promoteur et secrétaire du jury
Michel GHINS (UCLouvain), lecteur
Guido BACCIAGALUPPI (Utrecht University, Pays-Bas), lecteur extérieur
Simon FRIEDERICH (University of Groningen, Pays-Bas), lecteur extérieur
Jean-Michel COUNET (UCLouvain), président

Louvain-la-Neuve
Année académique 2018-2019

Place Blaise Pascal, 1 bte L3.03.11, 1348 Louvain-la-Neuve, Belgique www.uclouvain.be/fial

Contents

Acknowledgements

The present work is the result of my doctoral studies in 2013-2019. Most of the content of this work, including the proof, has been elaborated by myself. Nevertheless, I would like to thank some persons and organisations as follows.

I thank Guido Bacciagaluppi, Alexandre Guay and Jean-Pierre Marquis for having been the members of the accompanying committee for my doctoral studies and for having provided a feedback on my work in that context. I also thank Steven French and Guido Bacciagaluppi for having discussed my work during my research visits respectively to the University of Leeds (the UK) in 2016 and to the Utrecht University (the Netherlands) in 2017 and 2018.

I thank the participants of the conference "Direct empirical status and the ontology of symmetries in physics" (03-04/07/2017, Louvain-la-Neuve, Belgium), including Gordon Belot, Richard Healey, Simon Friederich, James Ladyman and David Wallace, for their contributions and for their interest in the topic. I also thank Alexandre Guay for helping me to organise this conference and more generally for all his valuable help with practical matters.

I am grateful to the Société de Philosophie des Sciences (SPS) for giving to a short (17-page) summary of the present work entitled *Local symmetries with direct empirical status, gauge symmetries, and the empirical approach* a 2nd place in the competition for their Young Researchers Prize in 2018. I am also grateful to the Fonds Spéciaux de Recherche (FSR) for sponsoring my doctoral studies in 2014-2018, as well as to the Fonds de la Recherche Scientifique – FNRS (F.R.S.-FNRS), the Faculté de philosophie, arts et lettres (FIAL) of the Université catholique de Louvain and the Descartes Centre of the Utrecht University for mobility fundings.

I thank particularly Alexandre Guay for having obtained the FSR funding for my doctoral studies, for having brought the topic of DES to my attention and for having been my research director for eight years in 2011-2019. I hope that he is overall happy with my development as a researcher during that time and that he has enjoyed our interactions as much as I did.

Finally, I wish to thank my family for all their material and moral support, in particular during my studies abroad.

Summary

The work provides a novel ontological analysis of direct empirical status (DES), i.e. of the relationship between theoretical symmetries from physics and empirical symmetries, where the latter are symmetries in the world similar to Galileo's ship thought experiment.

Part I explains why study the ontology of theoretical symmetries in physics in general, provides a survey of some of the usual ways of studying that topic and presents DES briefly in that context. Part II recounts and analyses in detail the four main texts on DES, namely [Kosso 2000], [Brading and Brown 2004], [Healey 2009] and [Greaves and Wallace 2014], and provides some details of my own account of DES. Part III presents my account in more generality and more fully, explaining in particular how to formalise the notion of empirical symmetry, why use the empirical approach rather than the theoretical approach when establishing DES, what theoretical symmetries with the observational DES look like in the empirical approach, whether the global/local distinction matters for DES and how gauge symmetries in the sense of observationally complete theoretical symmetries are linked with DES.

What follows from my account is that empirical symmetries mostly have relational nature and need references to be established; that there is an infinity of properly global, properly local and mixed theoretical symmetries which have the observational DES with respect to a given empirical symmetry; and that which theoretical symmetries have a stronger ontological DES may depend on whether gauge symmetries in the sense above have an independent ontological significance, i.e. match with unobservable transformations and differences in the world.

References

Afriat A. [2017], "Logic of gauge", manuscript.

Aharonov Y., and D. Bohm [1959], "Significance of electromagnetic potentials in the quantum theory", *Physical Review*, Vol. 115, No. 3, pp. 485-491.

Aharonov Y., and D. Bohm [1961], "Further considerations on electromagnetic potentials in the quantum theory", Physical Review, Vol. 123, No. 4, pp. 1511-1524.

Ainsworth P. [2010], "What is ontic structural realism?", *Studies in History and Philosophy of Modern Physics*, Vol. 41, pp. 50–57.

Al-Kuwari H. A., Taha M. O. [1991], "Noether's theorem and local gauge invariance", *American Journal of Physics*, Vol. 59, No. 4, pp. 363-365.

Auyang S. [1995], *How is Quantum Field Theory Possible?*, Oxford University Press.

Brading K. [2005], "A note on general relativity, energy conservation, and Noether's theorems", in Kox A. J., Eisenstaedt J. (eds.), *Einstein Studies Volume 11: The Universe of General Relativity*, Birkhäuser.

Brading K., Brown H. [2000], "Noether's theorems and gauge symmetries", *arXiv,* https://arxiv.org/abs/hep-th/0009058 .

Brading K., Brown H. [2003], "Symmetries and Noether's theorems", in Brading K., Castellani E. (eds.), *Symmetries in Physics: Philosophical Reflections*, Cambridge University Press, pp. 89-109.

Brading K., Brown H. [2004], "Are gauge symmetry transformations observable?", *The British Journal for the Philosophy of Science*, Vol. 55, No. 4, pp. 645-665.

Brown H., Holland P. [2004], "Simple applications of Noether's first theorem in quantum mechanics and electromagnetism", *American Journal of Physics*, Vol. 72, No. 1, pp. 34-39.

Brown H., Sypel R. [1995], "On the meaning of the relativity principle and other symmetries", *International Studies in the Philosophy of Science*, Vol. 9, No. 3, pp. 235-253.

Budden T. [1997], "Galileo's ship and spacetime symmetry", *The British Journal for the Philosophy of Science*, Vol. 48, No. 4, pp. 483-516.

Clarke S. [1717], *A Collection of Papers, Which passed between the late Learned Mr. Leibnitz, and Dr. Clarke, in the years 1715 and 1716*, available online at http://www.newtonproject.ox.ac.uk/view/texts/normalized/THEM00224 .

Dorato M., Morganti M. [2013], "Grades of individuality. A pluralistic view of identity in quantum mechanics and in the sciences", *Philosophical Studies*, Vol. 163, pp. 591-610.

Earman J.. [1989], *World Enough and Space-Time: Absolute versus Relational Theories of Space and Time*, MIT Press.

Earman J., Norton J. [1987], "What price spacetime substantivalism? The hole story", *The British Journal for the Philosophy of Science*, Vol. 38, No. 4, pp. 515-525.

Englert F., Brout R. [1964], "Broken symmetry and the mass of gauge vector mesons", *Physical Review Letters*, Vol. 13, No. 9, pp. 321-323.

Fonda L., Ghirardi G. C. [1970], *Symmetry Principles in Quantum Physics*, New York, Marcel Dekker.

French S. [2014], *The Structure of the World: Metaphysics and Representation*, Oxford University Press.

French S., Ladyman J. [2003], "Remodelling structural realism: Quantum physics and the metaphysics of structure", *Synthese*, Vol. 136, pp. 31-56.

French S., Redhead M. [1988], "Quantum physics and the identity of indiscernibles", *The British Journal for the Philosophy of Science*, Vol. 39, pp. 233-246.

Friederich S. [2015], "Symmetry, empirical equivalence, and identity", *The British Journal for the Philosophy of Science*, Vol. 66, pp. 537-559.

Friederich S. [2017], "Symmetries and the identity of physical states", pp. 153-165 in Massimi M., Romeijn J.-W., Schurz G. [2017], *EPSA15 Selected Papers*, Springer.

Galilei G. [1632], *Dialogo sopra i due massimi sistemi del mondo*, Florence. Translated by Drake S., with foreword by Einstein A., as Galilei G. [1967], *Dialogue Concerning the Two Chief World Systems – Ptolemaic & Copernican*, University of California Press, Berkeley and Los Angeles, 2nd edition.

Geroch R. [1978], *General Relativity from A to B*, Chicago Univeristy Press.

Ghins M., Budden T. [2001], "The principle of equivalence", *Studies in History and Philosophy of Modern Physics*, Vol. 32, No. 1, pp. 33-51.

Greaves H., Wallace D. [2014], "Empirical consequences of symmetries", *The British Journal for the Philosophy of Science*, Vol. 65, pp. 59-89.

Guay A. [2008], "A partial elucidation of the gauge principle", *Studies in History and Philosophy of Modern Physics*, Vol. 39, pp. 346-363.

Guay A., Hebpurn B. [2009], "Symmetry and its formalisms: Mathematical aspects", *Philosophy of Science*, Vol. 76, pp. 160-178.

Guralnik G. S., Hagen C. R., Kibble T. W. B. [1964], "Global conservation laws and massless particles", *Physical Review Letters*, Vol. 13, No. 20, pp. 585-587.

Healey R. [2007], *Gauging What's Real: The Conceptual Foundations of Gauge Theories*, Oxford University Press.

Healey R. [2009], "Perfect symmetries", *The British Journal for the Philosophy of Science*, Vol. 60, pp. 697-720.

Higgs P. [1964], "Broken symmetries and the masses of gauge bosons", *Physical Review Letters*, Vol. 13, No. 9, pp. 508-509.

Higgs P. [1966], "Spontaneous symmetry breakdown without massless bosons", *Physical Review*, Vol. 145, No. 4, pp. 1156-1163.

Ismael J., van Fraassen B. [2003], "Symmetry as a guide to superfluous theoretical structure", in Brading K., Castellani E. (eds.), *Symmetries in Physics: Philosophical Reflections*, Cambridge University Press, pp. 371-392.

Kent A. [2013], "Path integrals and reality", *arXiv,* https://arxiv.org/abs/1305.6565 .

Kibble T. W. B. [1967], "Symmetry breaking in non-Abelian gauge theories", *Physical Review*, Vol. 155, No. 5, pp. 1554-1561.

Kobe D. H. [2007], "Lagrangian densities and principle of least action in non-relativistic quantum mechanics", *arXiv,* https://arxiv.org/abs/0712.1608v1 .

Kosso P. [2000], "The empirical status of symmetries in physics", *The British Journal for the Philosophy of Science*, Vol. 51, No. 1, pp. 81-98.

Ladyman J. [1998], "What is structural realism?", *Studies in History and Philosophy of Science Part A*, Vol. 29, pp. 409–424.

Ladyman J. [2007], "On the identity and diversity of objects in a structure", *Proceedings of the Aristotelian Society*, Supplementary Vol. 81, pp. 23-43.

Ladyman J., Presnell S. [2016/01/08], "Representation and symmetry in physics", manuscript.

Ladyman J., Ross D. (with D. Spurrett and J. Collier) [2007], *Every Thing Must Go: Metaphysics Naturalised*, Oxford University Press.

Lange M. [2007], "Laws and meta-laws of nature: Conservation laws and symmetries", *Studies in History and Philosophy of Modern Physics*, Vol. 38, pp. 457-481.

Laudan L. [1981], "A Confutation of Convergent Realism", Philosophy of Science, Vol. 48, No. 1, pp. 19-49.

Lewis D. [1986], *On the Plurality of Worlds*, Oxford, Blackwell.

Liddell H. G., Scott R. [1940], *A Greek-English Lexicon*, revised and augmented throughout by Sir Jones H. S., with the assistance of McKenzie R., Oxford, Clarendon Press, available online at http://www.perseus.tufts.edu/hopper/text?doc=Perseus:text:1999.04.0057 .

Mainzer K. [1996], *Symmetries of Nature*, Walter de Gruyter.

Martin C. A. [2003], "On continuous symmetries and the foundations of modern physics", pp. 29-60 in Brading K., Castellani E. [2003], *Symmetries in Physics: Philosophical Reflections*, Cambridge University Press.

Maudlin T. [1990], "Substances and space-time: What Aristotle would have said to Einstein", *Studies in the History and Philosophy of Science*, Vol. 21, No. 4, pp. 531-561.

Maxwell J. C. [1881], *An Elementary Treatise on Electricity*, Oxford, Clarendon Press.

Misner C. W., Thorne K. S., Wheeler J. A. [1973], *Gravitation*, San Francisco, W. H. Freeman and Company.

Morganti M. [2011], "Is there a compelling argument for ontic structural realism?", *Philosophy of Science*, Vol. 78, No. 5, pp. 1165-1176.

Muller F. A., Saunders S. [2008], "Discerning fermions", *The British Journal for the Philosophy of Science*, Vol. 59, pp. 499-548.

Muller F. A., Seevinck M. P. [2009], "Discerning elementary particles", *Philosophy of Science*, Vol. 76, No. 2, pp. 179-200.

Noether E. [1918], "Invariante Variationsprobleme", *Nachrichten von der Gesellschaft der Wissenschaften zu Göttingen, Mathematisch-Physikalische Klasse*, pp. 235-257. Translated by Tavel M. A. as Noether E. [1971], "Invariant variation problems", *Transport Theory and*

Statistical Physics, Vol. 1, No. 3, pp. 183-207. Also translated as Noether E. [2011], "Invariant variational problems", in Kosmann-Schwarzbach Y. [2011], *The Noether's Theorems: Invariance and Conservation Laws in the Twentieth Century*, Springer, pp. 3-22.

Norton J. [1985], "What was Einstein's principle of equivalence?", *Studies in History and Philosophy of Science*, Vol. 16, No. 3, pp. 203-246.

Nounou A. [2003], "A fourth way to the Aharonov-Bohm effect", in Brading K., Castellani E. (eds.), *Symmetries in Physics: Philosophical Reflections*, Cambridge University Press, pp. 174-199.

Nounou A. [2010], "Holonomy interpretation and time: An incompatible match? A critical discussion of R. Healey's *Gauging What's Real: The Conceptual Foundations of Contemporary Gauge Theories*", *Erkenntnis*, Vol. 72, pp. 387-409.

O'Raifeartaigh L. [1997], *The Dawning of Gauge Theory*, Princeton University Press.

Putnam H. [1975], *Mathematics, Matter and Method*, Cambridge University Press.

Putnam H. [1981], *Reason, Truth and History*, Cambridge University Press.

Redhead M. [1982], "Quantum field theory for philosophers", *PSA: Proceedings of the Biennial Meeting of the Philosophy of Science Association*, Vol. 1982, Volume Two: Symposia and Invited Papers, pp. 57-99.

Redhead M. [1988], "A philosopher looks at quantum field theory", in Brown H., Harré R. (eds.), *Philosophical Foundations of Quantum Field Theory*, Oxford, Clarendon Press, pp. 9-23.

Rosen J. [1990], "Fundamental manifestations of symmetry in physics", *Foundations of Physics*, Vol. 20, No. 3, pp. 283-307.

Saunders S. [2003], "Physics and Leibniz's principles", in Brading K., Castellani E. (eds.), *Symmetries in Physics: Philosophical Reflections*, Cambridge University Press, pp. 289-307.

Saunders S. [2006], "Are quantum particles objects?", *Analysis*, Vol. 66, pp. 52-63.

Shaw R. [1955], "Invariance under general isotopic spin transformations", pp. 200-207 in O'Raifeartaigh L. [1997], *The Dawning of Gauge Theory*, Princeton University Press.

Struyve W. [2011], "Gauge invariant accounts of the Higgs mechanism", *Studies in History and Philosophy of Modern Physics*, Vol. 42, pp. 226-236.

't Hooft G. [1980], "Gauge theories of the forces between elementary particles", *Scientific American*, Vol. 242, No. 6, pp. 104-138.

Teh N. [2016], "Galileo's gauge: Understanding the empirical significance of gauge symmetry", *Philosophy of Science*, Vol. 83, pp. 93-118.

Terekhovich V. [2018], "Metaphysics of the principle of least action", *Studies in History and Philosophy of Modern Physics*, Vol. 62, pp. 189-201.

Trautman A. [1962], "Conservation laws in general relativity", in *Gravitation: An Introduction to Current Research*, Witten L. (ed.), New York, John Wiley & Sons, pp. 169-198.

Utiyama R. [1956], "Invariant theoretical interpretation of interaction", *Physical Review*, Vol. 101, No. 5, pp. 1597-1607.

Utiyama R. [1959], "Theory of invariant variation and generalised canonical dynamics", *Progress*

of Theoretical Physics Supplement, Vol. 9, pp. 19-44.

Weingard R. [1984], "Grand unified gauge theories and the number of elementary particles", *Philosophy of Science*, Vol. 51, No. 1, pp. 150-155.

Weyl H. [1918], "Gravitation und Elektrizität", *Sitzungsberichte der Königlich Preussischen Akademie der Wissenschaften*, pp. 465-480. Translated as Weyl H. [1952], "Gravitation and electricity", in *The Principle of Relativity*, Dover Publications, pp. 200-216. Also translated (including three postscripts) as Weyl H. [1997], "Gravitation and electricity", in O'Raifeartaigh L., *The Dawning of Gauge Theory*, Princeton University Press, pp. 24-37.

Weyl H. [1929], "Electron and Gravitation", pp. 121-144 in O'Raifeartaigh L. [1997], *The Dawning of Gauge Theory*, Princeton University Press.

Wigner E. [1967], *Symmetries and Reflections*, Ox Bow Press, Woodbridge, Connecticut.

Worrall J. [1989], "Structural realism: The best of both worlds?", *Dialectica*, Vol. 43, No. 1-2, pp. 99-124.

Wu T. T. , Yang C. N. [1975], "Concept of nonintegrable phase factors and global formulation of gauge fields", *Physical Review D*, Vol. 12, No. 12, pp. 3845-3857.

Yang C. N., Mills R. L. [1954], "Conservation of isotopic spin and isotopic gauge invariance", *Physical Review*, Vol. 96, No. 1, pp. 191-195.