S.I.: FORM, STRUCTURE AND HYLOMORPHISM

Check for updates

Thermal substances: a Neo-Aristotelian ontology of the quantum world

Robert C. Koons[1]

Abstract

The paper addresses a problem for the unification of quantum physics with the new Aristotelianism: the identification of the members of the category of substance (ousia). I outline briefly the role that substance plays in Aristotelian metaphysics, leading to the postulating of the Tiling Constraint. I then turn to the question of which entities in quantum physics can qualify as Aristotelian substances. I offer an answer: the theory of thermal substances, and I construct a fivefold case for thermal substances, based on the irreversibility of time, the definition of thermodynamic concepts, spontaneous symmetry breaking, phase transitions, and chemical form.

Keywords Aristotle · Quantum physics · Substance · Hylomorphism · Emergence · Substantial form · Philosophy of chemistry · Thermodynamics · Superselection · Measurement problem · Aristotelian metaphysics

As I have argued elsewhere (Koons 2018a, b), the quantum revolution in physics has re-opened the question of the soundness of Aristotelian metaphysics as a basis for natural philosophy, long thought to be settled by the revolution of the seventeenth century. This new openness can be seen at a number of different levels: the replacement of reductive atomism with an irreducible holism, the reification of physical potentiality, the central role of teleology in the form of least action principles, the multiplication of real natures and essences in the Standard Model of particle physics, to name a few.

In this paper, I address a problem for the incorporation of quantum physics within the new Aristotelianism: the identification of the members of the category of *substance* (*ousia*). In Sect. 1, I will outline briefly the role that substance plays in Aristotelian

✉ Robert C. Koons
  koons@austin.utexas.edu

1 Department of Philosophy, University of Texas at Austin, Austin, TX, USA

🖄 Springer

metaphysics, a role that can be used to define *substantiality*. In Sect. 2, I turn to the question of which entities in modern physics can qualify as Aristotelian substances. In particular, I argue that organisms can do so but that artifacts, groups, elementary particles, and the cosmos as a whole cannot. This raises the problem of where to locate the substances in the inorganic world. I offer my answer to this question in Sect. 3: the theory of thermal substances, reflected in the use of infinite, non-separable models in quantum thermodynamics for phenomena like phase transitions. I give four additional reasons in "Appendix" for taking the continuum limit of quantum statistical mechanics realistically, based on the irreversibility of time, the definition of thermodynamic properties, spontaneous symmetry breaking, and the persistence of chemical form.

1 What is it to be a substance?

Substances are entities that *exist* in the most central, focal meaning of that analogous term. To use the language of grounding, the existence and nature of every other entity are grounded in the existence, nature, and activity of the world's substances. Substances constitute the uniquely fundamental level of reality. As a consequence of this metaphysical fundamentality, substances have per se unity to the maximal degree: their unity, both spatially (synchronically) and temporally (diachronically), is metaphysically ungrounded, not dependent on anything else.

Therefore, to the extent that a substance is spatially or materially composite, it must be metaphysically prior to its own material parts. Its material (spatially defined) parts are dependent, for their existence, their mutual relations, their intrinsic natures, and their causal agency, on the substantial whole to which they belong.

The nature of substances is also the ultimate ground for temporal change. These natures ground the basic causal powers and potentialities of substances. Substances are among the ultimate source of change in other substances, through the exercise of active causal powers, and the substances contain, in the form of a set of passive powers or potentialities, principles for explaining their own constancy and intrinsic change. In other words, substances contain their own principles of "rest and motion," as Aristotle puts it. The causal laws of nature are, on this view, nothing more than convenient summaries of the sort of changes that substantial natures induce and undergo in various contexts, by virtue of the substances' belonging to a relatively sparse set of natural kinds or species. The members of a single species are substances whose natures are functionally equivalent.

This metaphysical model generates what Jonathan Schaffer (2010, p. 38) has called "the tiling constraint." The tiling constraint consists of two requirements: (i) no two substances overlap, and (ii) everything is wholly contained in the sum of all the substances—that is, every part of every material entity overlaps some substance.[1] The substances of the world are like the tiles that cover a tessellated floor—there are no gaps between substances, and the substances jointly exhaust natural reality.

---

[1] By 'overlap', I mean sharing an integral or material part in common. I do not intend for the tiling constraint to rule out overlapping metaphysical parts or constituents—e.g., it should not be taken as ruling out the existence of the same substantial form in multiple natural substances or intellects. Neither am I endorsing such overlap here. Thanks to an anonymous referee for help in clarifying this point.

A view of *emergent wholes*, like that of van Inwagen (1990), Merricks (2003), O'Connor (1994), or O'Connor and Wong (2005), does not satisfy the tiling constraint, since these views posit that some substances (the simple particles) are proper parts of other substances (the emergent wholes). There are two problems with such emergentist alternatives to Aristotelian substances.

First, there is the problem of spatial occupation. What is the ultimate ground of the total location of an emergent whole? Is this location a fundamental fact about the emergent whole, or is it derived from the location of the simple substances that compose the whole? If the former, there is a sub-dilemma. Either the locations of the simple parts are also metaphysically fundamental, or the locations of the parts are grounded in the location of the whole. The first horn of this sub-dilemma results in an unacceptable duplication and coincidence at the level of fundamental facts: the location of the whole is improperly over-determined. The second horn of the dilemma undermines the substantiality of the parts. Exact spatial location is essential to the existence and identity of the simple parts: if this location is grounded in some feature of the whole, then the simple parts are dependent entities and not substances. Finally, if the location of the whole is grounded in the location of the parts, this fact is incompatible with the substantiality of the whole, reducing the whole to a mere heap of simple parts with no per se unity of its own. In this version, the so-called emergent whole is merely an aggregate of simple substances, and its emergent powers are simply latent joint powers of those parts (as argued by Meehl and Sellars 1956).

Second, emergent holism faces the dilemma of reductionism or dualism. If the powers of the whole can be explained entirely in terms of the natures of the simple parts, then the whole is reducible to the aggregate of those parts, and the whole does not count as a fundamental entity. On the other hand, if the powers of the whole cannot be explained in terms of those natures, then the so-called *whole* must really be an independent entity that interacts with those simple substances and is not in any sense "composed" of them.

2 What are the world's substances?

If we accept the tiling constraint, then we must be able to divide physical reality into a class of mutually exclusive and jointly exhaustive entities. What sort of entities could these substances be, given our current state of scientific knowledge? Here is a list of possible candidates:

1. Organisms
2. Artifacts
3. Groups of organisms
4. Elementary particles
5. The cosmos as a whole

I will argue that only the first member of this list, the class of organisms, qualifies. Given the tiling constraint, this means that we must find a sixth candidate, a class of entities that is both limited to and exhausts the inorganic world.

2.1 Organisms as paradigm substances

For Aristotle and Aristotelians, organisms are paradigm cases of substances (see footnote 3 below). A living organism has causal powers and potentialities, like the powers of self-reproduction, sensation (in the case of sentient organisms), and (in the case of human beings) rational deliberation, that are wholly irreducible to the powers and processes of their constituent parts, although they do depend causally on having parts that are in good working order.

The integral parts of organisms satisfy the Homonymy Principle.[2] That is, each integral part of the organism is essentially a part of that organism (or one of the same natural kind). A human hand is essentially a part of a human being: a detached "hand" is a *hand* only in an equivocal or homonymous sense. The non-homonymous parts of an organism, such as its molecules, atoms, and sub-atomic particles, are only potential or virtual parts: they exist only as potential products of division or death, and as metaphysically derivative, localized aspects of the powers and potentialities of the whole substance. The powers and potentialities of these virtual parts are wholly grounded in the substantial organism as a whole (see Koons 2014).

2.2 Why artifacts and groups are not substantial

Despite Aristotle's occasional use of artifacts like statues or axes as examples of the form/matter composition of substances, Aristotle leans toward the view that internally heterogeneous artifacts are mere heaps of smaller substances and not substances in their own right.[3] Aristotelians have several compelling reasons for following Aristotle's lead. First, such artifacts have no emergent powers. We can explain what an artifact does entirely in terms of the joint actions and passions of its proper parts.

Second, the existence of an artifact depends on extrinsic facts. Two duplicate rocks could be such that one is an ax, crafted by a human being, and another is not an artifact at all, chipped into an ax-like shape by blind, natural processes. Similarly, the hunk of rock composing Michelangelo's David is intrinsically identical to many chunks of marble unseparated from their homogeneous marble contexts. The only difference is that the David has been isolated spatially from other bits of marble. Thus, artifacts lack per se unity, both synchronic and diachronic.

Third, the identity and persistence of artifacts are subject to vagueness—and, apparently, to arbitrary human stipulation. Does an artifact like a restaurant survive its relocation, or a complete change in ownership and management? A change in name

---

[2] By an 'integral part' of a substance, Aristotelians mean a material part, in an ordinary, common-sense parlance. A hand is an intergral part of a body, the top half of a sphere is an integral part of the sphere. A non-integral part of a substance would be a metaphysical constituent, like a substantial or accidental form or a quantity of mass-energy.

[3] See *Metaphysics*, Book Zeta, chapters 7 (1032a19) and 17 (1041b28-31), and Book Eta, chapter 3 (1043b22-24). See also Aquinas (1995), Book 7, lesson 17, paragraph 1679 and Book 8, lesson 3, par. 1719. To clarify, Aristotle and Aquinas are merely denying that there are individual substances that are internally heterogeneous and unified by some artificially created form. This does not rule out the possibility of homogeneous substances whose chemical composition is of an artificial type, like wine or vinegar. On my view also, there can be homogeneous thermal substances of artificial chemical composition. (Thanks to an anonymous referee for help on this point.).

or menu? There seems to be no fact of the matter here: we can simply stipulate what we shall mean by 'the same restaurant'. Such arbitrary stipulations are impermissible in the case of substances.

Fourth, artifacts can be composed of living organisms. One could make a swing by lacing several living vines together. The vines continue to be substances, and so the swing cannot be one, without violating the tiling constraint. Moreover, artifacts can be composed of mere absences—like holes or depressions (think of a moat, for example). Concrete substances, in contrast, must have a material substrate.

Social groups, like clubs, teams, or nations, are like artifacts in all three respects and so cannot be substantial.

2.3 Why fundamental particles are not substances

What about fundamental particles? Are some of them substances? As we have seen, a substance must have its own per se unity through time, an identity distinct from that of all other substances. In quantum mechanics, elementary particles do not qualify.

In quantum mechanics, particles lose their individual identities as a result of being incorporated into quantum systems (Redhead and Teller 1991, 1992). When two particles become entangled or correlated, a unified system results, one that in some sense contains *two* particles, and yet in which there is no distinct identity associated with either particle.

This results in the replacement of classical Maxwell–Boltzmann statistics with Bose–Einstein or Fermi–Dirac statistics. For example, photons can be in one of two spin states: either spin + 1 or spin − 1. When we have two unrelated photons, classical statistics applies, resulting in four possible states (each with an equal, 25% probability): both photons + 1, both photons − 1, the first photon + 1 and the second − 1, and the second + 1 and the first − 1. However, when two photons fuse into a single, emergent system, the photons lose their individual identities. As a result, Einstein-Bose statistics apply, with three possible states (each with an equal 1/3 probability): two photons + 1, two photons − 1, and one photon in each state. There is no distinction, in the fused case, between two possible ways for one photon to be + 1 and one − 1. The individuality of each photon has been absorbed into that of the whole, two-photon system. Something analogous happens in Fermi–Dirac statistics to fermions like electrons and protons.

In relativistic quantum field theory, the challenge to the individuality of particles is even greater, since even the number of particles involved in a system can vary according to one's frame of reference (Teller 1995; Clifton and Halvorson 2001; Fraser 2008). The very same system might at the same time consist of two particles relative to one inertial frame and three particles relative to another. Such relativity of existence is incompatible with substantiality, since the fundamental entities define the very framework of reality.

Finally, in all interpretations of quantum mechanics except Bohmian mechanics, particles lack definite position most of the time and do not follow definite trajectories through space. In fact, Malament and Halvorson and Clifton show that in relativistic quantum theory, every particle has a finite probability of being located anywhere in the universe at any time (Malament 1996; Clifton and Halvorson 2001). As a result,

we cannot assign definite active or passive powers to any particle *in isolation*. Only in the context of a measurement event, or within the context of the cosmos as a whole (Simpson 2019a), can such definite powers and physical characteristics be assigned, and even then, only some of them and only momentarily; thanks to the uncertainty principle, we cannot measure non-commuting properties of a particle at the same time.[4] As noted by Teller (1986), Healey (1991), Silberstein and McGeever (1999, pp. 186–190), Kronz and Tiehen (2002, pp. 325–330), along with many others, the quantum state of a pair of entangled particles is irreducibly a state of the pair as such: it does not even supervene on the intrinsic properties or spatial distance between the particles (at any point in time).

From an Aristotelian point of view, there is good reason to think that the "fundamental" particles of contemporary physics are merely virtual parts of larger substances, which, unlike these particles, have more-or-less definite location and intrinsic characters, and with enduring identities.

2.4 Why the whole cosmos is not a single substance

Schaffer (2010) has recently argued that there is only one fundamental entity, the whole cosmos. One of his arguments turns on the fact that there are cosmological reasons for supposing that the entire universe constitutes a single, entangled system. Schaffer convincingly argues that this fact disqualifies individual particles from being substantial, and he suggests that it is arbitrary to stop the progress of ontological holism anywhere short of the entire universe.

Aristotelians have at least three reasons for demurring. First, as we have seen, Aristotelians have good reason to take organisms as substances. Organismic powers and processes are irreducible to either the microscopic or the cosmic levels. One can no more explain an organism's sentience in terms of its place in the universe than one can from the interaction of its microscopic parts. If organisms are substances, then the tiling constraint rules out the possibility that the cosmos is also a substance.

Second, the Aristotelian account of empirical knowledge, both of sense perception and of scientific induction, requires the causal interaction between sensory and cognitive powers of human beings, on the one hand, and the active and passive causal powers of the entities being investigated, on the other hand. As Cartwright (1994) has convincingly shown, an adequate account of scientific experimental knowledge requires the causal isolation of the target of the investigation from its environment. Cosmic monism entails that any such isolation is merely apparent. We cannot interact with the whole universe, since we are inextricably part of it.

Third, Schaffer's argument depends on a no-collapse interpretation of quantum mechanics, since collapse events would have the effect of disentangling previously

---

[4] Similar restrictions apply in the case of one-world no-collapse interpretations, such as the modal interpretation or Bohmian mechanics. In recent work on the Bohmian theory (Esfeld 2017; Allori et al. 2002), no particle possesses an active power intrinsically (even properties like spin, mass, and charge are merely contextual)—or, if Bohmian particles do possess intrinsic powers, they must co-manifest their powers as a cosmic whole (Simpson 2019a)—and the Bell-Kochen-Specker theorem places restrictions on the number and type of the intrinsic properties of particles in modal interpretations.

entangled systems. I have argued (Koons 2018b) against the viability of such no-collapse arguments.

Can Schaffer's monism allow for the various proper parts of the universe to be causally isolated from each other, even though all are metaphysically grounded in the nature of the whole? (Schaffer 2012, 2013) Much depends on how we think of causal powers. If we follow the Neo-Humean project of David Lewis and attempt to reduce causation to counterfactual conditionals, while simultaneously grounding the truth of such conditionals in brute facts about the pattern of instantiation of essentially inert qualities, then cosmic monism could be compatible with approximately isolated causal powers in many cases. However, such a route is unavailable to the Aristotelian, and recent work in metaphysics suggests that it cannot succeed [see Koons and Pickavance (2017, pp. 95–104) for an overview of objections to the Neo-Humean project].

If we take real causal powers as part of the fundamental structure of the world, with causal powers entailed by the natures of substances, then such real causal powers cannot be detached from their ultimate substantial bearers, and causal isolation of parts of the universe from other parts becomes unattainable for the cosmic monist [see Tahko (2018) and Simpson (2018)]. In contrast, it was easy to obtain derived causal powers for macroscopic entities in a bottom-up way under the assumption of *microphysicalism*: any spatial arrangement of powerful microscopic entities would give rise to derived powers for the corresponding composite (assuming that there is one). The resulting composite entity would have, as its derived powers, whatever joint dispositions result from the combined action of the microscopic parts.

However, there is no counterpart to this composition-of-agency model for Schaffer's *priority monism*, according to which all fundamental causal powers belong to the universe as a whole. There is no *natural* way to divide the powers of the whole cosmos into derived powers of its proper parts. The best we can do is to look to various counterfactual conditionals: if part x were to act in way F, then part y would act in way G. But that is to abandon the causal-powers ontology that is essential to Aristotelianism.

2.5 Tiling requires inorganic substances

Thus, the Aristotelian seems to have only one plausible candidate for the role of substance: the living organism. However, the tiling constraint requires that the class of substances exhaust all of nature. Organic substances came late to the history of the cosmos. Unless we are willing to embrace Leibniz's somewhat wild speculation and assume that the world is full of living organisms, we must do something about the inorganic world.

2.6 My proposal: thermal substances

My proposal is that we subdivide the inorganic world into thermal substances. A thermal substance is a body of matter with thermal, thermodynamic, and chemical properties. Some very large molecules, like DNA molecules, may constitute single thermal substances. Smaller molecules, like atoms and sub-atomic particles, are typically merely virtual parts of thermal substances (although there is, in principle, no minimum size required).

Organisms may have integral parts–like bodies of tissue or blood—that may be, empirically speaking and for all practical purposes, chemically and thermodynamically indistinguishable from inorganic thermal substances. Nonetheless, in deference to the tiling constraint, we should not say that organisms have other thermal substances as parts. Rather, in the process of organismic development or ingestion, some thermal substances are destroyed and replaced by empirically and qualitatively indistinguishable copies that form virtual parts of the organism. The converse process is involved in processes of extrusion, excision, and death.

3 Thermal substances, virtual parts, and quantum entanglement[5]

From the 1950's onward, much of quantum theory (especially that concerned with chemistry, thermodynamics, and solid-state physics) moved from what the theoretical physical chemist Hans Primas called "the pioneer period" to that of *generalized* (algebraic) quantum mechanics. Generalized QM moved away from the Hilbert-space representation of quantum systems[6] to that of an algebra, in which both quantum and classical observables could be combined in a single formal representation.[7] The algebras of generalized QM can have non-trivial *centers*, consisting of the classical properties that *commute* with every other property, representing exceptions to the mutual complementarity of the quantum properties.[8] In practice, this means representing the classical properties of complex systems as metaphysically fundamental, since the classical properties do not merely appear as a result of human measurement (as in the Wigner–von Neumann version of the Copenhagen interpretation), nor are they merely contextual, dependent on human choices of experimental design (as on Bohr's version), nor are they mere approximations, good enough "for all practical purposes" (as in pragmatic versions of the decoherence program), nor are they merely functional descriptions realized by the quantum properties (as on the Oxford Everettian program). They are as fundamental in nature as any other physical parameter, including the purely quantal "observables".

---

[5] In this section and in "Appendix", I draw on my previous work in Koons (2018c).

[6] A Hilbert space is a space with a completely defined inner product: a function that maps any two vectors in the space to a complex number. The state of the system can be represented by a single unit vector in this space. Each physical parameter (like a particle's position or momentum) is represented by an operator of a certain kind on this space. A vector in the Hilbert space is called an 'eigenvector' of a parameter when its direction is fixed uniquely by the operator: that is, when the operator is applied to the vector, a vector with the same direction is obtained. To get the probability of a parameter's taking a certain value, we project the system's unit vector onto the corresponding eigenvector and square the resulting amplitude (Born's rule). The result is a value between 0 and 1. In the Heisenberg version of the Hilbert-space representation, it is not the vector that "moves" in the space: instead, it is the correspondence between physical parameters and operators that evolves over time. In the Schrödinger version, it is the vector itself that moves in response to the dynamical equation. (Thanks to an anonymous referee for help with the details.).

[7] Primas, Sewell, and others working in this program have not explicitly addressed questions of relativistic quantum mechanics, but I am not aware of any special obstacle to the construction of Lorentz-invariant versions of the algebraic representations.

[8] The fact that quantum properties (modeled as operators) do not commute with each other or with the classical properties is the formal counterpart of Heisenberg's uncertainty principle and of Bohr's complementarity principle.

3.1 The continuum limit as a representation of reality

In applied physics, it is common to take some parameter to infinity: that is, to replace the original model having some finite parameter with a new model in which that parameter takes the value of infinity. For example, in the so-called "thermodynamic" limit, a system containing n molecules and a fixed volume V is replaced by one in which both the number of molecules and the volume go to infinity, while keeping the density n/V constant. As Compagner explains (Compagner 1989), this thermodynamic limit is mathematically equivalent to the *continuum limit*: keeping the volume constant and letting the number of molecules go to infinity, while the size of each molecule shrinks to zero.[9] In many applications, such as the understanding of capillary action or the formation of droplets, the continuum limit is the right way to conceptualize the problem, since infinite volumes have no external surfaces and cannot interact with their containers.

As Hans Primas has pointed out (Primas 1983), there are three reasons for taking infinite limits in physics: (1) for mathematical convenience, (2) in order to isolate some factor from others, and (3) in order to introduce new structure into the representation. The continuum limit in generalized quantum mechanics is an example of the third reason. In 1931, John von Neumann and Marshall Stone proved that finite systems admit of only one irreducible Hilbert-space representation (von Neumann 1931).[10] Infinite systems, in contrast, admit of infinitely many inequivalent Hilbert-space representations.[11] This apparent embarrassment of riches in the infinite case turns out to be crucial for the representation of phase transitions, ergodicity, and thermodynamic phenomena. As Geoffrey Sewell explains:

> For infinite systems, the algebraic picture [with its infinite number of subsystems] is richer than that provided by any irreducible [single Hilbert-space] representation of observables…. Furthermore, the wealth of inequivalent representations of the observables permits a natural classification of the states in both microscopic and macroscopic terms. To be specific, the vectors in a [single Hilbert] representation space correspond to states that are macroscopically equivalent but microscopically different, while those carried by different [inequivalent] repre-

---

[9] Compagner has in mind the Aristotelian conception of the *continuum* (as discussed in Brentano 1988) rather than the mathematical conception developed by Karl Weierstrass and Richard Dedekind in the nineteenth century. An Aristotelian continuum is simply a body that lacks actual internal boundaries, which will certainly be true of the collection of molecules at the continuum limit, since molecules with zero volume do not have finite surfaces.

[10] An algebraic representation is *irreducible* if and only if it does not have any proper sub-representations that are closed under the relevant functions. Stone and von Neumann proved that any two irreducible groups of the appropriate kind (one-parameter unitary groups) are *unitarily equivalent*. Two representations or groups are unitarily equivalent when there is a unitary transformation of one into the other (a transformation involving a *unitary*—that is, a linear, amplitude-preserving—operator). In this case, the two representations can be treated as simply two different ways of representing the same physical situation, analogous to the way that changes in units of measurement or the location of the axes of space produce physically equivalent representations.

[11] As Kronz and Lupher (2005, pp. 1242–1243) point out, an infinite system is one that has infinitely many particles or sub-systems, resulting in a *non-separable* Hilbert space. (A separable space has a countable "dense" subset: a set that contains at least one element of every nonempty open subset of the space.) It is necessary but *not sufficient* for the system to have infinitely many degrees of freedom.

sentations are macroscopically distinct. Hence, the macrostate corresponds to a representation [space] and the microstate to a vector in the representation space (Sewell 2002, pp. 4–5).

In addition, by moving to the thermodynamic or *continuum* limit, which involves treating a system with (apparently) only finitely many particles as though there were infinitely many, algebraic QM enabled theorists to introduce *superselection rules*,[12] which could be used to distinguish the different *phases* of matter that can co-exist under the same conditions (such as gas, liquid, solid, ferromagnetized, superconducting). I will argue that the use of the continuum limit can best be interpreted as representing an *ontological* difference between two irreducibly thermodynamic conditions, providing strong evidence for the existence of fundamental thermal substances.

If these infinite models are to be genuinely explanatory, the use of the continuum limit has to be justified in *ontological* terms, and not merely as a useful fiction. We don't have to suppose that there be literally an infinite number (whether countable or uncountable) of infinitesimal molecules (and so, to that extent, the model may indeed be fictional), but we must suppose (as Simpson 2019b has suggested) that the matter of the thermal substance *really functions in such a way as to constitute a dynamic Aristotelian (undivided) continuum*. We might think of the elementary particles of finite quantum systems as composing a thermal substance by fusing into a continuous *field* of matter, with a literally infinite number of distinct sub-systems, each sub-system corresponding to a different finite spatial region (not to a fictional molecule of zero volume). This is an account of what a thermal substance really is at each point in time, not an account of how thermal substances are generated in time.[13] Each subsystem is a sub-algebra of the von Neumann algebra for the whole universe: one supported by the classical observable restricted to some spatiotemporal region.

The fusion of quantum particles into such a material continuum results in a different way for the particles to relate to our three-dimensional space: not as discrete, separate units but as a single, cooperating mass, resulting in an entirely new dynamical situation, with a new Hamiltonian function defined on an infinite model.

I propose that the *substantial form* or *essence* of each thermal substance defines an appropriate *topology* on the corresponding C*-algebra (which represents the potentialities of the substance's *matter*, i.e., its infinitely many sub-systems), generating a W*-algebra of observable properties for the whole substance (Primas 1990a, p. 248).[14]

---

[12] In algebraic QM, a superselection "rule" is actually a property of a system that cannot change through local, microscopic perturbations. The different, mutually incompatible values of this quantity are called superselection sectors. Such distinct sectors can never be found in quantum superpositions, unlike all *quantal* observables.

[13] Thermal substances are always generated by the destruction of pre-existing thermal substances or organisms. What is really transferred to the new substances in cases of substantial change are parcels of mass-energy, charge, baryon number, and other conserved quantities. My point is that this mass-energy is really distributed continuously in the thermal substance (as the infinite models at the continuum limit represent), with particular particles and molecules as merely potential or virtual parts of the whole.

[14] An algebra is a *-algebra if it is closed over an inflection operation * such that $(A*)* = A$, $(AB)* = B*A*$, and $(cA)* = conjugate(c)A*$, for all complex numbers c. A *norm-complete* *-algebra includes a mapping (its *norm*) from vector A to nonnegative real number $\|A\|$ such that $\|A*\| = \|A\|$, $\|cA\| = |c| \cdot \|A\|$, $\|A\| + \|B\| \geq \|A + B\|$, and $\|A\| \|B\| \geq \|AB\|$. A C*-algebra is a norm-complete *-algebra possessing the property that $\|A*A\| = \|A\|^2$. A W*-algebra or von Neumann algebra is a *-algebra of bounded operators

This W*-algebra is derived from the underlying C*-algebra by a GNS construction, based upon an appropriate reference vector in the thermal substance's Hilbert space (a reference vector that reflects the thermal substance's essence). The Hilbert space represents the microstates within each representation (which corresponds to the substance's observable macrostates). When a set of thermal substances interact, the ontic states of each substance correspond one-to-one with a disjoint subset of the extremal, normalized positive linear functionals on that substance's W*-algebra.

Each thermal substance thus corresponds to a set of values for classical (mutually commuting) observables in the quantum algebra, the values representing that substance's classical properties, both essential and accidental. Since these observables commute, the Kochen–Specker theorem does not apply, and we can suppose that all such observables have definite values at all times. The classical observables are represented *by disjoint spaces and not by vectors*. Since the classical observables commute with all the other operators in the quantum algebra, and the microstate of the substance corresponds to an irreducible *representation* of the quantum algebra, it follows that classical observables do not enter into superpositions.[15] Thermal substances are never in superposed states with respect to their *essential* properties (including their chemical composition), although they will have virtual parts that are in superposed states, and they may have quantal properties as accidents. For example, supercooled fluids will have both classical and quantal properties.

3.2 The infinite algebraic model and the measurement problem

The so-called measurement problem arises from the formulation of quantum mechanics as a theory about the probabilities of certain measurement results. The quantum wavefunction evolves in a deterministic manner, by the unitary dynamics of Schrödinger's equation. In order to test the theory, some observable results must be deduced from the theory. It is Born's rule that enables us to move from some parameter value in the wavefunction (the wave amplitude) to something testable: namely, certain probabilities about the result of measuring one or other classical parameter (such as position or momentum). This early model (as developed by Bohr and Heisenberg) assumed that we could continue to use classical language in describing the experimental setup and the measurement devices. Critics have argued that this involves an implicit inconsistency, since physicists assume that these classical instruments are wholly composed of quantum systems and so should be, in principle, describable in *quantum* and not classical terms.

Primas's algebraic approach promises to shed light on the quantum measurement problem. Primas argues:

Footnote 14 continued

in a Hilbert space H that is closed with respect to the weak operator topology of H. A state on a C*- or W*-algebra is a positive, normalized linear functional. A *representation* of a C*-algebra *A* into a Hilbert space H is a mapping from *A* into the bounded operators of H that preserves the *-algebraic structure. A *GNS representation* is a representation based on a single vector in H (a so-called "cyclic vector"), from which the whole of H can be generated. The existence and uniqueness of such a representation is established by the Gelfand–Naimark–Segal theorem (Sewell 2002, pp. 19–20, 27).

[15] Thanks to an anonymous *Synthese* reviewer for help on this point.

Algebraic quantum mechanics gives us the tools to come to grips with the measurement problem. Furthermore, one can define rigorously an *object* as an open quantum system which is characterized by a complete set of intrinsic potential properties and which is distinguished from arbitrary open quantum systems by its individuality. This concept paves the way for an *individual and ontic* interpretation of quantum theory (Primas 1990a, p. 234).

Primas interprets the pure states of quantum theory as ontic states (states about objective reality), and mixed states as representing our uncertainty about systems' ontic (pure) states. (A *pure* state is a quantum state that cannot be represented as a probabilistic mixture of other states. All other states are *mixed* states.)

This Primas tradition provides the basis for a set of solutions to the measurement problem that is quite different from those considered in the recent philosophical literature, which include Bohmian mechanics, Everettian many-worlds theories, and GRW, quantum-gravity and other objective collapse modifications to Schrödinger dynamics (Bell 1990; Maudlin 1995; Wallace 2008), in addition to Bohr's original (Copenhagen) interpretation.

Bohr's interpretation required that reality be divided into two disjoint realms, the classical and the quantum, with a measurement involving any setup in which a quantum system is made to act upon a classical observer or instrument. This foundered on the fact that some systems, like supercooled fluids or quantum computer chips, bridge the gap between the two realms. We cannot consistently describe all macroscopic objects in purely classical terms, as Bohr's program seems to require, since it is interaction with the classically described realm of measurement devices that collapses the wavefunction in Bohr's model. In contrast, on the Primas model, we could postulate that the wave packet associated with a quantal property has "collapsed" whenever it becomes correlated with a classical *property* of a disjoint system.[16] Even though *entities* cannot be neatly divided into two disjoint domains, this is not true of physical *properties*.

Primas demonstrates that interaction with the classical properties of entities in the environment will drive quantal vectors to eigenstates with a high probability in a short period of time. The Primas solution is, consequently, one of continuous rather not discrete collapse (unlike, for example, most versions of the GRW model of objective collapse).

Cosmologists object to Bohr's interpretation for another reason: Bohr could not make sense of a universal quantum representation of the entire universe. There is, in contrast, no obstacle to an *algebraic* representation of the cosmos as a whole. This unified, cosmic representation is compatible with hylomorphism, since it is the individual thermal substances that are responsible for the existence of the continuous fields of matter (with their infinitely many degrees of freedom) that are responsible for the mathematical structure of the cosmic algebra.

---

[16] As Primas pointed out, his use of 'classical' has nothing to do with "classical" Newtonian–Maxwellian dynamics nor with the relative size of Planck's constant. It refers simply to the center of an infinite *-algebra, the set of mutually commuting observables. Although we cannot sort objects into disjoint classical and quantal realms, there is a strict dichotomy between classical and quantal properties (or "observables", as physicists call them): two quantal properties do not commute with each other, while classical properties form a mutually commuting center.

The Primas algebraic version of objective collapse theory does not require adding any speculative modifications to the pure Schrödinger dynamics, in contrast to GRW or Penrose's quantum gravity proposal. Instead, we simply replace models having finitely many sub-components with infinite models, moving from traditional Hilbert-space representations to generalized algebras. The Schrödinger dynamics for separable Hilbert spaces is linear. Primas proved that, in contrast, the Schrödinger dynamics for the non-separable models of generalized algebraic QM is non-linear and reduces, in important cases (for example, a boson interacting with a harmonic environment, or ferromagnetic spin relaxation), to a function that is stochastic (Primas 1990b, pp. 271–278). The non-linearity of the Hamiltonian depends crucially on interaction with infinitely many degrees of freedom in the environment. It is this non-linear dynamics that permits Primas to derive the statistical predictions of Born's rule. No new or speculative dynamics is needed (in contrast to GRW or quantum gravity collapse theories), since the dynamics of these infinite algebraic models have been applied successfully for many years in chemistry, thermodynamics, and solid-state physics. They are the natural extension of finite Hamiltonians to the infinite case via the continuum limit (see also Amann and Atmanspacher 2013).

In addition, the infinite algebraic models are needed as an account of chemical form and of distinct phase states (see Sects. 3.4 and "The Persistence of Chemical Form" section of "Appendix"), and the phenomenon of *decoherence* requires chemical form and the solid state in order to be able to postulate the rigid bodies (e.g., pointers) needed for the macroscopic shifts in centers of mass.

Primas defended a perspectivalist interpretation of quantum mechanics, in which the objective truth of statements about classical observables is relative to our explanatory interests or stance (Primas 1980, pp. 41–44, 97–98, 100–107). I am applying Primas's model to an Aristotelian interpretation in which there is a uniquely correct "perspective," one corresponding to the real division of the world into thermal substances. This avoids the regress or circularity that looms over Primas's picture: the experimenter, whose interests and choices determine the perspectives, must have a perspective-independent existence.

The hylomorphic version of the Primas model thus provides solutions to each of the three measurement problems identified by Maudlin (1995): the problems of completeness (and nonlinearity), of the interpretation of quantum statistics (and Born's rule), and of the dynamic relevance of measured outcomes for future predictions. First, the model resolves the incompleteness problem by adding new, classical observables at the thermodynamic and chemical levels (through infinite models at the continuum limit). As a result, the fundamental dynamics of the world are governed by a *nonlinear* Schrödinger equation, and collapse occurs continuously. Second, it is able to solve the problem of statistics by showing that the dynamics resolves quantal properties to eigenvalues in measurement settings in a way that verifies Born's rule. Finally, and unlike early versions of the modal interpretation, the model explains how and why observed values affect the future evolution of the system.

3.3 The algebraic model and non-locality

It is plausible to suppose that quantum entanglement is a phenomenon that can span astronomical distances. On the theory of the thermal substances, such entanglement between separated thermal substances occurs only at the level of their virtual parts. The classical properties of thermal substances (including superselection sectors, phase of matter, temperature, chemical composition) are never in a state of superposition and so are exempt from entanglement. Thermal substances can be isolated causally from their environments at the level of classical properties, regardless of the quantum entanglement of their virtual parts. Consequently, the theory of thermal substances can adopt a simple account of causal interaction between the experimenter and some isolated portion of the world (Cartwright 1994), in contrast to Schaffer's monism.

The quantal properties of the virtual parts (including particles, atoms, small molecules) of a thermal substance are determined by the *substantial form* of that thermal substance. The autonomous *evolution* of these quantal properties is in each case fully localized, even though the properties themselves are non-local (non-separable) in character. When a virtual part of one substance interacts with another thermal substance, even when widely separated from its containing substance, any EPR-style coordination simply reflects the fact that the quantal properties of the relevant virtual parts are not localized. This fact does require an important departure from Aristotle's own cosmological picture: although thermal substances have definite spatial locations at each time, the same is *not* true of their virtual parts at the quantum scale. Virtual parts at the quantum level do not have classical properties, such as definite location or momentum. As we've seen, any quantal part of a thermal substance has a finite probability of being found in any region of the universe, and the measured properties of such virtual parts can exhibit "spooky" EPR correlations over great distances, without superluminal signaling (Healey 1991). The correlations can be explained by the operation of a common cause: the action of the substantial form of the thermal substance to which the particles belong, and the action of this form is, in a certain sense, superluminal in character, but limited to the coordinated determination of the expression of certain localized active causal powers (see Cartwright 1994, Chapter 6).

3.4 A case for the continuum limit: phase transitions

The best Aristotelian framework for quantum mechanics, therefore, requires something like thermal substances. Does the state of quantum science invite such an interpretation? In "Appendix", I will argue that it does, since quantum thermodynamics and the fields that depend upon it (such as quantum chemistry and solid-state physics) require the use of the continuum limit. For reasons of space, I cannot respond to the objections and counter-arguments here, but my intention is simply to build a *prima facie* case for taking the thermal-substance view seriously as an alternative.

There are five reasons for taking the use of the continuum limit in quantum thermodynamics as marking an ontological difference between thermal substances and quantum virtual parts:

1. The objective irreversibility of time

2. The rigorous definability of thermodynamic concepts
3. The explanation of spontaneous symmetry breaking
4. The persistence of chemical form
5. The reality of phase transitions.

I will discuss the first four reasons in "Appendix". I turn now to the fifth point: the nature of phase transitions.

P*hase transitions*, such as those between the solid, liquid, gas states, and between conditions before and after the onset of coherent ferromagnetism or superconductivity in metals, require the use of infinite models (models involving the continuum limit): see Liu (1999), Ruetsche (2006) and Bangu (2009). Phase transitions are an important case of spontaneous symmetry breaking. Geoffrey Sewell provides a clear explanation of this:

> Thus, we have a spontaneous symmetry breakdown, as each phase lacks the rotational symmetry of the interactions in the system. This is a situation which typifies a class of phase transitions. We emphasize here that this situation could not be covered by a model of a finite system, since that would admit only one representation of its observables and therefore would not present the phase structure we have just described….
> We have seen in the preceding Sections that the idealization, whereby a macroscopic system is represented as infinite, provides new structures, which form a natural framework for theories of collective phenomena (Sewell 1986, pp. 19, 34).

As Laura Ruetsche has explained recently:

> Only in the thermodynamic limit can one introduce a notion of equilibrium that allows what the Gibbs notion of equilibrium for finite systems disallows: the multiplicity of equilibrium states at a finite temperature implicated in phase structure (Ruetsche 2006, p. 474).

If we assume that an explanation in terms of a model is successful only if the model faithfully represents the relevant features of the actual phenomenon, then we must conclude that our current scientific explanations of phase transitions are successful only if it is the infinite, continuum-limit model that faithfully represents the facts, requiring exactly the kind of real thermodynamic fusion that I have described. The required introduction of the continuum limit in our models must represent a real ontological break between the microscopic and the macroscopic, a break of exactly the kind posited by the theory of thermal substances.

The theory of decoherence assumes the existence of solid, rigid bodies, but they depend in turn on chemistry and thermodynamics (phases of matter). A rigid body must be solid or a viscous liquid. Gaseous bodies don't decohere. Decoherence is essential to the theory of measurement for nearly all modern interpretations of quantum mechanics, including Bohm, modal, and Everett interpretations (Schlosshauer 2005).

As I discussed in 2018 (Koons 2018c), Mainwood (2006, pp. 238–243) and Butterfield (2011, pp. 1123–1130) have defended the view that the continuum-limit model is a mere idealization, adopted for mathematical convenience only. This approach runs up

against the hard, mathematical fact of the von Neumann-Stone theorem: finitary models simply do not have enough states to represent the different phases of matter. The microphysical reductionist must claim that every physical system can be correctly modeled by such finite systems, while the hylomorphist insists that some systems cannot be so modeled, because of the existence of real thermal substances, requiring an infinite algebraic model. Mainwood proposes that a finite system be counted as undergoing a phase transition just in case there are distinct states (separated by a superselection rule) in the corresponding infinite model, but neither he nor Butterfield can explain how a model with only one state can be a good approximation to a model with a great many. Every finite model necessarily represents the situation as one without a real distinction between phases. How then, can the finite model be literally true of a situation in which a phase transition exists, while the infinite model is supposedly a mere "useful fiction"? It is far more reasonable to suppose that it is the discreteness of the finite number of molecules that is the useful fiction, and the infinite model that represents the sober truth.

As Earman has put it (2004, p. 191): "A sound principle of interpretation would seem to be that no effect can be counted as a genuine physical effect if it disappears when the idealizations are removed." Yet this is exactly what Mainwood and Butterfield attempt to do. Phase transitions are genuine physical effects, and yet they disappear once the "idealization" of infinite degrees of freedom is removed. The only way to acknowledge the genuineness of these effects is to deny that the use of infinite models is a mere idealization in the first place.

If we assume that an explanation in terms of a model is successful only if the model faithfully represents the relevant features of the actual phenomenon, then we must conclude that our current scientific explanations of phase transitions are successful only if it is the infinite, continuum-limit model that faithfully represents the facts. The required introduction of the continuum limit in our models must represent a real ontological break between the microscopic and the macroscopic, a break of exactly the kind posited by the theory of thermal substances.

4 Conclusion

The Aristotelian interpretation of quantum statistical mechanics and quantum chemistry can be summarized in three points.

1. The presence of the substantial form (unifying essence) of a thermal substance grounds the fact that the substance constitutes a thermodynamic system with infinitely many virtual parts, each corresponding to a finite sub-region of a continuum of matter (represented by the "continuum limit").
2. The virtual presence of infinitely many sub-systems grounds the fundamental properties of thermodynamics (heat, temperature), classical superselection sectors (phase transitions and other broken symmetries), and temporal irreversibility.
3. These thermal properties ground (in a top-down fashion) enduring chemical structures, with molecules (including chiral molecules) as either virtual or integral parts of the thermal substance (depending on context and history).

As I will argue in "Appendix", spontaneous symmetry-breaking, including spatially asymmetrical molecular structures, arise naturally in the setting of infinite quantum–mechanical models. We can therefore explain why large molecules and other molecules in dynamic interaction with their environment have stable molecular structures, despite the prevalence of superpositions at the quantum level.

The world is composed entirely of living organisms and extra-organismic thermal substances (we might count organisms as a special case of thermal substance). Everything else is either a virtual or integral part of such a substance, or a heap or aggregate of such substances. Generalized quantum mechanics gives us good grounds for believing in the existence of exactly the sort of thermal substances needed to satisfy the tiling constraint. The chemical and thermodynamic properties of the thermal substances constitute their form; the quantum potentialities of their virtual parts, their matter. The virtual, quantum parts of substances lack definite location (contrary to Aristotle's expectation), enabling the possibility of long-range entanglement at that level.

Appendix: The case for a realistic interpretation of the continuum limit

The objective irreversibility of time

As Prigogine (1997, p. 49) explains, the *objective irreversibility of time* is essential to the very idea of observation or measurement, and without observation and measurement, science is of course impossible:

> If the arrow of time existed only because our human consciousness interfered with a world otherwise ruled by time-symmetrical laws, the very acquisition of knowledge would become paradoxical, since any measure already implies an irreversible process. If we wish to learn anything at all about a time-reversible object, we cannot avoid the irreversible processes involved in measurement, whether at the level of an apparatus or of our own sensory mechanisms.

Woolley (1988, p. 56) argues that true irreversibility is possible only at the continuum limit, when the number of degrees of freedom is infinite:

> [The work of] Ilya Prigogine and his collaborators…highlights the fact that irreversible processes in quantum mechanics are only possible in the limit of a continuous spectrum; an immediate consequence of this restriction is that no finite quantum system, for example a molecule or finite collection of N molecules with intermolecular interactions, can show irreversible behavior, and the Second Law of Thermodynamics cannot be applied to such systems.

The continuum limit is needed to ground true thermodynamic irreversibility, as noted by Compagner 1989, p. 115: "The relative measure in phase space occupied by exceptional microstates vanishes in the continuum limit." Sewell (1986, p. 30) explains why: "The dynamics of a finite system is quasi-periodic, due to the discreteness of its Hamiltonian."

Rigorous definitions of thermodynamic properties

The infinite algebraic models of generalized QM provide, for the first time, the possibility of rigorous and non-arbitrary *definitions of the basic thermodynamic properties* of states of matter (liquid, solid, gas), temperature, and chemical potential (see Sewell 2002).

Contrary to what many philosophers believe, science does *not* suppose that temperature is the mean kinetic energy of molecules! Vemulapalli and Byerly (1999, pp. 28–32) explain:

> If the system is not at equilibrium, temperature is not well-defined, though the mean kinetic energy is…. Temperature is a characteristic of equilibrium distribution and not of either individual molecules or their kinetic energy. When there is no equilibrium between different kinds of motion (translations, rotations, and vibrations), as in the case of molecular beams, temperature is an artificial construct (Vemulapalli and Byerly 1999, pp. 31–32; See also Primas 1983, pp. 312–313).

Robert Bishop and Harald Atmanspacher agree:

> Since thermal equilibrium is not defined at the level of [finite] statistical mechanics, temperature is not a mechanical property but, rather, emerges as a novel property at the level of thermodynamics (Bishop and Atmanspacher 2006, p. 1769).

Spontaneous symmetry breaking

Strocchi (1985) explains that the continuum limit is needed to explain any *spontaneous symmetry breaking* in quantum–mechanical terms:

> In the past, the description of physical system exhibiting approximate symmetries was reduced to the problem of identifying explicit "forces" or "perturbations" responsible for such asymmetric effects…. The progress of the last years has shown that the above strategy is not only unconvenient from a practical point of view, since the existence of asymmetric terms complicates the equations of motion and their identification is somewhat arbitrary, but *it is actually unacceptable on general grounds*, because it is often impossible to reduce symmetry breaking effects to asymmetric terms in the Hamiltonian…. The result is that the dynamics must be defined in terms of a symmetric Hamiltonian and that the symmetry breaking is due to a dynamic instability according to which symmetric equations of motion may nevertheless lead to an asymmetric physical descrip-

tion… As we have seen, *such phenomena are possible only for infinite quantum mechanical systems* (Strocchi 1985, pp. 117–118; emphases mine).

The persistence of chemical form

Infinite models are needed to explain the *persistence of chemical form*. The Schrödinger equation for a finite system of particles is spherically symmetrical. Thus, there is no explanation in the standard Copenhagen interpretation for the emergence and observed persistence of chemical structure, with its breaking of spatial symmetry.

The key datum here is that of molecular stability. We know that complex molecules (including chiral molecules—molecules with distinct left- and right-handed versions) can be stable for millions of years, a conclusion based on both experimental data and theoretical reasoning.

Yet, from the point of view of finite, elementary quantum mechanics, any molecular structure, including chirality, should be transient, in the sense that it corresponds to some observable (operator) in the Hilbert space. Pure, finite quantum mechanical algebras have no non-trivial core: for every operator, there is some observable that does not commute with it. Hence, if a chiral molecule undergoes a measurement-like interaction with its environment with respect to one of those non-commuting observables, its chirality (either left- or right-handed) should go immediately into a superposition of the two states (see Amann 1993, p. 139). Yet we never observe large chiral molecules in such superposed states.

In addition, measurement collapse cannot produce the key features of symmetry breaking (Earman 2004, p. 180): "in particular, a symmetric vacuum [ground or equilibrium] state cannot be built as a superposition of degenerate,[17] asymmetric vacuum states." Earman continues:

> If one tries to think of the different degenerate states as belonging to the same Hilbert space, then these states must lie in different 'superselection' sectors between which a meaningful superposition is impossible…. By the same token, a measurement collapse of a superposition cannot produce an asymmetric vacuum state from a symmetric one (p. 185).

Quantum chemists work around this problem in one of two ways. First, they employ "generalized quantum mechanics," (as discussed in Sect. 3.1 above) in which they simply add classical observables and a non-trivial core to the algebra. Generalized quantum mechanics attributes both classical (mutually commuting) and quantum properties to objects. The modern quantum theory of molecular structure is a perfect example. The structure of a molecule, that which distinguishes one isomer from another, including right-handed chiral molecules from left-handed ones, depends entirely on the classical properties of precise location applied to atomic nuclei. This is an exact counterpart to Aristotle's form/matter distinction, with the quantal observables corresponding to the proximate matter and the classical observables to the form.

---

[17] In quantum mechanics, two states are *degenerate* when they have the same energy but very different wave functions. So, the two forms of handedness (left and right) are degenerate states of a chiral molecule, for example.

The second work-around involves taking the continuum limit, which introduces the possibility of unitarily inequivalent representations and superselection sectors. This too acknowledges the reality of *fundamental thermal substances*: the individual particles and electrons merge together into a continuous chemical soup, which is only *potentially and virtually* particulate in nature.

The chemical form of the thermal substance is thus an aspect of its Aristotelian form. Chemical form contributes to exactly those functions that substantial form serves in Aristotle's system: it grounds the classification of a thermal substance by means of natural kinds in terms of its chemical composition, it grounds the persistence of a thermal substance as the same substance over time, and it grounds the substance's active and passive powers in its interactions with other substances. Individual molecules should be thought of as integral parts of thermal substances, just as eyes and hands are integral parts of organisms. A hand cannot be a hand except as part of an organism, and a right-handed chiral molecule cannot be right-handed except as part of a thermal substance.

There is, however, a complication, in that some molecules can be treated as pure quantum systems (modeled by finite quantum mechanical models) and others cannot. In order to explain the difference, quantum chemists look at two factors: the difference in internal energy between the various molecular structures, and the molecule's degree of interaction with its environment, especially the long-wave radiation field that cannot be excluded or screened off. In effect, relatively small molecules can "inherit" or "acquire" classical properties from their environments, despite the fact that they can be observed in superposed quantal states when isolated.

The introduction of the environment does not threaten the metaphysical fundamentality of thermal substances, since it is only a partially *classical* environment that can induce the quasi-classical properties of the dressed molecule: in order to produce the superselection rules needed to distinguish stable molecular structures, the environment must have infinitely many degrees of freedom, due to its own thermodynamic fusion (Primas 1980, pp. 102–105; Primas 1983, pp. 157–159).

As R. F. Hendry points out, a molecule's acquisition of classical properties from its classical environment, thereby breaking its microscopic symmetry, should count as form of "downward causation":

> This supersystem (molecule plus environment) has the power to break the symmetry of the states of its subsystems without acquiring that power from its subsystems in any obvious way. That looks like downward causation (Hendry 2006, pp. 215–216).

References

Allori, V., Dürr, D., Goldstein, S., & Zanghì, N. (2002). Seven steps towards the classical world. *Journal of Optics B, 4,* S482–S488.

Amann, A. (1993). The gestalt problem in quantum theory: Generation of molecular shape by the environment. *Synthese, 97,* 125–156.

Amann, A., & Atmanspacher, H. (2013). C*- and W*-algebras of observables, their interpretations, and the problem of measurement. In H. Atmanspacher (Ed.), *On quanta, mind and matter—Hans primas in context* (pp. 57–79). Berlin: Springer.

Aquinas, T. (1995). *Commentary on Aristotle's metaphysics* (J. P. Rowan, Trans.). Notre Dame, IN: Dumb Ox Books.

Bangu, S. (2009). Understanding thermodynamic singularities: Phase transitions, data and phenomena. *Philosophy of Science, 76,* 488–505.

Bell, J. S. (1990). Against measurement. In A. I. Miller (Ed.), *Sixty-two years of uncertainty: Philosophical, historical, and physical inquiries into the foundations of quantum mechanics* (pp. 17–32). New York: Plenum Press.

Bishop, R. C., & Atmanspacher, H. (2006). Contextual emergence in the description of properties. *Foundations of Physics, 36,* 1753–1777.

Brentano, F. (1988). *Philosophical investigations on space, time and the continuum* (S. Körner & R. M. Chisholm (Eds), B. Smith, Trans.). London: Croom Helm.

Butterfield, J. (2011). Less is different: Emergence and reduction reconciled. *Foundations of Physics*, *41*, 1065–1135.

Cartwright, N. (1994). *Nature's capacities and their measurement*. Oxford: Oxford University Press.

Clifton, R., & Halvorson, H. (2001). Entanglement and open systems in algebraic quantum field theory. *Studies in History and Philosophy of Modern Physics, 32,* 1–31.

Compagner, A. (1989). Thermodynamics as the continuum limit of statistical mechanics. *American Journal of Physics, 57*(2), 106–117.

Earman, J. (2004). Curie's principle and spontaneous symmetry breaking. *International Studies in Philosophy of Science, 18,* 173–198.

Esfeld, M. (2017). A proposal for a minimalist ontology. *Synthese*. https://doi.org/10.1007/s11229-017-1426-8.

Fraser, D. (2008). The fate of 'particles' in quantum field theories with interactions. *Studies in History and Philosophy of Modern Physics, 39,* 841–859.

Healey, R. (1991). Holism and nonseparability. *Journal of Philosophy, 88,* 393–421.

Hendry, R. F. (2006). Is There Downward Causation in Chemistry? In D. Baird, E. Scerri, & L. McIntyre (Eds.), *Philosophy of chemistry: Synthesis of a new discipline* (pp. 173–189). Dordrecht: Springer.

Koons, R. C. (2014). Staunch vs. faint-hearted hylomorphism: Toward an aristotelian account of composition. *Res Philosophica, 91,* 1–27.

Koons, R. C. (2018a). The many worlds interpretation of quantum mechanics: A hylomorphic critique and alternative. In W. M. R. Simpson, R. C. Koons, & N. Teh (Eds.), *Neo-Aristotelian perspectives on contemporary science*. London: Routledge.

Koons, R. C. (2018b). Aristotle, god, and the quantum. In A. Torrance & T. H. McCall (Eds.), *Knowing creation: Perspectives from theology, philosophy, and science*. New York: HarperCollins.

Koons, R. C. (2018c). Hylomorphic escalation: A hylomorphic interpretation of quantum thermodynamics and chemistry. *American Catholic Philosophical Quarterly, 92,* 159–178.

Koons, R. C., & Pickavance, T. H. (2017). *The atlas of reality: A comprehensive guide to metaphysics*. Malden, MA: Wiley Blackwell.

Kronz, F. M., & Lupher, T. A. (2005). Unitarily inequivalent representations in algebraic quantum theory. *International Journal of Theoretical Physics, 44*(3), 1239–1258.

Kronz, F., & Tiehen, J. (2002). Emergence and quantum mechanics. *Philosophy of Science, 69,* 324–347.

Liu, C. (1999). Explaining the emergence of cooperative phenomena. *Philosophy of Science, 66*(Proceedings), S92–S106.

Mainwood, P (2006). Is more different? Emergent properties in physics, D. Phil. dissertation, Oxford University.

Malament, D. (1996). In defense of dogma: Why there cannot be a relativistic quantum mechanical theory of (localizable) particles. In R. Clifton (Ed.), *Perspectives on quantum reality* (pp. 1–10). Dordrecht: Springer.

Maudlin, T. (1995). Four measurement problems. *Topoi, 14,* 7–15.

Meehl, P., & Sellars, W. (1956). The concept of emergence. In M. Scriven & H. Feigl (Eds.), *Minnesota studies in the philosophy of science* (Vol. 1, pp. 239–252). Minneapolis: University of Minnesota Press.

Merricks, T. (2003). *Objects and persons*. Oxford: Oxford University Press.

O'Connor, T. (1994). Emergent properties. *American Philosophical Quarterly, 31,* 91–104.

O'Connor, T., & Wong, H. Y. (2005). The metaphysics of emergence. *Nôus, 39,* 658–678.

Prigogine, I. (1997). *The end of certainty: Time, chaos, and the new laws of nature*. New York: Free Press.

Primas, H. (1980). Foundations of theoretical chemistry. In R. G. Woolley (Ed.), *Quantum dynamics for molecules: The new experimental challenge to theorists* (pp. 39–114). New York: Plenum Press.

Primas, H. (1983). *Chemistry, quantum mechanics, and reductionism: Perspectives in theoretical chemistry*. Berlin: Springer.

Primas, H. (1990a). Mathematical and philosophical questions in the theory of open and macroscopic quantum systems. In A. I. Miller (Ed.), *Sixty-two years of uncertainty: Historical, philosophical, and physical inquiries into the foundations of quantum mechanics* (pp. 233–258). New York: Plenum Press.

Primas, H. (1990b). Induced nonlinear time evolution of open quantum objects. In A. I. Miller (Ed.), *Sixty-two years of uncertainty: Historical, philosophical, and physical inquiries into the foundations of quantum mechanics* (pp. 259–280). New York: Plenum Press.

Redhead, M., & Teller, P. (1991). Particles, particle labels, and quanta: The toll of unacknowledged metaphysics. *Foundations of Physics, 21,* 43–62.

Redhead, M., & Teller, P. (1992). Particle labels and the theory of indistinguishable particles in quantum mechanics. *British Journal for the Philosophy of Science, 43,* 201–218.

Ruetsche, L. (2006). Johnny's so long at the ferromagnet. *Philosophy of Science, 73,* 473–486.

Schaffer, J. (2010). Monism: The priority of the whole. *Philosophical Review, 119,* 31–76.

Schaffer, J. (2012). Why the world has parts: Reply to Horgan and Potrč. In P. Goff (Ed.), *Spinoza on monism* (pp. 77–91). Basingstoke: Palgrave Macmillan.

Schaffer, J. (2013). The action of the whole. In *Proceedings of the Aristotelian Society Supp.* (Vol. 87, pp. 67–87).

Schlosshauer, M. (2005). Decoherence, the measurement problem, and the interpretation of quantum mechanics. *Reviews of Modern Physics, 76,* 1268–1305.

Sewell, G. L. (1986). *Quantum theory of collective phenomena*. Oxford: Clarendon Press.

Sewell, G. L. (2002). *Quantum mechanics and its emergent macrophysics*. Princeton, NJ: Princeton University Press.

Silberstein, M., & McGeever, J. (1999). The search for ontological emergence. *Philosophical Quarterly, 49,* 182–200.

Simpson, W. M. R. (2018). Half-baked humeanism. In W. M. R. Simpson, R. C. Koons, & N. Teh (Eds.), *Neo-Aristotelian perspectives on contemporary science* (pp. 123–145). New York: Routledge.

Simpson, W. M. R. (2019a). *Power monism*. Unpublished manuscript, presented at The Warburg Institute, London, November, 2017.

Simpson, W. M. R. (2019b). *In-formed observations*. Unpublished manuscript, presented at Corpus Christ College, Oxford, 7th Feb 2019.

Strocchi, F. (1985). *Elements of quantum mechanics of infinite systems*. Singapore: World Scientific.

Tahko, T. E. (2018). Disentangling Nature's Joints. In W. M. R. Simpson, R. C. Koons, & N. Teh (Eds.), *Neo-Aristotelian perspectives on contemporary science* (pp. 147–166). New York: Routledge.

Teller, P. (1986). Relational holism and quantum mechanics. *British Journal for the Philosophy of Science, 37*(1), 71–81.

Teller, P. (1995). *An interpretative introduction to quantum field theory*. Princeton: Princeton University Press.

van Inwagen, P. (1990). *Material beings*. Ithaca: Cornell University Press.

Vemulapalli, G. Krishna, & Byerly, H. (1999). Remnants of reductionism. *Foundations of Chemistry, 1,* 17–41.

von Neumann, J. (1931). Die Eindeutigkeit der Schrödingerschen Operatoren. *Mathematische Annalen, 104,* 570–588.

Wallace, D. (2008). Philosophy of quantum mechanics. In D. Rickles (Ed.), *The Ashgate companion to contemporary philosophy of physics* (pp. 16–98). Oxford: Routledge.

Woolley, R. G. (1988). Quantum theory and the molecular hypothesis. In J. Maruani (Ed.), *Molecules in physics, chemistry, and biology* (Vol. I, pp. 45–89). Dordrecht: Kluwer Academic.