Causal Loops and Collapse in the Transactional Interpretation of Quantum Mechanics

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Abstract

Cramer’s transactional interpretation of quantum mechanics is reviewed, and a number of issues related to advanced interactions and state vector collapse are analyzed. Where some have suggested that Cramer’s predictions may not be correct or definite, I argue that they are, but I point out that the classical-quantum distinction problem in the Copenhagen interpretation has its parallel in the transactional interpretation.

Résumé

L’interprétation transactionnelle de la mécanique quantique, proposée par J. G. Cramer, est sommairement revue, et quelques questions liées aux interactions avancées et à l’effondrement du vecteur d’état sont analysées. Certains ont suggéré que les prédictions de l’interprétation de Cramer ne sont pas correctes ou ne sont pas bien définies. Je cherche à montrer qu’au contraire elles le sont, mais je signale que le problème de la distinction du classique et du quantique, inhérent à l’interprétation de Copenhague, a son parallèle dans l’interprétation transactionnelle.

KEY WORDS: quantum mechanics; transactional interpretation; causal loops; advanced interactions; collapse.
1 Introduction

State vector collapse is one of the great foundational problems of quantum mechanics. It was postulated by von Neumann in his theory of measurement [1], as a process wherein the Schrödinger equation ceases to be valid. Although von Neumann kept his discussion to a general framework, specific models of collapse were proposed later on, the best known being the spontaneous localization theories [2].

In contradistinction with von Neumann, most approaches to the quantum measurement problem have tried to retain the universal validity of the Schrödinger equation (or of a suitable relativistic generalization). Decoherence theory, in this context, goes a long way towards identifying the physical variables relevant to an effective collapsed state [3]. Yet many believe that decoherence by itself does not solve the measurement problem [4]. Nor does the epistemic view of quantum states [4, 6], according to which the state vector represents knowledge, or information, rather than the state of a physical system. One way to obtain the effect of collapse without modifying the Schrödinger equation consists in introducing additional structure to the Hilbert space formalism. Bohmian mechanics [8] and modal interpretations [9] implement such a program.

Cramer’s transactional interpretation [10, 11, 12, 13, 14], which has received comparatively little attention, is another attempt to understand the effect of collapse while keeping as close as possible to the framework of the Schrödinger (or some appropriate relativistic) equation. In Cramer’s approach, a quantum measurement or, more generally, a quantum process involving the transfer of conserved quantities should not be viewed as involving the collapse of the state vector at a specific time, but rather as a transaction involving many potential outcomes and, most importantly, the exchange of both retarded and advanced waves. Cramer argues that such an outlook helps in making sense of many otherwise paradoxical features of quantum mechanics.

In this paper I will first give an overview of the transactional interpretation, and then proceed to analyze a number of issues raised in its wake. Any theory that introduces advanced as well as retarded interactions raises the specter of causal loops. In Cramer’s approach advanced waves do not allow an observer to change its own past, but some investigators have argued that they entail indefinite or incorrect predictions. I will review these arguments, and propose a way to understand the transactional interpretation.
that saves its full predictive power. As a by-product of the analysis, some consequences of the atemporal view of a transaction will be brought to light. In the end I will argue that the problem of the classical-quantum distinction in the Copenhagen interpretation corresponds, in Cramer’s interpretation, to the one of making precise the notion of a transaction.

2 The transactional interpretation

Cramer’s transactional interpretation of quantum mechanics is inspired by the electromagnetic theory of Wheeler and Feynman [15, 16]. In this time-symmetric theory, advanced solutions of Maxwell’s equations are just as important as retarded ones. The electromagnetic field acting on a charged particle comes from the other charged particles only, and is equal to half the sum of the retarded and advanced Liénard-Wiechert solutions of Maxwell’s equations. Wheeler and Feynman succeeded in recovering the usual electromagnetic results, including the expression for radiation reaction, by postulating in addition that the universe is a perfect absorber of all the electromagnetic radiation coming from inside it. In the Wheeler-Feynman approach, an accelerated charge does not radiate if there are no absorbers, and the experimentally confirmed radiation formula is recovered if there is complete absorption. Cramer, in the spirit of Wheeler and Feynman, attributes physical reality both to a given solution of the Schrödinger equation (propagating forward in time) and to its complex conjugate (propagating backward in time).

An example of a quantum-mechanical interaction is the emission of a microscopic particle (say an electron) at some time $t_0$, followed by its absorption at a later time $t_1$. Originating at $t_0$, the usual solution $\psi$ of the Schrödinger equation propagates through $t > t_0$, and is called by Cramer an offer wave. Also associated with $t_0$ is the complex conjugate $\psi^*$, which propagates through $t < t_0$. The solution $\psi$ reaches all potential detectors, its amplitude $\psi(r_i, t_i)$ at detector $i$ being given by the Schrödinger equation. Each detector in turn emits both retarded and advanced (or confirmation) waves. Cramer argues that the confirmation wave coming from detector $i$ reaches the source with an amplitude proportional to

$$|\psi(r_i, t_i)|^2 = \psi(r_i, t_i)\psi^*(r_i, t_i),$$

(1)

where the first factor on the right-hand side coincides with the amplitude
of the stimulating offer wave at \( i \), and the second one comes from the fact that the confirmation wave develops as the time reverse of the offer wave. Advanced waves reaching the source in turn stimulate a new cycle of offer and confirmation waves, and so on. For \( t < t_0 \), under appropriate boundary conditions, the waves coming from all the potential absorbers cancel the advanced wave coming from the emitter. Eventually, a transaction is established between the emitter and one of the detectors, and the process is complete. If the probability that the transaction be established with detector \( i \) is taken to be proportional to the amplitude \( |\psi| \) of the confirmation wave coming from that detector, Born’s quantum-mechanical probabilistic rule follows. (See Sec. 6 for a more complete analysis of this assertion.)

To illustrate how a transaction works, let us consider one of the examples analyzed by Cramer, a variant of the negative-result experiment of Renninger \[17\] (Fig. 1). A source \( S \) sits at the center of a spherical shell \( E_2 \) of radius \( R_2 \). On the interior of the shell are perfect absorbers that will detect any particle leaving \( S \) and reaching \( E_2 \). Inside \( E_2 \) is a portion \( E_1 \) of a concentric shell of radius \( R_1 \), whose interior is also lined with perfect detectors. The solid angle subtended at \( S \) by \( E_1 \) is equal to \( \Omega_1 \), whereas the solid angle subtended by the portion of \( E_2 \) visible from \( S \) is equal to \( \Omega_2 = 4\pi - \Omega_1 \).

![Figure 1: A negative-result experiment.](image)

The system is set up so that at time \( t_0 \), the source emits exactly one particle with speed approximately equal to \( v \) and with a wave function independent of angles. For \( t_0 < t < t_1 = t_0 + R_1/v \), the state vector can be
represented as

\[ |\psi\rangle = c_1|E_1\rangle + c_2|E_2\rangle, \tag{2} \]

where each vector \(|E_i\rangle\) is associated with detection at the corresponding shell \(E_i\), and where \(|c_i|^2 = \Omega_i/4\pi\).

Now suppose that at some time \(t > t_1\), no detector at \(E_1\) has fired. In most interpretations of quantum mechanics, the particle’s state vector is thereafter taken to be equal to \(|E_2\rangle\). This is certainly good enough for the purpose of predicting results of subsequent experiments. Thus it seems that the null result at \(t_1\) has produced the collapse of the state vector (2) into \(|E_2\rangle\).

Different views of the process of collapse may have more or less problems in explaining how such a mechanism can be triggered by what appears to be the absence of a physical interaction.

In Cramer’s interpretation, there is no such thing as a collapse occurring at a specific time \(t_1\) or \(t_2 = t_0 + R_2/v\). The collapse is interpreted as the completion of the transaction. The whole process is viewed atemporally in four-dimensional space-time, along the full interval between emission and absorption. The condition that only one particle is emitted at the source translates into the fact that only one transaction is established in the end, either between \(S\) and \(E_1\) (with probability \(\Omega_1/4\pi\) proportional to the amplitude of the confirmation wave received at \(S\) from \(E_1\)) or between \(S\) and \(E_2\) (with corresponding probability \(\Omega_2/4\pi\)).

### 3 Maudlin’s challenge

It is well known that in many circumstances, advanced interactions can lead to causal paradoxes. Such problems may be compounded in stochastic theories, where the present doesn’t uniquely determine the future. In quantum mechanics for instance, the state vector at \(t_0\) may specify probabilities of measurement results at \(t_1\), and various measurement outcomes may lead to different macroscopic configurations at \(t_2\). Hence the configuration of absorbers at \(t_2\) is not determined by the state vector at \(t_0\). Maudlin has argued that the stochasticity of the sources of advanced waves inherent in Cramer’s theory renders his approach inconsistent.

Maudlin considers the situation depicted in Fig. 2. A source \(S\) can emit, at a prescribed time \(t_0\), a particle of approximate speed \(v\). The particle goes either to the left or to the right, with equal probability. To the right of the source is a detector \(A\) at a distance \(R_1\), and a detector \(B\) at a larger distance.
The experiment is set up so that if A has not detected a particle soon after \( t_1 = t_0 + R_1/v \), detector B is quickly moved to a distance \( R_2 \) to the left of the source, in time to detect the incoming particle at \( t_2 = t_0 + R_2/v \). (Note that a practical realization of Maudlin’s experiment would require careful monitoring of the particle’s emission time and speed, as well as velocity spread about the two back-to-back directions. All of this can be implemented within the constraints of the uncertainty principle.)

\[
|\psi\rangle = \frac{1}{\sqrt{2}}(|L\rangle + |R\rangle),
\]  

Figure 2: Detector B quickly moves to the left if and only if detector A does not fire.

Maudlin claims that Cramer’s interpretation cannot deal with this situation. For the retarded wave emitted by the source has the form

\[
|\psi\rangle = \frac{1}{\sqrt{2}}(|L\rangle + |R\rangle),
\]  

where \(|L\rangle\) and \(|R\rangle\) represent states of the particle going to the left or to the right. Detector A, fixed on the right-hand side, always receives the retarded wave of amplitude \(1/\sqrt{2}\), and always sends a confirmation wave of amplitude proportional to \((1/\sqrt{2})(1/\sqrt{2})^* = 1/2\), so that Cramer’s theory correctly predicts that it will absorb the particle with probability 1/2. But detector B receives an offer wave and sends a confirmation wave only when it swings to the left. The confirmation wave again has amplitude proportional to 1/2. Cramer’s theory therefore predicts, according to Maudlin, that B should absorb the particle half the times the offer wave reaches it. But in fact it absorbs it every time the offer wave reaches it. Maudlin concludes that Cramer’s theory collapses.
4 Berkovitz’ and Kastner’s answers

Maudlin’s challenge was answered in two different ways by Berkowitz [19] and Kastner [20]. Both of them make use of the distinction, introduced by Butterfield [21], between big-space and many-spaces probabilities.

Without going into all details, one can say that the distinction is relevant in situations where an experiment can be carried out using different setups, or initial conditions. Take for instance the negative-result experiment introduced in Sec. 2. Suppose the experimenter decides to run it in two different ways, either as described in Sec. 2, or without the larger shell $E_2$. In each run the choice of setup can be made by the experimenter’s direct intervention, or through some automated device picking the setup either deterministically or randomly.

In this context, big-space probabilities are defined by considering the experimental setup $\Sigma$, as well as the system’s initial state $\Lambda$ if it is allowed to change over runs, as random variables just like the measurement outcome $X$. A general probability function $P(\Sigma, \Lambda, X)$ is therefore introduced. The specific probability function of outcomes for a given setup $\Sigma_i$ and a given initial state $\Lambda_k$ is then viewed as a conditional probability, that is,

$$P(X|\Sigma_i, \Lambda_k) = \frac{P(\Sigma_i, \Lambda_k, X)}{P(\Sigma_i, \Lambda_k)}, \quad (4)$$

where

$$P(\Sigma_i, \Lambda_k) = \sum_{\{X\}} P(\Sigma_i, \Lambda_k, X). \quad (5)$$

Many-spaces probabilities, in contrast, do not consider the setup and initial state as random variables, and do not assign them probabilities. Independent probability spaces are defined for each value of the setup and initial state, the outcome being the only random variable. The independent probability functions are denoted as $P_{\Sigma_i, \Lambda_k}(X)$.

In answering Maudlin’s challenge, Berkovitz first points out that Cramer’s offer waves and confirmation waves should better be viewed as forward and backward causal connections. He then argues that the confirmation waves are different in the two cases where detector B in Fig. 2 is or is not swung to the left. For if B is swung, the source receives confirmation waves from both A and B, whereas if B is not swung, the source receives a confirmation wave from A only. The backward causes being different, so should the source’s
initial states be. One can accordingly use $|\psi\rangle$ to denote the source’s initial state in cases where B is swung to the left, and $|\psi'\rangle$ in cases where B is not swung.

Following Butterfield, Berkovitz then argues for the priority of many-spaces probabilities over big-space probabilities, on the grounds that there is little justification for assigning probabilities to states and setups. He then notes that in situations where causal loops are present, one should not expect the many-spaces probabilities (which are properties of the setup and state specification) to coincide with the long-term relative frequencies. This, he claims, answers Maudlin’s challenge, for in the causal loop where B is swung to the left, the long-term relative frequency of detection (equal to 1) should not be expected to coincide with the many-spaces probability of detection in the initial state $|\psi\rangle$ (equal to 1/2). There is a price to pay for this, however. Since one cannot assign probabilities to $|\psi\rangle$ and $|\psi'\rangle$, Cramer’s theory can no longer be used to calculate the unconditional relative frequencies of left and right detection.

It is true that, in general, backward causal connections can have the effect described by Berkovitz. But here the question is whether in Cramer’s theory they do or do not have that effect. I will argue that they most likely do not. The reason is that if we follow Berkovitz’ argument, Cramer’s theory will loose predictive power in contexts much wider than the one introduced by Maudlin. Consider for instance the following two experimental setups: (i) there is only a detector A in Fig. 2; (ii) there is a detector A to the right and a detector B to the left in Fig. 2, both fixed in their respective positions. In both cases, the source receives a confirmation wave from A, while it receives a confirmation wave from B only in case (ii). If different confirmation waves mean different causal connections in the strong sense suggested by Berkovitz, then Cramer’s theory could not be used to predict that A would fire with the same frequency in cases (i) and (ii). Indeed it could not compare any setups where the configuration of any detector would change. This, I submit, entails either that the causal connections carried by the confirmation wave should not be as strong as envisaged by Berkovitz, or that if they are, they should be the same irrespective of B’s position. Support for the latter possibility will be offered in the next section.

In her response to Maudlin’s challenge, Kastner argues that Cramer’s theory will keep its predictive power intact if it uses big-space instead of many-spaces probabilities. This, she claims, implies that Cramer’s account of transactions occurring in pseudotime, an account arguably not essential.
Kastner first points out that a simple inspection of Maudlin’s setup (Fig. 2) already renders the pseudotime account suspect. Indeed the echoing process between emitter and absorbers, which is supposed to determine the absorption probabilities, presumably requires a fixed configuration of absorbers, which is not the case in Fig. 2. An echo between source S and absorber B occurs if and only if no detection has been registered at A.

In Cramer’s approach, when the source in Fig. 2 emits the offer wave \( \langle \psi \rangle \), it also emits the advanced wave

\[
\langle \psi \rangle = \frac{1}{\sqrt{2}} (\langle L \rangle + \langle R \rangle),
\]

propagating backward in time. If the particle is not absorbed by A and, consequently, B swings to the left, the confirmation waves sent by A and B cancel the source’s advanced wave at all times \( t < t_0 \). But if the particle is absorbed by A, no confirmation wave is sent by B. In this case, Kastner argues, nothing will cancel the \( \langle L \rangle \) part of the advanced wave emitted by the source. The upshot is that the total wave configuration at times \( t < t_0 \) is different depending on whether the particle is or is not absorbed by A. Therefore the emission event, although it opens up different possible futures, cannot be considered as a branch point before which the past is fixed.

Kastner then points out that what is common to the two cases where B does or does not swing is the overlap between the offer and confirmation waves between the source and A. This, now taken as a suitable branch point, allows the partitioning of a big probability space into a subspace where the transaction is indeed completed between the source and A, and a subspace where it is completed between the source and B. Both are associated with probabilities of 1/2. Since the partition is based on the connection between the source and A, it does not depend in any way on an eventual echoing between S and B. The pseudotime account of the transaction, therefore, cannot be maintained.

5 A different solution

Berkovitz and Kastner proposed two different ways to meet Maudlin’s challenge. I will offer a third one which, I believe, is much in the spirit of the Wheeler-Feynman theory of advanced actions.
Let us first consider the experimental setup depicted in Fig. 3, which is slightly different than Maudlin’s. In fact the only difference between Fig. 2 and Fig. 3 is that a detector C has been added to the left, farther from the source than detector B. In most interpretations of quantum mechanics, the presence or absence of detector C is completely immaterial, as no particle ever reaches it. Indeed in all cases where a particle emitted by the source is not absorbed by A, detector B swings to the left and absorbs it. The particle therefore never reaches C, and its Schrödinger wave function in no way depends on the presence or absence of that additional detector.

In Cramer’s interpretation, however, the presence of C is relevant. For in cases where the particle is absorbed by A and B does not swing, a confirmation wave is sent by C back to the source. In all cases, therefore, offer waves are sent both to the right and to the left, and confirmation waves are received both from the right and from the left, with amplitudes proportional to \((1/\sqrt{2})^2\). As expected, the probability of absorption on the left side is proportional to the amplitude of the corresponding confirmation wave.

Now how does this argument deal with the problem in Maudlin’s own situation, where no detector sits at C? It does so by making a suitable hypothesis on the long-distance boundary conditions. The simplest such hypothesis is the one made in the original approach of Wheeler and Feynman, who postulated that the universe is a perfect absorber of all radiation emitted within it. Under this assumption, no matter that B does or does not swing, the offer wave emitted by the source to the left will sooner or later reach an absorber, which will send a confirmation wave arriving at the source at \(t_0\) exactly. Just like the \(\langle R|\) component in Eq. \((\text{5})\), the \(\langle L|\) component of the advanced wave emitted by the source will then always be cancelled by a confirmation wave for all \(t < t_0\). The probabilities of absorption at the left and
at the right will both be proportional to the amplitude of the corresponding confirmation waves, that is, to $1/2$.

Thus the Wheeler-Feynman hypothesis of perfect absorption can fulfill the function of detector C in Fig. 3. One should point out, however, that it is not the only assumption that will do so. This is so much the better, since the hypothesis has never achieved consensus. Particles with very low interaction rates, like neutrinos, may never find a suitable absorber. But Cramer has shown [11] that an assumption on the Big Bang singularity can have the same effect on these particles as universal absorption. The idea is that any advanced wave reaching the $t = 0$ singularity backward from $t > 0$ is assumed to be reflected forward with a phase difference of $180^\circ$. The upshot is that the advanced wave sent by an emitter at $t = t_0$ is cancelled for $t < t_0$ by the reflected advanced wave, which for $t > t_0$ reinforces the retarded wave sent by the emitter. To an observer who in the end reinterprets all advanced waves moving backward in time as retarded waves moving forward in time with opposite momentum, reflection from the Big Bang singularity is equivalent to perfect absorption.

To sum up, with either the hypothesis of perfect absorption “à la” Wheeler and Feynman, or Cramer’s assumption about the Big Bang singularity, one can conclude that Fig. 3 correctly describes the complete setup of Maudlin’s experiment.

6 Pseudotime and collapse

In their answers to Maudlin’s challenge, Berkovitz and Kastner relied on two different interpretations of probabilities: Berkovitz used the many-spaces approach, whereas Kastner worked with the big space. In the solution proposed here, by contrast, the distinction is not particularly critical. The setup and initial state can be construed as adequately specified by the experimental protocol in place at $t_0$ (which determines the quantum-mechanical initial wave function). Since the offer and confirmation waves in place at $t_0$ do not depend on whether or not B will swing to the left, the distinction introduced by Berkovitz between initial states $|\psi\rangle$ and $|\psi'\rangle$ is not relevant. Should the experiment be run with different setups or initial wave functions, a many-spaces or a big-space approach could both be put forward.

The solution proposed here also helps to clarify the meaning of the pseudotime account of transactions. On the assumption that the universe is a
perfect absorber (or that advanced waves are reflected at the Big Bang), Cramer’s theory correctly predicts that in the setup of Fig. 2, absorption occurs on the left in 50% of the runs. Yet it so happens that the transaction is completed with the left absorber if and only if detector B has swung to the left. Although the confirmation wave coming from the left originates from a remote absorber just as often as it originates from B, the transaction is never completed with the remote absorber. It is as if the confirmation wave “knew” that it cannot effect a transaction in cases where it is emitted by the remote absorber.

This can be taken as paradoxical, but I suggest it is viewed more aptly as specifying better the significance of a transaction. The whole process is laid out in four-dimensional space-time. The future, though not predictable, is well defined. The offer and confirmation waves must adapt to the requirement that the four-dimensional process be consistent with the boundary conditions. In the present case, these conditions are that B absorbs the particle if and only if A does not absorb it. The forward and backward causal connections must be strong enough to satisfy the boundary conditions, but not so strong as to allow information transfer or macroscopic communication. That tension reflects the delicate locality balance inherent in the quantum world, as well as the transactional interpretation’s objective to avoid the notion of collapse at a specific time.

In a general transaction, offer and confirmation waves are exchanged between the emitter and all possible absorbers. It is constitutive of the transactional interpretation that a confirmation wave sent back from absorber $i$ at the space-time point $(r_i, t_i)$ arrives at the emitter with an amplitude proportional to $|\psi(r_i, t_i)|^2$. This appears to reproduce Born’s rule with no further ado. But in fact the matter is more subtle.

It is well known that if $\psi(r, t)$ is a solution of the one-particle Schrödinger equation, the integral

$$P_{\text{tot}} = \int |\psi(r, t)|^2 \, dr,$$

carried over all three-dimensional space, does not depend on time. The identification of $|\psi(r, t)|^2$ with the particle’s position probability density at time $t$ then implies that the total probability is conserved, as it should. In Cramer’s approach, however, we are instructed to associate the probability of a transaction with $|\psi(r_i, t_i)|^2$. It turns out that in general, an integral similar to the one on the right-hand side of Eq. (7), but with the integrand evaluated at different times, will not represent a conserved probability. Does
this mean that probabilities are not conserved in Cramer’s approach? The answer is no, for the following reason.

Suppose that among all detectors susceptible to send a confirmation wave back to the source, detector 1 receives the offer wave first. Owing to the particle-detector interaction Hamiltonian, the particle and detector wave functions thereafter become entangled, in a process that can be schematized as

\[ \psi(r, t) \Phi^i_D \rightarrow c_1 \psi_1(r, t) \Phi^{(a)}_D + c_2 \psi_2(r, t) \Phi^{(f)}_D. \]  

(8)

Here \( \Phi^i_D \) and \( \Phi^{(a)}_D \) represent ready and activated states of the detector. The normalized wave function \( \psi_1(r, t) \) evolves from the part of \( \psi(r, t) \) that interacts with the detector, while the normalized \( \psi_2(r, t) \) evolves from the part that doesn’t. The coefficients \( c_1 \) and \( c_2 \) satisfy \( |c_1|^2 + |c_2|^2 = 1 \). A process like (8) occurs for each further interaction with each available detector. In the end probability is conserved, not because a conserved integral similar to (7) can be written down with an integrand defined at different times, but because the particle’s reduced density matrix always has unit trace.

This takes care of the probability question, but it raises another issue. As the particle outgoing from the source interacts with various objects, its wave function becomes entangled. Clearly, such entanglement is a necessary condition for a confirmation wave to be sent back to the source, and a transaction to be eventually completed. But it is by no means a sufficient condition. Any entanglement process that is easily reversible (i.e. one between the outgoing particle and another microscopic object) ought not to give rise to a confirmation wave. For if it did lead to a transaction, the latter would be reversible, which is impossible. A transaction represents a completed quantum-mechanical process.

The question now is: What distinguishes a reversible entanglement process, which gives rise to no confirmation wave and no transaction, from an irreversible one, which does give rise to a confirmation wave and, possibly, to a transaction. Of course, this question has no answer within the strict Hilbert space formalism of quantum mechanics, where all entanglement is in principle reversible. The upshot is that a transaction finds no room within the limits of that formalism. Just like the notion of a classical apparatus in the Copenhagen interpretation, or the one of wave function collapse in von Neumann’s theory of measurement, the notion of a transaction must be added to the minimal quantum-mechanical formalism. In particular, the transactional interpretation cannot be considered complete unless the conditions for the
possible occurrence of a transaction are spelled out in detail.

I should note that in contrasting collapse interpretations with his own, Cramer pointed out that collapse models “beg the question of borders: Where precisely is the border between macrophysics and microphysics and the border at which irreversibility begins?” [12, p. 683] He seemed to imply that this problem does not show up in the transactional interpretation. But elsewhere he acknowledged that “[the transactional interpretation’s] nonlocal collapse mechanism is strictly at the interpretational level. It cannot supply mechanisms missing from the formalism.” [13, p. 235] See also Ref. [22] for additional remarks on the Copenhagen and transactional interpretations.

7 Conclusion

Cramer’s transactional interpretation uses the notion of advanced waves in an effort to make paradoxical quantum-mechanical processes more intelligible. I have argued that the stochastic character of quantum mechanics and the resulting unpredictability of the future does not introduce inconsistency or loss of predictive power in Cramer’s theory. The notion of transaction, however, lies outside the minimal formalism, and is in need of further specification.

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