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The Quantum Measurement Problem

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Abstract: The quantum measurement problem is the most fundamental question of all: How the ghostly quantum mechanical coexistence of many mutually incompatible possibilities result in the concrete reality of the normal world, even though we and our measuring instruments are all made of atoms obeying quantum mechanics. In this brief article we lay down the criteria for such a mechanism.

Keywords: Quantum measurement problem; nonlinearity; nonlocality

In quantum mechanics the act of measurement is postulated to be an irreversible [1], non-invertible transition [2], instantly and discontinuously transforming a superposition of (potentially infinitely) many coexisting quantum states, *i.e.* indefinite and mutually contradictory possibilities, into one single objective experimental result: a multitude of mere possibility turning into actual fact. Each individual outcome is furthermore supposed to occur completely randomly, and it is *only* here that uncertainty enters quantum mechanics - in stark contrast its normal evolution is completely smooth: linear, deterministic[1], continuous and unitary, preserving superpositions indefinitely.

In the orthodox Copenhagen interpretation of quantum mechanics the measurement thus clearly has the character of "and then a miracle happens" - there is no physical mechanism for it at all, and Bohr even argued that it is futile to search for one [1]. Furthermore, the classical world is a necessary additional assumption (the primary unanalyzable reality

[1] Starting with wavefunction $\psi(x,t)$ the Schrödinger equation can be integrated backwards in time recovering $\psi(x,0)$. For nonlinear deterministic chaos this is impossible as there is no analytical solution and numerical integration introduces errors that grow exponentially ("exponential loss of memory").

of ordinary experience) and not a derived concept[2]. Both the quantum mechanical and classical level (in terms of measuring devices and observers) are independently required. The Copenhagen interpretation does not solve the quantum measurement problem but merely conceals it. This was probably the right strategy at the outset but now, almost 100 years later, a real physical explanation should be sought.

From what we today know about nature the measurement process must be:

- *Nonlinear* - No amount of linear "decoherence" [3] (phase randomization), neither internal nor environmental, can ever explain the disappearance of coexisting quantum possibilies [4], [5] as everything, including measuring instruments and observers, consists of quantum entities. This is demonstrated very nicely and transparently in *e.g.* [6]. No matter how large a mathematically linear system is it cannot magically turn nonlinear all by itself - that too amounts to "miracle", not physics. In any purely linear quantum model the superpositions persist indefinitely, obeying unitary evolution. And through an infinite-regress of ever larger superpositions of subsystems, the "von Neumann-chain", this inexorably leads to the conclusion that in a linear model *nothing ever can be measured* (!)[3] [8], or to a many-worlds picture [9] but apart from it being both untestable and devoid of scientific predictability (as anything that is not absolutely forbidden is guaranteed to happen in some of the co-existing, linearly superposed, parallel worlds) even for the many-worlds the actual branching points are the equivalent of the normal measurement problem and remains unexplained (*e.g.* how do probabilities, the "Born rule", arise for the different worlds? In orthodox quantum mechanics this only happens as a result of non-unitary nonlinear measurement *collapse*).

  An additional, separate reason for nonlinearity is that our "normal" world in general is nonlinear, often chaotic, but quantum mechanics is not [10][4]. And only nonlinear equations can support chaos[5]. And the obvious place to put it in quantum mechanics

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[2] Even apart from the fundamental persistence of linear superpositions in the absence of measurement, the "correspondence principle" is for example not true in general (neither for $\hbar \to 0$, nor for large quantum numbers $n \to \infty$) but only for regular/"orderly" classical systems.

[3] Wigner [7], and also von Neumann [2], argues that the nonlinear collapse, finally allowing definite outcomes to be realized, happens when the consciousness of the observer (somehow) terminates the von Neumann-chain of ever larger linear superpositions. However, where and how does consciousness first enter in the hierarchy of life (human/cat/cockroach/amoeba/...)? The problem is then just replaced by an even trickier one.

[4] "Quantum Chaos" concerns only how the (non-chaotic) quantum system is affected if its classical analog is chaotic. We are here interested in exactly the opposite question: How can fundamental microscopic theory give rise to chaos in our "normal" classical world of everyday phenomena *at all*?

[5] To obtain N bits of information regarding its future dynamics a chaotic system requires $\sim N$ bits of input information, a linear system only $\sim logN$.

is in the measuring process: Apart from explaining how the classical world can be chaotic at all, a nonlinear measuring mechanism could be the source of the apparent randomness in quantum mechanics. A quantitative physical mechanism would also be amenable to experimental tests, which is not the case for the “miracle" of measurement collapse in orthodox (Copenhagen) quantum mechanics which is *postulated* to be fundamentally random.

- *Nonlocal* - Required by Bell’s theorem [11] and its numerous experimental tests [12–15] showing correlation of space-like separated events.

One specific crude prototype of this sort has long existed: the de Broglie-Bohm pilot-wave theory [16], [17]. In it particles objectively are particles all the time, not only during measurement. It is deterministic, but the pilot-wave guiding the particle trajectories reproduces the apparently “random" character of quantum measurements due to the particles separately postulated dynamics. It is nonlocal, as the pilot-wave is global and reacts instantaneously to changes, such as measurements, alterations to experimental setup while entangled particles are “in-flight" [13], etc. However, as it, by construction, reproduces the predictions of orthodox quantum mechanics (albeit without measurement collapse) it is not really testable in the usual empirical sense.

A more natural and automatic path, not requiring additional structure, is to utilize nonlinear instabilities already present in fundamental interactions [18]. (There are also other suggestions too numerous to mention in this short note.)

In any case, a quantum measurement mechanism should be amenable to normal scientific methods of testing, *e.g.* is it instantaneous, and if not, what is its spatiotemporal dynamics and how is it reconciled with Bell’s theorem, etc. This should be done for individual events, including space-like correlated ones, and not only for expectation values as they tend to conceal many of the relevant points due to their merely statistical average nature.

Finally, any real solution to the quantum measurement problem should not be allowed to dodge the real issues with “and then a miracle happens".

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