Haunted Quantum Contextuality versus Value Indefiniteness

Karl Svozil

Institute of Theoretical Physics, Vienna University of Technology, Wiedner Hauptstraße 8-10/136, A-1040 Vienna, Austria
svozil@tuwien.ac.at

Abstract. Physical entities are ultimately (re)constructed from elementary yes/no events, in particular clicks in detectors or measurement devices recording quanta. Recently, the interpretation of certain such clicks has given rise to unfounded claims which are neither necessary nor sufficient, although they are presented in that way. In particular, clicks can neither inductively support nor "(dis)prove" the Kochen-Specker theorem, which is a formal result that has a deductive proof by contradiction. More importantly, the alleged empirical evidence of quantum contextuality, which is "inferred" from violations of bounds of classical probabilities by quantum correlations, is based on highly nontrivial assumptions, in particular on physical omniscience.

Discussion

Time and again, in coffee houses and elsewhere, members of the Viennese experimental physics community reminded me always to keep in mind that all our physical "facts" are ultimately derived and constructed from detector clicks. It is this basic wisdom that, when consequentially applied to recent experiments, suggests to rethink certain claims of empirical proof.

Let us, for the sake of properly assessing the situation, review some historical cornerstones. Motivated by certain, as it turned out inapplicable, no-go theorems by von Neumann regarding hidden parameters, Bell came forward with criteria for classical probabilities and expectations, resembling the *conditions of possible experience* that had been contemplated by Boole a century earlier [18]. Essentially, these criteria state that, if one forces the (counterfactual) physical co-existence upon certain finite sets of complementary, incompatible, potential observables—meaning that every single one could be measured, although due to complementarity it is impossible to simultaneously measure all of them—the associated potential measurement outcomes are subject to certain algebraic bounds.

As these probabilistic bounds are not satisfied by quantum observables, the respective measurements outcomes cannot consistently co-exist [16]; at least not under the classical presumptions entering the calculations leading to these bounds. These arguments have subsequently been strengthened by the Kochen-Specker and the Greenberger-Horne-Zeilinger theorems, as for the latter ones

M.J. Dinneen et al. (Eds.): WTCS 2012 (Calude Festschrift), LNCS 7160, pp. 309–314, 2012.

any violations of the conditions of possible experience must occur on every single quantum and at least for a single observable [24] rather than occasionally.

Those results relate to situations in which *omniscience* is assumed; that is, all observables which could potentially be observed can indeed be associated with actual elements of physical reality of a single quantum. For a realist this might appear self-evident [20]. Also for experimentalists this seems to be obvious; after all, any particular observation renders outcomes, regardless of the mutual complementarity of some of the observables involved; in this view, "potentially operational" means "existence." By this inkling, the situation suggests that the measurement "reveals" a pre-existing element of physical reality of the quantum observed. Stated pointedly, registration of some detector clicks is interpreted as a revelation about what is taken as the quantized object.

If these pre-existing elements of physical reality are taken for granted, it is not unreasonable to "solve" or "explain" the conundrum imposed by the various aforementioned theorems by assuming that any potential measurement outcome may depend on whatever other maximal co-measurable collection of observables (the context, interpretable as maximal operator [11, sect. 84]) are co-measured alongside. This dependence of the outcome of a single quantum measurement on its context—that is, the influence of what is (sometimes implicitly) co-measured alongside this single quantum measurement—is termed *quantum contextuality.*

Note that the Born rule, and also Gleason's theorem, requires the quantum probabilities and expectations, and thus all quantum statistical properties, to be *noncontextual.* Notice also that contextuality attempts to maintain a realistic, omniscient, quasi-classical framework by abandoning context independence for single quantum observables.

Now, if one maintains realistic omniscience—that is, the pre-existence of all outcomes of complementary potential observables (as is implicitly assumed in Bell- and Kochen-Specker-type arguments)—then it is indeed true that, as stated by Cabello [5], "the immense majority of the experimental violations of Bell inequalities [[proves]] quantum contextuality." Actually, the only difference between older evidence of violations of Bell-type inequalities and more recent ones ([12], [2], [13], [1] and [14]) seems to be based on the fact that the prior ones rely on spatially separated quanta in Einstein-Podolsky-Rosen "explosion" type schemes, whereas more recent ones are based on single quanta—a concept which appears to be more in the spirit of Kochen-Specker type theorems which apply to the structure of observables of single quanta [7]. But even these sorts of empirical findings referring to single quanta rely on the non-instantaneous measurement of all but a few (mostly two or three in cases involving two- or three-particle Einstein-Podolsky-Rosen and Greenberger-Horne-Zeilinger type) configurations, and therefore cannot even counterfactually assure the operational existence of all elements of physical reality at once [22].

Alas, these assumptions are neither necessary (and sufficient), as other, rather exotic options [15, 17] demonstrate, nor is there any more direct empirical evidence in their support. Indeed, quantum predictions of Einstein-Podolsky-Rosen type setups involving singlet states of qutrits suggest that contextuality cannot be observed [23], although a direct experimental test is still lacking.

Thus with regards to quantum contextuality, that is, the "explanation" of Bell- and Kochen-Specker-type arguments, the situation is rather discomforting: insofar as contextuality seems to "explain" various findings related to quantum predictions and correlations, it can only be indirectly inferred by assuming some extra assumptions, including classical omniscience; otherwise it is not necessary. And insofar it could be directly testable it is very unlikely to show up. Because of this dilemma, it is suggested to re-evaluate recent empirical findings in terms of a much broader picture of *value indefiniteness;* including also the possibility that there needs not exist a pre-existing element of physical reality associated with certain observables.

Stated pointedly, value indefiniteness is the assumption that, with regards to certain potential observables, a quantum system cannot prepared to be in a specific, definite state, because the quantum system has been prepared in a definite state of a different, complementary observable. Hence there does not exist any entity or property of a physical system under observation which determines a measurement outcome of such a value indefinite observable completely. If some observer chooses to measure any such value indefinite observable—thus "forcing" an observation upon the *combined* system of measurement apparatus and quantum—the actual measurement outcome or event is also (if not entirely) determined by the disposition of the measurement apparatus [3]. This should be contrasted to the definition of an element of physical reality in the sense of Einstein, Podolsky, and Rosen [10]: in the latter case the measurement outcome is defined or linked to a physical property of the quantum measured, rather than to the combination of both measurement apparatus and the quantum measured.

Thus in situations involving counterfactual potential observables, such as in Bell- and Kochen-Specker-type arguments, the experimental outcomes actually measured might not originate from such pre-existence, but might depend on the interaction between the quantum measured and the measurement apparatus. Pointedly stated, the outcome might not reflect an intrinsic objective physical property of the quantized object, but rather originate in the way a measurement apparatus generates the outcome by interacting with the quantum. Already Bell [3] suggested that (cf. also Refs. [6, 8] for related experiments) "the result of an observation may reasonably depend ... on the complete disposition of the apparatus." Perhaps this was also what Bohr had in mind by mentioning [4] "the impossibility of any sharp separation between the behavior of atomic objects and the interaction with the measuring instruments which serve to define the conditions under which the phenomena appear."

So far no experiments have been performed to quantify the different empirical consequences of the assumption of quantum contextuality versus the assumption of quantum value indefiniteness. One possibility would be to measure the varying capacities of the measurement apparatus to translate between the context observed and a different context in which a quantum was prepared [21].

These considerations are highly relevant for the computational capacities of quantized system exhibiting incomputability [9], because, as it is commonly assumed [25], quantum systems are irreducibly indeterministic. How can we conceptualize and justify such computational capacities, in particular in view of the uniform one-to-oneness of the quantum evolution at certain devices such as fifty-fifty beam splitters generating a coherent superposition of classical states [19]? One possibility would take into account the combined action of a single quantum system, registered by a macroscopic measurement device with many degrees of freedom.

Acknowledgements. This research was partly supported by Seventh Framework Program for research and technological development (FP7), PIRSES-2010-269151-RANPHYS.

References

[1] Amselem, E., Rådmark, M., Bourennane, M., Cabello, A.: State-independent quantum contextuality with single photons. Physical Review Letters 103(16), 160405 (2009), http://dx.doi.org/10.1103/PhysRevLett.103.160405, doi:10.1103/PhysRevLett.103.160405

[2] Bartosik, H., Klepp, J., Schmitzer, C., Sponar, S., Cabello, A., Rauch, H., Hasegawa, Y.: Experimental test of quantum contextuality in neutron interferometry. Physical Review Letters 103(4), 040403 (2009), http://dx.doi.org/10.1103/PhysRevLett.103.040403, doi:10.1103/PhysRevLett.103.040403

[3] Bell, J.S.: On the problem of hidden variables in quantum mechanics. Reviews of Modern Physics 38, 447–452 (1966), http://dx.doi.org/10.1103/RevModPhys.38.447, doi:10.1103/RevModPhys.38.447

[4] Bohr, N.: Discussion with Einstein on epistemological problems in atomic physics. In: Schilpp, P.A. (ed.) Albert Einstein: Philosopher-Scientist, pp. 200–241. The Library of Living Philosophers, Evanston (1949), http://dx.doi.org/10.1016/S1876-05030870379-7, doi:10.1016/S1876-05030870379-7

[5] Cabello, A.: Experimentally testable state-independent quantum contextuality. Physical Review Letters 101(21), 210401 (2008), http://dx.doi.org/10.1103/PhysRevLett.101.210401, doi:10.1103/PhysRevLett.101.210401

[6] Cabello, A.: Proposal for revealing quantum nonlocality via local contextuality. Physical Review Letters 104, 220401 (2010), http://dx.doi.org/10.1103/PhysRevLett.104.220401, doi:10.1103/PhysRevLett.104.220401

[7] Cabello, A.: Quantum physics: Correlations without parts. Nature 474(7352), 456–458 (2011), http://dx.doi.org/10.1038/474456a, doi:10.1038/474456a

[8] Cabello, A., Cunha, M.T.: Proposal of a two-qutrit contextuality test free of the finite precision and compatibility loopholes. Physical Review Letters 106, 190401 (2011), http://dx.doi.org/10.1103/PhysRevLett.106.190401, doi:10.1103/PhysRevLett.106.190401

[9] Calude, C.S., Svozil, K.: Quantum randomness and value indefiniteness. Advanced Science Letters 1(2), 165–168 (2008), http://www.ingentaconnect.com/content/asp/asl/2008/00000001/00000002/art00004, doi:10.1166/asl.2008.016

[10] Einstein, A., Podolsky, B., Rosen, N.: Can quantum-mechanical description of physical reality be considered complete? Physical Review 47(10), 777–780 (1935), http://dx.doi.org/10.1103/PhysRev.47.777, doi:10.1103/PhysRev.47.777

[11] Halmos, P.R.: Finite-dimensional Vector Spaces. Springer, New York (1974)

[12] Hasegawa, Y., Loidl, R., Badurek, G., Baron, M., Rauch, H.: Quantum contextuality in a single-neutron optical experiment. Physical Review Letters 97(23), 230401 (2006), http://dx.doi.org/10.1103/PhysRevLett.97.230401, doi:10.1103/PhysRevLett.97.230401

[13] Kirchmair, G., Zähringer, F., Gerritsma, R., Kleinmann, M., Gühne, O., Cabello, A., Blatt, R., Roos, C.F.: State-independent experimental test of quantum contextuality. Nature 460, 494–497 (2009), http://dx.doi.org/10.1038/nature08172, doi:10.1038/nature08172

[14] Lapkiewicz, R., Li, P., Schaeff, C., Langford, N.K., Ramelow, S., Wieśniak, M., Zeilinger, A.: Experimental non-classicality of an indivisible quantum system. Nature 474, 490–493 (2011), http://dx.doi.org/10.1038/nature10119, doi:10.1038/nature10119

[15] Meyer, D.A.: Finite precision measurement nullifies the Kochen-Specker theorem. Physical Review Letters 83(19), 3751–3754 (1999), http://dx.doi.org/10.1103/PhysRevLett.83.3751, doi:10.1103/PhysRevLett.83.3751

[16] Peres, A.: Unperformed experiments have no results. American Journal of Physics 46, 745–747 (1978), http://dx.doi.org/10.1119/1.11393, doi:10.1119/1.11393

[17] Pitowsky, I.: Resolution of the Einstein-Podolsky-Rosen and Bell paradoxes. Physical Review Letters 48, 1299–1302 (1982), http://dx.doi.org/10.1103/PhysRevLett.48.1299, doi:10.1103/PhysRevLett.48.1299

[18] Pitowsky, I.: George Boole's 'conditions of possible experience' and the quantum puzzle. The British Journal for the Philosophy of Science 45, 95–125 (1994), http://dx.doi.org/10.1093/bjps/45.1.95, doi:10.1093/bjps/45.1.95

[19] Schrödinger, E.: The Interpretation of Quantum Mechanics. Dublin Seminars (1949-1955) and Other Unpublished Essays. Ox Bow Press, Woodbridge, Connecticut (1995)

[20] Stace, W.T.: The refutation of realism. In: Feigl, H., Sellars, W. (eds.) Readings in Philosophical Analysis, pp. 364–372. Appleton-Century-Crofts, New York (1949); previously published in Mind 53, 349–353 (1934)

[21] Svozil, K.: Quantum information via state partitions and the context translation principle. Journal of Modern Optics 51, 811–819 (2004), http://dx.doi.org/10.1080/09500340410001664179, doi:10.1080/09500340410001664179

[22] Svozil, K.: Are simultaneous Bell measurements possible? New Journal of Physics 8(39), 1–8 (2006), http://dx.doi.org/10.1088/1367-2630/8/3/039, doi:10.1088/1367-2630/8/3/039

[23] Svozil, K.: Proposed direct test of a certain type of noncontextuality in quantum mechanics. Physical Review A 80(4), 040102 (2009), http://dx.doi.org/10.1103/PhysRevA.80.040102, doi:10.1103/PhysRevA.80.040102
[24] Svozil, K.: Quantum value indefiniteness. Natural Computing online first, 1–12 (2010) ISSN 1567-7818, http://dx.doi.org/10.1007/s11047-010-9241-x, doi:10.1007/s11047-010-9241-x
[25] Zeilinger, A.: The message of the quantum. Nature 438, 743 (2005), http://dx.doi.org/10.1038/438743a, doi:10.1038/438743a