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*Original Paper*

# OBITUARY FOR HEINZ-DIETER ZEH (1932 – 2018)

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Heinz-Dieter Zeh, the pioneer of the theory of decoherence, passed away on April 15, 2018, while being on holiday in the Black Forest, Germany. Zeh was born in Braunschweig, Germany, on May 8, 1932. He studied physics in Braunschweig and in Heidelberg, where he began work on theoretical nuclear physics. He made his PhD in Heidelberg under the supervision of Nobel laureate Hans Jensen and Hans-Jörg Mang in 1962. After a year of research at the California Institute of Technology (1965), he moved to the University of California in San Diego (1966/67) to work on the synthesis of the heavy elements, before returning to the University of Heidelberg, where he later became professor of theoretical physics, and where he stayed during the rest of his life.

Zeh's main contribution to physics is the discovery of the process of decoherence, which is crucial for understanding the relation between quantum theory and its classical limit. In his seminal paper of 1970, Zeh has shown that the natural environment of a quantum system plays a crucial role in obtaining this limit (Zeh 1970). Here, "environment" means other (typically many) degrees of freedom that couple to the quantum system, but are not under control. Before that work, it was always assumed that objects can be isolated, at least in principle. Zeh has convincingly shown that this is usually not the case if the system is mesoscopic or macroscopic. The interaction with the environment is essential for the classical limit. One important example discussed in that paper is the emergence of chirality as a stable property for sugar molecules.

Concrete calculations address the behaviour of the local (reduced) density matrix. Using simplified models, Kübler and Zeh were able to show why coherent states are the most classical states for harmonic oscillators, and why superpositions of, for example, a neutron and a proton can never be observed (Kübler and Zeh 1973). It is, however, not enough to discuss the local density matrix. As was emphasized by Zeh in 1973, one also has to find out the preferred classical basis of quantum states (Zeh 1973).

Important further work along these lines were started in the beginning of the 1980s, mainly by the work of Zurek, see Zurek (1981, 1982, 2003). The first paper, however, which treated *realistic physical systems* was an article by Zeh and his student Joos, see Joos and Zeh (1985). In this paper, they present detailed calculations for many systems and their natural environment; they considered, for example, the interaction of charges with radiation, of macroscopic bodies with air molecules, and other situations. It is thus not surprising that these results had been of central importance for many of the experiments that were performed twenty years later (see e.g. Hackermüller *et al.* 2003, 2004).

This quantum-to-classical transition by the unavoidable and irreversible coupling of a quantum system to its environment was later (around 1989) dubbed *decoherence*. The first experimental tests of decoherence were performed in 1996 and later, notably by the groups of Haroche in France and Wineland in the US (Nobel Prize winners of 2012).[1] Impressive tests of decoherence have also been performed by Zeilinger's group in Vienna, see again Hackermüller *et al.* (2003, 2004). The Vienna group performed interferometry with massive molecules and demonstrated how the interference pattern decreases as a result of switching on an environment in a controlled way. The latter is performed by either increasing the pressure of a surrounding gas or heating up the molecules so that they can emit photons. Many more experimental confirmations exist by now (see e.g. Schlosshauer 2007, Chap. 6).

Decoherence has become a central concept in all fields where quantum aspects play an important role. This holds, in particular, for the modern field of quantum information where decoherence is the major obstacle in building an efficient quantum computer. Decoherence also plays an important role in solid state physics and the physics of the early universe. It has become a standard topic in quantum theory.[2]

The main impetus for Zeh in introducing and elaborating on the concept of decoherence was the *understanding* of quantum theory. Motivated by issues arising in nuclear physics, his field of research in the 1960s, he arrived independently at the Everett interpretation, not known to him at that time (Becker 2018, Camilleri 2009, Zeh 2006). He recognized that this interpretation can only be consistently formulated if decoherence is included as an essential part, and that decoherence finds it natural place within the Everett interpretation. The last word on interpretation has certainly not been spoken, but so far all existing experiments are consistent with the Everett interpretation, and the interpretation is minimalistic with regard to the mathematical formalism.

The process of decoherence can only work in an irreversible situation, because it

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1 See, for example, Haroche (2014).

2 As of November 8, 2018, 1477 articles with *decoherence* in the title can be found on arXiv:quant-ph. For detailed reviews, see Joos *et al.* (2003), Zurek (2003), and Schlosshauer (2007).

relies on the formation of entanglement with the environment; this entanglement will not disappear in any reasonable timescale. It is thus not surprising that Zeh had a deep and enduring interest in the origin of irreversibility of our world. This is testified in his influential monograph on the direction of time, which has gone through five editions (Zeh 2007). It was in the course of these investigations that Zeh also developed interest in general relativity and its quantization.

In a short letter, Zeh outlined the idea that relevant gravitational degrees of freedom, if treated in a quantum theory of gravity, can assume classical properties by interaction with "environmental" degrees of freedom such as gravitational waves (Zeh 1986). "Environmental", as always, refers to irrelevant degrees of freedom in full configuration space. This was the starting point of my own PhD thesis with Zeh, in which I treated, among other things, the decoherence process in quantum cosmology in quantitative detail (Kiefer 1987). Since then, decoherence for gravitational degrees of freedom has received various applications; see, for example, Chap. 4 in Joos *et al.* (2003).

In spite of his pioneering work on decoherence, Zeh did not receive much recognition during his lifetime. The story of this is told in Becker (2018) and Camilleri (2009) and sheds much light on the role of non-scientific influences on scientific work. Still, there were notable exceptions, such as Eugene Wigner and Murray Gell-Mann, the latter mentioning Zeh's (and Joos') work even in his obituary for Richard Feynman, see Gell-Mann (1989). There exist also textbooks such as the one written by Bernard d'Espagnat in which this work figures prominently (d'Espagnat 1995).

After having completed my PhD with Zeh in 1988, I have been mostly working on quantum aspects of gravity. But the contact with my former supervisor has never been interrupted. In the years from 1989 to 1995, we had the opportunity to meet regularly in Heidelberg and to discuss in a small group of six persons questions related to the foundations of quantum theory in general and to decoherence in particular. Out of this grew the first monograph on decoherence: the first edition appeared in 1996 and the second one in 2003, see Joos *et al.* (2003). The participants always appreciated the critical spirit of Dieter Zeh and his deep insight on conceptual questions in physics. Many of his papers and general essays can be found on his former homepage, which is archived at the University of Cologne, see http://www.thp.uni-koeln.de/gravitation/zeh/. It is through these writings that he will continue to live.

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