

Quantum Contextuality and the Ontology of Causality

Summary

The ontology of microcausation is one of the most controversial and complex topics in the philosophy of physics. After the formulation of the Bell inequalities, and their first experimental tests in the 1980s, most philosophical discussions focused on subtle problems concerning an apparent clash between quantum nonlocal effects and the cone structure of spacetime. This book explores the more fundamental and profound question of the tension between classical causal structure and quantum contextuality. In particular, it deals with the philosophical issue of whether there is any plausible possibility to introduce ontic causation (not just the presence of some causal order of events, but also the real physical production of causal links and effects) and causal powers into relativistic quantum theory, whose structure permits maximal contextuality and which does not violate spacetime symmetries (according to the best experimental tests available to date). We answer that question affirmatively and propose construction of a stochastic model of such a kind.

Ontic contextuality is *the* fundamental physical property in microphysics. In Ch. 3.1 we give a general, sheaf-theoretic formulation of the (Bell-)Kochen-Specker theorem, and construe ontic contextuality (Ch. 3 and 4) as a strictly topological feature of quantum histories *in time*, as well as a physical resource for quantum work, which induces a generic, highly non-classical regime of information processing, obeying the principles of no-cloning, no-broadcasting and no-deleting. Moreover, we claim that it makes the very notions of ‘state’ and ‘measurement’ in quantum theory highly questionable, if not untenable, so that quantum mechanics is in fact a nonseparable mechanics without states and detections, which should be exchanged for ‘pseudo-states’ and ‘pseudo-measurements’ in the terminology. We show that the same structure which produces such an obstruction, interestingly, also renders the concept of dispositions of local particulars useless and any putative ‘quantum ether’ undetectable – quantum causation is (by all appearances) relativistically local causation by principle. It is argued that contextuality should be construed as a nontrivial, global topological structure of quantum histories, which takes the temporal and dynamical aspect of quantum ontology to the fore, as manifested in the effects analyzed, such as different variants of the quantum interrogation, the quantum liar paradox, the three-box paradox, the Hardy paradox, and the so-called logical pre- and postselection paradoxes in general. Nonlocal effects are a particular sort of contextuality defined for compound systems separated in space, and the no-signalling as well as undetectability of any quantum ether are presented as deep topolo-

gical properties of contextual quantum dynamics itself, and not as a by-product of some kind of thermodynamical masking by noise (as in Bohmian mechanics, for example).

In Ch. 2 we construct a *Gedankenexperiment* consisting in the cosmic-scale interferometric ‘interaction-free’ measurement (or quantum interrogation) of a quantum black hole by single quanta, which demonstrates in a dramatic fashion the extent of tension between the topology of quantum histories and the spacetime causal structure. We show that there is never any real causal paradox set in those quantum causal-dynamical peculiarities, and the quantum causal structure of histories is perfectly self-consistent, as well as consistent with the spacetime structure. We also argue, using time-symmetrized scenarios of this kind, that ontic contextuality points to the deep time symmetry of quantum theory, resulting from the fact that it treats independent initial and final conditions of dynamics of the histories on an equal footing. A positive conclusion is that: (i) quantum ontic contextuality permits, or even suggests, some generalized time symmetric form of causation, which is not, contrary to some apparent impression, a real threat to relativity, and (ii) the histories basis (*H*-basis) is much more convenient for a temporally nonseparable ontology than the events basis (*E*-basis). In fact, we show in Ch. 3.2 and 4 that that deep nonclassical time symmetry is buried at the centre of the quantum (noncommutative) measure theory and the generic features of quantum entropies in time. We analyze (Ch. 4.1) the thermodynamic properties of quantum histories and construe them as a direct manifestation of ontic contextuality, which makes the idea of separable events aggregating into derivative classical histories implausible. The same is shown in Ch. 4.3 for quantum weak values, which cannot be construed as ‘elements of reality’ with any classical flavour. We argue in line with Tollaksen, Leifer and Pusey that superweak values for pre- and post-selection are direct proofs of contextuality in time, which has fundamental significance for causal models.

A possible time symmetry of causation certainly creates serious problems for any attempt to construct a model of the causal spacetime network with asymmetric causal links and non-illusory time asymmetry. There are two general types of approaches to the ontology of causality, with different sets of metaphysical intuitions and assumptions at play, which have been developed during the history of natural philosophy: the first has its roots in Aristotelian metaphysics, and the second one in the radical atomistic streams of medieval Arabic metaphysics. We call the former a *particularist-dispositionalist scheme* (PDS), and the latter an *atomistic-aggregational scheme* (AAS), which evolved into a *geometric-configurational scheme* (GCS) within the framework of modern physical mechanics following Descartes and Newton. They produced two different metaphysical preferences in the analysis of causality: the *temporal preference* linked to the idea of the real, dynamic becoming (change) of separable individuals in the case of PDS, and the *spatial preference* linked to an intuition of a mosaic of momentarily coexisting, fully separable events, distributed in physical space and constrained by laws, in the case of AAS (which is deflationist or straightforward eliminativist about causation and causal properties themselves). We show that both PDS and AAS are deeply problematic in the context of quantum relativistic theory, and quantum mechanics may even be perceived as ‘causally pathological’ from that point of view.

In Ch. 2.3 we critically review the ‘Cartesian’ (kinematical-configurational) Bohmian mechanics as an example of the conservative, ‘step back’ strategy of maximally restricting the reach of ontic contextuality for observables, and re-enforcing the spatial preference of AAS, which immediately cramps ontology down to kinematics (re-separating it from dynamics),

produces some variant of quantum ether, and degrades the generic manifestations of contextuality (quantum probabilistic measure – Born rule, negative conditional entropies in time, no cloning, no deleting etc.) to a status of derivative effects. We hold that there are no plausible reasons for such a restricting of the reach of ontic contextuality for quantum causal networks if one recognizes it as their fundamental topological property. Furthermore, we also insist that although deterministic Bohmian theory is indeed causal, it does not need any real ontic causation (like every deterministic theory), which is also a *sui generis* partial recreation of the anti-causal AAS after all. Thus, we assess any ‘step back’ strategy in ontology of contextuality as deeply problematic, and make a case for treating each internal event of any quantum history, even spatial localization, as purely relational and contextual, in line with e.g. Carlo Rovelli’s relational interpretation.

We analyze five types of serious quantum ‘causal pathologies’ (as judged from the classical perspective): (i) spatial; (ii) temporal; (iii) spatial-dynamical; (iv) interactional; (v) resulting in an indefiniteness of the causal ordering of events in spacetime. We argue that any realist causal ontology has to subsume these ‘pathologies’ as its generic features resulting from a suitably generalized, nonclassical definition of causation. Furthermore, we hold that a causal realist should try to accommodate a dynamical-dispositional core of PDS to quantum theory in order to defend a real ontic causation (production of the partially ordered, linked events composing the causal spacetime network), in stark contrast to AAS, which does not need any real causal ‘tie’/‘connexion’ (Hume) or ‘glue’ (Descartes) beyond the categorical properties. Thus, not only does quantum time symmetry prove to be a problem for such an accommodation, but also a plethora of quantum causal pathologies destroying the classical PDS and AAS, as well as an apparent lack of a real, causal ‘glue’ of histories, which is important for a dispositionalist naturalistic-physicalist ontology with causal properties. However, relativistic quantum theory and quantum field theory are physically consistent and free of causal paradoxes (physical contradictions), which suggests that a causal realist, who rejects any quantum ether and objects to addressing relativity as only epistemic, is not occupying a lost position. The basic problem turns out to be finding a way to incorporate ontic contextuality as a *global temporal* property into indeterministic models of quantum causal networks with dispositions (without the metaphysical spatial preference, hence without any nonlocality as an action-at-a-distance, and even without any nonlocal ‘ether of dispositions’).

In Ch. 5.2 and 5.3 we examine two classes of time symmetric causal models with relational, contextual events, which we call (in some historical analogy to McTaggart’s *A*- and *B*-series) *A*-model and *B*-model, the former being indeterministic with the stochastic collapse, and the latter deterministic without any real collapse, with two sets of independent, actual boundary conditions (in the past and in the future). A concrete *A*-model is proposed with a two-tier or two-phase ontology for a *H*-basis: a highly time-symmetric physical regime of virtual processes, which seems to obey the purification principle; a low-symmetric regime as the ‘growing’ (time asymmetric) spacetime causal network; and a collapse construed analogically to the spontaneous symmetry breaking or a kind of a phase transition between them. It is argued that virtual processes in time, in particular entanglement in time and interference in time, should in general be taken seriously as real and physically effective in fundamental ontology (i.e. *everything which is allowed by time symmetry must physically occur in reality, but virtually*), not as a ‘thin’ formal artifact of the perturbative method in quantum field theory. It is also stressed that they shouldn’t be misconceived as classical, separable

possibilities demarcated from actual states of affairs, since the virtual phase, due to ontic contextuality, is always physically, inextricably coupled to the spacetime (actual) phase of the growing causal network (i.e. *no actuality without coupled virtuality of the field emissions and absorptions*).

We highlight how amplitudes of these time symmetric processes (fields) generate a quadratic form of the Born rule and the Kirkwood–Dirac quasiprobability, thus a quantum probabilistic measure in general, as well as negative conditional entropies for histories as a virtual resource for quantum work, not available for systems behaving classically. It is shown how ontic relationality of events in time, inducing also nonlocal effects in space, is a direct manifestation of virtual dynamics in such a model. Causal links (ontic ‘glue’) in a quantum network of histories are possible thanks to the reality of entanglement as a consequence of the purification principle and the pre-spacetime, virtual resource (i.e. *no emergent spacetime without real entanglement*). We insist that there should be only one global resource of such a kind, common to both local and nonlocal effects, because of the empirically confirmed quantum monogamy between local contextuality and nonlocal correlations. Hence, contrary to common opinion based on spatial preference, nonseparability is *not* a threat to spacetime order, but its ontological prerequisite. Causation is defined not as a process between individual systems endowed with dispositions in spacetime, but rather as a pre-spacetime process of the symmetry breaking, producing the emergent causal order of actual events, thus as directly linked to the stochastic collapse, which induces time asymmetric, purely local growth of the network. It is also demonstrated how the *A*-model explains rather naturally all the ‘causal pathologies’ (i)-(v), while the quantum liar paradox is not a paradox at all due to two-tier physics (in analogy with a solution of the semantic liar paradox) and nontrivial causal topology. Both weak values, and negative conditional entropies are then realistically interpreted in a *H*-basis as physical parameters of the quantum causal geometry of histories in time, as well as physical indicators of the virtual time symmetry of quantum (generalized) causation.

We question the plausibility of the deterministic, one-tier (one-phase) *B*-model as reproducing the basic structure of AAS and GCS without ontic causation, with the only interesting modification of having robustly relational events, which obey the principle of relativity. It is argued that the *B*-model needs cosmological fine-tuning, which only doubles the standard problems with the initial fine-tuning in cosmology. In fact, we suggest, in line with Wood and Spekkens (2015), that every retrocausal one-tier model must suffer from fine-tuning for its unique causal network. The *B*-model is not even retrocausal, since nothing really happens causally in the case of a single determined quantum history without real physical collapses (exactly as in Bohmian mechanics), hence ‘causation’ here is only *façon de parler* (doesn’t have any ontological meaning). Moreover, it treats the principles of no-cloning, no-deleting, no-disturbing etc., which we take as fundamental, as purely thermodynamical in origin.

We advance the thesis that a viable option for a causal realist-dispositionalist, who recognizes the ontic contextuality and (i)-(v), seems to be the *A*-model with primitive (not anchored in the spatio-temporal objects), *time-symmetric causal powers*. It is proposed that quantum causal powers might be seen as physically equivalent to the fields of the time-symmetric virtual processes, hence inextricably linked to real interference and entanglement in time. They differ drastically from the ontologically weak, classical possibilities (a tautolo-

gical 'what is possible, is only possible to occur') for they are much stronger as defined by the contingent rule for the Universe assumed to be asymptotically an effective perfect absorber: 'what is physically allowed under time symmetry (quantum emissions, absorptions and their compositions), must effectively occur in reality, but virtually'. The latter is, in fact, also the source of entanglement of compound systems as a virtual dynamics manifesting in spacetime in their actual correlations. Thus, we present an idea of time-symmetric quantum powers as an ontological upshot of the topological contextuality of histories, provided that one accepts the two-tier ontology (or two-phase physics, with the virtual/pre-spacetime and the actual/spacetime causal network regimes) enriched with some physical transition between them, which spontaneously generates the spacetime causal network. Our thesis is that ontic contextuality (general nonseparability) and ontic randomness are not hostile to quantum causation. On the contrary, they seem closely connected, almost like two sides of one coin, in stark contrast to classical physics where noncontextuality (general separability) and determinism enable strict causal eliminativism.