The physical motivations for a propensity interpretation of probability, and the reactions of the community of quantum physicists.

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Karl R. Popper has been perhaps the first modern philosopher of science to realise that 'quantum mechanics [(QM)] and probability theory share one peculiarity. Both have well established mathematical formalisms, yet both are subject to controversy about the meaning and interpretation of their basic concepts. Since probability plays a fundamental role in QM, the conceptual problems of one theory can affect the other.' (Ballentine, 2016). A fact that only recently found some support in the physics community.

As a matter of fact, with the pivotal work of John von Neumann (1932), QM was provided with a consistent axiomatic formulation: a physical system is represented by a vector Ψ (actually a ray) in a complex Hilbert space, which encompasses all the physical variables. What is, however, the ontological status of Ψ is still to date object of heated debate.

Roughly in the same year, probability theory underwent a systematization (as an axiomatic measure theory on a Boolean algebra), mostly thanks to Kolmogorov (1933). Popper's *Logik der Forschung* (1934) -although it owes its fame mainly to methodological issues and the novelty of falsification, therein proposed- was extensively devoted to probability (in particular to the frequency interpretation, see e.g. Miller 2016) and to some problems in quantum theory.

QM is indeed related to probability as follows: given a certain experiment with experimental settings x and a possible outcome a, quantum theory allows to compute the probability $p(a|x)$ of finding that outcome. Yet, there is to date no unique and satisfactory explanation of the mechanism that leads to the observation of a specific outcome in a certain experimental run (this has gone down in history as the quantum measurement problem, see e.g. Brukner 2017). On the other hand, despite the well-defined laws of formal calculus of probability, the symbols $p(a|x) = r$ (read: "the probability of a given x"; and where r is a real number between 0 and 1), as well as the arguments a and x are in general left open to interpretation (see e.g. Popper 1967, eight thesis).

For about 60 years, Popper has been one of the foremost critics of the "orthodox" Copenhagen Interpretation of Quantum Mechanics, the vastly accepted anti-realistic, subjectivist and instrumentalist viewpoint on how to interpret quantum formalism. Popper, indeed, strove for an objectivist, realistic interpretation of quantum theory, and only in his late years he gathered the support of illustrious physicists (see Del Santo 2017). At the same time, at least since 1934, Popper fought against subjectivist interpretations of probability (which interpret probability as a rational degree of belief of an event to occur, based on a subjective lack of knowledge). It is thus not a case that Popper's ideas on quantum mechanics and in probability co-evolved in a way that is impossible to disentangle. Despite the severe criticism levelled by Milne to Popper's own *propensity interpretation* of probability (PIP), he rightly encapsulated the importance of the relation that bonds quantum theory and the propensity interpretation in Popper's view: 'The support is mutual: propensity theory helps us to understand quantum mechanics, quantum mechanics provides evidence for, or naturally gives rise to, a propensity interpretation.' (Milne, 1985).

For many years, Popper had adhered to the (objective) frequency interpretation of probability (specifically as expounded by von Mises, and improved by Popper himself) that regards probability as the relative frequency of events a among the events b. Yet, from 1950 (see a letter from Popper to S. Körner on 21/04/1956. PA, 48/27) Popper started developing the PIP. Propensities were first presented in 1953, in the course of lectures (published in C. A. Mace, 1957), and eventually presented to the academic world, in 1957, at the Ninth Symposium of the Colston Research Society in Bristol (Popper 1957). There Popper started delineating the problems of the interpretations of probability, related to quantum theory. A major concern was how to treat the probability of a single event, something that frequency interpretation leaves uninterpreted. However, it ought to be stressed that the reasons that led Popper to abandon the frequency interpretation are not to be sought in an alleged untenability of the frequency interpretation. Indeed, Popper always maintained the frequency interpretation to be 'immune to usual objections' (Popper 1959); the actual motivation came, as anticipated, from physics. In fact, single-case probability 'is of importance in connection with quantum theory because the Ψ-function determines the probability of a *single electron* to take up a certain state, under certain conditions' (Popper 1957). In a second and more technical (not about physics though) paper on PIP, Popper explicitly stated: 'I gave up the frequency of probability in 1953 for two reasons.

(I) The first was connected with the problem of the of quantum theory.

(2) The second was that I found certain flaws in my treatment of the probability of single events (in contrast to sequences of events)

[…] the first point […] was the first in time and importance: it was only after I had developed […] the idea that probabilities are physical propensities, comparable to Newtonian forces, that I discovered the flaw' (Popper 1959).

It was in fact an attempt to interpret in a realistic and objective view the quantum double-slit experiment that led Popper to the conviction that 'probabilities must be "physically real" -they must be propensities, abstract relational properties of the physical situation […] and real not only in the sense that they could influence the experimental result, but also in the sense that they could, under certain circumstances (coherence), interfere, i.e. interact with one another.' (Popper 1959).

This revolutionary idea, despite having been presented for the first time in the course of what has been defined as 'the first major event after World War II" about foundations of quantum mechanics (Kožnjak, 2017), was completely ignored by physicists for at least a decade.

I will show that it is only with the publication of Quantum Mechanics without the Observer (Popper 1967) that Popper (i) for the first time fulfilled his original aim of applying propensity interpretation to quantum physics in a comprehensive way and, consequently, (ii) he received the first attention by the community of physicists concerned with quantum mechanics. I will try to offer an overview on the main reactions, both positive (D. Bohm, H. Bondi. B. van der Waerden, F. Selleri) and negative (J. Bub, P. Feyerabend, P. Milne). This reconstruction will be based on unpublished private correspondence between Popper and his major interlocutors among physicists, retrieved in Popper's Archive in Klagenfurt (Austria), as well as through a thorough analysis of the literature available.

Propensity interpretation has been expounded by Popper in a number of works, throughout about four decades, and went through many refinements. D. Miller (1991, 2016) has rightly highlighted that the PIP was not developed in its ultimate and most sophisticated formulation until the *Postscript* (Popper 1982), wherein propensities were eventually formulated as the first objective interpretation that could consistently deal with single case probabilities -and also frequency of events in the long run. According to this view, it is eventually the whole universe, everything that lies within the light cone of the considered event, that can possibly contribute to influence the probabilities (propensities). Although I fully agree with this view, I will focus on the local condition that determine physical experiments, namely the local experimental conditions that are directly controllable in scientific practice. Therefore, I maintain that for this purpose the PIP was already fully developed as it was expounded by Popper in his *Quantum Mechanics without the Observer* (Popper 1967).

I will then attempt a discussion of the main features that relate propensities to fundamental aspect of physics. In this regard, I will discuss, for instance, the role that determinism plays in quantum mechanics and support the fact that 'propensities […] can assume non-extreme values only in an indeterministic world.' (Miller 2016). Moreover, I will review the different definition of physical reality that Popper assumed in different period as the underlying assumption for a realistic interpretation of probability. In fact, it seems that in his first work on PIP (Popper 1957, 1959), Popper used (quantum) physics as a mere triggering motivation for a revision of the issue of single-case probability, but the ontology of the propensities was scarcely outlined. At first, Popper defined the propensities as ‘abstract relational facts [that] can be “causes” and in that sense physically real’ (Popper 1957). The ontology of propensities was however thoroughly discussed only later, when Popper maintained that it is not solely the one-direction causation to define what is physically real, but reality is attributed to an entity ‘if it can be kicked, and it can kick back’ (Popper, 1967, eight thesis).

Coming to quantum theory, the ontological problem in the microscopic world has puzzled physicists for over nine decades. Historically, the most prominent realistic class of interpretations of quantum theory was developed with the so-called *hidden variable* models. These all share the feature of ascribing the whole oddity of quantum theory (wave-particle duality, entanglement, etc.) to the existence of underlying hidden variables (HV), λ, not experimentally accessible (either in principle or provisionally). Albeit HV were firstly introduced to restore classical determinism (i.e. $p(a|x,\lambda) = 0$ or 1), and therefore supposed to account for the observed probabilistic behaviour of quantum mechanics, models of increasing complexity flourished throughout the 1960s-1970s, which did not rely on strict determinism, but still maintained a realistic description of the physical world (realism in this context means that physical objects have well defined values of all the physical variable at any instant in time). Following the idea of L. de Broglie of a pilot-wave guiding quantum particles, Bohm proposed the first fully developed model of QM in terms of deterministic HV. However, contrarily to what many physicists believe, Bohm himself was ready to abandon strict determinism. Popper and Bohm had a long and fruitful intellectual relationship (not free from tensions though), and their views on interpretations of quantum mechanics were convergent to a large extent, even more than Popper himself had possibly realised, according to Bohm (letter from Bohm to Popper on 13/07/1984. PA 278/2). I shall therefore draw a parallel between Popper’s physical propensities and hidden variables, showing that Popper’s physical probabilities (propensities) -even though, to my knowledge, never stated explicitly by Popper- are not only strongly related to the interpretation of quantum mechanics, as ceaselessly stated by Popper, but, given the fact that they are granted a status of physical reality, propensities are actually a form of hidden variables. Popper’s interpretation of quantum mechanics thus results composed of two elements: a corpuscular ontology of directly detectable particles, and physically real propensity fields (hidden variables) that can be indirectly manipulated by altering the experimental conditions. Admittedly, Bohm noticed that in his (non-deterministic) HV model one can regard ‘the stochastic movement of the particle as affected by a field of propensities’ (letter from Bohm to Popper on 13/07/1984. PA 278/2). In this light, propensities as hidden variables survive the fundamental limitation imposed by the Kochen-Specker theorem (Kochen and Specker, 1967), which states the incompatibility of non-contextual hidden variables (i.e. independent of the choice of the disposition of the measurement apparatus, called context) with quantum mechanics.

In conclusion, the aim of the present paper is to provide an historical account of the development of Popper’s propensity interpretation of probability, with a focus on the essential relation with (quantum) physics, as well as a brief reconstruction of the resonance of Popper’s proposal in the community of quantum physicists.

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