Article

A Physical Basis for the Second Law of Thermodynamics: Quantum Nonunitarity

Ruth E. Kastner

University of Maryland, College Park, MD 20742, USA; rkastner@umd.edu

Abstract: It is argued that if the non-unitary measurement transition, as codified by Von Neumann, is a real physical process, then the 'probability assumption' needed to derive the Second Law of Thermodynamics naturally enters at that point. The existence of a real, indeterministic physical process underlying the measurement transition would therefore provide an ontological basis for Boltzmann's *Stosszahlansatz* and thereby explain the unidirectional increase of entropy against a backdrop of otherwise time-reversible laws. It is noted that the Transactional Interpretation (TI) of quantum mechanics provides such a physical account of the non-unitary measurement transition, and TI is brought to bear in finding a physically complete, non-*ad hoc* grounding for the Second Law.

Keywords: Second Law of Thermodynamics; irreversibility; entropy; H-Theorem; transactional interpretation; wave function collapse

1. Introduction

Irreversible processes are described by the Second Law of Thermodynamics, the statement that entropy S can never decrease for closed systems: $\frac{dS}{dt} \geq 0$. This law is corroborated ubiquitously at the usual macroscopic level of experience. However, there remains great uncertainty and debate regarding exactly how it is that these commonplace irreversible processes arise from an ostensibly time-reversible level of description. Specifically, it is commonly assumed that the quantum level obeys only the unitary dynamics of the time-dependent Schrödinger equation, which is time-reversible. In addition, classical mechanics can be obtained as the small-wavelength limit of the quantum evolution, as Feynman showed in his sum-over-paths approach [1]. So where does the observed macroscopic irreversibility enter?

Boltzmann famously introduced irreversibility into his "H-Theorem," an attempted derivation of the Second Law, through his *Stosszahlansatz* (assumption of molecular chaos)[2]. This assumption consists of treating molecular and atomic state transitions as stochastic and independent, such that the joint probabilities applying to the state transitions in any given interaction are taken as equal to the product of the individual probabilities. At the quantum level, the same sort of statistical independence arises in 'master equations' specifying the changes in the probabilities of occupation of states of the interacting micro-systems comprising a macroscopic system of interest.

Thus the irreversibility in both the quantum and classical cases arises due to the presence of the *Stosszahlansatz* in various forms. (For a careful review of the historical debate concerning the content and bearing of the *Stosszahlansatz*, see Brown, Myrvold, and Uffink [3]). The H-Theorem has rightly been questioned as a circular, question-begging way of obtaining irreversibility. Loschmidt's reversibility challenge is probably the most well known criticism [4]. In addition, Poincaré's insight into the weakness of the theorem is evident in his observation that it contains "reversibility in the premises and irreversibility in the conclusion.''[5] He went on to conclude: "Thus the difficulties that concern us [with the kinetic theories] have not been overcome, and it is possible that they never will be. This would amount to a definite condemnation of mechanism, if the experimental laws should prove to be distinctly different from the theoretical ones."

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 25 January 2017 doi:10.20944/preprints201701.0108.v1

Peer-reviewed version available at Entropy 2017, 19, 106; doi:10.3390/e19030106

Meanwhile, Sklar has noted that "[t]he status and explanation of the initial probability assumption remains the central puzzle of non-equilibrium statistical mechanics"[6]. However, if there is a real, lawlike (even if indeterministic) physical origin for this statistical description of the state transitions of component systems, then the second law follows nomologically and non-circularly. In addition, Poincaré's suspicion that mechanism (meaning determinism in this context) is not the whole story behind the observed phenomena would be corroborated by a finding that ontological indeterminism is a crucial component of deriving the experimentally observed laws in an exact, self-consistent, and non-circular way.

Thus, the argument to be presented is:

- The H-Theorem and its quantum mechanical analogs are dependent on an unjustified premise P: the relevant processes are describable by statistically independent Kolmogorov (classical, Boolean) random variables.
- If P ceases to be a premise and becomes physically justified based on a specific model of quantum processes, then the H-Theorem becomes sound, and the Second Law is fully explained without inconsistency or circularity.

Such a model will be presented herein.[1] First, however, let us briefly review the basic problem.

2. Reversible vs non-reversible processes

Classical laws of motion are in-principle reversible with respect to time. There is a one-to-one relationship between an input *I* and an output *O*, where *I* and *O* are separated by a time interval Δt. If Δt is taken as positive, then *I* is the cause and *O* is the effect. If we reverse the sign of Δt, then the roles of the output and input are simply exchanged; the process can just as easily run backwards as forwards. The same applies to quantum processes described by the Schrödinger equation: the input and output states are linked in a one-to-one relationship by deterministic, unitary evolution.

Moreover, it is well established that the 'statistical operator' (density operator), ρ, applying to a quantum system obeys a unitary, time reversible dynamics, analogous to the Liouville equation for the phase space distribution of microstates in classical statistical mechanics. The general definition of the density operator (applying either to a pure or mixed state) is:

$$\rho = \sum_i P_i |\Psi_i\rangle\langle\Psi_i| \tag{1}$$

where P_i is the probability that the system is in the pure state $|\Psi_i\rangle$, and the P_i sum to unity. The states $|\Psi_i\rangle$ need not be orthogonal, so in general $\{|\Psi_i\rangle\}$ is not a basis.

From the Schrödinger equation and its adjoint, ones finds the time-evolution of ρ:

$$\frac{\partial\rho}{\partial t} = \frac{-i}{h}[H,\rho] \tag{2}$$

where *H* is the Hamiltonian. It is important however to note that ρ is not an observable; this is reflected in the sign difference between its time dependence and that of an observable *O*, which obeys $\frac{\partial O}{\partial t} = \frac{i}{h}[H,O]$. Significantly, ρ is defined independently of any particular basis. It must be distinguished from the so-called "density matrix," which we'll denote here by $\tilde{\rho}$. The latter is a particular *representation* of the density operator with respect to a given basis. Normally, this distinction is not considered particularly significant. However, in the proposed analysis, irreversibility enters through a non-unitary measurement transition yielding a diagonal density matrix whose basis is determined by the measurement process. The resulting density matrix represents a proper mixed state (one which can be interpreted epistemically—see, e.g. Hughes [8] for a discussion of this concept).

[1] The present author is well aware that there is a vast literature on this topic, and this paper makes no pretense of giving an exhaustive account of the research in this area. The present work provides an exact physical basis for the transition from unitary-only, reversible evolution to the explicitly irreversible evolution found in master equations, as opposed to extant approximate methods that attempt to account for thermodynamical phenomena under a unitary-only assumption (e.g., [7]). The reader is free to peruse the literature and to decide for him or herself which is the most effective and elegant solution to the problem pointed to by Sklar, and much earlier by Loschmidt, Poincaré, and others.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 25 January 2017 doi:10.20944/preprints201701.0108.v1

Peer-reviewed version available at *Entropy* **2017**, *19*, 106; doi:10.3390/e19030106

In contrast to the unitary evolution (2), non-unitary evolution such as that described by von Neumann's "Process 1," or measurement transition, is indeterministic [9]. An input pure state I is transformed to one of many possible output states O_i, elements of a particular basis, with no causal mechanism describing the occurrence of the observed output state O_k.[2] The different possible outcomes are statistically weighted by probabilities P_i according to the Born Rule. As a result of the measurement transition, the system is represented by a diagonal mixed state $\tilde{\rho}$. This one-to-many transition is inherently irreversible; once a final state occurs, the original state is not accessible to it through simple time reversal.

Of course, the status of the non-unitary measurement transition has long been very unclear. It is often thought of as epistemic in nature—i.e., describing only a Bayesian updating of an observer's knowledge. Such an epistemic view of quantum measurement has its own interpretive challenges, which we will not enter into here;[3] but it also can provide no ontological basis for the observed asymmetry described by the Second Law. On the other hand, if the measurement transition is a real (indeterministic) physical process, as suggested above, it is clearly a candidate for the ontological introduction of stochastic randomness--describable by probabilities such as those in master equations--and the resulting irreversibility described by the Second Law. In fact, Von Neumann himself showed that his 'Process 1' is irreversible and always entropy-increasing [5]. However, he seemed to have veered away from using that fact in deriving the Second Law, because he thought of the measurement transition as dependent on an external perceiving consciousness, and as such not a real physical process.

3. Standard Approaches to the Second Law; "Smuggling In" Non-unitarity

A typical 'derivation' of the Second Law begins with unitary evolution to obtain the basic transition rates between various states, but ends up with a master equation from which one finds that the time rate of change in entropy is always positive (or zero for equilibrium). We'll consider this seeming paradox in what follows. First, recall that a master equation relates the change in the probability P_i that a system is in state $|i>$ to the transition rates R_{ij} between that state and other states $|j>$. Specifically:

$$\frac{dP_i}{dt} = \sum_j R_{ij}P_j - R_{ji}P_i \equiv [M]P_i \qquad (3)$$

where [M] is the 'master operator.' Each diagonal element of [M] is the negative of the sum of all the off-diagonal elements in the same column (which are all positive). This property gives rise to a decaying exponential time-dependence, yielding an irreversible tendency to an equilibrium state, independently of the initial state of the system. As an illustration, consider a simple example in which the transition probabilities R_{ij} between states 1 and 2 are both ½. The solutions for P_i (i=1,2) will be:

$$P_1(t) = \frac{1}{2} + \frac{P_1(0) - P_2(0)}{2}e^{-2t}$$

$$P_2(t) = \frac{1}{2} + \frac{P_2(0) - P_1(0)}{2}e^{-2t} \qquad (4)$$

[2] Of course, hidden variables theories attempt to provide a causal mechanism by 'completing' quantum theory, but here we consider quantum mechanics as already complete and simply in need of a direct-action interpretation.

[3] For example, the Pusey-Rudolph-Barrett theorem [10] rules out most statistical interpretations of the quantum state.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 25 January 2017 doi:10.20944/preprints201701.0108.v1

Peer-reviewed version available at Entropy 2017, 19, 106; doi:10.3390/e19030106

We can see from the above that with increasing time, the second term, containing the initial state information, approaches zero and one is left with the equilibrium distribution $P_1(t_\infty) = P_2(t_\infty) = \frac{1}{2}$. Thus, the equilibrium distribution is the final result, without regard to the initial state. Determinism is broken.

Let us now examine how irreversibility 'sneaks in' between the time-reversible evolution of the basis-independent density operator ρ (obeying the Liouville equation) and that of the basis-dependent diagonal density matrix $\tilde{\rho}$ (whose diagonal entries P_i obey master equations employing the transition rates between the occupied states $|i>$). It must be noted that in this context, the latter is not just an arbitrary representation of the density operator; rather, it must reflect a physical determinacy of the relevant micro-properties in order to be used in the master equation that describes entropy increase. That determinacy of properties results from non-unitary projection into a particular distinguished basis.[4] Pauli's "random phase assumption" [11] is behind this crucial distinction.

First, recall that the Von Neumann entropy S_{VN} is defined in terms of the density operator in a basis-independent way as:

$$S_{VN} = -Tr(\rho ln\rho) \tag{5}$$

Now, in order to employ the back-and-forth 'detailed balance' between states needed for master equations, one must work within a particular basis $\{|i>\}$ corresponding to transitions between the relevant states. So rather than work with the density operator, one must use a diagonal density matrix:

$$\tilde{\rho} = \sum_i P_i \, |i\rangle\langle i| \tag{6}$$

where P_i is the probability that the system is in state $|i\rangle$. In that basis, (5) becomes

$$S = -\sum_i (P_i ln P_i) \tag{7}$$

This form (the Shannon entropy) is well-defined only for the basis in which ρ is diagonal, and that is the "smuggling in" of irreversibility. In effect, it assumes that the system has been projected into that basis, a non-unitary process.

3. The Transactional Interpretation

In view of the above considerations regarding the "Process 1" measurement transition, we explore herein the view that the puzzle of the "initial probability assumption" referred to by Sklar is traceable to the measurement transition. The Transactional Interpretation (TI) provides an ontological basis for the measurement transition, lacking in Von Neumann's formulation, and as such is in a position to solve this 'central puzzle.'

3.1. Background

---

[4] There is, of course, the special case in which an initial pure state $|\Psi>$ happens to be an eigenvector of the observable (or a commuting one) being measured; in this case the post-measurement density matrix appears 'pure' in that *(N×N)-1* of its entries are all zeros with a single value of unity. It is important to note, however, that irreversibility enters (entropy increases) even in the case of an initial pure state, as long as physical projection into that eigenspace has occurred. This can be seen by inputting the initial pure state probabilities (unity and zero) to solutions (4). It must be remembered that, in the absence of measurement (absorption in TI), a pure state is just a vector, independent of basis representation. If measurement occurred relative to a different basis, the same initial pure state $|\Psi>$ would end up mixed (i.e. described by a diagonal density matrix with entries different from unity and zero). The relevance of absorption for defining the physically applicable basis is discussed in Section 3.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 25 January 2017 doi:10.20944/preprints201701.0108.v1

Peer-reviewed version available at *Entropy* **2017**, *19*, 106; doi:10.3390/e19030106

Before turning to the specifics of TI, it is worth noting that Einstein himself posited a fundamental quantum irreversibility associated with the particle-like aspect of light. Since it is the latter that accounts for the measurement transition and accompanying irreversibility in the TI model, let us revisit his comments on this point:

> In the kinetic theory of molecules, for every process in which only a few elementary particles participate (e.g., molecular collisions), the inverse process also exists. But that is not the case for the elementary processes of radiation. According to our prevailing theory, an oscillating ion generates a spherical wave that propagates outwards. The inverse process does not exist as an elementary process. A converging spherical wave is mathematically possible, to be sure; but to approach its realization requires a vast number of emitting entities. *The elementary process of emission is not invertible*. In this, I believe, our oscillation theory does not hit the mark. Newton's emission theory of light seems to contain more truth with respect to this point than the oscillation theory since, first of all, the energy given to a light particle is not scattered over infinite space, but remains available for an elementary process of absorption. [12]; emphasis added]

Einstein thus recognizes that, for a single quantum, all the energy represented by an isotropically propagating wave ends up being delivered to only a single absorbing system; thus the process acquires a final anisotropy (i.e., a directional momentum) not present initially. Recalling our discussion about the transforming of a density operator (which could be a pure state) to a diagonal density matrix (which is a mixed state), we see that the final anisotropy is the realization of one of the momentum components of the mixed state—i.e., collapse. The latter is a feature of the particle-like aspect of light, and that is what makes the process non-invertible. (This microscopic origin of irreversibility was also pointed out by Doyle [13].) As we will see, TI acknowledges both a wavelike and particlelike aspect to light; however it is the latter that brings about the irreversibility, just as Einstein noted.

The Transactional Interpretation was first proposed by Cramer [14] based on the Wheeler-Feynman direct-action theory of classical fields [15,16]. Its recent development by the present author [17-22] is based on the fully relativistic direct-action quantum theory of Davies [23,24]. In view of this relativistic development, the model is now referred to as the Relativistic Transactional Interpretation (RTI). It should perhaps be noted at the outset that TI is not considered a 'mainstream' interpretation, since its underlying model of fields—the direct-action theory—has historically been viewed with various degrees of skepticism. Nevertheless, despite the counterintuitive nature of the model, which includes advanced solution to the field equations, there is nothing technically wrong with it. (See [22] for why Feynman's abandonment of his theory was unnecessary.) Moreover, no less a luminary than John A. Wheeler was recently attempting to resurrect the direct-action theory in the service of progress toward a theory of quantum gravity. It's worth quoting from that paper here, in order to allay any concerns about the basic soundness of the model:

> [WF] swept the electromagnetic field from between the charged particles and replaced it with "half-retarded, half advanced direct interaction" between particle and particle. It was the high point of this work to show that the standard and well-tested force of reaction of radiation on an accelerated charge is accounted for as the sum of the direct actions on that charge by all the charges of any distant complete absorber. Such a formulation enforces global physical laws, and results in a quantitatively correct description of radiative phenomena, without assigning stress-energy to the electromagnetic field. ([25], p. 427)

Thus, there is no technical reason to eliminate the direct-action approach, and every reason to reconsider it in connection with such longstanding problems as the basis of the Second Law.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 25 January 2017 doi:10.20944/preprints201701.0108.v1

Peer-reviewed version available at *Entropy* **2017**, *19*, 106; doi:10.3390/e19030106

3.2 Measurement in TI

An overview of TI is provided in [21] ; we will not repeat that background information in this section, but will focus here on the TI account of the measurement transition. For present purposes it is sufficient to recall that according to TI, the usual quantum state or 'ket' $|\Psi\rangle$ is referred to as an 'offer wave' (OW), or sometimes simply 'offer' for short. The unfamiliar and counter-intuitive aspect of the direct action theory is inclusion of the solution to the complex conjugate (advanced) Schrodinger equation; this is the dual or 'brac,' $\langle X_i|$, describing the response of one or more absorbers X_i to the component of the offer received by them. The advanced responses of absorbers are termed 'confirmation waves' (CW).[5] Specifically, an absorber X_k will receive an offer wave component $\langle X_k|\Psi\rangle|X_k\rangle$ and will respond with a matching adjoint confirmation $\langle\Psi| X_k\rangle\langle X_k|$. The product of the offer/confirmation exchange is a weighted projection operator, $\langle X_k|\Psi\rangle\, \langle\Psi| X_k\rangle\, |X_k\rangle\langle X_k| = |\langle X_k|\Psi\rangle|^2|X_k\rangle\langle X_k|$. Clearly, the weight is the Born Rule, and this is how TI provides a physical origin for this formerly ad hoc rule. When one takes into account the responses of all the other absorbers { X_i }, what we have is the von Neumann measurement transition from a pure state to a mixed state $\tilde{\rho}$:

$$|\Psi\rangle \;\rightarrow\; \tilde{\rho} = \sum_i |\langle\Psi|X_i\rangle|^2|X_i\rangle\langle X_i| \tag{8}$$

In the absence of absorber response, the emitted offer wave (OW), $|\Psi\rangle$, is described by the unitary evolution of the time-dependent Schrodinger equation. Equivalently, in terms of a density operator $\rho = |\Psi\rangle\langle\Psi|$, its evolution can be described by its commutation with the Hamiltonian, as in (2).[6] However, once the OW $|\Psi\rangle$ prompts response(s) $\langle X_i|$ from one or more absorbers $\{X_i\}$, the linearity of this deterministic propagation is broken, and we get the non-unitary transformation (8).

Thus, according to TI, absorber response is what triggers the measurement transition. (Precise quantitative, though indeterministic, conditions for this response are discussed in [19].) It is the response of absorbers that transforms the density operator ρ, not committed to any basis, to a diagonal density matrix $\tilde{\rho}$, now physically committed to the basis defined by the absorber response, as shown in (8). And in fact it is here that the "probability assumption" enters in a physically justified manner, since the system is now physically described by a set of random variables (the possible outcomes) subject to a Kolmogorov (classical) probability space.

The second step in the measurement transition is non-unitary collapse to one of the outcomes $|X_k\rangle\langle X_k|$ from the set of possible outcomes {i} represented by the weighted projection operators $|\langle\Psi|X_i\rangle|^2|X_i\rangle\langle X_i|$ in the density matrix $\tilde{\rho}$ above. This can be understood as a generalized form of spontaneous symmetry breaking, a weighted symmetry breaking: i.e., actualization of one of a set of possible states where in general the latter may not be equally probable. This is where Einstein's particle-like aspect enters. For example, an emitted isotropic (spherical) electromagnetic offer wave is ultimately absorbed by only one of the many possible absorbers that responded to it with CWs. The transferred quantum of electromagnetic energy acquires an anisotropy: a single directional momentum corresponding to the orientation of the 'winning' absorber (which is called the *receiving absorber* in RTI). All the other possible momentum directions are not realized. The anisotropic directedness of the actualized spatial momentum component corresponds to the particle-like aspect or photon. Since absorption involves a precise amount of energy, this process singles out the energy/momentum basis as distinguished. We return to the latter issue when we consider the relativistic level, in Section 4 below.

Thus, the measurement transition defines the point at which the unitary evolution ceases to apply, and the nonunitary 'master equation,' with probabilistic transition rates, enters as the correct physical description. Master equations necessarily work with well-defined probability spaces, with respect to particular bases corresponding to physically realized state transitions between emitters

---

[5] As their names indicate, both of these objects are wavelike entities—specifically, they are deBroglie waves.

[6] However, TI is best understood in the Heisenberg picture, in which the observables carry the time dependence and the offer wave is static; this is to be discussed in a separate work.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 25 January 2017 doi:10.20944/preprints201701.0108.v1

Peer-reviewed version available at *Entropy* **2017**, *19*, 106; doi:10.3390/e19030106

and absorbers in the studied thermodynamic system (e.g., a box of gas). Master equations cannot therefore apply to a system in the absence of absorber response, whose description is a ket $|\Psi\rangle$ or density operator ρ not committed to any particular basis (i.e., physical context). The apparent contradiction between the deterministic time-evolution of the density operator (2) and the indeterministic, probabilistic evolution respresented by master equations can be thereby resolved; the probabilistic description characterizing the transition from unitary to non-unitary evolution corresponds to the physical measurement transition triggered by absorber confirmations, which take the density operator ρ to the relevant density matrix , $\tilde{\rho}$.

In view of the above, it is apparent that a physically real measurement transition naturally fixes the basis (i.e. provides the context justifying (6)) and thus yields the well-defined probabilistic behavior instantiating Boltzmann's Stosszahlansatz. If interacting systems are engaging in continual emission/absorption events constituting 'Process 1,' these project the systems into specific quantum states, destroying the quantum coherence represented by the Von Neumann entropy (5). Between confirming interactions (those being inelastic as opposed to elastic), component systems may be described by deterministic (unitary) evolution; but with every such interaction, that evolution is randomized through the underlying quantum non-unitarity.

Thus, it is important to take into account that interacting atoms and molecules undergo state changes not simply due to elastic collisions (as in the usual classical picture), but due to inelastic interactions; i.e., absorption and re-emission of thermal photons. According to RTI, these are all transactions, accompanied by non-unitary collapses, and are therefore truly random processes. The thermodynamical implications are clear: in a closed interacting system described by the Second Law (such as a box of gas with internal energy U), the component systems are continually undergoing internal state changes, chiefly thermal excitations and de-excitations. Each such process is inherently random according to RTI. That is, the statistical description that Boltzmann derived based on his *Stosszahlansatz* is based on a real physical process.

4. The Relativistic Level: Further Roots of the Arrow of Time

At the deeper, relativistic level of RTI, the generation of absorber response (i.e. a confirmation) is itself a stochastic process described (in part) by coupling amplitudes between fields. For example, the random Poissonian probabilistic description of the decay of an atomic electron's excited state is understood in the transactional picture as reflecting a real ontological indeterminacy in the generation of both an offer and confirmation for the photon emitted. Details of the transactional model of the inherently probabilistic nature of atomic decays and excitations are given in [19]. The same basic picture applies to other kinds of decays (i.e. of nuclei or composite quanta), since all such decays occur due to coupling among the relevant fields.

Considering the relativistic level also allows us to identify a basic source of temporal asymmetry corresponding to that pointed out by Einstein above. In the direct-action theory, the state of the quantum electromagnetic field resulting from absorber response to the basic time-symmetric propagation from an emitter is a Fock state (or superposition of Fock states)[19]. These correspond to 'real photons; they are quantized, positive-energy excitations of the field (this applies to antiparticles as well; see [22]). Such states can be represented by the action of creation operators $\hat{a}^{\dagger}$ on the vacuum state of the field. E.g., a single photon state of energy k is given by:

$$|k\rangle = \hat{a}^{\dagger}{}_{k}|0\rangle$$

Meanwhile, the confirming response, a 'brac' or dual ket $\langle k|$, can be represented as the annihilation operator $\hat{a}_k$ acting to the left on the dual vacuum, i.e.:

$$\langle k| = \langle 0|\hat{a}_k$$

The relevant point is that there is an intrinsic temporal asymmetry here: *a field excitation must be created before it can be destroyed* (or, equivalently, responded to by an absorbing system). This seemingly obvious and mundane fact is actually a crucial ingredient in the origin of the temporal arrow: any emission must precede the corresponding absorption. An emission event therefore must always be in the past relative to its matching absorption event. This is simply because one cannot destroy something that does not exist: a thing must first exist in order to be destroyed. The basic

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 25 January 2017 doi:10.20944/preprints201701.0108.v1

Peer-reviewed version available at Entropy 2017, 19, 106; doi:10.3390/e19030106

relativistic field actions of creation and annihilation therefore presuppose temporal asymmetry. This asymmetry is reflected in the distinctly different actions of the creation and annihilation operators on the vacuum state:

$$\hat{a}^{\dagger}{}_k|0\rangle = |k\rangle; \quad \text{whereas} \quad a_k|0\rangle = 0.$$

Thus, if one tries to annihilate something that doesn't exist, one gets no state at all—not even the vacuum state.

The above is why the indeterministic collapse to one out of many possible outcomes also yields a temporal directionality—i.e., an arrow of time. The chosen outcome always corresponds to transfer of a quantum of energy (and, in general, other conserved quantities such as momentum, angular momentum, etc). Energy is the generator of temporal displacement, and since a quantum must be created before it is destroyed, the energy transfer always defines a temporal orientation *from* the emitter (locus of creation) *to* the absorber (locus of annihilation). Moreover, the delivered energy is always positive, corresponding to a positive temporal increment [22].[7]

Finally, it should be noted that taking the relativistic level into account provides a way of 'breaking the symmetry' of the various possible observables. It is commonly supposed that there is no fundamental way of identifying any distinguished observable (or set of observables), but that view arises from taking the nonrelativistic theory as a complete and sufficient representation of all the relevant aspects of Nature, when it is not: Nature is relativistic, and the nonrelativistic theory is only an approximate limit. At the relativistic level of quantum field theory, there is no well-defined position observable, since position state vectors are non-orthogonal; this fact provides a natural reason to consider the spacetime parameters as ineligible for a privileged basis.

In any case, at all levels, there is a fundamental distinction between the spacetime description and the energy/momentum description: the spacetime indices parametrize a symmetry manifold, while energy and momentum are conserved physical quantities (they are the Noether currents generating the symmetry properties of the spacetime manifold). In that sense, the two sorts of descriptors (spacetime vs energy/momentum) are very different physically. Moreover, there is no time observable, even at the nonrelativistic level. Thus, even apart from relativistic considerations, there are sound physical reasons to demote the spacetime quantities to mere parameters and to treat the energy/momentum basis as privileged. This approach is in contrast to unitary-only treatments, which typically help themselves to features of our macroscopic experience (e.g., apparent determinacy of position or at least quasi-localization of systems of interest) in order to specify preferred observables and/or Hilbert Space decompositions, rather than providing a specific theoretical justification for these choices at the fundamental microscopic level. In the approach presented here, quasi-localization arises because of the collapse to a particular spatial momentum singling out the receiving absorber, even though the distinguished basis, describing the transferred physical quantity, is energy/momentum.

5. Conclusion

It has been argued that if the non-unitary measurement transition of Von Neumann is a physically real component of quantum theory, then the representation of the system(s) under study by diagonal density matrices, subject to a probabilistic master equation description relative to a distinguished basis, becomes physically justified. This rectifies a weakness in the usual approach, which merely helps itself to the convenient basis and accompanying probabilistic description (effectively Pauli's "random phase assumption") without any theoretical justification. Once we have

[7] The direct action theory is subject to a choice of boundary conditions for the superposition of the time-symmetric fields from emitters and absorbers leading to the free field component needed for real (on-shell) energy propagation. The choice discussed herein corresponds to Feynman propagation. It is possible to choose Dyson rather than Feynman propagation, but the resulting world is indistinguishable from our own; the definition of 'negative' vs 'positive' energy is just a convention in that context. For further discussion of this issue, in terms of Gamow vectors and resulting microscopic proper time asymmetry, see [26].

Peer-reviewed version available at *Entropy* **2017**, *19*, 106; doi:10.3390/e19030106

that justification, we have the microscopic irreversibility needed to make the H-theorem consistent and non-circular.

According to the TI account of measurement, a quantum system undergoes a real, physical non-unitary state transition based on absorber response, which projects it into a Boolean probability space defined with respect to the observable being measured (typically energy in the context of thermodynamics). Thus the system's probabilistic description by random variables is justified; the non-unitary measurement transition can be understood as the physical origin of the 'initial probability assumption' referred to as puzzling by Sklar. In this model, it ceases to be an assumption and can be seen as describing a physical feature of Nature.

Another way to understand the irreversibility inherent in master equations such as (3), in contrast to the Liouville equation (2), is that the superposition of the two unitary processes from state i to state j and the reverse, from j to i, is inherently non-unitary. This is demonstrated by the exponentially decaying solutions (4). But the master equation (as opposed to the Liouville equation) is only justified if there is a Boolean probability space for the occupation of the states. This corresponds to the Shannon entropy rather than to the von Neumann entropy, in that the former singles out the basis for which the system has determinate properties. The determinacy arises through non-unitary collapse to the mixed state, which the von Neumann entropy omits. Thus, the master equations leading to entropy increase are strictly applicable only by way of non-unitarity; the latter is crucial in order to give a consistent derivation of the Second Law from the microscopic physics. Macroscopic irreversibility arises naturally from microscopic irreversibility.

In addition, the relativistic level of TI (referred to as RTI) provides a basis for the directionality of the irreversibility inherent in the measurement transition, thereby establishing an arrow of time consistent with the Second Law. In this respect, the arrow of time is not *explained by* entropy increase; rather, it is a component of the *explanation for* the increase in the entropy of closed systems towards what we call "the future."

Acknowledgments. The author would like to thank two anonymous referees for valuable comments.

References

1. Feynman, R. P.; Hibbs, A. R. *Quantum Mechanics and Path Integrals*. New York: McGraw-Hill, 1965.
2. Boltzmann,L. "Weitere Studien über das Wärmegleichgewicht unter Gasmolekülen." *Sitzungsberichte Akademie der Wissenschaften* **1872**, 66, 275-370.
3. Harvey R. Brown, Wayne Myrvold, Jos Uffink. Boltzmann's H-theorem, its discontents, and the birth of statistical mechanics. Studies in History and Philosophy of Modern Physics 40 (2009) 174–19
4. Loschmidt, J. *Sitzungsber. Kais. Akad. Wiss. Wien, Math. Naturwiss. Classe* **1876**, 73, 128–142.
5. Poincare, H. (1893). Le mecanisme et l'experience. Revue de Metaphysique et de Morale 1, 534–53.
6. Sklar, L. "Philosophy of Statistical Mechanics", The Stanford Encyclopedia of Philosophy (Fall 2015 Edition), Edward N. Zalta (ed.), URL = <http://plato.stanford.edu/archives/fall2015/entries/statphys-statmech/>. Accessed on 12 December 2016.
7. Popescu, S., Short, A., and Winter, A. Entanglement and the foundations of statistical mechanics. *Nature Physics* 2, 754-758 (2006).
8. Hughes, R.I.G. The Structure and Interpretation of Quantum Mechanics. Cambridge: Harvard University Press, 1992. Chapter 5.
9. Von Neumann, J. *Mathematical Foundations of Quantum Mechanics*. (Trans: Beyer, R.T.) Princeton: Princeton University Press, 1955, pp. 347-445.
10. Pusey, M., Barrett, J., and Rudolph,T. On the Reality of the Quantum State. *Nature Physics* 8, 475–478 (2012) doi:10.1038/nphys2309
11. Pauli, W. *Festschrift zum 60sten Geburtstag A. Sommerfelds*. Hirzel, Leipzig **1928**, p. 30.
12. Einstein, A. "On the Development of Our Views Concerning the Nature and Constitution of Radiation." *Einstein Collected Papers* **1909**, 2, p.387.
13. Doyle, R. O. "The continuous spectrum of the hydrogen quasi-molecule." *J. Quant. Spectrosc. Radiat. Transfer* **8**, 1555–1569 (1968).

14. Cramer J. G. ``The Transactional Interpretation of Quantum Mechanics." *Reviews of Modern Physics* 58, 647-688, 1986.
15. Wheeler, J.A. and R. P. Feynman, "Interaction with the Absorber as the Mechanism of Radiation," Reviews of Modern Physics, 17, 157–161 (1945).
16. Wheeler, J.A. and R. P. Feynman, "Classical Electrodynamics in Terms of Direct Interparticle Action," Reviews of Modern Physics, 21, 425–433 (1949).
17. Kastner, R. E. "The New Possibilist Transactional Interpretation and Relativity." Fnd. of Phys. **2012**, 42, 1094-1113.
18. Kastner, R. E. *The Transactional Interpretation of Quantum Mechanics: The Reality of Possibility*. Cambridge: Cambridge University Press, 2012.
19. Kastner, R. E. "On Real and Virtual Photons in the Davies Theory of Time-Symmetric Quantum Electrodynamics," *Electronic Journal of Theoretical Physics* **2014**, 11(30), 75–86.
20. Kastner, R. E. "The Emergence of Spacetime: Transactions and Causal Sets," in Licata, I. (Ed.), *Beyond Peaceful Coexistence*. Singapore: World Scientific, 2016.
21. Kastner, R. E. "The Transactional Interpretation: an Overview," *Philosophy Compass* **2016,** 11(12), 923-932.
22. Kastner, R. E. "Antimatter in the direct-action theory of fields," **2016**, *Quanta 5(1),* pp. 12-18. arXiv:1509.06040
23. Davies, P. C. W. Extension of Wheeler-Feynman Quantum Theory to the Relativistic Domain I. Scattering Processes," *J. Phys. A: Gen. Phys*. **1971**, 6, p. 836
24. Davies, P. C. W."Extension of Wheeler-Feynman Quantum Theory to the Relativistic Domain II. Emission Processes," J. Phys. A: Gen. Phys. **1972**, 5, p. 1025.
25. Wesley, D. and Wheeler, J. A., "Towards an action-at-a-distance concept of spacetime," In *Revisiting the Foundations of Relativistic Physics*: *Festschrift in Honor of John Stachel*, Boston Studies in the Philosophy and History of Science (Book 234), A. Ashtekar et al, eds.; Kluwer Academic Publishers, **1972**, pp. 421-436.
26. Gaioli, F.H., Garcia-Alvarez, E.T. & Castagnino, M.A. "The Gamow Vectors and the Schwinger Effect*." Int J Theor Phys* **1997**, 36, p. 2371. doi:10.1007/BF02768930