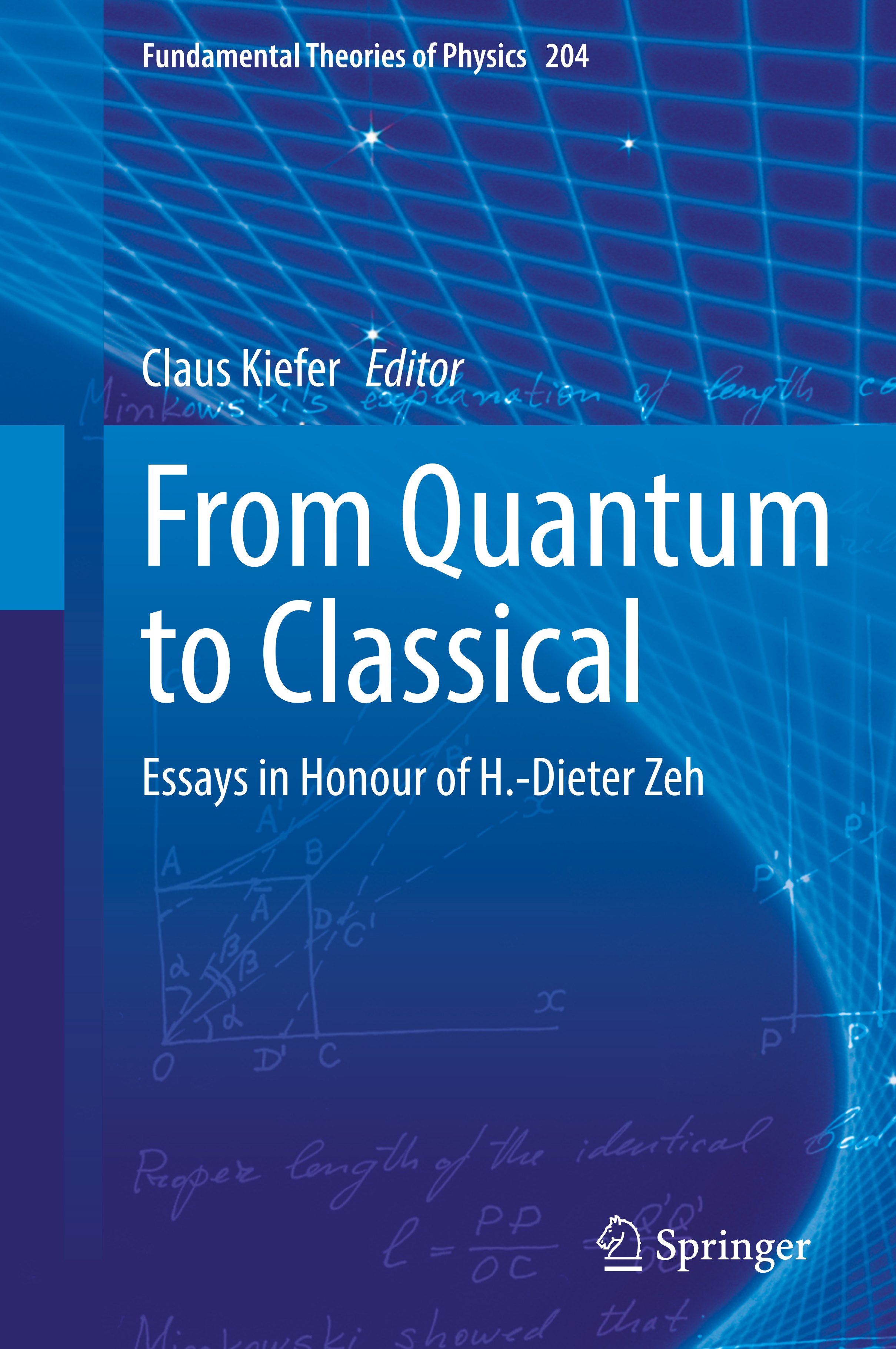
Fundamental Theories of Physics 204

Claus Kiefer *Editor*

From Quantum to Classical

Essays in Honour of H.-Dieter Zeh



Springer

Fundamental Theories of Physics

Volume 204

The international monograph series “Fundamental Theories of Physics” aims to stretch the boundaries of mainstream physics by clarifying and developing the theoretical and conceptual framework of physics and by applying it to a wide range of interdisciplinary scientific fields. Original contributions in well-established fields such as Quantum Physics, Relativity Theory, Cosmology, Quantum Field Theory, Statistical Mechanics and Nonlinear Dynamics are welcome. The series also provides a forum for non-conventional approaches to these fields. Publications should present new and promising ideas, with prospects for their further development, and carefully show how they connect to conventional views of the topic. Although the aim of this series is to go beyond established mainstream physics, a high profile and open-minded Editorial Board will evaluate all contributions carefully to ensure a high scientific standard.

More information about this series at https://link.springer.com/bookseries/6001

Claus Kiefer
Editor

From Quantum to Classical

Essays in Honour of H.-Dieter Zeh

Springer

Editor
Claus Kiefer
Institute for Theoretical Physics
University of Cologne
Köln, Nordrhein-Westfalen, Germany

ISSN 0168-1222 ISSN 2365-6425 (electronic)
Fundamental Theories of Physics
ISBN 978-3-030-88780-3 ISBN 978-3-030-88781-0 (eBook)
https://doi.org/10.1007/978-3-030-88781-0

© The Editor(s) (if applicable) and The Author(s), under exclusive license to Springer Nature Switzerland AG 2022
This work is subject to copyright. All rights are solely and exclusively licensed by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, expressed or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

H. Dieter Zeh in September 2005. Photo Rolf Kickuth

Preface

Why does a world described fundamentally by quantum theory look classical? Where does the observed arrow of time come from? Are these questions related? These are the questions that were at the heart of Dieter Zeh's thinking over many decades.

Dieter started his career as a theoretical physicist when working on nuclear physics in the sixties. His interests included the theory of α-decay, nucleosynthesis and the dynamics of deformed nuclei. It was his concrete research about the deformed nuclei that eventually led him, in 1968, to the discovery of what was later called decoherence.[1] Dieter was puzzled by the fact that individual nucleons could experience an orientation in spite of the whole nucleus being in a stationary quantum state. In his article on 'Roots and Fruits of Decoherence', he describes this as follows:

> If the nucleons in the deformed nucleus dynamically feel a definite orientation in spite of the global superposition, would an internal observer then not similarly have to become 'aware of' a certain measurement result?[2]

He then envisages a stationary quantum universe ('wave function of the universe') in which observers experience definite properties such as orientations in spite of the total quantum state being a superposition of all orientations. These observers are *decohered*, and this decoherence arises from their quantum correlation (entanglement) with many inaccessible degrees of freedom in the global superposition. Dieter identified this entanglement as the key to an understanding of the quantum-to-classical transition. This was not recognized by the physics community for many years. In his own words:

> I am indeed convinced that the importance of decoherence was overlooked for the first 60 years of quantum theory precisely because entanglement was misunderstood as no more than a statistical correlation between local objects.[3]

---

[1] His first paper on this subject could only appear in 1970, in the first volume of the newly created journal *Foundations of Physics.*

[2] H. D. Zeh, Roots and fruits of decoherence. In: *Quantum decoherence*, ed. by B. Duplantier, J.-M. Raimond, and V. Rivasseau (Birkhäuser, Boston, 2006), pp. 151–175.

[3] H. D. Zeh, *op. cit.*

Dieter always entertained a realistic interpretation of the wave function. Through this, he independently arrived at an Everett-type of interpretation without knowing about Everett's work. He was a proponent of this interpretation for the rest of his life, although he was not sympathetic to calling it a 'many-worlds interpretation', for the reason that we have only one quantum world (though with many quasi-classical branches). The only alternative to the Everett interpretation that Dieter accepted were theories with a dynamical collapse of the wave function, for the reason that these are realistic theories. But so far no empirical hint for collapse theories exists.

His later interests in the arrow of time and in quantum cosmology grew out of these early insights, because he recognized that the emergence of classical properties in quantum theory cannot be understood without understanding the irreversible nature of our Universe.[4] I had the pleasure to be a Ph.D. student under his supervision in the eighties and to apply his ideas on decoherence to quantum gravity and quantum cosmology. Even after my Ph.D., we stayed in close contact and participated in particular in a six-years project with six people organized in Heidelberg by Nucu Stamatescu, from 1990 to 1996, out of which our monograph on decoherence resulted.[5] During this project, we have met regularly for informal talks and discussion, more in the spirit of an eighteenth century academy than in the contemporary hectic and grant-driven academic atmosphere. It became evident there and elsewhere that Dieter was always interested in *understanding* things—in physics and beyond physics. He mentioned to me several times that he felt influenced by the Vienna Circle of Logical Empiricism about which he had heard for the first time in a radio talk by Ingeborg Bachmann in the fifties. Many of his general essays bear testimony of this influence.[6]

The present volume contains 13 articles in honour of Dieter Zeh and his work. They cover a wide range of topics. In the opening chapter, **Kristian Camilleri** focuses on the role Dieter Zeh played in the history of quantum mechanics and its interpretation. This is followed by **Wojciech Zurek**'s account on decoherence and, in particular, the important role of quantum Darwinism. The decoherence program is also the subject of **Maximilian Schlosshauer**'s contribution. He puts special emphasis on Zeh's commitment to a realistic interpretation of the wave function and discusses, in particular, the importance of experimental tests. Experimental decoherence in molecule interferometry is then discussed in detail in the contribution by **Markus Arndt, Stefan Gerlich** and **Klaus Hornberger**. This clearly demonstrates that decoherence has found its place in the centre of experimental physics, much different from the early years when Dieter had developed his ideas. Experiments also play a crucial role in **Markus Aspelmeyer**'s article. He focuses, in particular, on future experiments that involve superpositions of the gravitational field.

---

[4] See e.g. C. Kiefer, Obituary for Heinz-Dieter Zeh (1932--2018), in: *International Journal of Quantum Foundations*, **5**, 11–15 (2019).

[5] E. Joos, H. D. Zeh, D. Giulini, C. Kiefer, J. Kupsch, and I.-O. Stamatescu, *Decoherence and the Appearance of a Classical World in Quantum Theory*, second edition (Springer, Berlin, 2003).

[6] Dieter's former homepage, as he left it at the time of his death, can be found at http://www.thp.uni-koeln.de/gravitation/zeh/. It contains a collections of papers and essays.

Gravitation also plays a central role in the next contribution. **Andrei Barvinsky** and **Alexander Kamenshchik** discuss the meaning of the wave function of the Universe, in particular the role of the preferred basis for its interpretation. **Heinrich Päs**, in his article, focuses on Dieter's interpretation of the wave function and speculates on its relevance for developing and understanding a quantum theory of gravity. Time and gravity are also the subject of the next chapter written by **Henrique Gomes** and **Jeremy Butterfield**. They put emphasis on geometrodynamics and its connection with ideas of relational projects and shape dynamics.

The next three contributions focus on various aspects in which thermodynamics and statistical mechanics play a fundamental role. **Bei-Lok Hu** explains the connection between dissipation, fluctuations, noise, and decoherence in open quantum systems. **Lajos Diósi** presents various insights about quantum Brownian motion and its relation with decoherence and mentions important open problems for future research. **Domenico Giulini** discusses various subtle issues about the Second Law of thermodynamics and its statistical foundation on the basis of Ehrenfest's urn model. The next chapter by **Ion-Olimpiu Stamatescu** addresses issues in the theory of science, focusing on the role that computer simulations play for the understanding of physical theories. Last but not least, **Peter Byrne** presents a very personal account of Dieter and his commitment to the Everett interpretation of quantum theory.

I thank all the authors for their commitment and effort to produce such wonderful contributions. I am sure Dieter would have enjoyed to read them.

Cologne, Germany Claus Kiefer
August 2021

Contents

Contributors

Markus Arndt Faculty of Physics, University of Vienna, Vienna, Austria

Markus Aspelmeyer Faculty of Physics, University of Vienna, Vienna, Austria; Institute for Quantum Optics and Quantum Information (IQOQI) Vienna, Austrian Academy of Sciences, Vienna, Austria

Andrei O. Barvinsky Theory Department, Lebedev Physics Institute, Moscow, Russia

Jeremy Butterfield Trinity College, University of Cambridge, Cambridge, UK

Peter Byrne Ink, Petaluma, CA, USA

Kristian Camilleri School of Historical and Philosophical Studies, University of Melbourne, Parkville, Australia

Lajos Diósi Wigner Research Centre for Physics, Budapest, Hungary

Stefan Gerlich Faculty of Physics, University of Vienna, Vienna, Austria

Domenico Giulini Institute for Theoretical Physics, Leibniz University Hannover, Hannover, Germany

Henrique Gomes Trinity College, University of Cambridge, Cambridge, UK

Klaus Hornberger Faculty of Physics, University of Duisburg-Essen, Duisburg, Germany

Bei-Lok Hu University of Maryland, College Park, MD, USA

Alexander Yu. Kamenshchik Dipartimento di Fisica e Astronomia, Università di Bologna and INFN, Bologna, Italy;
Landau Institute for Theoretical Physics, Russian Academy of Sciences, Moscow, Russia

Heinrich Päs Fakultät Für Physik, Technische Universität Dortmund, Dortmund, Germany

Maximilian Schlosshauer Department of Physics, University of Portland, Portland, OR, USA

Ion-Olimpiu Stamatescu Institut für Theoretische Physik, Universität Heidelberg, Heidelberg, Germany;
Forschungsstätte der Evangelischen Studiengemeinschaft, Heidelberg, Germany

Wojciech Hubert Zurek Theory Division, MS B213, LANL Los Alamos, Los Alamos, NM, USA

H. Dieter Zeh and the History of the Foundations of Quantum Mechanics

Kristian Camilleri

1 Introduction

In the prologue to his 2011 book *Elegance and Enigma*, Max Schlosshauer notes that "the last two or three decades have witnessed a stunning renaissance of quantum foundations. Today we find ourselves in the fortunate situation where occupation with quantum-foundational matters is no longer inconceivably far from reaching mainstream status" ([42], pp. 20–1). Things were not always so. In the 1960s those who concerned themselves with the foundations of quantum theory and challenged the prevailing orthodoxy in quantum mechanics found themselves marginalized by the physics community and with limited career prospects. H. Dieter Zeh (1932–2018) was one of the pioneering figures in the revival of the foundations of quantum mechanics. As Guido [1] points out: "The modern beginnings of decoherence as a subject in its own right are arguably the papers by H. D. Zeh of the early 1970s". He was, to use Olival Freire's provocative term, one of the "quantum dissidents", who dared to challenge the prevailing orthodoxy in quantum mechanics in the 1960s and 70s. As with many others who pursued this course of research at the time, this came

---

This chapter is based on a paper presented at the second international conference of the History of Quantum Physics in Utrecht on 17 July 2008, which was later published [10]. I would especially like to thank H. Dieter Zeh and Wojciech Zurek for their time and assistance in answering my questions through our email correspondence and for allowing me to quote from our correspondence. I would also like to thank H. Dieter Zeh and Fábio Freitas for granting me permission to use the transcript of the interview conducted in July 2008 in preparing this paper. Thanks must also go to Olival Freire for allowing me to use correspondence he obtained from the Wheeler papers at the American Philosophical Society, Philadelphia. I would also like to thank Max Schlosshauer for sharing with me his insights and considerable knowledge of decoherence during our many stimulating conversations.

K. Camilleri (✉)
School of Historical and Philosophical Studies, University of Melbourne, Parkville 3010, Australia
e-mail: kcam@unimelb.edu.au

C. Kiefer (ed.), *From Quantum to Classical*, Fundamental Theories of Physics 204,
https://doi.org/10.1007/978-3-030-88781-0_1

at considerable cost. His ground-breaking work on decoherence would go largely unrecognized for more than a decade before the theoretical and experimental study of decoherence began to attract more widespread attention of physicists in the 1980s and 90s.

Zeh's early work on the foundations of quantum mechanics and his struggle for recognition provides an instructive case study in the history of the re-emergence of the foundations of quantum mechanics in the latter decades of the twentieth century. In this chapter I examine Zeh's early work on decoherence and the obstacles he faced in Heidelberg in winning support for his controversial ideas. Zeh's commitment to the Everett interpretation undoubtedly served as a major obstacle to the wider recognition of his early theoretical contributions to the understanding of decoherence. It was only through the divorcing of interpretation from the study of the dynamics of environment-induced decoherence in the 1980s that Zeh's work began to attract renewed attention from a number of physicists. This occurred largely through the work of Wojciech Zurek in the 1980s and 90s. However, Zeh's struggles were not simply the result of his unorthodox views on interpretation. Unlike Zurek, Zeh did not enjoy the luxury of the backing and support of senior colleagues who were sympathetic to his theoretical interests. Whereas Zurek benefitted immensely from his association with John Wheeler, whose reputation gave him the freedom to pursue foundational questions, Zeh found himself increasingly marginalized in Heidelberg with little prospect of professional advancement. The story of Zeh's early struggles thus constitute an important chapter in the history of the foundations of quantum mechanics.

2 H. Dieter Zeh and the Origins of Decoherence

The problem of explaining how the essentially 'classical' features of the macro-world emerge from a quantum theory of the micro-world has been one of the central problems for the interpretation of quantum mechanics since the 1930s. In the 1980s the study of the entanglement between quantum systems and their environments began to shed new light on the emergence of 'classicality' in quantum mechanics. As Erich Joos explains: "The interaction with the environment which is in principle present for all systems seems to play a decisive role for an understanding of classical properties in the framework of quantum theory" ([26], p. 12). This process, known as 'environment-induced decoherence' or simply 'decoherence', has been the subject of much recent interest and provides a new insight into explaining why quantum superpositions effectively disappear in the macroscopic world—in other words why we don't encounter 'Schrödinger cats'. While there continues to be much debate and disagreement about the extent to which decoherence can explain the appearance of the 'classical' world, the delocalization of interference resulting from quantum entanglement between a local subsystem and its environment is now an experimentally well-confirmed process [5, 12, 23, 34, 38, 39].

In 1970 Zeh proposed that it is precisely the openness of quantum systems, i.e. their interaction with the environment, which is *essential* to explaining why in a unitary dynamics of the Schrödinger equation, the interference terms approximately vanish, in other words, why the 'superposition' of states effectively disappears in the macroscopic world. Zeh's work on the dynamics of quantum entanglement began from the assumption of the universality of the wave function, which invariably led him to an Everett-like relative-state interpretation. Thus, decoherence, as it would later become known, was for Zeh, from its inception an integral part of the Everett picture. As will become clear, this was one of the reasons that Zeh's early papers remained largely ignored by physicists for over a decade. In the early 1980s Wojciech Zurek published two important papers in which he derived the preferred basis and the superselection rules on the basis on environment-induced decoherence. While Zurek's work arose independently of Zeh's and differed in its formal approach, it represented a renewed effort to engage in some of the key physical ideas which had appeared in Zeh's early papers. In spite of the similarities in their approaches to decoherence, Zurek's programmatic aims for decoherence and its relationship to interpretational issues have diverged in certain crucial respects from those of Zeh.

Zeh completed his PhD on nuclear physics at Heidelberg University, and after spending time at Berkeley, Cal Tech, and La Jolla, he returned to Heidelberg in 1966 to submit his *Habilitationsschrift* and take up a position there as a lecturer. In 1970 Zeh published a paper, 'On the interpretation of measurement in quantum theory', in which he discussed the consequences of the entanglement of a system with its environment, anticipating a number of the important insights behind decoherence. As the title of the paper suggests, this work was originally intended as a contribution to the discussion of the measurement problem. Zeh proposed that the difficulties which arise in this standard von Neumann treatment of measurement stem from the "invalid" assumption that a macroscopic system (in this case the quantum system interacting with the measuring apparatus) can be completely 'isolated' from its environment. The aim of the paper was to show that by taking into account the interaction with the environment—the "remainder of universe"—the dynamics would show why we do not observe superpositions of quantum states in macroscopic systems [55]. Proceeding from the assumption of the "universal validity of quantum theory", Zeh argued that strictly speaking "the only 'closed system' is the universe as a whole" ([55], p. 73).

Zeh proposed that by taking a realistic interpretation of the universality of the Schrödinger equation, one could derive certain 'superselection rules', which had been postulated to preclude the existence of certain superpositions which are quantum-mechanically possible, but which are in practice never observed (e.g. the superposition of negative and positive charges). Here he argued that the superposition of different charge numbers is in practice never observed because such a superposition is dynamically unstable as a result of its interaction with the environment ([55], p. 75). This, he argued, is also the case in the chiral states (left-handedness or right-handedness) of sugar molecules, which do not appear in a superposition of quantum states. Through their interaction with the environment, the interference terms practically vanish, effectively leaving two dynamically stable, 'decoupled' (quasi-classical) states. In an early version of his paper, in the form of a typescript entitled ‘*Probleme der Quantentheorie*’ written in German some time around 1966–7, Zeh spelled out this basic idea:

> The realistic interpretation of a universally valid quantum theory leads therefore to the superposition of these states becoming unobservable, if the difference of its interactions with the “remainder of the world” is effective enough to fix the state macroscopically. In particular, states that differ through the charge number, have a sufficiently different interaction with the environment in order to become always “automatically measured”. That explains the superselection rule which forbids superposition between such states ([53], p. 10).

This notion, which later became one of the cornerstone of the decoherence program in later years, was pursued in more rigorous fashion in a paper Zeh published with Kübler in 1973 entitled, ‘The Dynamics of Quantum Correlations’. Here the authors proposed that by taking as their starting point the universal validity of the Schrödinger wave equation, it was possible to use a density matrix to represent the state of a subsystem (which itself does not obey a von Neumann equation) in deriving the superselection rules as a dynamical consequence of universal entanglement [31].

Zeh recognised that the assumption of a universality of the superposition principle led to rather “unusual consequences”. Here Zeh proposed, in a manner strikingly similar to Everett, that in the case where we have “two different components”, (such as in the case of a spin state of an electron) only one of which is observed, the two final states “represent two completely *decoupled worlds*”. Because of the entanglement with the environment, the two angular momentum states would no longer be in a quantum superposition. Zeh argued that while “the ‘other’ component cannot be observed any more”, it is necessary to posit its existence if “only to save the consistency of the theory” ([55], p. 74). He acknowledged that while the question of “whether the other components “exist” after the measurement” might well be deemed meaningless from the positivist standpoint, “the question of whether or not the assumption of this existence (i.e. of an objective world) leads to a contradiction” *is* indeed a meaningful question. As Zeh later recalled, “From the beginning “decoherence” (uncontrollable entanglement) was for me an argument for the Everett interpretation (whose papers I did not know when I completed the first draft)” [51]. The concluding section of the early version of the paper (the 1967 typescript ‘*Probleme der Quantentheorie*’) is particularly illuminating:

> But how can one interpret this superposition? If (e.g. through a measurement) a superposition of (to simplify matters) two vector elements [*Zeigerstellungen*] has evolved ($\Psi = c_1\Psi_1 + c_2\Psi_2$), then the states Ψ_1 and Ψ_2 will become practically independently from one another after that, as the matrix element $< \Psi_1 | H | \Psi_2 >$ becomes negligibly small. One has to deal with two “worlds” which are practically independent from one another after the measurement. It appears impossible to escape this consequence as long as one accepts the universal validity of quantum theory. Both worlds differ macroscopically – including the observing organism. One must accept it however as an experience that “the” consciousness is only realized in one of these worlds at a time. This statement is similar to the one which tells us that the consciousness is only realized in one person at a time. One can describe the state of this partial-world however in very good approximation through Ψ_1 or Ψ_2 alone. That is the “reduction of the wave function”! In this sense, Schrödinger’s experiment with the cat would split the world into a continuum of worlds, in every one of which the cat is killed at a different time ([53], p. 9).

Zeh recalls that he only 'discovered' Everett after completing the preliminary draft of the paper. Having finished writing the paper, he went down to the library to do something "completely different", whereupon he stumbled upon an article by Bryce DeWitt on the quantum theory of gravity which made use of the universal wave function proposed by Everett [52].[1] Zeh subsequently referred to Everett's relative-state interpretation in the version of the paper published in *Foundations of Physics*, though he now added that his own work marked an advance upon Everett's in providing a basis for "the dynamical stability conditions" of the branches [55], p. 74).

Zeh's work can be seen as forming part of the renewed interest in the foundations of quantum mechanics which had emerged by the late 1960s. Zeh recalls, "I always had an interest in foundations, of course, and I knew there was something not understood in quantum theory" [52]. In the introductory section of the paper, Zeh discussed the contributions to "the problem of measurement and the related problem of how to describe classical phenomena in the framework of quantum theory" which had "received increased attention during recent years", citing the work of Wigner, Jauch, Shimony, Yansee, Ludwig, Daneiri, Prosperi, Loinger, Bell, Bohm and Bub [55], p. 69).

The genesis of Zeh's ideas on the interpretation of quantum mechanics can be traced to his research on low energy nuclear physics which formed the subject of his *Habilitationsschrift* in 1966 [54]. Zeh was at this time concerned with how to explain the collective degrees of freedom of nuclei. The standard method was to use what is called a Hartree–Fock approximation to describe 'stationary states' of heavy nuclei by means of determinants of time-dependent single-nucleon wave functions. In the case of deformed nuclei, however, each of the nuclei are in angular momentum eigenstates, but the nucleus as a whole will not be in an angular momentum eigenstate. Zeh felt that the key to the problem lay with accepting the fundamental role that entanglement plays in quantum theory, not merely as "a statistical correlation between local objects", but as a feature of the underlying 'reality' ([52], [61], pp. 2–3).[2] It dawned on Zeh that the "feeling" of a (fixed) orientation is a formal consequence" of the symmetry violation that occurs in "a strong entanglement between many nuclei". In other words, "the individual nucleons "observe" an apparent asymmetry in spite of the symmetric global superposition of all orientations". Zeh recalls that this situation led him to reflect on the possibility that the dynamical consequences of entanglement might well hold the key to a solution of the measurement problem ([61], p. 4). In this way, he speculated about the possibility of "a nucleus that is big enough to contain a complex subsystem which may resemble a registration device or even a conscious observer. It/she/he would then become entangled with its/her/his "relative world",

---

[1] As Osnaghi, Freitas and Freire point out in their paper on the history of the Everett interpretation: "The paper in which DeWitt presented his famous Wheeler-DeWitt equation relies on Everett's approach in order to provide an interpretive framework for 'the state functional of the actual universe'" [37].

[2] Zeh recalls that one important argument in convincing him of the 'reality' of the wave function was the "explanation of parity violation by means of the superposition of a K-meson and its antiparticle forming a new "real" particle" [51].

such as with a definite orientation”. Here the external observer is incorporated into quantum theory by becoming “*part of the environment* of the observed object” thereby becoming “entangled, too, with the property he is observing”. As a consequence the observer “thus feels part of a much bigger “nucleus” or closed system: the quantum universe” ([61], p. 5). Yet these early ideas, as Zeh says himself, “went beyond what is now called decoherence”.

As a student Zeh had entertained an interest in philosophy, particularly epistemology, and had in fact contemplated studying philosophy at university [51]. Though Zeh never undertook the study of philosophy in any systematic fashion, his concern with fundamental issues in physics and his interest in epistemological questions was evident in his defense of the Everett interpretation, reflecting his familiarity with logical positivism and perhaps more importantly, the work of the neo-Kantian philosopher Hans Vaihinger. Vaihinger had argued that the underlying reality of the world remains unknowable, but we behave “as if” the constructions of physics such as electrons, protons and electromagnetic waves exist, and to this extent such ‘heuristic fictions’ constitute our reality.[3] In this way, Zeh argued that the universal wave function may be employed as a ‘heuristic fiction’, but it is no less ‘real’ than the entities posited by other physical theories (e.g. quarks), the existence of which is routinely taken for granted.[4] In his 1967 manuscript, he wrote: “Because of their unobservability naturally one can deny the existence of the remaining [unobserved] partial worlds”, but we may assume they “exist in the same sense as do all ‘heuristic fictions’ of physics” ([53], p. 10). Elaborating on this point a few years later, he explained, we customarily “regard those things as ‘existing in reality’ which are extrapolated from the observed by means of established laws” ([57], p. 109). From this point of view, Zeh maintained that one can regard the unobserved branching states (worlds) of the universal state function as ‘real’ since they are an extrapolation of the superposition principle which plays a central role in the dynamics of quantum entanglement. Vaihinger’s epistemology thus plays a part in Zeh’s defence of the Everett interpretation [59].

3 Early Reception and the Dark Ages of Decoherence

Zeh initially submitted an early version of his paper to several journals, among them *Die Naturwissenschaften* and *Nuovo Cimento B*, only to have it repeatedly rejected.[5] Indeed, in the late 1960s, it was known that a number of prominent journals

---

[3] Vaihinger also argued that we act “as if” other minds exist as well, and take this to be part of psychic reality. Vaihinger’s *Die Philosophie des Als Ob* was first published in 1913, though it was probably written some years earlier [46, 47].

[4] Vaihinger is cited in Zeh’s paper ‘On the Problem of Conscious Observation in Quantum Mechanical Description’ circulated in the *Epistemological Letters* in 1981, which was later revised slightly and published in *Physics Foundation letters* ([59], p. 4).

[5] The reason cited was that “quantum theory does not apply to macroscopic objects”. Indeed according to Zeh, one reviewer commented that “This paper is completely senseless” [51].

adopted a strict editorial policy with regard to submissions dealing with foundations of quantum mechanics.[6] John Clauser recalled that during the 1960s "a very powerful secondary stigma began to develop within the physics community towards anyone who sacrilegiously was critical of quantum theory's fundamentals… Any student who questioned the theory's foundations, or, God forbid, considered studying the associated problems as a legitimate pursuit in physics was sternly advised that he would ruin his career by doing so" ([13], p. 72). This was precisely the advice that Zeh received. Zeh [62] later recalled, "An influential Heidelberg Nobel Prize winner frankly informed me that any further activities on this subject would end my academic career!" The Nobel Prize winner was J. Hans D. Jensen.[7] As Zeh later confirmed in an interview in 2008:

> When I wrote this paper … [Jensen] said he did not understand that, and he sent a copy unfortunately to Rosenfeld in Copenhagen… He wrote a letter to Jensen which Jensen never showed me where he must have been very cynical about what I had said, and I remember that Jensen told that to some other colleagues, then when I noticed they were talking about them, they were chuckling. But he never told me precisely what was in this letter… Then Jensen told me that I should not continue this work, and so then our relationship deteriorated [52].

The letter from Rosenfeld to Jensen that Zeh mentions here was recently discovered in the Rosenfeld Papers contained in the Niels Bohr Archive. It is dated February 14, 1968.

> I established a rule in my life never to step on anybody's toe, but a preprint written by a certain Dr 'Toe' [Zeh, in German] from your institute that I have received makes me deviate from this rule. I have all the reasons in the world to assume that such a concentrate of wildest nonsense is not being distributed around the world with your blessing, and I think to be of service to you by directing your attention to this calamity.[8]

---

[6] As Clauser recalls, "even as late as the early and mid seventies, whenever a manuscript discussing the foundations of quantum mechanics (and especially one discussing hidden variables) was submitted to either the *Physical Review* or *Physical Review Letters*, editor Samuel Goudsmit would, in turn, enclose a one-page APS policy statement along with it to the manuscript's referee. That policy, in essence, urged the referee summarily to reject any paper on this subject, unless the paper was both mathematically based *and* gave new quantitative experimental predictions. Bohr's response to EPR certainly could not have been published under Goudsmit's stated criteria" ([13], p. 72).

[7] In 1963 Jensen shared the Nobel prize with Maria Göppert-Mayer for their work on the shell nuclear model.

[8] The original German reads: "Ich mach es zu einer Lebensregel, so weit vermeidlich auf keinen Zeh zu treten, aber der Empfang eines von einem gewissen Dr. Zeh aus Ihrem Institut verfassten preprint veranlasst mich von dieser Regel abzuweichen. Ich habe allen Grund anzunehmen, dass ein solches Konzentrat wildesten Unsinnes nicht mit Ihrem Segen in die Welt verbreitet ist, und ich glaube Ihnen von Dienst zu sein, indem ich Ihre Aufmerksamkeit auf dieses Unglück richte". L. Rosenfeld to J. H. D. Jensen, 14 Feb 1968. A series of further letters were exchanged between Rosenfeld and Jensen on the matter: Jensen to Rosenfeld, 1 March 1968; Rosenfeld to Jensen, 6 March 1968; Jensen to Rosenfeld, 10 Apr 1968; 9 May 1968; Rosenfeld to Jensen, 25 Apr 1968. Rosenfeld Papers, Niels Bohr Archive, Copenhagen. Anja Jacobsen and Felicity Pors recovered these letters The German translation is mine. Quoted in Freire [19], p. 306.

This was certainly not the first time Rosenfeld had meddled in such matters by writing to the head of an Institute regarding the pretensions of a younger colleague. Just two years earlier, Rosenfeld had written to Abdus Salam, who was the Head of the International Centre of Theoretical Physics in Trieste, regarding a preprint written by a young Austrian physicist, K. S. Tausk that had come into his hands on the measurement problem.[9] Rosenfeld could be merciless on such occasions, and by the 1960s he seems to have taken it upon himself to police the orthodoxy. Zeh was certainly not the only physicist during this period to incur the wrath of Rosenfeld.

After sending a preliminary version of the paper to Eugene Wigner for comment, Wigner suggested that he should try to publish the paper with some revisions in the newly formed journal *Foundations of Physics* which would be more receptive to alternative approaches to quantum physics.[10] The paper was eventually accepted with some revisions and published in the inaugural volume of *Foundations of Physics*. It was later included among the seminal papers in the foundations of quantum mechanics that appeared in Wheeler and Zurek's *Quantum Theory and Measurement*, published in 1983. As Olival Freire has pointed out, Wigner was instrumental in encouraging further work in different directions on the foundations of quantum mechanics [17, 18]. Wigner also saw to it that Zeh was invited to a conference on the Foundations of Quantum Mechanics at the International School of Physics "Enrico Fermi" in Varenna in the summer of 1970, which was organised by Bernard d'Espagnat [15].[11] There Zeh presented a paper on the quantum theory of measurement based on his earlier considerations. Here he again emphasised that the description of a measurement by means of the Schrödinger wave equation is "unrealistic" because "it assumes a macroscopic system can be isolated" ([56], p. 269). Zeh was explicitly critical of the Copenhagen interpretation and reiterated his own version of the Everett interpretation, according to which "consciousness appears to be connected with dynamically stable branches of the universal wave function" ([56], p. 270). DeWitt, who also presented a paper on the many worlds view at the same conference, welcomed Zeh's work as an important contribution to the Everett interpretation.

Throughout the 1970s Wigner remained open to the possibility of a fundamental revision of quantum mechanics, and he became increasingly convinced that "far more

---

[9] Rosenfeld described Tausk's preprint, entitled on 'Relation of Measurement with Ergodicity, Macroscopic Systems, Information and Conservation Laws', as "such incredible thrash [sic] that I hardly could believe my eyes when I read it. I feel that I ought to write you about it in the event that (as I hope) this masterpiece has just escaped your attention…. The author is, I suppose, very young and inexperienced; one good turn you could do him, since you presumably know him better than I do, would be to represent that before blandly assuming that the trivialities which fill his paper could have been overlooked by such people as Niels Bohr and Heisenberg, he might perhaps reflect that he could be the one who misses the point" (Rosenfeld to Salam, Copenhagen, 20 Sep 20 1966. Quoted in Freire [19], p. 182).

[10] The editorial board was made up of physicists with a range of differing views on quantum mechanics including Henry Margenau, Louis de Broglie, David Bohm, Wigner himself, and Vladimir Fock, many of whom were critical of the orthodox view.

[11] The participants of the conference presented a wide range of views on the interpretation of quantum mechanics. Among them were Wigner, Jauch, Yanase, d'Espagnat, Prosperi, Bell, Shimony, DeWitt, Zeh, Selleri and Bohm.

fundamental changes will be necessary" (Wigner to Shimony, 12 Oct 1977 in Freire [19], p. 167). He encouraged other physicists to pursue a range of alternative solutions to the measurement problem in the 1960s and 70 s, and in doing so, "helped to legitimize heterodoxy on this subject" ([19], p. 167). Abner Shimony, who completed his Ph.D. in physics under Wigner's supervision in Princeton, later remarked that "Wigner's authority as one of the great pioneers and masters of quantum mechanics" and his encouragement and support was instrumental in his own "decision to devote much research effort to these problems" ([43], p. xii). Wigner was critical of some aspects of Zeh's work, and objected to the "extrapolation of the superposition principle to the entire universe", on the grounds that experimental evidence for the principle was limited almost entirely to microscopic systems. Yet, he was adamant that Zeh was "unquestionably correct" in his observation "that it is practically impossible to isolate a macroscopic object from its surroundings" ([49], p. 380).[12] Wigner seems to have been acutely aware of the difficulties faced by younger researchers who had an interest in foundations. As he put it in a letter to Joseph Jauch, "I am less concerned about myself than about other people who are much younger than I am and whose future careers such statements may hurt".[13]

Relations between Zeh and Jensen deteriorated in Heidelberg, and Zeh effectively became a *persona non grata.*[14] Yet he continued to pursue his work on quantum mechanics, publishing another article in *Foundations of Physics* in 1973 entitled 'Towards a Quantum Theory of Observation'. Elaborating on his earlier work, Zeh defended the Everett interpretation, and argued that it may even be possible that there may be dynamical consequences of this interpretation which differ from collapse models. Zeh investigated the possibility that in certain cases, the world components (or Everett branches) which are not observed (but which we may assume still *exist*), could interact with one another in the global superposition, which in turn would have dynamical consequences for the time dependent behaviour of the "observed component" [57]. Physicists, for the most part, tended to ignore Zeh's work. *Foundations of Physics* did not enjoy a reputation as a 'respectable' physics journal, and while there was some interest in new approaches to quantum mechanics, this remained a rather marginalised area within the broader physics community.

Even when physicists did engage in debate over the interpretation of quantum mechanics in the 1970s, these discussions typically focused on hidden variables or proposals to modify the unitary Schrödinger dynamics with physical collapse models. As Zeh recalls, many of those physicists 'who were interested in the foundation of quantum theory saw in decoherence an unwelcome competition to their own ideas,

---

[12] At the 1970 Varenna conference Wigner included Zeh's proposal among the six approaches to the measurement problem ([48], pp. 17–18).

[13] Eugene Wigner to Josef M. Jauch, 6 September 1966. Wigner Papers, box 94, folder 7. Quoted in Freire [19], p. 250.

[14] Zeh recalls that whenever his attention turned to 'fundamental questions' in Heidelberg, Jensen told him to 'let sleeping dogs lie' [52]. The transcript of the interview contains the phrase, 'Don't wake up sleeping dogs', which is a direct translation of the German idiom '*Schlafende Hunde soll man nicht wecken'* but I have taken the liberty of rephrasing this in the more commonly used expression in English.

since they usually wanted to *change* quantum theory, while we maintained there is no reason to do so if you accept Everett' [51]. Having decided that his career prospects had been irreparably damaged, Zeh decided to continue to work on the foundations of quantum mechanics in relative isolation, and ceased publishing in physics journals. He instead chose to circulate his ideas by means of 'unofficial publications', notably *The Epistemological Letters* of the Ferdinand-Gonseth Association in Biel (Switzerland), which provided a discussion forum for many prominent dissenting voices in the quantum debate, among them Bell, Bohm and Popper.[15]

Zeh would later label this period 'the dark ages of decoherence' ([61], p. 10). This period only came to end with the publication of two important papers by Wojciech Zurek in *Physical Review*, which treated the problem of the preferred basis and the derivation of superselection rules from the perspective of environment-induced decoherence [64, 65]. In his 1981 paper Zurek spelt out that "interaction with the environment is the key feature that distinguishes the here-proposed model of the apparatus from the manifestly quantum systems" as a result of which "the apparatus cannot be observed in a superposition of the pointer-basis states because its state vector is being continuously collapsed" ([64], p. 1522). These papers provided the most important impetus for the renewed interest in the dynamical consequences of environmental entanglement for the emergence of 'classicality' in quantum systems. Zurek was careful to point that one could not answer the "insoluble question" of "what causes the collapse of the apparatus-environment combined wave function" ([64], p. 1517). However, "the question 'what mixture does the wave packet collapse into?' acquires a definite answer" ([64], p. 1522). This also provides a dynamical explanation of superselection rules, which are usually postulated for the purpose of eliminating superpositions of the pointer-basis states ([65, 70], pp. 87–89). Zurek coined the term 'environment-induced superselection' for this feature of quantum decoherence, which he later termed 'einselection'.

As noted earlier, Zeh's work had found very little support from colleagues in Heidelberg. By contrast, Zurek's early interest in decoherence, while he was in Austin and then later at Caltech, was encouraged and supported by John Wheeler, under whose direction Zurek undertook postdoctoral research in 1979–1981. During this period Wheeler engaged in many stimulating discussions on quantum theory with Zurek. As Zurek recalls, "Wheeler was absolutely essential in defining the problem, or rather, the whole set of problems" which were critical in the way he approached environment-induced decoherence [63]. We find Wheeler frequently acknowledged in many of Zurek's papers on decoherence spanning more than two decades.[16]

This brings to light a crucially important difference in the social and intellectual contexts in which Zeh and Zurek had formulated their early ideas on decoherence.

---

[15] In 1981 Zeh informally circulated a paper on 'The Problem of Conscious Observation in Quantum Mechanical Description', in which he presented a 'multi-consciousness interpretation' which appears to be one of the earliest formulations of the many-minds interpretations of quantum mechanics.

[16] It is quite likely that he was also important in ensuring that Zurek was invited to participate in conferences where his ideas on decoherence could be discussed, in an environment when foundational questions in quantum mechanics were usually reserved for more senior colleagues.

As Zurek put it in a letter to Fritz Rohrlich in 1982, “I credit John Wheeler with my interest in the fundamental issues raised by the quantum theory of measurement” (Zurek to Fritz Rohrlich, 11 November 1982. Quoted in Kaiser [30], p. 313). After a particularly inspiring visit to Wheeler’s summer cottage in Maine, Zurek wrote to Wheeler “Every day I come back to our discussions on physics and philosophy” (Wocjek Zurek to John Wheeler, 10 August 1979. Quoted in Kaiser [30], p. 313). This was a privilege not afforded to Zeh. As David Kaiser explains:

> Wheeler’s reputation helped to shield the young students from other professors’ disdain for such philosophical patter. Aside from Wheeler’s strong backing, Zurek recalls the general attitude in the hallways at that time: graduate students like himself and Wootters had received a very obvious and loud message that thinking seriously about foundations was a waste of time and a detriment to one’s career. Nonetheless Wheeler and his small circle of students soldiered on. Wheeler brought in a steady stream of visiting scholars to keep discussion fresh. He also organized a brand new seminar on quantum measurement … an entire semester spent puzzling over paradoxes like Schrödinger’s cat… The following year, PhD in hand, Zurek helped Wheeler coteach the seminar ([30], pp. 216–7).[17]

This underscores the crucial importance of the support of senior colleagues for younger researchers wishing to pursue research in the foundations of quantum mechanics. Zurek recalled that after his 1981 pointer basis paper, he was “pleasantly surprised” to receive several invitations to attend meetings, where he encountered was an “atmosphere of intellectual fellowships and excitement”, which he had not been expecting ([42], p. 37).

4 Decoherence and Its Interpretation

There was, however, a further important difference in the way Zeh and Zurek each approached the foundations of quantum mechanics. Their different attitudes to interpretational problems reflect the different origins, motivations and philosophical perspectives that guided their early work on decoherence. Zeh’s early papers originated in his early interest in the dynamical consequences of the Everett interpretation.[18] Decoherence, as he would often later insist, does “not by itself solve the measurement problem” [62]. Zurek, on the other hand, steered away from ‘interpretational’ issues in his early papers. In the dynamical models developed by Zurek, Caldeira, and Leggett in the 1980s, the study of decoherence was divorced from the interpretational context in which Zeh had first considered it. As Zeh remarked: “The emphasis on ‘decoherence by itself’ … became a concept only during the ‘80s” [51]. Thus, in contrast to Zeh’s views that decoherence forces a radical departure from

---

[17] This readings set for the class would eventually serve as the basis for the 800 + page edited volume *Quantum Theory and Measurement*, which Zurek edited with Wheeler.

[18] In his *Philosophy of Quantum Mechanics* published in 1974, Max Jammer cited [55] paper as one of the few contributions to the measurement problem sympathetic to the many-worlds interpretation of quantum mechanics ([24], p. 519).

the Copenhagen orthodoxy, Zurek advanced the view that decoherence is compatible with, or even provides a confirmation of, many of Bohr's insights into quantum mechanics. By attending to the different interpretive frameworks in which Zeh and Zurek presented their work on decoherence that we can better understand why Zeh's work was largely ignored, while Zurek's work attracted considerable interest. Put simply, in the case of decoherence, interpretation influenced reception.

Zurek's early thinking on the role of the environment in decoherence can be traced back to a term paper he had written as a doctoral student for Wheeler's class on the Einstein-Bohr debate involving the double-slit experiment. At the 1927 Solvay conference Einstein argued that by measuring the recoil imparted to the measuring apparatus by the photon passing through one the slits, one could determine the trajectory of the individual photon in the construction of the interference pattern. Bohr responded by pointing out that Einstein had failed to take into account the indeterminacy in the momentum of the measuring apparatus which would preclude a precise determination of the path of the photon ([4], pp. 211–224). Zurek thus set about "to examine Bohr's idea in detail" by determining "exactly what interference pattern is produced when we attempt to determine the slit through which each photon passes" ([50], p. 474). Encouraged by Wheeler, the paper was revised in collaboration with Bill Wootters and submitted to the journal *Physical Review* where it was published in 1979. The title of the paper: 'Complementarity in the double-slit experiment: quantum nonseparability and a quantitative statement of Bohr's principle', makes clear the extent to which the authors saw their work as an extension of Bohr's views.

However, whereas Bohr had treated the measuring apparatus *classically*, albeit with the limitations imposed by the uncertainty relations, Wooters and Zurek represented "the plate (with recoil) as a *quantum–mechanical* harmonic oscillator. The photon and the plate, having once interacted, become *nonseparable parts of a single quantum–mechanical system*. This forces us to consider the effect of our measurement of the plate on the photon wave function, and consequently on the interference pattern produced by these photons" ([50], p. 474 emphasis added). This allowed a quantitative analysis of the two-slit experiment. In the concluding section of the paper, the authors proposed a reformulation of Bohr's principle of complementarity "in terms of an inequality which sets the limit on the amount of retrievable information about the photon's paths (photon-particle) for an assumed sharpness of the interference pattern (photon-wave)" ([50], p. 474). In providing a quantum–mechanical treatment of the measuring instrument, Wooters and Zurek departed from Bohr's insistence on the primacy of classical concepts. However in a different sense, the paper can also be read as a *confirmation* of Bohr's intuition that only through the interaction with the measuring apparatus does the quantum system become describable by means of classical concepts. Far from constituting an attempt to contradict Bohr, for Zurek, the analysis of complementarity formed an important point of departure in his thinking about the role of the environment in the decoherence of quantum systems.

Zurek's approach to quantum entanglement thus differed from Zeh's. Zurek concentrated on the local dynamics of the reduced density matrix rather than sweeping interpretational questions. In a symposium on the foundations of quantum mechanics in 1981, Zurek explained that the "problem of the preferred basis which arises in the context of quantum theory of measurement" is "virtually independent of the interpretation of quantum theory" ([70], p. 85). Zurek's approach was to focus on dynamical problems, leaving interpretational issues largely to one side. It was his hope that through a deeper understanding of the process of decoherence in quantum mechanics, one could eventually shed important new light on some of the foundational questions in the theory. As he would later put it:

> I think the whole point of the paper (and more broadly, of my approach to decoherence) was that I could say things that were relevant to foundational questions and that followed directly from quantum theory, without any interpretational baggage attached. (I think that was one difference with Dieter Zeh, who was more interested in interpretational aspects.) And that – using decoherence as a vantage point – it was possible to do calculations that had implications for experiments, and make statements that were "interpretationally non-committal" [63].

Note the contrast with Zeh's view:

> I am indeed surprised about the indifference of most physicists regarding the potential consequences of decoherence [for the interpretation of quantum mechanics] …, since this concept arose as a by-product of arguments favouring … an Everett-type interpretation. In contrast to the Copenhagen interpretation, which insists on fundamental classical concepts … [decoherence rests on an interpretation of] the wave function as a complete and universal representation of reality ([61], p. 1).

As these passages show, the attitudes of both physicists to the relevance of decoherence for the interpretation of quantum mechanics reveal their own individual experiences of the history of decoherence and its conceptual development. For Zeh, decoherence had emerged from considerations in nuclear physics which led him to explore the dynamical consequences of the assumption of a universal wave function (essentially an Everett-type interpretation), whereas Zurek's work on decoherence had originated in his treatment of the two-slit experiment and the dynamical consequences of the interaction of a measuring apparatus and the environment. The different attitudes to the interpretation of decoherence are, to some extent, expressions of the 'hidden historicity'—to use Ulrich Röseberg's term—of the development of their theoretical insights [40].

The 1980s witnessed a renewed interest in the dynamics of entanglement and its consequences for decoherence of quantum systems. In particular, the papers of Caldeira and Leggett were instrumental in the development of new models based on quantum Brownian motion, for the study of the effect of the environment in dissipating quantum interference [7–9, 32].[19] In 1984 Zurek widely circulated a paper, 'On the Reduction of the Wavepacket: How Long does it Take?", in which

---

[19] These models typically used a master equation to describe the dynamics of a particle moving in one dimension, interacting with an environment represented by independent harmonic oscillators in thermal equilibrium. Such models could be used to formulate a dynamical equation for the reduced density matrix representing the local quantum sub-system. While these early models marked important theoretical progress in the field, they were applicable only in highly idealized situations, such as the short wavelength limit which set an upper bound to the decoherence rate, and the high temperature limit. It was not until the later papers by Unruh and Zurek [45] and Hu et al. [22], which modelled the environment as a massless scalar field, that a generalized master equation for deriving the decoherence rate of a superposition of wave packets for a single particle was formulated.

he drew on the Caldeira-Leggett master-equation to calculate the time rate of the vanishing of interference terms due to decoherence effects [66]. The results showed that decoherence occurs incredibly rapidly—of the order of 10^{40} times faster than the ‘relaxation time (the time a system in interaction with its environment takes to reach thermal equilibrium)! For all practical purposes, the decoherence effect is “virtually instantaneous”.

The appearance of Zurek’s papers in the early 1980s also reignited Zeh’s interest in pursuing the decoherence program, and sensing that the time was now right “to improve things” he agreed to take on Erich Joos as a doctoral student [51]. The subject of Joos’ thesis was a study of the dynamics of decoherence, specifically through a comparison of master equations with the Zeno effect, which had up until that time been claimed to require a collapse of the wave function.[20] In 1985 Joos and Zeh published a seminal paper expanding on the theoretical work Joos had carried out in his dissertation, in which they showed that the scattering of photons and air molecules leads to the rapid decoherence, which continuously ‘localises’ a wave packet, thereby preventing it from dispersing as predicted by the Schrödinger equation for a single particle [28]. In this way the authors drew the conclusion that “the ‘classical’ properties of macroscopic systems’ have “their origin in the nonlocal character of quantum states” (p. 223). The paper presented one of the first models of scattering-induced decoherence using master equations derived from the density matrix. As Joos would put it later: “‘Particles’ appear localised in space not because there are particles, but because the environment continually measures position. The concept of a particle seems to be derivable from the quantum concept of state” ([26], p. 12). However, Zeh and Joos steered clear of any interpretational statements in their joint paper. Indeed Zeh recalls that he advised Joos to concentrate on the dynamical part of the problem “without ever talking about Everett”, and focus his attention on the consequences for the reduced density matrix [52]. Indeed after Zurek’s papers appeared in 1981/2, Zeh deliberately refrained from mentioning Everett, partly so as not to jeopardize Joos’ academic career [51].

Zurek’s classic article ‘Decoherence and the Transition from Quantum to Classical’ in the October 1991 in *Physics Today* is often seen as marking a turning point in the recognition of decoherence among the wider community of quantum physicists. There Zurek took a somewhat cautious, if not ambivalent, stance on the question of interpretation, arguing that: “Decoherence is of use within the framework of either of the two interpretations: it can supply a definition of the branches in Everett’s Many Worlds Interpretation, but it can also delineate the border that is so central to Bohr’s point of view” ([67], p. 44). According to Zurek: “The key feature of the Copenhagen Interpretation is the dividing line between quantum and classical. Bohr emphasized that the border must be mobile” ([67], p. 36). Decoherence provides a dynamical answer to why this is so. As he later put it:

---

[20] The ‘quantum Zeno effect’ was the term first coined by George Sudarshan and Baidyanaith Misra for the situation in which an unstable particle, if observed continuously, does not undergo unitary dynamical evolution but remains ‘frozen’. The term now denotes the situation where time evolution is suppressed by interactions with the environment, scattering of particles, stochastic fields, etc.

> The role of decoherence is to establish a boundary between quantum and classical. The boundary is in principle moveable, but in practice largely immobilized by the irreversibility of the process of decoherence… The equivalence between 'macroscopic' and 'classical' is then validated by the decoherence considerations, but only as a consequence of the practical impossibility of keeping objects which are macroscopic perfectly isolated ([68], p. 311).

In this way, for Zurek contended that decoherence was able to 'explain' the classical-quantum divide, in a manner which "occurs in complete accord with Bohr's 'Copenhagen Interpretation'" ([68], p. 311). But in same breath, he contended that the "interpretation that emerges from these considerations is obviously consistent with Everett's 'Relative State' point of view" ([68], p. 311). This rapprochement of Bohr and Everett would become characteristic of Zurek's work. As he wrote in another paper: "*In spite of the Everett-like framework of this discussion, the picture that emerges in the end—when described from the point of view of the observer—is very much in accord with the views of Bohr*" ([69], pp. 89–90 emphasis mine). For Zeh, this nod to Bohr was little more than "political correctness". In his view, Bohr's insistence of the primacy of classical concepts was diametrically opposed to the very possibility of a dynamical understanding of the emergence of classicality. In the end, disagreements of this kind may amount to nothing more than differing ways of reading Bohr.

Nevertheless, as the history of quantum mechanics shows, different readings of Bohr were often not mere hermeneutic exercises, but could have important consequences. By aligning oneself with the so-called "Copenhagen interpretation", one could avoid the retributions of defenders of the orthodoxy. Indeed such branding strategies could have dramatic implications for the reception of ideas. H. D. Zeh's early work on decoherence was ignored in the 1970s, largely because of his unapologetic commitment to an Everett-type interpretation. By contrast, Zurek's early work on decoherence, which had the backing of Wheeler, was carried out with a far more conciliatory rhetorical approach to the "Copenhagen interpretation". This, I would suggest, contributed to its greater acceptance. Labelling oneself as "pro-" or "anti-Copenhagen" was thus strategically important for physicists in certain institutional and cultural contexts. The term 'Copenhagen' carried important connotations in the foundations of quantum mechanics, which could make or break a career in physics.

5 Decoherence and the 'New Orthodoxy'

By the 1990s the idea that decoherence can be regarded as a justification or completion of the Copenhagen interpretation began to find favour among a number of physicists. In his book *The Interpretation of Quantum Mechanics* published in 1994 Roland Omnès presented the newly emerging views on decoherence as signifying a new period of "renewal of the conventional interpretation" which "began in the period 1975–1982 with the discovery and understanding of the decoherence effect" has now arisen ([35], p. xii). Such a revival, made possible by the recent developments in theory and experiment, as Omnès explained, mark a crucial "transition between a period when Bell's ideas and questions concerning hidden variables were dominant and a return to the origins—the basic problems first envisioned by Bohr, Heisenberg and Pauli" ([36], p. 69). Here Zeh's contribution is effectively written out of the history of decoherence.[21] Thus for Omnès, after a period of challenges to the orthodox viewpoint, emerging largely from an interest in hidden variables theories and Bell's work in the 1950s and 1960s, "a new effort aiming … at a clarification and a justification of Bohr's interpretation has now followed" ([35], xii). A somewhat similar view is expressed in Jeffrey Bub's *Interpreting the Quantum World* in which he devotes a chapter to what he terms the 'new orthodoxy' in quantum mechanics.

> The 'new orthodoxy' appears to centre now on the idea that the original Copenhagen interpretation has been vindicated by the recent technical results on environmental decoherence. Sophisticated versions of this view are formulated in terms of 'consistent histories' or 'decoherent histories' and trade on features of Everett's 'relative state' interpretation… There seems to be a growing consensus that a modern, definitive version of the Copenhagen interpretation has emerged, in terms of which the Bohr-Einstein debate can be seen as a rather old-fashioned way of dealing with issues that are now more clearly understood. This 'new orthodoxy' weaves together several strands: [including] the physical phenomenon of environment-induced decoherence ([6], pp. 6, 212).

Whether such a consensus did indeed emerge in the 1990s now seems doubtful. It may appear remarkable that an interpretation that purports to weave together elements of decoherence, the consistent histories approach and the Everett interpretation could be called a 'modification', or even a 'vindication' of Bohr's views ([6], p. 212). Joos and Zeh remained adamant that, far from vindicating Bohr, these developments reflect a decisive break with the "orthodoxy of the Copenhagen school" and a "desire to achieve a better understanding of the quantum–classical relation" ([27], p. 54). Murray Gell-Mann and James Hartle also saw these developments in decoherence and the consistent histories approach as pointing to an "extension, clarification, and completion of the Everett interpretation" ([20], p. 306). Yet, it is clear that many physicists now see those very same developments as having contributed decisively to a "modernized version of the interpretation first proposed by Bohr in the early days of quantum mechanics" ([35], p. 498).

Later interpretations of decoherence have in some cases led to clear divisions in the programmatic aims and the interpretational commitments of decoherence theorists. This is clearly evident in the revised second edition of *Decoherence and the Appearance of a Classical World in Quantum Theory* which includes chapters from Joos and Zeh, as well contributions from Claus Kiefer, Domenico Giulini, Joachim Kupsch, and Ion-Olimpiu Stametescu. The book arose from a series of seminars on the foundations of quantum theory organised by Stamatescu, which were held at the *Forschungstätte der Evangelischen Studiengemeinschaft* (The Protestant Institute for Interdisciplinary Research) in Heidelberg, outside of the university. In the Preface

---

[21] While the Joos-Zeh 1985 paper on the dynamical treatment of scattering and the timescales for decoherence, noteworthy for its avoidance of any strong interpretational commitments, is cited by Omnès in his 1994 book *The Interpretation of Quantum Mechanics*, none of Zeh's early papers are mentioned. Omnès does, however, cite Zeh's early work in his later book *Understanding Quantum Mechanics* ([36], pp. 74, 290).

to the 2003s edition, the authors explained that differences of opinion had arisen regarding the basic conceptions, aims and motivations of decoherence, leading to minor revision:

> For this reason we have rearranged the order of the authors: they now appear in the same order as the chapters, such that *those most closely related to the "early" and most ambitious concept of decoherence* are listed first. The first three authors (Joos, Zeh, Kiefer) agree with one another that decoherence (in contradistinction to the Copenhagen interpretation) allows one to eliminate primary classical concepts, thus neither relying on an axiomatic concept of observables nor on a probability interpretation of the wave function in terms of classical concepts. While the fourth and fifth authors (Giulini and Kupsch) still regard the probability interpretation (expressed by means of expectation values, for example) as basic for an interpretation of the formalism, the sixth author (Stamatescu) critically reviews collapse models, which put all quantum probabilistic aspects into their (novel) dynamics [29], v emphasis added).

The 1990s saw a number of important experimental breakthroughs which confirmed many of the basic assumptions and theoretical predictions made using decoherence models. In 1996 a team at Boulder, Colorado generated a superposition of two spatially separated but localised wave packets of a single trapped $^{9}\text{Be}^{+}$ ion and measure the way the superposition was gradually destroyed through its interaction with a external radiation field serving as the 'environment' [34]. In 1997 Zeh commented that reality of the wave function "is now strongly supported by the beautiful experiments with individual atoms in activities (Schrödinger cat states, quantum engineering, phase space tomography etc.)" ([58], p. 449). Yet the experiments on decoherence did not prove as decisive on this point as Zeh had hoped.

In 1996, the experimental group at the École Normale Supérieure in Paris led by Michel Brune, Serge Haroche and Jean-Michel Raimond, published a preliminary letter in which they proposed to study the "disappearance of decoherence" by an experiment involving the manipulation of electromagnetic fields into a Schrödinger cat-like superposition using rubidium atoms [14]. The authors cited the early papers by Zeh and Zurek, as well the more recent publications from Zurek and Unruh. However, in the subsequent papers, which provided further confirmation of the predictions of decoherence models, the references to Zeh disappeared, whereas Zurek's publications continued to be cited extensively along with the [35] book [3, 33, 38, 39].

In 1997, Raimond, Brune and Haroche proposed an experiment to measure the 'reversible decoherence of a mesoscopic superposition of field states'. The authors stated that "the proposed experiment would demonstrate *the essential role of complementarity* in the decoherence process". Further, it was claimed that as the onset of decoherence "becomes increasingly faster with the size of the system" in such a way that "can easily be *interpreted in terms of complementarity*" ([38], p. 1964). Zeh recalls that he was surprised at this turn of events: "At first I expected that these results … would be seen as a confirmation of universal entanglement, and hence Everett, or at least as a severe argument against Copenhagen. But it turned out to be just the opposite—they later regarded entanglement as a form of complementarity!" [51]. When decoherence was taken up by experimentalists in the 1990s, it was often