The measurement problem in QM:
two comments and a possible solution

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Abstract: The identification of ‘measurement’ in QM as a human action is a source of profound confusion. We propose a solution to the measurement problem based on a reconsideration of the nature of particles.

March 26, 2019

1 Measurement is not just by humans

John Bell, in his article ‘Against Measurement’ [1], was right to deplore the way the way the word ‘measurement’ is applied in physics. But he did not stress the way in which the common application of the word makes it impossible to disassociate from human agency a natural process that has been occurring since long before the appearance of humans.

Consider an experiment that might be performed in the absence of gravity, on the ISS perhaps. A nucleus of $^{238}\text{U}$ is somehow levitated alone at the center of a sphere the inner surface of which can detect swift charged particles: leaving a spot. After a wait, the nucleus will undergo $\alpha$ decay. This can be described in terms of an S-wave ($l = 0$) representing an entangled pair, a nucleus of $^{4}\text{He}$ and a recoiling nucleus of $^{234}\text{Th}$. Eventually, a spot will appear on the detecting surface as the alpha particle hits it. It can then be predicted with certainty that a spot will very soon appear on the exact opposite location on the detecting surface. The second spot records the arrival of the thorium nucleus. This whole process places a natural event in a very artificial setup, but it is, in essence, something that occurs everywhere and all the time. It is not insignificant since, as Feynman has noted [2], it makes history strictly unpredictable. But what occurs in this staged situation involves the essence of what is called ‘measurement’ in the context of quantum mechanics. Somehow, the transformation of an S-wave (more strictly, something described by an S-wave) into a spot (strictly, a highly localized region where a detecting surface has changed its physical nature), a process sometimes called an ‘expansion into the macroscopic world’, has taken place. There has not been a human measurer in sight. Yet, we commonly read, in defence of Qbism, for example, that measurement can be understood in terms of the change in the understanding of a human observer. This is a measure of the extent that ‘measure’ has become entangled with measuring by humans.

Of course, someone is going to argue that the spots only appear much later when a person inspects the detecting surface of the sphere. Such a someone is also obliged, of course, to claim that the pleochroic haloes, which are found [3] surrounding uranium- or thorium-bearing inclusions in mica, only occur when the mica is examined in the...
laboratory. The haloes of course, are literally as old as the hills. Arguably, then, the situation deplored by Bell might be considered even worse. It is surely time that discussions of measurement in quantum mechanics should treat all situations that involve the process that is commonly described as the collapse of the wave packet, or expansion into the macroscopic domain. Most such situations involve no human activity. Whatever the deeper ontology that might eventually emerge, the idea of a wave packet collapsing does, after all, seem a fair way of characterizing the transformation of something represented by an entangled S-wave, of $4\pi$ angular reach, into something characterized by two spots on precisely opposite sides of a spherical detecting surface.

Arguably, we need a new word to replace ‘measurement’. Perhaps ‘actualization’ or ‘actualize’ would indicate something that the system does rather than something a person does, as is suggested by ‘measurement’.

2 Two slits or one?

We now argue that Einstein’s 1927 single hole experiment gets closer to the central mysteries of quantum mechanics than Feynman’s two slits. Richard Feynman famously declared that all the mysteries of quantum mechanics are exposed in the two slit experiment. In introducing the two slit experiment, he said: ‘I will take just this one experiment, which has been designed to contain all the mysteries of quantum mechanics, to put you up against the paradoxes and mysteries and peculiarities of nature one hundred percent.’ [4]. He went on to say: ‘Any other situation in nature, it turns out, can always be explained by saying “remember the case of the experiment with the two holes? It’s the same thing.” ’ [4] He pointed out that the electrons or photons behave as waves in that they give rise to a diffraction pattern, and as particles when they each arrive at a single spot on the detecting screen; in his words: ‘Electrons behave in this respect in exactly the same way as photons; they are both screwy, but in exactly the same way.’ [5] We can agree with that, but the unique role of the two slit experiment can be questioned.

Many didactic accounts of quantum mechanics introduce the same two slit example, and it is certainly true that it is a fine illustration of a key quantum property, the superposition of amplitudes and the need to add amplitudes before squaring. It also leads to a discussion of wave particle duality. According to the standard Copenhagen interpretation, attributed to Bohr (but widely applied in a form due more to Heisenberg [6]), wave-like and particle-like properties are complementary, so the two slit experiment exemplifies this. If you ask where a single electron or photon arrives, you get a particle-like answer: at a single place. But the distribution of places of individual electrons or photons is wave-like: the two-slit diffraction pattern, effectively an interference pattern corresponding to interference between the amplitudes for going through one slit or the other.

But is it really true that the two slit problem contains ‘... all the mysteries of quantum mechanics ...’? Electrons, photons, or Bucky balls for that matter, are still described by a wave function or wave packet even if one slit is closed. So, is one slit diffraction
just as good an exemplar of complementarity? Students should be encouraged to do thought experiments, and one by Galileo is inspirational. Two separate falling balls would not, if joined together, fall faster as a result. A faster drop would be in accord with Aristotelian physics in which heavier objects fall faster. Imagine then moving the two slits, step by step, closer together: the diffraction pattern will change continuously as the slits approach each other. Eventually, they will become a single slit, and there will be a single slit diffraction pattern in which particles appear according to the laws of single slit (or single hole) diffraction. But nothing deep has changed. Those who like Bohr’s complementarity can still have it. There are still particles (appearing) and still waves (determining their distribution). The single slit, or hole, experiment was actually done in 1910 by Taylor [7] with very low intensity light; the diffraction pattern appeared, spot by spot, with light of an intensity that we can now interpret as ‘one photon at a time’.

In fact, it was the single slit (or single hole) case that was the basis of Einstein’s declaration in 1927, see Ref. [8] p 195, that quantum mechanics is incomplete; unless, that is, some interpretation like that of de Broglie (later the de Broglie Bohm (dBB) theory) was applied. When de Broglie’s interpretation dipped out of fashion, Einstein persisted in his belief in the incompleteness of quantum mechanics. Thus EPR [9] devised their famous argument, involving two particles, to demonstrate this incompleteness. As we all know, Bell [10] later showed that their model implied just what Einstein most abhorred: non-locality. Ironically, for two particles the later dBB theory is also highly non-local, and is therefore very problematical as a salvation for Einstein’s 1927 example. Thus, it is single slit diffraction that most directly exhibits the deepest mysteries of QM pace Feynman: non-locality and (at least apparent) wave function collapse. Regarding collapse, whatever your ontology of the wave packet, the wave packet for the single particle leaving the slit or hole no longer exists after the spot appears on the screen. That applies to both ‘wave packet’ in the logical category of elements of a formalism, or in the category of whatever physical entities are described by that formalism.

Notwithstanding the above, the two slit experiment is valuable for teaching the superposition principle. In fact, as Jammer points out [11], the double slit initially appeared to be a stumbling block for Born’s interpretation. Evidently, the above thought experiment was not considered.

Finally, another quote from Feynman: ‘A philosopher once said “It is necessary for the very existence of science that the same conditions always produce the same result”. Well, they do not.’ [12]. Even here there is a qualification: if many people do the same diffraction experiment, with the same hole, the same screen, with particles having the same mass and energy, they would get (with many particles) the same diffraction pattern. There is a case to say that this qualifies as realism, but a realism of quantum entities, propensities. So maybe the serious question now is ‘How identical are identically prepared states?’
3 A proposed solution to the measurement problem

To some, calling a photon a particle seems odd, on the grounds that it seems nothing like an electron, which all agree is a particle. The position coordinates of an electron appear in Schrödinger's equation while those of a photon do not appear in Maxwell's equation. Moreover, an electron appears to have a definite location in its rest frame, even if this position is indeterminate in line with the uncertainty principle; a photon has no rest frame in which to have a definite position. Perhaps this fact eases the conscience of neo-Bohmians who point to the evident particleness of electrons etc. in the dBB picture, and declare this to be a strength of the dBB picture. At the same time, it makes the inability of dBB to treat photons in the way its treats electrons a real problem.

But there is a perspective from which electrons and photons do share the essence of particleness. I refer to the perspective in which a particle is exactly an entity that declares one place (within the resolution of the measurer) when we ask where it is. Photons and electrons share this property; it’s part of their being ‘screwy in exactly the same way’ as Feynman said. This frees photons and W and Z bosons the indignity of being in entirely different ontological categories. From this perspective, the collapse of the wave function in a position measurement is a key aspect of the nature of a particle, suggesting that collapsability is a key defining property of particles rather than of the theory that governs their behaviour. The theory that governs their behaviour up to the point where the wave packet meets a detecting screen or a silicon detector is standard quantum mechanics. Following the first interaction, the subsequent motion is as explained by Mott [13] long ago. In the case of alpha decay of $^{238}\text{U}$, the alpha particle will most probably have a well defined momentum when the other particle, that is entangled with it in an S-wave, i.e. the remaining mass $^{234}\text{Th}$ nucleus, interacts with its crystal lattice.

Is an alpha particle a ‘particle’ in the above sense? Yes. It certainly leaves a single spot on a detecting screen etc. Within any composite particle made of fermions, such as an alpha particle, the individual fermions are strongly entangled. The simplest possible structure will be a Slater determinant. A two fermion particle will therefore have a structure at least as complex as that historic entangled system: the two electrons in the helium atom. Apparently this was one thing that made the quantum pioneers aware of the essence of entanglement long before Schrödinger introduced the word now translated as ‘entanglement’. The characteristic of an entangled state is that the individual particles do not have a complete independent set of properties. We conclude that a composite particle acts as a unit, with a non-local cooperative response. The collapse of the wave packet of a propagating alpha particle is, in this light, no more surprising than electrons or photons leaving spots, or the non-local collapse of an entangled pair in an EPR experiment.

An important consequence of this characterization of particleness follows if, as has been proposed, any measurement is in essence a position measurement; this is certainly the case for a spin measurement in a Stern-Gerlach experiment. If this is generally true, then the collapse at the core of the measurement problem is not a wave function collapse...
but simply a consequence of the defining property, as proposed here, of a particle.

This proposed characterization of ‘particle’ supports a realistic interpretation in which probabilities amount to propensities of the particles to appear in accordance with the Born postulate. This makes the concept of ‘identically prepared states’ a key element of QM. In fact, a basic postulate often introduced is the supposition that a second measurement of some observable immediately after a first measurement leads to the same result. This suggests that it is reasonable to believe that truly identically prepared states are practical. It seems likely that if the general uncertainty principle, GUP, as derived by Robertson [14] had appeared before Heisenberg’s heuristic argument, in which the actions of a ‘measurer’ are implicitly present, the subsequent history of the interpretation of QM would have been quite different. At the heart of the GUP are objective uncertainties which are defined in terms of expectation values. These latter can be calculated in a simple way from the theory, but, more importantly they could be measured in a mechanized way without intervention of a human measurer as part of the measurement itself. That is, unless the designer of the equipment, which we suppose general enough to apply in a variety of cases, can be considered a measurer. But it seems un-natural to consider this mechanical proxy as disturbing the system in the Heisenberg sense. Of course, the key enabling concept behind expectation values is that of identically prepared states, something that does not appear to be sufficiently stressed in didactic works.

In summary: the licence for non-locality, granted by the EPR experiments that were inspired by Bell’s inequalities, together with the status of position measurements, permit a simple interpretation of ‘measurement’ in terms of a defining property of ‘particle’, a definition that applies to photons, electrons, nuclei, and (to date) quite large molecules. The particle-ness of the decay product in Schrödinger’s famous thought experiment leads to a macroscopic event long before the feline joins the experiment. Wigner’s friend would have a more pleasant reporting job if Mott’s cloud chamber were employed rather than Schrödinger’s fiendish device: cloud chambers are not usually considered to be in a superposition of ‘with track’ and ‘without track’.

In the words of John Bell [15]: ‘It may be that what we need is just some small change in the point of view, and everything will fall into a coherent whole, but it is extremely frustrating and also extremely interesting that we have not yet found this slight change in perspective.’

References

[1] J.S. Bell, Physics World, 3, 33 (1990); Speakable and Unspeakable in Quantum Mechanics, 2nd edition, (Cambridge University Press, Cambridge, 2004), p 213.

[2] R.P. Feynman, The Character of Physical Law, (Penguin Books, London, 1992), p. 147.

[3] J. Joly, Phil. Mag. 19, 327 (1910); Phil. Trans. Roy. Soc., London Ser. A 217, 51 (1917).
[4] R.P. Feynman *The Character of physical law*, (Penguin Books, London, 1992), p. 130.

[5] R.P. Feynman *The Character of physical law*, (Penguin Books, London, 1992), p. 128.

[6] Don Howard, Philosophy of Science 71, 669 (2004).

[7] G.I. Taylor, Proc. Camb. Phil. Soc. 15, 114 (1909).

[8] G. Bacciagaluppi and A. Valentini *Quantum Theory at the Crossroads* (Cambridge University Press, Cambridge, 2009), p 175.

[9] A. Einstein, N. Rosen, and B. Podolsky, Phys. Rev. 47, 777 (1935).

[10] J.S. Bell, Physics 1, 195 (1964).

[11] M. Jammer *The Philosophy of Quantum Mechanics*, (John Wiley, New York, 1974), pp 43 - 44.

[12] R.P. Feynman *The Character of physical law*, (Penguin Books, London, 1992), p. 147.

[13] N.F. Mott, Proc. Roy. Soc. A 118, 542 (1928).

[14] H.P. Robertson, Phys. Rev. 34, 163 (1929).

[15] J.S. Bell, Video discussion for Open University quantum mechanics ccourse, SM355, (1986).