Foundations of Quantum Mechanics

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The subgroup concerned with the *Foundations of Quantum Mechanics* has worked on different but interconnected research topics.

Firstly, a research activity on the elaboration of a new theory (the *ESR model*) which avoids the problems and paradoxes of the standard interpretation of quantum mechanics (QM) has been developed. The ESR model embodies the mathematical formalism of QM into a broader mathematical framework, reinterpreting quantum probabilities as conditional on detection rather than absolute. Because of these features the ESR model avoids the basic problem of the quantum theory of measurement (the *objectification problem*), together with the related paradoxes (*Schrödinger's cat*, *Wigner's friend*, etc.). At the beginning of 2011 a review article which expounds in a unified way the main features of the ESR model was completed [1]. Three further papers were then published in 2011. The first of them [2] shows that each proper mixture is represented by a family of density operators parametrized by the set of all properties of the physical system that is considered in the ESR model, which leads to a modification and generalization of the Lüders postulate and avoids the interpretative difficulties that afflict the standard representation of mixtures in QM. The second paper [3] shows that *local realism* holds in the ESR model, and yet Bell's inequality must be substituted by a *modified Bell's inequality* which is not violated by the standard quantum expectation values if these values are reinterpreted as proposed by the ESR model. The third paper [4] shows that quantum logic can be recovered within a classical language as a theory formalizing the properties of the metalinguistic notion of testability in QM, which proves that no notion of quantum truth opposing the classical notion of truth as correspondence is needed if the reinterpretation of QM proposed by the ESR model is accepted. Finally, another article was completed and accepted for publication in 2011 but published in 2012 [5]. This article provides an improved version of the ESR model and compares the mathematical representation of proper mixtures with the mathematical representation of improper mixtures in the ESR model, showing that the latter coincides with the standard representation of mixtures in QM and proposing on this basis a scheme of an experiment aiming to confirm or disprove the ESR model.

Secondly, a research activity on the identification and application of quantum structures in disciplines different from physics has been developed in collaboration with the Brussels research group.

Psychology. A *SCoP formalism* has been employed to model the data collected in some experiments carried out to estimate typicalities and membership weights of exemplars of concepts and their combinations. The empirical results contrasted the predictions that could be obtained by interpreting combinations of concepts in terms of classical logic and set theory (*Pet-Fish problem*). By adopting the SCoP formalism and elaborating a quantum model one can instead describe and explain experimental data in terms of contextual influence between concepts. The presence of quantum effects, i.e. contextual influence, superposition, interference, emergence and entanglement, has been identified in the mechanisms of concept combinations [8,11]. Some applications of this approach to information retrieval, artificial intelligence and robotics have also been discussed [10].

Biology. In spite of their predictive success, population dynamics and evolutionary game theory still pose fundamental problems (*paradox of the plankton*). Game theoretical aspects of the paradox are reducible to appropriate competition mechanisms and there are reasons to believe that plankton–type biodiversity is a consequence of cyclic competition. But cyclic competition is an evolutionary analogue of the classical scissors-paper-rock (SPR) game, which cannot be modeled in a single classical probabilistic framework [6]. This is why one has to resort non–Kolmogorovian probability models, such as those employed in QM. On the other hand, the territorial behavior of three side–blotched lizard morphs follows an SPR dynamics. We have thus used a set of experimental data collected on lizards since 1990 to show that a single Kolmogorovian space

does not exist. Then, we have elaborated a quantum model in Hilbert space that accords with the collected probabilities [16].

Economics. The *expected utility hypothesis* is violated in real life decisions (*Allais* and *Ellsberg paradoxes*). The popular explanation in terms of *ambiguity aversion* is not completely accepted. On the other hand, context plays a relevant role in human decisions under uncertainty, and any probabilistic structure modeling contextual interactions between systems needs a non–Kolmogorovian framework with a (generalized) quantum representation. A notion of *contextual risk* has thus been proposed to capture situations in which uncertainty occurs. The contextual risk approach has been applied to the Ellsberg paradox, a sphere model has been elaborated within a *hidden measurement formalism* which reveals that it is the overall conceptual landscape that is responsible of the disagreement between actual human decisions and the predictions of expected utility theory, which generates the paradox [9,12–14]. Some results pointing to the existence of quantum structures in option pricing have also been attained in quantitative finance [15].

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