Chapter 9

On the Nature of Measurement Records in Relativistic Quantum Field Theory

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Abstract. *A resolution of the quantum measurement problem would require one to explain how it is that we end up with determinate records at the end of our measurements. Metaphysical commitments typically do real work in such an explanation. Indeed, one should not be satisfied with one's metaphysical commitments unless one can provide some account of determinate measurement records. I will explain some of the problems in getting determinate records in relativistic quantum field theory and pay particular attention to the relationship between the measurement problem and a generalized version of Malament's theorem.*

9.1 Introduction

Does relativistic quantum field theory tell us that the world is made of fields or particles or something else? One difficulty in answering this is that physical theories typically do not pin down a single preferred ontology. This can be seen in classical mechanics where we are some 350 years on, and we have nothing like a canonical metaphysics for the theory. Are the fundamental entities of classical mechanics point particles or are they extended objects? Does the theory tell us that there is an absolute substantival space or are positions only relative to other objects? Of course, part of the problem here is that it is not entirely clear what classical mechanics is. But even if one does the reconstruction work that it would take to get a sharp formal theory, one can always provide alternative metaphysical interpretations. This can be seen as an aspect of a general underdetermination problem: not only are physical theories typically underdetermined by empirical evidence, but one's ontological commitments are typically underdetermined by the physical theory one adopts.

If our physical theories are in fact always subject to interpretation, then one might take the debate over the proper ontology of relativistic quantum field theory to be futile. While there is something right in this reaction, metaphysical considerations have in the past proven important to understanding and to clearly formulating physical theories, and we could certainly use all the clarity we can get in finding a satisfactory formulation of relativistic quantum field theory. If one could cook up a satisfactory ontology for some formulation of relativistic quantum field theory, then it would mean that that formulation of the theory could be understood as descriptive of the physical world, and in the context of relativistic quantum field theory, this would be something new. What is required here is not just showing that the particular theory is logically consistent by providing a model; what we want is to show that the theory could be descriptive of *our* physical world.

One of the features of our world is that we have determinate measurement records. We perform experiments, record the results, then compare these results against the predictions of our physical theories. Measurement records then should somehow show up in the ontology that we associate with our best physical theory. Indeed, if not for the existence of such records, it would be difficult to account for the possibility of empirical science all.

I mention this aspect of our world because the existence of determinate records is something that is difficult to get in nonrelativistic quantum mechanics and more difficult to get in relativistic quantum mechanics. The problem of getting determinate measurement records is the quantum measurement problem.

Metaphysics typically does real work in solutions to the quantum measurement problem by providing the raw material for explaining how it is that we have determinate measurement records. We see this in solutions to the quantum measurement problem in nonrelativistic quantum mechanics. In Bohm's theory it is the always determinate particle positions that provide determinate measurement records. In many-world interpretations it is the determinate facts in the world inhabited by a particular observer that determines the content of that observer's records.

The point here is just that in quantum mechanics one's metaphysical commitments must be sensitive to how one goes about solving the measurement problem. Indeed, it seems to me that no metaphysics for relativistic quantum field theory can be considered satisfactory unless determinate measurement records somehow show up in one's description of the world. Put another way, one must have a solution to the quantum measurement problem before one can trust any specific interpretation of relativistic quantum field theory.

9.2 The Measurement Problem

The measurement problem arises in nonrelativistic quantum mechanics when one tries to explain how it is that we get determinate measurement records. If the deterministic unitary dynamics (the time-dependent Schrödinger equation in nonrelativistic quantum mechanics) described all physical interactions, then a measurement would typically result in an entangled superposition of one's measuring apparatus recording mutually contradictory outcomes. If one has a good measuring apparatus that starts ready to make a measurement, the linear dynamics predicts one would typically end up with something like:

$$\sum a_i |p_i\rangle_S \, |\text{“}p_i\text{”}\rangle_M \tag{9.1}$$

This is a state where (the measured system S having property p_1 and the measuring apparatus M recording that the measured system has property p_1) is superposed with (the measured system S having property p_2 and the measuring apparatus M recording that the measured system has property p_2) etc. And this clearly does not describe the measuring apparatus M as recording any particular determinate measurement record.[1]

This indeterminacy problem is solved on the standard von Neumann-Dirac formulation of nonrelativistic quantum mechanics by stipulating that the state of the measured system randomly collapses to an eigenstate of the observable being measured whenever one makes a measurement, where the probability of collapse to the state $|p_k\rangle_S \, |\text{“}p_k\text{”}\rangle_M$ is $|a_k|^2$. It is this collapse of the state that generates a determinate measurement record ($|p_k\rangle_S \, |\text{“}p_k\text{”}\rangle_M$ is a state

where S determinately has property p_k and M determinately records that S has property p_k). But it is notoriously difficult to provide an account of how and when collapses occur that does not look blatantly ad hoc and

[1]See Barrett (1999) for a detailed account of what it means to have a good measuring device and why it would necessarily end up in this sort of entangled state.

even harder to provide and account that is consistent with the demands of relativity.[2]

If there is no collapse of the quantum mechanical state on measurement, then one might try adding something to the usual quantum-mechanical state that represents the values of the determinate physical records. This so-called hidden variable would determine the value of one's determinate measurement record even when the usual quantum-mechanical state represents an entangled superposition of incompatible records. But it has proven difficult to describe the evolution of this extra component of the physical state in a way that is compatible with relativity.[3]

It is orthodox dogma that it is only possible to reconcile quantum mechanics and relativity in the context of a quantum field theory, where the fundamental entities are fields rather than particles.[4] While there may be other reasons for believing that we need a field theory in order to reconcile quantum mechanics and relativity (and we will consider one of these shortly), relativistic quantum field theory does nothing to solve the quantum measurement problem and it is easy to see why.

In relativistic quantum field theory one starts by adopting an appropriate relativistic generalization of the nonrelativistic unitary dynamics. The relativistic dynamics describes the relations that must hold between quantum-mechanical field states in neighboring space-time regions. By knowing how the field states in different space-time regions are related, one can then make statistical predictions concerning expected correlations between measurements performed on the various field quantities. But relativistic quantum field theory provides no account whatsoever for how determinate measurement records might be generated.

The problem here is analogous to the problem that arises in nonrelativistic quantum mechanics. If the possible determinate measurement records are supposed to be represented by the elements of some set of orthogonal field configurations, then there typically are no determinate measurement

[2]For two related attempts to get a collapse theory that satisfies the demands of relativity see Aharonov and Albert (1980) and Fleming (1988 and 1996).

[3]Much of the literature on this topic is concerned with either trying to find a version of Bohm's theory that is compatible with relativity or trying to explain why strict compatibility between the two theories is not really necessary. See Barrett (2000) for a discussion of Bohm's theory and relativity.

[4]This is the position expressed, for example, by Steven Weinberg (1987, 78–9). See also David Malament (1996, 1–9)

records since (given the relativistic unitary dynamics) the state of the field in a given space-time region will typically be an entangled superposition of different elements of the orthogonal set of field configurations. An appropriate collapse of the field would generate a determinate local field configuration which might in turn represent a determinate measurement result, but such an evolution of the state would violate the relativistic unitary dynamics. And, as it is usually presented, relativistic quantum field theory has nothing to say about the conditions under which a such a collapse might occur, nor does it have anything to say about how such an evolution might be made compatible with relativity. One might try adding a new physical parameter to the usual quantum mechanical state that represents the values of one's determinate measurement records. But relativistic quantum field theory has nothing to say about how to do this or about how one might then give a relativity-compatible dynamics for the new physical parameter.[5]

So relativistic quantum field theory does nothing to solve the quantum measurement problem. Indeed, because of the additional relativistic constraints, accounting for determinate measurement records is more difficult than ever.

In what follows, I will explain another sense in which the metaphysics of relativistic quantum mechanics must be sensitive to measurement considerations and why we are far from having a clear account of measurement in relativistic quantum mechanics.

9.3 Malament's Theorem

David Malament (1996) presented his local entities no-go theorem in defense of the dogma that a field ontology, not a particle ontology, is appropriate to relativistic quantum mechanics. The theorem follows from four apparently weak conditions that most physicists would expect to be satisfied by

[5]That one can predict statistical correlations between measurement results but cannot explain the determinate measurement results has led some (see Rovelli (1997) and Mermin (1998) for example), to conclude that relativistic quantum field theory (and quantum mechanics more generally) predicts statistical correlations without there being anything that is in fact statistically correlated—"correlations without correlata." The natural objection to this conclusion is that the very notion of there being statistical correlations between measurement records presumably requires that there be determinate measurement records.

the structure one would use to represent the state of a single particle in relativistic quantum mechanics. If these conditions are satisfied, then the theorem entails that the probability of finding the particle in any closed spatial region must be zero, and this presumably violates the assumption that there is a (detectable) particle at all. Malament thus concludes that a particle ontology is inappropriate for relativistic quantum mechanics.

A version of Malament's theorem can be proven that applies equally well to point particles or extended objects. I will describe this version of the theorem without proof.[6] The statement of the theorem below and its physical interpretation follows Malament (1996) with a few supporting comments.

Let M be Minkowski space-time, and let $\mathcal{H}$ be a Hilbert space where a ray in $\mathcal{H}$ represents the pure state of the object S. Let P_Δ be the projection operator on $\mathcal{H}$ that represents the proposition that the object S would be detected to be *entirely* within spatial set Δ if a detection experiment were performed. Relativistic quantum mechanics presumably requires one to satisfy at least the following four conditions.

(1) *Dynamics Translation Covariance Condition*: For all vectors a in M and for all spatial sets Δ

$$P_{\Delta+a} = U(a)P_\Delta U(-a) \tag{9.2}$$

where $a \mapsto U(a)$ is a strongly continuous, unitary representation in $\mathcal{H}$ of the translation group in M and $\Delta+a$ is the set that results from translating Δ by the vector a.

This condition stipulates that the dynamics is represented by a family of unitary operators. More specifically, it says that the projection operator that represents the proposition that the object would be detected within spatial region $\Delta + a$ can be obtained by a unitary transformation that depends only on a of the projection operator that represents the proposition that the object would be detected within region Δ. Note that if this condition is universally satisfied, then there can be no collapse of the quantum-mechanical state.

[6]The proof of this version of the theorem is essentially the same as the proof in Malament (1996). The only difference is the physical interpretation of P_Δ. Malament's theorem relies on a lemma by Borchers (1967).

(2) *Finite Energy Condition*: For all future-directed time-like vectors a in M, if $H(a)$ is the unique self-adjoint operator satisfying

$$U(ta) = \exp -itH(a), \tag{9.3}$$

then the spectrum of H(a) is bounded below.

$H(a)$ is the Hamiltonian of the system S. It represents the energy properties of the system and determines the unitary dynamics (by the relation above). Supposing that the spectrum of the Hamiltonian is bounded below amounts to supposing that S has a finite (energy) ground state.

(3) *Hyperplane Localizability Condition*: If Δ_1 and Δ_2 are disjoint spatial sets in the same hyperplane,

$$P_{\Delta_1}P_{\Delta_2} = P_{\Delta_2}P_{\Delta_1} = \mathbf{0} \tag{9.4}$$

where $\mathbf{0}$ is the zero operator on $\mathcal{H}$.

This condition is supposed to capture the intuition that a single object S cannot be entirely within any two disjoint regions at the same time (relative to any inertial frame). This is presumably part of what it would mean to say that there is *just one* spatially extended object.

(4) *General Locality Condition*: If Δ_1 and Δ_2 are any two disjoint spatial sets that are spacelike related (perhaps not on the same hyperplane!),

$$P_{\Delta_1}P_{\Delta_2} = P_{\Delta_2}P_{\Delta_1}. \tag{9.5}$$

Relativity together with what it means to be an object presumably requires that if an object were detected to be entirely within one spatial region, then since an object cannot travel faster than light, it could not also be detected to be entirely within a disjoint, space-like related region in any inertial frame. If this is right, then one would expect the following to hold

($\diamondsuit$) *Relativistic Object Condition*: For *any* two spacelike related spatial regions Δ_1 and Δ_2 (not just any two in the same hyperplane!)

$$P_{\Delta_1}P_{\Delta_2} = P_{\Delta_2}P_{\Delta_1} = \mathbf{0}. \tag{9.6}$$

Condition ($\diamondsuit$) is strictly stronger than the conjunction of conditions (3) and (4). The idea behind condition (4) is that even if it *were* possible to detect S to be entirely within two disjoint spacelike related spatial regions and if condition (3) were still satisfied (because the two detectors were in different inertial frames and Δ_1 and Δ_2 were consequently not in the same hyperplane), then the probability of detecting the object to be entirely within Δ_1 should at least be statistically independent of the probability of detecting it to be entirely within Δ_2. That is, proving the theorem from conditions (3) and (4) rather than the strictly stronger (but very plausible!) condition ($\Diamond$) allows for the possibility that particle detection in a particular space-time region might be hyperplane dependent. While this is certainly something that Malament would want to allow for (since he was responding to Fleming's hyperplane-dependent formulation of quantum mechanics), it is probably not a possibility that most physicists would worry about much. If this is right, then one might be perfectly happy replacing conditions (3) and (4) by condition ($\Diamond$).

The theorem is that if conditions (1)–(4) are satisfied (or conditions (1), (2), and ($\Diamond$)), then $P_\Delta = \mathbf{0}$ for all compact closed spatial sets Δ. This means that the only extended object possible (or, perhaps better, the only *detectable* extended object possible) is one with infinite extension. And this conclusion is taken to favor a field ontology. It may also have curious implications for the nature of one's measurement records in relativistic quantum mechanics. Or it may be that getting determinate measurement records in relativistic quantum mechanics requires one to violate one or more of the four conditions that make the theorem possible.

9.4 Measurement Records

In the broadest sense, a good measurement consists in correlating the state of a record with the physical property being measured. The goal is to produce a detectable, reliable, and stable record. It might be made in terms of ink marks on paper, the final position of the pointer on a measuring device, the bio-chemical state of an observer's brain, or the arrangement of megaliths on the Salisbury Plain; but whatever the medium, useful measurement records must be detectable (so that one can know the value of the record), reliable (so that one can correctly infer the value of the physical property that one wanted to measure), and stable (so that one can make reliable inferences concerning physical states at different times). Such measurement records provide the evidence on which empirical science is grounded.

Consider the following simple experiment where I test my one-handed typing skills. This experiment involves, as all do, making a measurement.

> The time it took me to type this sentence one-handed (because I am holding a stopwatch in the other hand) up to the following colon: **41.29 seconds**.

I am indeed a slow typist, but that is not the point. The point is that I measured then recorded how long it took me to type the above sentence fragment one-handed; and because I have a determinate, detectable, reliable, and stable record token, I know how long it took to type the sentence fragment, and you do too if you have interacted with the above token of the measurement record in an appropriate way.

Setting aside the question of exactly what it might mean for a measurement record to be reliable and stable, let's consider the detectability condition. For a record token to be detectable, it must presumably be the sort of thing one can find. And in order to be the sort of thing one can find, the presence or absence of a detectable record token R must presumably be something that can be represented in quantum mechanics as a projection operator on a finite spatial region. That is, there must be a projection operator R_Δ that represents the proposition that there is an R-record in region Δ. This is apparently just part of what it means for a record to be detectable in relativistic quantum mechanics.

Now consider the bold-faced typing-speed record token above. It is detectable. Not only can you find and read it, but you can find and read it in a finite time. If we rule out superluminal effects, then it seems that the *detected record token* must occupy a finite spatial region. Call this spatial region S. Given the way that observables are represented in relativistic quantum mechanics, this means that there must be a projection operator R_S that represents the proposition that there is a token of the **41.29 seconds** record in region S.

The problem with this is that Malament's theorem tells us that there can be no such record-detection operator. More specifically, it tells us that $R_\Delta = \mathbf{0}$ for all closed sets Δ, which means that the probability of finding the record token in the spatial set S is zero. Indeed, the probability of finding the (above!?) record token anywhere is zero. But how can this be if there is in fact a detectable record token? And if there is no detectable record token, then how can you and I know the result of my typing-speed measurement as we both presumably do?

A natural reaction would be to deny the assumption that a detectable record token is a detectable entity that occupies a finite spatial region and insist that in relativistic quantum field theory, as one would expect, all determinate record tokens are represented in the determinate configuration of some unbounded field. After all, this is presumably how records would have to be represented in *any* field theory.

More concretely, couldn't a determinate measurement record be represented, say, in the local configuration of an unbounded field? Sure, but there are a couple of problems one would still have to solve in order to have a satisfactory account of determinate measurement records.

One problem, of course, is the old one. Given the unitary dynamics and the standard interpretation of states, relativistic quantum field theory would typically not predict a determinate local field configuration in a spacetime region. But let's set the traditional measurement problem aside for a moment and suppose that we can somehow cook up a formulation of the theory where one typically does have a determinate local field configurations at the end of a measurement.

If one could somehow get determinate local field configurations that are appropriately correlated, then one could explain how it is possible for me to know my typing speed by stipulating that my mental state supervenes on the determinate value of some field quantity in a some spatial region region that, in turn, is reliably correlated with my typing speed. So not only is it possible for a local field configuration to represent a determinate measurement result, but one can explain how it is possible for an observer to know the value of the record by stipulating an appropriate supervenience relation between mental and physical states. What more could one want?

It seems to me that one should ultimately want to explain how our actual measurements might yield determinate records. But to do this, one needs an account of measurement records that makes sense of the experiments that we in fact perform. The problem here is that our measurement records seem to have locations; they are the sort of things that one can find, lose, and move from one place to another. Indeed, we use their spacio-temporal properties to individuate our records. In order to know how fast I typed the sentence, I must be able to find the right record, and this (apparently) amounts to looking for it in the right place. It seems then that we know where our records are, and this is good because, given the way that we individuate our records, one must know where a record is in order to read it and to know what one is reading! This is just a point about our experimental practice and conventions.

So it seems that our actual records are in fact detectable in particular spacetime regions. But if this is right, then there must be detection-of-a-record-at-a-location operators (R_Δ that represent the proposition that there is a record in region Δ). And if these are subject to Malament's theorem, then we have a puzzle: there apparently cannot be detectable records of just the sort that we take ourselves to have.

This is particularly puzzling when one considers the sort of records that are supposed to provide the empirical support for relativistic quantum field theory itself. These records are supposed to include such things as photographs of the trajectories of fundamental particles, but if there are no detectable spacio-temporal entities, then how could there be a photographic trajectory record with a detectable shape? The shape of the trajectory is supposed to represent all of the empirical evidence that one has, but it seems, at least at first pass, that there can be no detectable entities with determinate shapes given Malament's theorem. From this perspective, the problem is to account for our particular-like measurement phenomena using a theory that apparently has nothing with particle-like structure.

While Malament's theorem arguably does nothing to prohibit an entity from having a determinate position, it does seem to prohibit anything from having a *detectable* position. But detectable positions are just what our records apparently have: they are typically individuated by position, so one must be able to find a record at a location to read it and to know what one is reading, and, given our practice and conventions, the records themselves are typically supposed to be made in terms of the detectable position or shape of something.

One might argue that one does not need to know where a record is in order to set up the appropriate correlations needed to read a record or that one can know where the record is and thus set up the appropriate correlations to read it without the position of the record itself being detectable. And while one might easily see how each of these lines of argument would go, it seems to me that our actual practice ultimately renders such arguments implausible. If I forget what my typing speed was, then I need to find a stable reliable record, and, given the way that I recorded it and the way that I individuate my records, in order to find one, I must do a series of position detection observations: Only if I can find *where* the record token is, can I then determine *what* it is.

The situation is made more puzzling by the fact that we are used to treating observers themselves as localizable entities in order to get specific empirical predictions out of our physical theories.[7] The location an observer occupies provides the observer with the spacio-temporal perspective that we use to explain why the world appears the way it does to that observer and not the way it might to another. We also use the fact that an observer occupies a location to explain why her empirical knowledge has spatio-temporal constraints.[8]

If detectable spatio-temporal objects are incompatible with relativistic quantum mechanics, then the challenge is to explain why it seems that we and those physical objects to which we have the most direct epistemic access (our measurement records) are just such objects.[9] As far as I can tell, it is possible that all observers and their records are somehow represented in field configurations; it is just unclear how the making, finding, and reading of such records is supposed to work in relativistic quantum field theory. Perhaps one could argue that observers and their records have only approximate positions and that this is enough for us to individuate them (and make sense of what it means for theory to be empirically adequate for a given observer), then argue that there is nothing analogous to Malament's theorem in relativistic quantum mechanics that prevents there from being detectable entities with only approximately determinate positions. Our standard talk of detectable localized objects might then be translated into the physics of such quasi-detectable, quasi-localized objects. But again this would require some careful explaining.

On the other hand, it may well be that none of this matters after all. The difficult problem, the one on which the solution to the others must

[7] Consider, for example, Galileo comparing the motions of the planets against theoretical predictions. That the observer has a specifiable relative position is needed for the theory to make any empirical predictions, and without comparing such predictions against what he actually sees, he would never be able to judge the empirical merits of the theory.

[8] If *I* am represented in the configuration of an *unbounded* relativistic field, then why don't I know what is happening around α-Centauri right now (in my inertial frame—whatever that might be if I have no fully determinate position!)? After all, on this representation of me, I would be there now. Or, for that matter, why would I not know what will happen here two minutes from now?

[9] Note that the problem of explaining how we could have the records we have without there being detectable spatio-temporal objects is more basic than the problem of explaining why it appears that there are detectable particles or other extended objects since the only way that we know of other spatio-temporal objects is via our records of them (in terms of patches of photographic pigment, or patterns of neurons firing on one's retina, etc.).

hang, is the one we set aside earlier in this section. The real problem for finding a satisfactory interpretation of relativistic quantum field theory is the quantum measurement problem.

While theorems like Malament's might be relevant to what metaphysical morals one should draw from relativistic quantum mechanics, whether such theorems hold or not is itself contingent on how one goes about solving the quantum measurement problem. A collapse formulation of quantum mechanics would, for example, typically violate condition (1): The dynamics translation covariance condition is an assumption concerning how physical states in different space-time regions are related, and it is incompatible with a collapse of the quantum mechanical state on measurement. But if we might have to violate the apparently weak and obvious assumptions that go into proving Malament's theorem in order to get a satisfactory solution to the measurement problem, then all bets are off concerning the applicability of the theorem to the detectable entities that inhabit our world.[10]

The upshot of these reflections is that we are very nearly back where we started: one cannot trust any specific metaphysical conclusions one draws from relativistic quantum field theory without a solution to the quantum measurement problem, and we have every reason to suppose that the constraints imposed by relativity will make finding a satisfactory solution more difficult than ever.

9.5 Conclusion

An adequate resolution of the quantum measurement problem would explain how it is that we have the determinate measurement records that we take ourselves to have. It has proven difficult to find a satisfactory resolution of the measurement problem in the context of nonrelativistic quantum mechanics, and relativistic quantum mechanics does nothing to make the task any easier. Indeed, the constraints imposed by relativity make explaining how we end up with the determinate, detectable, physical records all the more difficult.

Since one's ontological commitments typically do real work in proposed resolutions to the quantum measurement problem in nonrelativistic quan-

[10]That a solution to the quantum measurement problem might require one to violate such conditions might be taken to illustrate how difficult it is to solve the measurement problem and satisfy relativistic constraints as they are typically understood.

tum mechanics, it would be a mistake to try to draw any conclusions concerning the proper ontology of relativistic quantum field theory without a particular resolution to the measurement problem in mind. This point is clearly made by the fact that one cannot even know whether the so-called local entities no-go theorems are relevant to one's theory if one does not know what to do about the quantum measurement problem.

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