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Consistent quantum measurements

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ABSTRACT

In response to recent criticisms by Okon and Sudarsky, various aspects of the consistent histories (CH) resolution of the quantum measurement problem(s) are discussed using a simple Stern-Gerlach device, and compared with the alternative approaches to the measurement problem provided by spontaneous localization (GRW), Bohmian mechanics, many worlds, and standard (textbook) quantum mechanics. Among these CH is unique in solving the second measurement problem: inferring from the measurement outcome a property of the measured system at a time before the measurement took place, as is done routinely by experimental physicists. The main respect in which CH differs from other quantum interpretations is in allowing multiple stochastic descriptions of a given measurement situation, from which one (or more) can be selected on the basis of its utility. This requires abandoning a principle (termed unicity), central to classical physics, that at any instant of time there is only a single correct description of the world.

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1. Introduction

The immediate motivation for this paper comes from criticisms by Okon and Sudarsky (2014), recently published in this journal, of the *consistent histories* (CH) interpretation of quantum mechanics. These authors claim that CH does not provide a satisfactory resolution of the quantum measurement problem. Such criticism deserves to be taken seriously, for the CH approach claims to resolve *all* the standard problems of quantum interpretation which form the bread and butter of quantum foundations research: it is local (Griffiths, 2011), so there are no conflicts with special relativity; it is noncontextual (Griffiths, 2013b), in contrast to hidden variable interpretations; it resolves the EPR, BKS, Hardy, three boxes, etc., etc. paradoxes, see of Griffiths (2002, chaps. 19–25). And while it may be defective, its (purported) solutions to the full gamut of quantum conceptual difficulties have been published in detail and are available right now for critical inspection, not just as promissory notes for some future time. Thus the Okon and Sudarsky criticisms, while based (we believe) on an imperfect understanding of the CH approach, are dealing with important issues that need to be discussed.

Of particular significance is the fact that the CH approach does *not* include *any* reference to measurements among its basic principles for interpreting quantum mechanics. Measurements are simply treated as a particular type of physical process to which the same quantum principles apply as to any other physical process. When understood in this way quantum mechanics no longer has a *measurement problem* as that term is generally used in quantum foundations: a conflict between unitary time development of a combined system plus measuring device and a macroscopic outcome or “pointer position.” Not only so, in addition CH shows how the outcome of a measurement can be shown to reveal the presence of a microscopic quantum property possessed by the measured system just *before* the measurement took place, in accordance with the belief, common among experimental physicists, that the apparatus they have built performs the function for which it was constructed. This *second* measurement problem has received far too little attention in the quantum foundations literature, and resolving it is no less important than the first problem if the entire measuring process is to be understood in fully quantum-mechanical terms.

Rather than an abstract discussion, the present paper examines a particular measurement scenario, using it as an example of the application of CH principles, and also a basis for comparison with some other interpretations of quantum mechanics mentioned in Okon and Sudarsky (2014). These include the *spontaneous localization* approach developed by Ghirardi et al. and Pearle, see Ghirardi, Rimini, and Weber (1985, 1986), Pearle (1989), Frigg (2009), and Ghirardi (2011), often abbreviated as GRW (the initials of the

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authors of Ghirardi et al., 1985), and the pilot wave approach of de Broglie and Bohm, which we shall refer to as *Bohmian mechanics* (Bohm, 1952; de Broglie, 1927; Holland, 1993; Goldstein, 2012). Textbook or *standard quantum mechanics* and the *many worlds* interpretation of Everett and his successors, Everett (1957), DeWitt and Graham (1973), and Saunders, Barrett, Kent, and Wallace (2010) also enter the discussion from time to time. Since details of the CH approach are readily available in the literature, e.g., Griffiths (2002, 2009, 2013, 2014a,b) and Hartle (2011), only those aspects needed to make the discussion reasonably self-contained are included in this paper.

Our aim is to present and discuss as clearly as possible the central features of the CH approach that have given rise to the criticisms in Okon and Sudarsky (2014), and which are undoubtedly shared by other critics, e.g., Kent (1998), Bassi and Ghirardi (2000), Pearle (2005), and Mermin (2013). Of particular importance is the fact that CH abandons a principle, here called *unicity*, which is deeply embedded in both conventional and scientific thought, and is taken for granted in classical physics. It is the idea that at any instant of time there is precisely one exact description of the state of the world which is true. If the CH understanding is correct, quantum mechanics has made unicity obsolete in somewhat the same way as modern astronomy has replaced an unmovable earth at the center of the universe with our current understanding of the solar system, and ignoring this feature of the quantum world is what has given rise to so many conceptual difficulties.

The contents of the remainder of the paper are as follows. The measurement problem(s) of quantum foundations are discussed in general terms in Section 2, followed in Section 3 by a specific measurement model, a modernized version of the famous experiment of Stern and Gerlach (Stern, 1921; Gerlach & Stern, 1922). Its description in CH terms begins in Section 4 with a discussion of the first measurement problem, whose solution is compared with some other approaches in Section 4.2. The CH solution to the second measurement problem is the subject of Section 5, and it is compared with standard quantum mechanics, spontaneous localization, many worlds, and Bohmian mechanics in Section 6. Our response to the specific criticisms of Okon and Sudarsky occupies (Section 7). Section 8 is a brief summary of the whole paper.

2. The quantum measurement problem

Physics is an experimental science, and measurements and observations play a central role in testing the empirical contents of its theories. This was also the case before the quantum revolution of the twentieth century, and yet classical physics had no measurement problem. Why, then, is the measurement problem considered *the* central issue in quantum foundations, the one that must be resolved if progress is to be made in this field? The essence of the measurement problem is easy to state. If quantum mechanics applies not only to the microscopic world of nuclei and atoms, but also to macroscopic objects and things that are even larger—from the quarks to the quasars—then the measurement process in which an earlier microscopic property is revealed in a macroscopic outcome should itself be describable, at least in principle, in fully *quantum mechanical* terms. Applied equally to the system being measured and to the macroscopic apparatus, and without the evasion and equivocation ridiculed by Bell (1990). It is indeed a scandal that the quantum physics community has not been able to agree on a solution to this problem. Would not the stories told by modern cosmologists be dismissed as pure fantasy if astronomers did not understand the operation of their telescopes?

It is useful to separate the general quantum measurement problem into two parts. The better known *first* measurement problem arises when the initial state of the measured system—hereafter for convenience thought of as a particle—is such that the unitary time development resulting from coupling it to a measurement apparatus results in a superposition of two or more states in which the apparatus pointer (in the archaic but picturesque language of quantum foundations) points in different directions. How is this "Schrödinger cat" to be interpreted, given that in the laboratory the pointer always points in a definite direction? The *second* measurement problem is to explain how the actual (single) pointer direction is related to the property of the particle the apparatus was designed to measure, at a time *before* the measurement took place? Unfortunately, many textbooks speak of a "measurement" not as revealing a pre-existing property, but as a correlation between the pointer and the particle *after* the measurement has taken place. The latter should be called a *preparation* rather than a measurement; for a discussion of this from the CH perspective see Section 3.5 of Griffiths (2014a) and Section 7.3 of Griffiths (2014b).

It is perhaps worth mentioning that in textbooks *probabilities* are introduced in connection with measurements, and not as a separate topic. As a consequence the perplexities associated with an unresolved measurement problem are transferred to an inconsistent discussion of probabilities. Thus cleaning up the quantum measurement problem is intimately connected with introducing probabilities in quantum mechanics in a consistent way, not associated with measurements, something which is not present in any textbook of which we are aware.

3. Stern Gerlach spin measurement

3.1. Description

Fig. 1 is a schematic diagram of a Stern Gerlach device to measure the spin of a spin-half particle. The particle arrives from the left and its initial state at time t_0 is $|\omega_0\rangle \otimes |\chi_0\rangle$, where $|\omega_0\rangle$ refers to its position, corresponding to a wavepacket $\omega_0(\mathbf{r}) = \langle \mathbf{r}|\omega_0\rangle$, and $|\chi_0\rangle$ denotes the spin, with $|z^+\rangle$ and $|z^-\rangle$ being the eigenstates of S_z. The unitary time development of the particle state at successive times $t_0 < t_1 < t_2$ as it passes through the magnetic field gradient is given by

$$|\omega_0\rangle \otimes |z^+\rangle \to |\omega_1\rangle \otimes |z^+\rangle \to |\omega_2^a\rangle \otimes |z^+\rangle; \quad |\omega_0\rangle \otimes |z^-\rangle \to |\omega_1\rangle \otimes |z^-\rangle \to |\omega_2^b\rangle \otimes |z^-\rangle, \tag{1}$$

where $|\omega_j\rangle$ gives the (approximate) location of the particle at time t_j. The trajectories of a particle with $S_z = +1/2$ and one with $S_z = -1/2$ are initially identical, but at time t_2 there is a small but macroscopic separation between the wave packet $\omega_2^a(\mathbf{r})$, the particle moving upwards towards detector D^a, and $\omega_2^b(\mathbf{r})$, the particle moving downwards towards detector D^b. By time t_3 the detector D^a will have triggered if the particle had $S_z = +1/2$, and D^b if the particle had $S_z = -1/2$. We assume that these detectors are capable of detecting individual atoms, as is possible nowadays by first ionizing the atom and then using an electron multiplier to convert the emerging electron into a macroscopic current pulse.

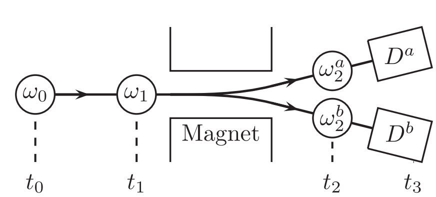

Fig. 1. Stern Gerlach apparatus for measuring spin half.