Studies in History and Philosophy of Modern Physics 53 (2016) 54–72

Contents lists available at ScienceDirect

Studies in History and Philosophy of Modern Physics

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

Interpretation neutrality in the classical domain of quantum theory

Joshua Rosaler

University of Minnesota Center for Philosophy of Science Heller Hall, 271 19th Ave S Minneapolis, MN 55455, United States

ARTICLE INFO

Article history:
Received 19 February 2015
Received in revised form
17 September 2015
Accepted 5 October 2015
Available online 30 December 2015

Keywords:
Quantum
Classical
Classical limit
Classical domain
Decoherence
Measurement problem
Branching
Collapse
Reduction
Emergence
Correspondence principle
Interpretation
Interpretations of quantum mechanics
Everett
de Broglie–Bohm
Bohm
GRW

ABSTRACT

I show explicitly how concerns about wave function collapse and ontology can be decoupled from the bulk of technical analysis necessary to recover localized, approximately Newtonian trajectories from quantum theory. In doing so, I demonstrate that the account of classical behavior provided by decoherence theory can be straightforwardly tailored to give accounts of classical behavior on multiple interpretations of quantum theory, including the Everett, de Broglie–Bohm and GRW interpretations. I further show that this interpretation-neutral, decoherence-based account conforms to a general view of inter-theoretic reduction in physics that I have elaborated elsewhere, which differs from the over-simplified picture that treats reduction as a matter of simply taking limits. This interpretation-neutral account rests on a general three-pronged strategy for reduction between quantum and classical theories that combines decoherence, an appropriate form of Ehrenfest's Theorem, and a decoherence-compatible mechanism for collapse. It also incorporates a novel argument as to why branch-relative trajectories should be approximately Newtonian, which is based on a little-discussed extension of Ehrenfest's Theorem to open systems, rather than on the more commonly cited but less germane closed-systems version. In the Conclusion, I briefly suggest how the strategy for quantum-classical reduction described here might be extended to reduction between other classical and quantum theories, including classical and quantum field theory and classical and quantum gravity.

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

1. Introduction

As several authors have noted, a full quantum-mechanical account of classical behavior requires an explanation of both the "kinematical" and "dynamical" features of classicality. Kinematical features include determinate values for properties such as position and momentum, separability or effective separability of states across different subsystems, and others. Dynamical features of classicality, on the other hand, consist primarily in the approximate validity of classical equations of motion. Most work on quantum-classical relations focuses on recovering one or the other aspect of classicality, but not both together.[1] For example, literature on semi-classical analysis, including discussions of the WKB approximation, $\hbar \to 0$ limits and various formal quantization procedures, focuses primarily on the recovery of classical equations of motion and related mathematical structures of classical mechanics but tends to sidestep questions about the recovery of determinate measurement outcomes and other kinematical features of classical behavior. On the other hand, most literature on quantum measurement focuses on kinematical features of classicality while paying relatively little attention to the problem of explaining the approximate validity of Newton's equations.

However, an important subset of the literature on decoherence theory goes further toward recovering both the kinematical and dynamical features of classicality in a unified way. Predictably, though, where the recovery of kinematical features is concerned, these analyses come up against the notorious difficulties associated with collapse of the quantum state.[2] While decoherence offers a promising mechanism for suppressing interference among, and in some sense defining, the

[1] The kinematical/dynamical terminology employed here follows Bacciagaluppi (2011).

[2] I will take the term "collapse" here to encompass both real, dynamical collapse processes as well as processes in which collapse of the quantum state is merely effective or apparent.

http://dx.doi.org/10.1016/j.shpsb.2015.10.001
1355-2198/

various possible "outcomes" represented by the quantum state, it does not by itself explain why only one of these alternatives appears to be realized, much less with the specific probabilities given by the Born Rule. Further explanation, which goes beyond the resources furnished by decoherence theory, is required to account for the phenomenology of Born Rule collapse. The present investigation shows how results from decoherence theory can be combined with the specific collapse mechanisms and ontologies associated with different realist interpretations of quantum theory in order to give a more complete – if also more speculative – account of both the kinematical and dynamical features of classical behavior. While the strategy for quantum–classical reduction summarized here reflects an understanding of classical behavior that is implicitly held – at least in its broad outlines – by many experts on decoherence theory, I seek to bring this picture into sharper focus by consolidating insights that remain dispersed across the literature and by making explicit several points that have not been sufficiently emphasized or developed. In particular, my analysis here aims to bring out two important features of the decoherence-based framework for recovering classical behavior:

(1) *Interpretation neutrality*: I show in detail how the bulk of technical analysis needed to recover classical behavior from quantum theory is largely independent of the precise features of the collapse mechanism and ontology of the quantum state. The analysis below demonstrates that concerns about wave function collapse and ontology can be addressed as a coda – albeit a necessary one – to the interpretation-neutral account of classical behavior suggested by decoherence theory, so that one need not start anew in the recovery of classical behavior with each new interpretation[3] of quantum theory that is considered. The interpretation-neutral strategy for recovering classical behavior summarized here rests on three central pillars: decoherence, which generates a branching structure from the unitary quantum state evolution, such that the state of the system of interest relative to each branch is well-localized; Ehrenfest's Theorem for open quantum systems, which ensures that the only branches with non-negligible weight are branches relative to which the system's trajectory is approximately Newtonian; a decoherence-compatible prescription for collapse, which serves at each moment to select just one of the branches defined by decoherence in accordance with the Born Rule. The underlying physical mechanism (associated with some particular interpretation of quantum mechanics) for this decoherence-compatible collapse is left unspecified.

This analysis counters the notion promulgated by some authors that recovering classical behavior from quantum theory is a highly interpretation-dependent affair. For example, many advocates of the de Broglie–Bohm (dBB) interpretation have defended an approach built entirely around a condition that is more or less unique to dBB theory: namely, the requirement that the "quantum potential" or "quantum force," which generates deviations of Bohmian trajectories from Newtonian ones, go to zero.[4] Elsewhere, I have argued that the quantum potential is something of a red herring and that the most transparent route to recovering classicality in dBB theory relies primarily on structures common to many interpretations, associated with decoherence theory (Rosaler, 2015c). The present article extends this analysis of classical behavior beyond the context of dBB theory to consider other realist interpretations as well, including the Everett and GRW interpretations. It also provides a more detailed elaboration and consolidation of the interpretation-neutral, decoherence-based framework for recovering classical behavior.

(2) *A specific sense of "Reduction"*: Second, I show that the interpretation-neutral framework for recovering classical behavior provided by decoherence theory fits a more general model-based picture of inter-theoretic reduction in physics that I have elaborated and defended elsewhere, according to which reduction between theories is based on a more fundamental concept of reduction between two models of a single, fixed system (Rosaler, 2015b). Here, I understand a "model" to be specified by some choice of mathematical state space (e.g., phase space, Hilbert space) and some additional structures on that space that serve to constrain the behavior of the state (e.g., Hamilton's equations, Schrodinger's equation). This approach differs in important respects from the more conventional approach to reduction in physics that seeks to recover one theory simply as a mathematical limit of another – typically, in the case of quantum-classical relations, by taking the limit $\hbar \to 0$ or $N \to \infty$ – while recognizing that limits still carry a strong relevance for inter-theory relations in physics. It also differs from approaches to reduction that have been emphasized in the philosophical literature, which aspire to give a completely general account of reduction across the sciences and so fail to capture the strongly mathematical character of reductions specifically within physics. One feature that distinguishes the view of reduction employed here from these other approaches is that, rather than attempting to give criteria for reduction directly between *theories* as these other approaches do, it is grounded in a more fundamental and more local concept of reduction between two *models* of a single physical system. Moreover, reduction between models of a single system on this approach is an empirical, *a posteriori* relation between models rather than a formal, *a priori* relation that can be assessed on purely logical or mathematical grounds. While this account of inter-theoretic reduction incorporates insights about reduction previously highlighted by other accounts, its novelty lies in the particular combination of features that it possesses: namely, that it is model-based rather than theory-based, "local" rather than "global", and *a posteriori* rather than *a priori*. By highlighting an important sense of reduction and showing how decoherence theory provides a viable framework for effecting this kind of reduction between quantum and classical theories, I seek to provide a counterweight to recent discussions – in particular, by Batterman, Berry and Bokulich – that have urged a move away from thinking about quantum-classical relations as an instance of reduction (Batterman, 2002; Berry, 1994; Bokulich, 2008). In a separate article, I argue that the singular mathematical limits that Batterman and Berry take to block reduction between classical and quantum mechanics do not block reduction between these theories in the particular sense described here (Rosaler, 2015).

Beyond its defense of these two points, much of the novelty of the present discussion lies in its explicit synthesis of various elements from different parts of the literature on decoherence, the measurement problem and the quantum-classical correspondence, and in its attentiveness to nuances that arise when joining these elements. These nuances include the explicit requirement that an interpretation-neutral collapse prescription be decoherence-compatible, subtle variations in the decoherence conditions required for effective collapse across different interpretations, and the implementation of the open-systems form of Ehrenfest's Theorem rather than the more commonly discussed but less appropriate closed-system form.

The discussion is structured as follows. Section 2 provides an overview of sources in the decoherence literature that attempt to explain the validity of classical equations of motion and highlights points on which the present discussion serves to complement these investigations. Section 3 discusses several important points of terminology and methodology, including my usage of the term

[3] As several authors have noted, different "interpretations" of quantum mechanics, such as the Everett, de Broglie–Bohm and GRW interpretations, are more properly regarded as separate *theories* since they differ in the accounts of physical reality (in particular, the laws and ontology) that they take to underwrite the success of the quantum formalism. Nevertheless, I will conform to common usage in referring to them as "interpretations" of quantum theory.

[4] It is possible to define the quantum potential and force in other interpretions, but because these other interpretations do not possess localized trajectories at a fundamental level, the quantum potential and force lack the immediate and obvious significance that they possess in dBB theory.