Quantum Mechanical Explanation, Causation and Nonseparability

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1 Introduction

In "Nonseparable Processes and Causal Explanation"[1], Richard Healey defends the use of nonseparable processes in scientific explanations of quantum mechanical phenomena (**QM**). The motivation for this defense: Healey's resolution of the *measurement problem* relies on non-separability as a primitive notion irreducible to other processes. If, however, like Wesley Salmon[2], we take valid scientific explanation to be causal explanation, then the introduction of nonseparable processes doesn't get us any closer to providing a valid explanation for quantum mechanical phenomena; causal explanations should only talk about causal processes and nonseparable processes are non-causal or pseudo processes.

Nevertheless, it is crucial to Healey's interpretation of **QM** that his resolution count as valid scientific explanation. It must be shown that the appeal to non-separability does not invalidate this approach since one standard source of dissatisfaction with **QM** is that it appears to be acausal. Healey's defense shows the high value placed upon causal explanation as a part of scientific explanation. If, like Healey, we believe in the message contained in the abstract below, we find ourselves in the position of having our *concepts of causation and explanation revised*[3]:

> ..we find such [**QM**I phenomena puzzling since they threaten cherished conceptions of how causes operate to produce their effects. But nonseparable processes offer us an alternative deal of natural order, conformity to which makes such phenomena seem quite normal and not at all unexpected. Attempts to answer the further question, as to whether an appeal to a nonseparable process provides a genuine causal explanation, have something to teach us about our concept of causation, but do not threaten to undermine the value of the explanation itself.

The value of an explanation, then, is not diminished by the fact that it is (perhaps, on one reckoning) not a causal explanation; a good explanation has other attributes besides just being a causal one.

The sequence of discussion in this paper will run thus: I will analyze Healey's classification of processes[4] and contrast it with Salmon's. I will include an analysis

[1] Richard Healey. Nonseparable Processes and Causal Explanation. *Journal of the History and Philosophy of Modern Physics*, Vol 25, No. 3, pp 337-374, April 1994

[2] Wesley Salmon. *Scientific Explanation and the Causal Structure of the World*, Chapter 5

[3] Healey, page 337

[4] It may be possible to show that separability or, as it might also be called, *intrinsicality*, is a methodological approach to science, but I will not bother trying to defend or attack that notion. By its very status as a novel idea, I will take non-separability to indicate some sort of paradigm shift, in that the questioning of an accepted standard of individuation and classification of physical processes is implied.

of Healey's notion that the existence of nonseparable processes does not violate the special theory of relativity (hereafter **STR**); a knockdown objection to the use of these processes in scientific explanation is that this violation is present. Healey's thesis is directed against Salmon's causal mechanical (hereafter **CM**) model. The **CM** model has two central theses: the role of causal processes in explanation and the role of causal explanation in scientific explanation. To bring some important disagreements with these theses to light, I will analyze criticisms mounted by Woodward[5]. I will conclude with some arguments in favor of a more flexible concept of causation and what it should/could look like in light of Healey's claims and make some prescriptive claims about what sorts of restrictions can be placed on the content of scientific explanations.

2 Separable and Nonseparable Processes

The concept of a physical process can be interpreted in a manner that does not, *a priori*, rule out nonseparable processes. Is there any difference at this level? What is a physical process?[6]:

> A particular process consists of a suitably continuous set of stages, typically involving one or more enduring systems ... A process may be spatially localized ... it may occur over an extended spatial region

A process of the type described above will not ordinarily be representable by a line in a spacetime diagram; a straightforward conflict with a definition offered by Salmon in which he distinguishes between processes and events as a means of establishing a fundamental ontology of processes for all physical theories[7]:

> The main difference between processes and events is that events are relatively localized in space-time, while processes have much greater temporal duration, and in many cases much greater spatial extent. In spacetime diagrams, events are represented by points, processes by lines..A baseball colliding with a window is an event; the baseball traveling from the bat to the window would constitute a process.

Salmon admits that his distinction is imprecise and suggests, as above, that the difference between a process and events is something to do with their temporal length. That is, processes occur in a much greater time than events. There are, I think, fatal problems with this sort of classification.

[5]James Woodward. The Causal Mechanical Model of Explanation. *Scientific Explanation: Minnesota Studies in the Philosophy of Science*, Kitcher and Salmon eds., University of Minnesota Press, Minneapolis, 1989

[6]Healey, page 341

[7]Salmon, page 139

2.1 Problems with Salmon on processes

Healey's examples of processes that occur in a much shorter time than events notwithstanding, part of the distinction between processes and events as put forward by Salmon is simply not conducive to establishing an ontology of processes. A plausible case could be made for reclassifying processes as compound sets of events or of a particular event, say the explosion of a supernova, as being a process. Salmon attempts to justify his adoption of a process ontology by saying that the **STR** (as a fundamental physical theory) does not mandate an event ontology. This doesn't help however: if the **STR** does not mandate an event ontology and if an analysis that shows processes to be reducible to events would do rather well, then, whence the justification for saying that we have a process ontology?

At the best, we have some sort of appeal to *natural language*; a kind of appeal that seems inappropriate given the nature of the question at hand. Consider someone who terms the year-end Philosophy Department party "a big event". If two competing ontologies, in the form of a process ontology and an event ontology in this case, are reducible to one another (shades of the *notational variant* problem in empirically equivalent theories), then the only reason for preferring one to the other is going to be pragmatic, conventionalist and so forth. If its only pragmatic, how does Salmon's analysis derive the authority to make *realist claims* about the nature of causal mechanisms (as the **CM** model does)? It is a prima facie problem, then, with Salmon's analysis that it takes as the basis for much of its further claims an ontology that is not intuitive at all.

2.2 Back to Processes

Healey and Salmon agree that a physical process may be uncontroversially defined as occurring within some region of four dimensional spacetime. In conformance with classical intuitions, we can define a typical process in Newtonian spacetime as consisting of[8]:

> a sequence of stages which can be given a unique, continuous ordering with respect to absolute time.

A "unique, continuous ordering" with respect to absolute time is obviously not available for relativistic spacetimes.

What is a separable process? A physical process is spatio-temporally separable in spacetime region R if and only if it is supervenient upon an assignment of qualitative intrinsic physical properties at spacetime points in R[9]. Therefore, a physical process is separable if it is determined completely by events occurring at each spacetime point where the process is going on; an exhaustive description of the properties of

[8] Healey, page 339
[9] Healey, page 338

its constituent spacetime points gives us the properties of the process (this could be called the *intrinsicality* thesis for physical processes). Any physical process that forms a part of a *local* spacetime theory such as classical physics will be spatio-temporally separable in the manner described above. Even the appearance of nonseparability (e.g., action at a distance) in classical theories of gravitation or electromagnetism may be explained away by showing them to be separable in the spacetime regions that include all the sources of forces acting on particles. A nonseparable process, then, is a process composed of a continuous, temporally ordered sequence of instantaneous stages at least one stage of which is not supervenient upon ascription of qualitative intrinsic properties at spacetime points within the spacetime region occupied by it[10].

2.3 Do nonseparable processes violate the STR? Part I

In a relativistic spacetime, nonseparable processes can be described as linking *spacelike* separated events, a real difference from any nonseparable process in Newtonian spacetime. The postulation of nonseparable processes would only be a problem for a purported explanation if they came into conflict with some fundamental physical theory. The only physical theory that appears to be a candidate for being such a spoilsport is the **STR**.

The **STR**, however, doesn't lay down any explicit restrictions on *kinds* of processes *per se*. The substantive objection to nonseparable processes from the **STR** comes not from problems with Lorentz invariance (the prohibition of preferred frames of reference), but from something far more nebulous; the relativistic locality requirement. The argument for relativistic locality is reliant, however, upon "causal considerations." That is, *pace* Salmon, the only kind of genuine process that can connect two events, e and f directly must be a causal process; but, it can't be for spacelike separated events since if there were a causal process directly linking e and f then e and f must be related as cause and effect. Now, since a cause must invariantly precede its effect and since e and f are spacelike separated events, they have no invariant time order. Hence no process can directly connect them[11].

So the only restriction placed on causal processes (that is, invariant precession of effect by cause) by the constraints of the **STR** is not based on a demand made explicitly by the theory itself. The only relevant restriction seems to be one that would ask us to come up with an unambiguous temporal ordering of the two events connected by the nonseparable process at hand. This injunction says nothing about it as a process and only concerns itself with the temporal order of the events connected by the process. A violation of this injunction would be a denial of the requirement that events have unambiguous temporal ordering rather than some part of the **STR**; the invariant precession of cause by effect is a methodological (or metaphysical, its often hard to tell which is which) principle. If we agree that the resolution of any situation involving the precession of cause by effect can be done in a fashion that has logically

[10]Healey, page 348
[11]Healey, page 353

consistent consequences (such as the Feynman-Wheeler thought experiments), then our case for rejecting any theory that uses the precession of cause by effect is weakened. What if we do not identify the events as a cause and effect pair? Problems with explaining the temporal asymmetry of causation (and its subsequent resolution by explaining it away due to the initial conditions of the universe) might convince us that this principle need not be elevated to metaphysical status.

No matter how that line of reasoning works out, it seems there is no conflict with the letter or the spirit of the **STR** (more on this below). The putative conflict arises instead, from Salmon's classificatory scheme that terms certain processes as being pseudo processes. If this classification is flawed, we might not be justified in rejecting the existence of nonseparable processes.

Does the use of spacelike separated events in explanations lead to causal paradoxes? Arguments that utilize tachyons to connect spacelike separated events and set up paradoxes will work only if certain assumptions are violated. These should be amenable to resolution then, *via* rejection of one of these assumptions. What assumptions are these? Consider the following[12]:

> each event in the [causal] chain is assumed to be causally connectable to every other event by two independent causal paths, and each link in the chain is assumed to be causally ordered.

Spacelike nonseparable processes whose existence is suggested by **QM** phenomena meet *neither* of these assumptions. Why, though, postulate nonseparable processes when our ordinary notions of separable processes have done well so far? The answer lies in pressure from the phenomena[13]. When we have phenomena that can be explained by a classical theory employing separable processes, the need for the postulation of nonseparable processes does not arise.

3 Nonseparable processes in QM explanation

Consider two spacelike separated particles that were created in a joint singlet spin state (the total spin of each pair is zero) and then separated. Spin detection along the z axis is carried out for each particle in every pair for which both particles are detected. It is a standard prediction of quantum mechanics that these spin detections will display perfect anti-correlations: if one particle of the pair is found to have a $z-$ spin, its partner will be found to have $z+$ spin. How does one explain these

[12] Healey, page 354

[13] The advocacy of non-separability or non-intrinsicality as an explanatory device for quantum mechanical phenomena is perhaps not new. David Bohm's theory is explicitly non-local and holistic (David Bohm and BJ Hiley. *The Undivided Universe*, Routledge, 1993). For a good explication of the non-separability thesis: Don Howard. Holism, Separability, and the Metaphysical Implications of the Beell Experiments. *Philosophical Conequences of Quantum Theory*, James Cushing and Ernan McMullin eds., University of Notre Dame Press, 1989

correlations that seem not to be affected by the spacelike separation of the detectors? An explanation (Healey's) couched in terms of nonseparable processes deals with these phenomena in the following fashion.

A particle pair **AB** possesses a spin property termed $(+) \equiv (-)$. *This property is a property of the pair and not the individual particles.* Neither **A** nor **B** possesses any individual spin property other than the trivial property **I** which a system always possesses. As a result, the spin states of **A, B** separately do not determine that **AB** has the correlational property $(+) \equiv (-)$. The pair **AB** then, may be considered nonseparable or as possessing a holistic property[14]:

> Even if **A, B** were each located at definite spatial points throughout, they would not always coincide spatially. It follows that the ascription to **AB** of the property $(+) \equiv (-)$ at a time is not always determined by any ascription of properties to **A, B** or spacetime points simultaneous with that time. *The evolution of **AB** from its emission to the performance of the first $z-$spin measurement is consequently a phase of a nonseparable process.* [my italics]

Suppose that A is measured first (call this measurement, M_A, of course, if the two are spacelike separated, there is no matter of the fact as to which is first) and found to be $z-$. At this time, **B** still possesses the trivial spin property **I**. Importantly, **B** does not as yet have the $z+$ value for its spin, though it will be found to possess this value if a measurement is carried out. However, the properties of the pair have changed[15]:

> **AB** no longer has the correlational property $(+) \equiv (-)$: instead it will have the weaker correlational property $(z+) \equiv (z-)$, corresponding to the fact that anticorrelations will only be observed in the $z-$direction from now on.

A measurement could be carried out along the $x-$axis but that would not let us make any statements about the spin of the particle in the $z-$direction since spin along the z and x axes are *incompatible observables.* The nonseparable process consists in the persistence of these two properties of **AB** from the time immediately following the measurement on **A** till the time of the measurement on **B**[16]:

> This phase of the process is nonseparable since even though **AB**'s possession of the property $(z+) \oplus$ **I** is determined by **A**'s possession of $z+$ which could be ascribed to spacetime points (at least if **A** were located at a spatial point), **AB**'s possession of the property $(z+) \equiv (z-)$ is not determined by **A**, **B** separately and so is not fixed by any ascription of properties to spacetime points.

[14] Healey, page 363
[15] Healey, page 364
[16] Healey, page 364

The result $z-$ on the measurement of **B** now is a direct consequence of the possession of these properties by **AB**. After the **B** measurement, **AB** possesses the property $(z+)(z-)$ which it only has if **A** has $(z+)$ and **B** has $(z-)$. Crucially, the **B** measurement has no effect on **A**. By explaining the measurement process in this fashion, Healey's explanation does away with the need to believe in intrinsic, non- relational, properties of spacelike separated particles being *created* by the act of measurement (the primary reason for the implausibility of the standard interpretation of **QM**) . A similar resolution is available if the measurement on **B**, M_B, is carried out first.

3.1 Do nonseparable processes violate the STR? Part II

Why doesn't this nonseparable process violate any "defensible requirement" of the **STR**[17] such as the invalidity of a preferred frame or a violation of the principle of local action? The latter is most closely related to causal issues. Consider the following: when M_A invariantly precedes M_B, we might say that before a measurement was carried out on **A**, the probability of the result $z+$ obtaining was the same as the probability $z-$ obtaining. Once the measurement was carried out however, the probability changed *instantaneously* implying a corresponding change in the properties of **B**. Any instantaneous change would seem to require a preferred plane of simultaneity. This isn't a problem however; by the explanation provided above, it is not the properties of B that have been changed but rather the properties of **AB**. The objection can be raised that the dispositional properties of the two have changed. However, the straightforward reply to this is that even those properties supervene on the holistic properties $(z+) \equiv (z-)$, $(z+) \oplus$ **I** of **AB**.

In the case in which M_A and M_B are spacelike separated, we may consider ourselves to have a violation of the condition for relativistic locality on our hands. The significance of this is that a violation of this condition could give rise to causal paradoxes such as the precession of cause by effect. The nonseparable process, though, could be used to generate a paradox if and only if we could insert additional causal links between the two events to set up a causal chain. This is not possible however: there are no intervening stages or events. It isn't clear that the process connecting M_A and M_B is causal anyway. Since these events are linked in a completely symmetric way (the measurement statistics remain the same regardless of the order of measurement of spin on the two particles) we have no justification for identifying one as cause and the other as effect. Such an identification is necessary if one is attempting to show the presence of a causal paradox.

In addition, there is no hope of manipulating one event to change the other. This lack of manipulability also maintains the relativistic requirement that signals

[17] Before considering these objections however, it is worth noting that once the assumption that these events occur in Newtonian spacetime is replaced by the assumption that they occur in Minkowski spacetime, we are on our way to resolving problems that might occur if these phenomena required a preferred frame.

not be propagated faster than light. A manipulation would enable us to send a signal superluminal and we do not have the means to do so in the case under consideration. What other opposition does an explanation utilizing nonseparable processes run into? As suggested before, it faces objections from the **CM** model of explanation in which the concept of a causal process is fundamental.

4 Causality, causal explanation and scientific explanation

The **CM**model offers an *ontic* conception of explanation to supplement an analysis based on statistical relevance relations between pairs of events; these statistical relevance relations are to be explained by talk of causal relations in the explanation.

The **CM** model can be roughly summarized as follows:

CM_l. All valid scientific explanation is causal explanation.

CM_2. All valid causal explanation consists in the detailing of the causal processes at play in the phenomena that we are attempting to explain. That is, identify the cause and effect pair in the phenomena that you are interested in and then describe the causal process that connects the two of them. If you can't find a causal process connecting the pair at hand, you don't have a real cause-effect pair at hand.

CM_3. The way you recognize a causal process is that they are the only ones capable of leaving a *mark*.

4.1 Problems with Salmon on explanation

Woodward asks two important questions of the causal mechanical model of explanation: (1) Is it reasonable to suppose that all scientific explanations will meet the requirements of the causal mechanical model? and: (2) Does Salmon's model capture all of the features which are relevant to the assessment of scientific explanation? Woodward argues that on both counts the answer is no (Healey's analysis and explanation benefits from such a denial.)

Firstly, scientific explanations which make no use of causal processes (and thereby are not causal explanations) abound such as variational principle type explanations (Hamilton's principle of least action and the General Theory of Relativity are good examples of this) . For Woodward, the difference between explanation in a theory like the **STR** and explanation in a theory like Lorentz's is the use of non-causal effects in the first theory. The causal statements of that theory would then supervene on non-causal states of affairs.

Secondly, the **CM** model does not adequately describe good explanations in science. Take as an example, the explanation of the failure of the Michelson-Morley experiments by the **STR**. I don't think it can be seriously disputed that the **STR** provided a good explanation for the failure of the Michelson-Morley experiment. This point is perhaps a crucial one. We have an explanation (the **STR**) that is, by all accounts, a satisfactory one. One that struck its audience as counterintuitive initially because of a clash with dominant paradigms. The **STR**, though, held the day because of its simplicity, reduction of arbitrariness (with respect to Lorentz-Fitzgerald-Larmor effects), obviation of need for an unobservable ether, unification of theories of diverse phenomena, elegance and flexibility. Not bad characteristics to have in an explanation. The rejection of the **CM** as providing a good model to base explanations of **QM** phenomena on is warranted then, by the success, in the past, of explanations that do not conform to this model.

This point done, we are left with a situation where the phenomena have steadfastly resisted causal explanation: quantum mechanics. But now, the issue of whether a demand for a certain kind of explanation is reasonable isn't settled by recourse to an abstract model of explanation, but is dependent on the results of empirical inquiry. A demand for a causal explanation in **QM** then, might just be shortsighted hankering after a principle of dubious universal validity. In addition, it reveals a bias in favor of a realism that has been shown to be untenable in light of Bell's theorem (any theory aiming to meet the predictions of **QM** must be non-local). On Salmon's reckoning, **QM** lacks explanatory power since it fails to provide an explanation in this fashion. Woodward disagrees with Salmon by characterizing **QM** as being a "satisfactory explanatory theory." Here, I think Woodward is wrong. **QM** isn't a "satisfactory explanatory theory." The most ardent physicist will admit that the presence of separate dynamics for systems being measured and systems not being measured is a weakness unlikely to contribute to a satisfactory explanation.

The demand, though, for a causal explanation in terms of causal processes should be rejected. While **QM** is not a satisfactory explanatory theory, it isn't so *because of the lack of causal processes*. We have independent grounds for not considering it to be satisfactory. There is dissatisfaction with the structure of **QM** that has nothing to do with the non-existence of causal processes. **QM** can be accused of logical inconsistency; there is certainly no mention of causal processes here. Current quantum mechanical explanation is failing on one count, and that is on realist interpretations.

The **CM** model makes all explanation into causal explanation by its insistence that all explanation deal with causal processes. It is open, then, to criticisms that show the possibility of the existence of processes that aren't causal and yet are capable of playing a perfectly sensible role in a scientific explanation. Part of the justification for taking causal processes to be the primary mechanism underlying our world is the primacy, in Salmon's analysis, of a process ontology. This, as I have already noted, is problematic.

The **CM** model itself is metaphysically laden; we might demand an explanation of the very existence of spatio-temporary continuous causal processes as well[18]:

> the existence of spatio-temporary continuous causal processes is itself something that needs of explanation-one can perfectly intelligibly ask why the world should have this feature.

Why just this feature? Why not others? There is perhaps enough contention here with the **CM** model to suggest that an explanation that gives a good understanding of which mechanisms are at play in certain physical phenomena not be rejected *just because* it comes into conflict with a non-universal principle.

There are more problems with the **CM** model. It characterizes explanations that postulate nonseparable processes as pseudo- explanations. Nonseparable processes aren't causal processes since only causal processes have the capacity to transmit marks. This distinction, however, has more to do with manipulation and signaling than with the value of a theoretical explanation; a curiously anthropocentric view. Even worse, it runs the risk of circularity. We decide whether a process is causal or not by deciding whether it is a genuine process or not. But we decide whether a process is genuine or not is by figuring out whether it is causal or not using the mark criteria. Finally, it is implied that causal processes are the only ones that can be genuine, i.e. a non-causal process is a pseudo process; a strangely restrictive view of the processes that can exist in the world. The earlier discussion of processes didn't hinge so much on their causal nature as on their spatiotemporal properties.

5 Models of Explanation and Causation

The model of explanation that Healey is arguing against is that to explain an event is to show its position in the causal network of the world. Or, Healey is arguing against CM_2 above when he says that[19]: theoretical explanations that appeal to timelike or spacelike nonseparable processes may be evaluated just as favorably as theoretical explanations based on separable processes. But, if appeal to nonseparable processes is to lead to a good theoretical explanation, that process should not be parasitic on other processes whose "continued operation is left unaccounted for." Healey seems to be saying then, that non-separability should be regarded as a primitive notion. This is not an argument in favor of it at all. This is simply an assertion to the effect that it be regarded as primitive or irreducible in our explanation: a seemingly *ad-hoc* move?

Healey anticipates this objection and points out that he has postulated non-separability as a fundamental kind of process in order to facilitate one kind of explanation and to do away with some of the difficulties created by ordinary resolutions of **QM**[20]:

[18] Woodward, page 359
[19] Healey, page 354
[20] Healey, page 359

> It may seem that nonparasitism is achieved only vacuously. But that is surely how it is with the adoption of new ideals of natural order. They are offered as bedrock explanations, and do not lose any explanatory power by being themselves unexplained. Thus if nonseparable processes do indeed present us with an alternative ideal of natural order, then acceptance of that ideal cannot be conditional on explaining how these are possible, or why they occur.

Consider phenomena that we classify as being irreducibly indeterministic. We don't stop using them in explanation just because we think that our characterization of them as being indeterministic is only a reflection of our epistemic ignorance. One might see an analogy here as well with the postulation of the existence of theoretical entities such as particles in modem physics[21]. There is a bit of vagueness here, sure, in that one isn't clear on how to avoid being excessively arbitrary.

Healey does not make the additional claim that his explanation of **QM** phenomena has the virtue of being a causal one just because there exists a problem with the classification of processes[22]:

> This value does not rest on the further claim that spacelike nonseparable processes are not pseudo-processes but causal processes which is just as well since the content of that claim remains unclear.

We have stepped away from the idea of simply having to evaluate the quality of an explanation with the sole criteria being whether it employs causal (and therefore separable) processes or not. The evaluation of explanations is to be done according to the idea of explanatory power rather than what kinds of processes are used in the explanation; 'causal processes' are badly defined and lacking in clarity. The standards for evaluation need to rest on something else. I don't think it's the case that *no restriction* should be placed on the content of an explanation. It is the case, however, that the use of processes seems to be flawed and perhaps unworthy of being the grand clinching factor in an argument about whether a scientific explanation is a good one or not.

There exists a general account of explanation (theoretical unification[23] being one of its desirable attributes) to which Healey's explanation conforms rather than one which places restrictions on the kinds of processes postulated therein. If the model of explanation propounded by Salmon is that explanation only be extended to those genuine processes, then there is not much dispute here. In that case, Salmon-Explanation is that species of intellectual activity that deals with "genuine" processes. But the general notion of explanation is more inclusive than what Salmon has in mind. So, maybe Healey isn't giving a Salmon-Explanation but he certainly is providing an explanation. In all of this, it shouldn't be forgotten that objections raised to the **CM** model are substantive precisely because of pressure from **QM** phenomena.

[21] Such as the postulation of the existence of the neutrino by Pauli to explain beta decay

[22] Healey, page 355

[23] The Kitcher-Friedman model, for example

5.1 Are explanations utilizing nonseparable processes causal explanations?

What sorts of explanations of **QM** phenomena does one obtain using nonseparable processes? Are they causal explanations? Is it possible to classify them as such? Consider first, the famous two-slit experiment[24]:

> That process is initiated by the emission of the electron from the source, and concluded by its detection at the screen. A continuous process connects these events, each stage of which is linked to earlier and later stages, both spatiotemporally, and by their joint instantiation of the dynamical law governing the time development of the electron's state. Moreover, there is no reason to suppose that this process is parasitic on any more fundamental processes involving the electron. If the electron had not been emitted, no subsequent stage of the process would have occurred, and the electron would not have been detected at the screen. The electron transmits energy and momentum to the screen, and may be used to transmit signals.

Under a transference of energy analysis, this is a causal process; we have an explanation on our hands of the electron's detection in that it was emitted from the source and then passed through the slits. Its emission is easily identified as a cause of its passage which in turn was a cause of its detection.

A similar analysis is also possible for an explanation of EPR correlations[25]:

> Suppose first that M_A occurs invariantly earlier than M_B. Then one can give a satisfactory theoretical explanation as to why the outcome of the latter event is $z-$ by showing how the nonseparable process initiated by the emission e of the singlet pair from the source connected that outcome continuously and in accordance with the basic laws of nature to the earlier outcome $z+$ of M_A.

As Healey points out, this explanation looks a lot like a typical causal explanation. Should we then, call it as such? There are problems with such a characterization[26]:

> should we accept that the outcome $z+$ of M_A *caused* the outcome $z-$ of M_B? [my italics] To do so would be to do violence with other intuitions concerning causation. There is no way of manipulating M_A to secure, or even render more likely, the outcome $(Z-)$ of M_B; the outcome of M_B is wholly uncontrollable.

[24] Healey, page 370
[25] Healey, page 371
[26] Healey, page 371

This is not an analysis that succeeds in being termed as a case of causation under the transfer of conserved quantities analysis, or under any manipulability restrictions. Neither does it succeed in doing so under the mark analysis since no mark is applied to any of the constituent processes. The temporal order of the two events seems also to be irrelevant; the precession of M_B by M_A is just as likely as the precession of M_A by M_B since the two events are spacelike separated.

5.2 Bad News[tm] for the concept of causation?

In this analysis, on one approach, we have a case of causation on our hands and in one case we don't. What exactly is going on? Healey suggests that the problem lies with what he terms the "cluster concept" of causation and identifies it as follows: Causes precede their effects rather than succeeding them. Causes are manipulable in principle (if not in practice) in order to bring about their effects. Causes transfer conserved quantities to their effects; and so on. These criteria work most of the time[27]:

> In paradigm cases, these criteria count the same pairs of events as cause/effect pairs. Moreover, there are very many such paradigm cases. But there is no a priori guarantee that the criteria should always deliver the same verdict.

When our concept fails to deliver an unambiguous verdict, the concept has broken down. Deciding which part of the cluster concept we choose to use guides us in our decision of whether the **QM** phenomena represent genuinely causal processes. Healey suggests that[28]:

> if our interest is in theoretical explanation, then we may deploy a concept of causal explanation in accordance with which the outcome $(z+)$ of M_A does indeed contribute to the causal explanation of the outcome $(z-)$ of M_B.

But[29]:

> if our interest is in manipulability, then we shall deny that the outcome $(z+)$ of M_A is even a partial cause of the outcome $(z-)$ of M_B and deny also that the process connecting them is causal in the manipulability sense

This should cause us (no pun intended) to pause for thought. Do we have an unproblematic paradigm of causation if, when confronted with phenomena all it can say is that on one reading the phenomena are causal and not on another? One would only characterize ourselves as possessing a satisfactory concept of causation only if we were

[27] Healey, page 371
[28] Healey, page 372
[29] Healey, page 372

able to come up with straightforward characterizations for such cases. Healey suggests that the concept has "broken down." This might strike some as strong language but I think the spirit is accurate.

If we are interested in classifying all mechanisms in this world as being causal in nature, then I suggest that the only way out for proponents of such a view is that they expand or make more flexible, their concept of causation. If not, then acknowledge that some explanations that we provide for certain phenomena will not be causal in nature. *Something has to give.* I don't think the phenomena can be wished away. They will persist. Our classification and understanding of them are the area of dispute, not their existence.

The analysis above of the cluster concept of causation is indicative of its largely descriptive nature (though, as we have seen these concepts bring some metaphysical weight as well). The significant point is the *descriptive nature* of these concepts. Some of the concepts that make up this cluster concept have been put together after the fact; that is, they have been used to indicate and categorize all previously known processes. Some of this categorization is done on empirical grounds. For example, we might link asymmetries existing at the level of statistical macro laws (Boltzmann thermodynamics) to the asymmetry of causation. None of this, however, precludes the discovery of new processes and therefore the expansion of the concept of causation to include these new kinds of processes.

If so, the argument for revision of the concept of causation should (or could) run along the following lines. Causal explanation is merely one kind of explanation amongst different types of explanation (albeit a large and important part of the explanations that we use to make sense of the world.) Under what we take to be causal explanation, various concepts are assumed. When we render our causal explanation, we take it for granted that the person who is the beneficiary of our explanation is privy to and shares in our approval of the concepts that constitute our concept of causation. Only then would our explanation be reckoned a "good" explanation. For a person inclined to think that the success of explanations hinges on the use of causal processes in the explanation, we have the following line of defense. If it can be shown that nonseparable processes are genuine processes then it might be argued that the concept of causation be expanded to include it. Surely, an analysis of causation should concern itself with all kinds of physical processes? Otherwise, we can reject the the notion of causal processes (and its attendant classification of nonseparable processes as pseudo processes) being the only legitimate kinds of processes to be used in explanation.

The **QM** case shows that we are at a point where several concepts that we have taken to be fundamental to causation need to be revised. This revision is *not restricted* to foundational concepts of causation alone. *Any interpretation* of **QM** will have to make use of concepts that were formerly held to be unpalatable. Up for grabs are non-locality, indeterminism and an instrumentalist reading of the **STR**. Why not revise our concepts of causation? What grants it protection in this case? In fact, one might say that part of the hard work has been done; we are already stuck with a theory that is explicitly non-local in its formulation. The wave function collapses all over space at the time of measurement and any theory (by Bell's theorem) that has **QM**'s probability distributions for particle measurements will have to be non-local.

Does the presence of **QM** phenomena show a breakdown of the current concept of causation? Their presence has certainly done damage to standard realist accounts of causation. In any case, most analyses of causation seem to come packaged with an attached disclaimer with respect to **QM**[30]. What is curious, of course, about such disclaimers is that they are made with respect to the most fundamental physical theory availabled (and the most empirically successful in the history of modern science.)

6 Conclusion

What does the current analysis tell us about explanations of **QM** phenomena? Perhaps, that rather than there being an explanatory gap in quantum mechanics, it is our theory of explanation and our pre-theoretic intuitions that certain kinds of explanations always be provided which need revising. More than anything else, it shows us that explanation needs to be a rather more flexible concept than has been formerly envisaged. While the setting of guidelines to be followed by explanation for empirical phenomena is a worthwhile and philosophically justifiable task, at no point does the elevation of these guidelines to *metaphysically necessary* status seem justified. Why isn't it plausible that any reasonably good theory of scientific explanation must be flexible enough to consider possible something that the **CM** model rejects?: that the phenomena can force on us the conclusion that not only are certain candidates for an explanation defective but that the demand for an explanation of some very general type is misguided.

If a model of explanation has failed to work for physical phenomena whose presence is indisputable, then it is time to revise *that model*. Certainly no one seems to be suggesting that **QM** phenomena are merely illusory or any such thing. It is their explanation that doesn't seem to be making any progress. I'd suggest that this is because of the application of an inflexible paradigm of causation. Some flexibility already existsSome flexibility already exists. As an example, it is often held that transitivity, temporal ordering, and locality are crucial to any analysis of causation. But we have the counterfactual account that violates all of these injunctions and still gives respectable causal analyses.

Does Healey's explanation meet other standards for explanation? I suggest this question will have to wait for an answer till the time we have devised a new set of standards for **QM** explanation. Judging by our classical standards is not going to result in a favorable verdict. The metaphysical import of Bell's theorem is not to be ignored; any theory that aims to match the empirical standards of **QM** will discard some classical paradigms along the way. Would it force a revision of the concept of

[30]An empirical observation about Philosophy conferences might be the amount of headshaking that greets the introduction of **QM** in any discussion on causation

causation within explanation whereby one might say that our explanation is causal? Causal in the sense that it uses a new cluster concept of causation?

Our concept of explanation, while utilizing the causal concept of explanation, should do so with a flexible one, one that reflects the diversity of phenomena that make up this world. It seems hardly controversial to assert that physics works with a certain set of metaphysical assumptions. Given that, why should it be surprising that a new physics, one that is more empirically successful, requires a new metaphysical world view? Why should intuitions trained in pre-quantum physics be our only guides in deciding what form explanations of **QM** should take?