

## A (So-So) Novel No-Go: Heisenberg on Hidden Variables (1927-1935)

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Philosophers and historians of science have long been engaged in discussing the importance of the 1935 Einstein-Podolsky-Rosen paper (EPR) arguing for the incompleteness of quantum mechanics, and Bohr's immediate response to this critique. Very few are aware, however, of a response to EPR written by Heisenberg in Leipzig at the same time Bohr was crafting his more famous response in Copenhagen.

After the EPR paper was published in *Physical Review*, Pauli wrote to Heisenberg, suggesting that Heisenberg develop his own response to EPR, despite the fact that Bohr was already working on a draft. The implication was that, as Pauli well knew, Heisenberg would likely provide a rather different argument in defense of quantum mechanics (or, rather, against the possibility of ever rendering it "complete", as the authors of EPR desired) than the sort of tactics it was assumed Bohr would employ against this criticism of the theory.

Heisenberg took up Pauli's suggestion. On July 2, 1935 he replied to Pauli's letter, enclosing a draft of his response to EPR, titled: "Ist eine deterministische Ergänzung der Quantenmechanik möglich?" This paper would never be published, save for a transcription, in German, in the multi-volume collection of Pauli's scientific correspondence (K. von Meyenn 1985).

I recently completed the first English translation of this work of Heisenberg's, and have found that it is fascinating not only in its historical significance as a defense of quantum mechanics quite different from Bohr's (thereby providing further ammunition against the so-called "Copenhagen interpretation"), but furthermore, it is a document rich with philosophical implications. For example, Heisenberg's response does not focus on the *gedanken* experiment presented by EPR, as does Bohr's; rather, Heisenberg frames his defense of the completeness of quantum mechanics in terms of the more difficult conceptual question concerning the placement of the "cut" between classical descriptions of physical processes and quantum mechanical descriptions.

Though Heisenberg had spoken of the "cut" several times in the years prior to 1935 and would continue to use this specific argument in writings and lectures afterward, it is within his response to EPR that we find the most carefully laid-out and detailed description of this argument. Furthermore, it is within the wider context of Heisenberg's cut argument as presented in his 1935 that we find also his fullest argumentation against the possibility of hidden variables—a potential remedy postulated by de Broglie (1926), Einstein (1927) and others to resolve the perceived incompleteness of quantum mechanics.

A detailed exploration of Heisenberg's response to EPR promises to yield a rich and

varied harvest; however, it is a harvest that exceeds the limitations of one talk. In this presentation, I focus on Heisenberg's thinking regarding hidden variables in the period from 1927 to 1935. My investigation will take Heisenberg's treatment of hidden variables in the EPR draft as central, but will consider more broadly the conceptual space that led Heisenberg to the specific no-go argument developed in response to EPR. In order to clarify this conceptual space, I will consider three relevant aspects of Heisenberg's thought from 1927 to 1935 that merge to form his best-articulated argument against the possibility of hidden variables. These three aspects are as follows: (i) Heisenberg's earliest no-go argument, which targeted Einstein's 1927 unpublished paper on hidden-variables, (ii) the central role of interference phenomena in Heisenberg's approach, and (iii) the cut argument, which Heisenberg believes ultimately demonstrates the incompleteable nature of quantum mechanics, granting only its most fundamental assumptions.

By investigating the connection between these three crucial components in Heisenberg's thinking prior to EPR and the response to EPR itself, some striking features of this argument emerge. One significant feature of Heisenberg's work on hidden variables in 1935 concerns a matter of historical priority: it appears that in his draft, Heisenberg makes explicit for the first time in the literature the importance of assumptions regarding the context dependence of hidden variables. As far as my historical work reveals, Heisenberg's separate treatment of a case wherein hidden variables depend on context versus the usual case, in which the hidden variables are assumed to be *independent* of observational context, anticipates Bell's (1966) famous realization concerning these two separate "classes" of hidden variables theories by nearly thirty years. The argument Heisenberg eventually gives against context-dependent hidden variables is hand-wavy at best; yet the historical point remains.

The argument he deploys against the existence of the usual, context-*independent* hidden variables is not much good, either. However, one is struck upon closer analysis of these arguments that despite their shortcomings, Heisenberg has nevertheless done something quite novel in developing them—something that none of his contemporaries had attempted, or perhaps even appreciated. My collaborator Guido Bacciagaluppi and I (forthcoming) have concluded, based on examination of Heisenberg and comparing his work to other no-go arguments being put forward at the time, that Heisenberg's particular approach is significantly distinct from the usual method employed by, for example, von Neumann in his *Mathematische Grundlagen der Quantenmechanik*, Pauli, Schrödinger, and Grete Hermann—a neo-Kantian philosopher and student of Emmy Noether's who visited Leipzig during the early 1930's and who, after many interactions with both Heisenberg and von Weizsäcker, composed one of (if not *the*) first philosophical treatises on quantum mechanics.

The second part of my presentation will serve as a historical sketch of "fashionable" no-go arguments for hidden variables employed by these four important figures. A comparison will then expose the difference of approach adopted by Heisenberg. Bacciagaluppi and I argue that Heisenberg's surprisingly unique treatment of hidden variables aids us in understanding why it was *Heisenberg* who first grasped the

importance of the assumption of context dependence. We further argue that it is the unique character of this argument that may resolve certain historical puzzles regarding Heisenberg's 1935 draft and the response (or lack thereof) to it.