# Quantum Entanglements: Editors' Introduction

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The aim of this volume is to provide a representative sample of Clifton's research articles during the second half of his career, from 1995 to 2002. (A full bibliography of Clifton's publications is included at the end of the volume.) We have chosen not to follow a strict chronological order, but have divided the papers under four major headings: I. Modal interpretations; II. Foundations of algebraic quantum field theory; III. The concept of a particle; IV. New light on complementarity, hidden variables and entanglement.

Chronologically, Section I corresponds to a phase of Clifton's career (approximately 1994 to 1997) during which he focused on modal interpretations of elementary quantum mechanics. Sections II and III contain papers drawn from a short, but highly productive period (approximately 1999 to 2001) when Clifton was working primarily on the foundations of quantum field theory: Section II contains papers on nonlocality, and on the modal interpretation in quantum field theory; and Section III contains papers on the particle aspect of quantum field theory. Section IV collects some of Clifton's papers from 1999 to 2002 that are not on the topic of quantum field theory.

Of the fourteen papers in this volume, ten have one or more co-authors. This high proportion is evidence of Clifton's penchant and gift for collaborative research. It was not only that his talent and enthusiasm — and his temperamental inclination to dive in and struggle with any problem that came up — attracted many people, especially aspiring doctoral students and younger colleagues (or e-correspondents!), to work with him. Also, he had a knack for articulating joint projects appropriate to his and the other person's interests and strengths. Furthermore, the enterprise was always underpinned by his sense of fun, and his great intellectual and personal generosity.

We will now proceed to give a slightly more detailed description of the papers in this volume, and of their place in the development of the philosophical foundations of contemporary physics.

## 1 The modal interpretation of quantum mechanics

The so-called 'orthodox' interpretation of quantum mechanics faces a serious difficulty in its description of measurement: If we assume that the standard law of dynamical evolution (i.e., the Schrödinger equation) holds universally, and if we talk in the normal way about when quantities possess values, then it follows that measurements do not usually have results — contrary to our experience. Attempts to solve this measurement problem have been the driving force in the development of contemporary interpretations of quantum mechanics.

There are essentially two routes toward a solution of the measurement problem: One can modify the standard dynamics by introducing a collapse of the wavefunction, or one can keep the standard dynamics but supplement the standard rule for assigning values to quantities. Each route comes with its own perils. On the one hand, those who want to modify the dynamics must not only devise a new dynamical law that is approximated by the Schrödinger equation, but they must also show that this new dynamical law is consistent with the relativity of simultaneity. On the other hand, modifying the orthodox interpretation's way of assigning values to quantities is a nontrivial task, since the Kochen-Specker theorem entails that not all quantities can possess values simultaneously.

The modal interpretation of quantum mechanics follows the second route — i.e., it is a 'no collapse' interpretation. It goes back to the work of van Fraassen in the 1970s, but came to fruition in papers by Kochen (1985) and Dieks (1989), and in the monograph by Healey (1989). However, the modal interpretation soon faced several philosophical challenges. For example, Arntzenius (1990) pointed out some of the more bizarre metaphysical consequences of Kochen's modal interpretation, and Albert & Loewer (1990) argued that the modal interpretation cannot explain why 'error-prone' measurements have outcomes. Similarly, Elby (1993) argued against the modal interpretation's ability to solve the measurement problem.

These challenges were met by a 'second generation' of workers on the modal interpretation, who developed it to a higher level of sophistication. First, Bub (1993), Dieks (1993), Healey (1993), and Dickson (1994) all defended the modal interpretation's solution of the measurement problem. These responses were then followed by papers in which it was argued that decoherence considerations are sufficient to ensure that the modal interpretation gives the right predictions for the outcomes of measurements (Bacciagaluppi & Hemmo 1996), and in which it was shown that the modal interpretation's assignment of definite values can be extended to deal with troublesome degenerate cases (Bacciagaluppi et al. 1995).

Clifton was obviously adept at working out intricate technical details. But what really set his work apart was his ability to translate 'big' philosophical questions into tractable technical problems. For example, while some researchers were continuing to fine-tune the modal interpretation's account of measurement, Clifton raised a more fundamental motivational question: Is there an independent reason, besides its potential for solving the measurement problem, to adopt the modal interpretation? The result of Clifton's investigations into this question is the first chapter of this volume: 'Independently motivating the Kochen-Dieks modal interpretation of quantum mechanics' (1995). The style of argument in this paper is characteristic of Clifton's approach: He first transforms intuitive desiderata (in this case, desiderata for an interpretation of quantum mechanics) into precise mathematical conditions; and he then proves — via an existence and uniqueness theorem — that there is precisely one 'object' (in this case, the Kochen-Dieks (KD) modal interpretation) that satisfies these desiderata.

Of Clifton's desiderata for interpretations of quantum mechanics, the foremost is the definability condition. An interpretation satisfies the definability condition just in case its choice of definite-valued observables can be defined in terms of the quantum state alone. But what is the physical or metaphysical motivation for this condition? It is highly doubtful that Clifton thought that there is some *a priori* metaphysical warrant for the definability condition. It is more likely that Clifton chose the definability condition as a means for avoiding metaphysical disputes about which quantities are the most 'fundamental'. For example, the best known hidden variable theory — the de Broglie-Bohm theory — assigns a privileged role to *position*: it asserts that, no matter what the quantum state is, there are point particles with definite positions, and the distribution of these particles agrees with the probabilities predicted by the quantum state. Granted that the de Broglie-Bohm theory does in fact solve the measurement problem, what is *its* motivation? A quick perusal of the literature indicates that the motivations are usually of either an ontological or of an epistemological sort. For example, it is sometimes claimed that an ontology of particles is more 'intelligible' than, say, the ontology we would get if we required that momentum is always definite. Or, it might be argued that measurements have results if and only if there are particles with definite positions. But since these arguments are controversial and philosophically nontrivial, it might be seen as desirable to find a purely mathematical criterion for selection of the definite-valued observables.

Clifton's 1995 paper on the KD modal interpretation was soon followed by a paper, 'A uniqueness theorem for 'no collapse' interpretations of quantum mechanics' (Chap. 2; 1996), written jointly with Jeffrey Bub. Bub, one of the pioneering advocates of modal interpretations, had recently argued that any interpretation which solves the measurement problem (without abandoning Schrödinger dynamics) must be a 'Bohm-like' hidden variable interpretation (Bub 1994). Bub and Clifton provide support for this claim by means of a characterization theorem which parameterizes 'no collapse' interpretations by the observable that they choose to privilege.

The Kochen-Specker theorem shows that we cannot consistently assign determinate values to all quantum mechanical observables; if we try, we will eventually run into an 'obstruction'. Bub and Clifton turn the Kochen-Specker theorem on its head by asking: What are the *largest* sets of observables that *can* be assigned determinate values without generating a Kochen-Specker contradiction? They then supply a recipe which permits them, for any chosen privileged observable, to construct one of these maximal sets which contains that observable; and, conversely, they show that each such maximal set is generated by a privileged observable.

One of the potential motivations for the KD modal interpretation was the hope that it would provide a 'realistic' interpretation of quantum mechanics that upholds the completeness of the theory, in spirit if not in letter. (The contrast here is with the de Broglie-Bohm theory, which is the paradigm example of an interpretation that concedes the incompleteness of quantum mechanics.) However, the Bub-Clifton theorem — in combination with Clifton's 1995 theorem — shows that this motivation is not completely well-founded. For both the KD modal interpretation and the de Broglie-Bohm theory concede the incompleteness of quantum mechanics in the sense that the quantum state itself is not taken to determine what is actual (i.e., the so-called value state).

In Bub and Clifton's paper we also encounter a thread that runs throughout Clifton's later work: Clifton claims — contrary to the traditional view — that Bohr's complementarity interpretation should be thought of as a modal interpretation (like the KD interpretation, or the de Broglie-Bohm theory). This description of Bohr's interpretation might seem surprising since Bohr was the primary defender of the completeness of quantum mechanics, and since Bohr is often thought to have endorsed (if only tacitly) the collapse of the wavefunction upon measurement. (For a more detailed explanation of why Clifton rejected the traditional view of Bohr's interpretation, see Chap. 12.)

After Bub and Clifton's paper had appeared, they joined forces with Sheldon Goldstein to give a simplified proof of the classification theorem. Since the resulting proof clarifies the conceptual situation, we chose to include it as Chapter 3 of this volume.

In his 1995 paper, Clifton motivates the KD modal interpretation by showing that it satisfies several intuitively plausible criteria. However, there was one motivation for the KD modal interpretation that Clifton does not mention explicitly — viz., the hope that it would prove (unlike the de Broglie-Bohm theory) to be strictly consistent with the relativity of simultaneity. This question — or more specifically, the question whether the KD modal interpretation is consistent with Lorentz invariance — was explored in a collaboration between Clifton and Michael Dickson, which resulted in the 1998 paper 'Lorentz-invariance in modal interpretations' (Chap. 4). Clifton and Dickson argue that the KD modal interpretation must assume that there is a preferred frame of reference, and therefore cannot maintain 'fundamental' Lorentz invariance. They go on to argue, however, that the KD modal interpretation is 'empirically' Lorentz invariant in the sense that no observer can determine which frame is privileged; and they conclude that the KD modal interpretation is on exactly the same footing — in terms of its relationship to relativity theory — as the de Broglie-Bohm theory.

Clifton went on to write a few more papers on the modal interpretation, focusing primarily on extending it to the context of algebraic quantum theory (see papers **??** and **??** of Clifton's publication list on p. **??**). However, it appears that after realizing that the KD interpretation violates Lorentz invariance, Clifton ceased to think of it as providing a promising approach to solving the measurement problem.

# 2 Foundations of algebraic quantum field theory

After 1997, Clifton directed much of his effort at quantum field theory (QFT), especially algebraic QFT: an approach to the theory that is mathematically rigorous and so well suited to foundational investigations. In this endeavor, Clifton was striking out into a territory largely uncharted by philosophers of physics. For though philosophers of physics have written reams about the foundations of elementary non-relativistic quantum mechanics, especially about the measurement problem and nonlocality, the philosophical literature on QFT is small. There is just a handful of books: for example, Brown & Harré (1988) and Teller (1995). This situation is understandable, since QFT is a much more technically demanding theory than elementary quantum mechanics. But it is regrettable, not least because QFT is, after all, the most predictively accurate theory in history, and so seems the obvious place to seek the raw materials for a 'metaphysic of nature'.

Our selection of Clifton's work on QFT comprises Parts II and III, and even the first chapter of Part IV. To introduce this material, it will be clearest not to discuss the papers *seriatim*, but to discuss in order the following topics: nonlocality and the vacuum; the Reeh-Schlieder theorem; the modal interpretation in QFT; and finally, the concept of a particle in QFT.

## 2.1 Nonlocality and the vacuum

The vacuum state of a relativistic quantum field is very different from our intuitive notion of a state in which 'nothing is happening'. To describe this, let us begin with the article 'More ado about nothing', by Redhead, who had been Clifton's graduate adviser (Redhead 1995). In this article, Redhead discusses how in the relativistic vacuum state, any local event has a nonzero probability of occurrence, and two events in mutually distant regions can display strong correlations.

However, Redhead did not establish that the vacuum state is *nonlocally* correlated in the sense of Bell (1964). Recall that Bell provides a rigorous method for displaying the nonlocality of states: there is a family of inequalities (Bell's inequalities) about the expectation values of local measurements, such that, if a state's predictions violate one of these inequalities, then these predictions cannot be reproduced by a local hidden variable model. Such a state is now called *Bell correlated*.

The question whether the vacuum state is Bell correlated had been floating around for some years before Redhead's paper. For example, in the mid 1980s and early 1990s, the mathematical physicists Summers and Werner obtained a series of deep mathematical results on Bell's inequality in rigorous QFT (Summers & Werner 1985, 1987*a*,*b*,*c*, 1988, 1995). For example, Summers and Werner showed that the vacuum state does violate Bell's inequality (in fact, violates it maximally) relative to measurements that can be performed in tangent wedges of Minkowski spacetime.

Despite the power of Summers and Werner's results, they leave open some interesting questions about nonlocality in QFT. According to oral history, Malament pointed out to Clifton in 1998 that they do not settle the question whether the vacuum state violates Bell's inequality relative to measurements performed in *any* pair of spacelike separated regions (no matter how small these regions are, and no matter how far apart they are). Clifton immediately realized the interest of this question; and he was in a good position to see the difficulties in proving 'Malament's conjecture'. For Mermin (1996) had recently emphasized (at a conference at the University of Western Ontario, organized by Clifton) the foundational relevance of 'Werner states', which had recently been discovered by Werner (1989). To see the importance of Werner states, recall that a state of a composite system in quantum mechanics is called *separable* if it can be decomposed as a mixture of product states (i.e., states for which the two subsystems are completely uncorrelated); if a state is not separable, it is called *nonseparable*. Now, all states that are nonseparable and *pure* (i.e., vector states) violate a Bell's inequality (Popescu & Rohrlich 1992). But Werner discovered that some nonseparable mixed states do *not* violate a Bell's inequality: such states are now called 'Werner states' in honour of their discoverer.

Clifton and Malament knew that the vacuum state is nonseparable. However, when restricted to bounded regions of spacetime, the vacuum state is a mixed state — so that it might be a Werner state, i.e., a state that does not violate Bell's inequality.

History shows that many of the most interesting scientific discoveries are the by-products of failure. For example, it has been said that most advances in number theory over the past 300 years were the results of failed attempts to prove Fermat's last theorem. A similar thing might be said about Clifton's work on Malament's conjecture: Although Clifton was frustrated in his attempts to solve the conjecture, his attempts led to a number of unexpected, fruitful, and perhaps even more interesting results.

For example, in the paper 'Nonlocal correlations are generic in infinite dimensional bipartite systems' (2000; Chap. 10), Clifton, along with collaborators Hans Halvorson and Adrian Kent, shows that a pair of infinite dimensional elementary quantum systems has a dense set of Bell correlated states. (Recall that a subset $S$ of $X$ is dense just in case any element of $X$ can be approximated arbitrarily closely — in the relevant topology — by elements of $S$.) As Clifton *et al.* point out, this density result is not only foundationally interesting (since it shows that the 'quantumness' of a system 'varies in proportion' to the number of degrees of freedom): It is also of practical interest for quantum information theory, where one wishes to use entanglement as a physical resource to perform certain information processing tasks.

Nonetheless, this Clifton-Halvorson-Kent result does not provide any information directly relevant to Malament's conjecture — which is specifically about the vacuum state in relativistic QFT. Most particularly, the algebras of local observables in relativistic QFT are not isomorphic to the algebra of all bounded operators on a Hilbert space, and so the Clifton-Halvorson-Kent result is simply inapplicable to relativistic QFT. (In fact, the algebras of local observables in relativistic QFT are typically type III von Neumann algebras, whereas the algebras of local observables in nonrelativistic QM are type I von Neumann algebras.)

Very shortly after the appearance of the Clifton-Halvorson-Kent paper, a second paper (by Clifton and Halvorson) appeared: 'Generic Bell correlation between arbitrary local algebras in quantum field theory' (2000; Chap. 6). In this paper, Clifton and Halvorson generalize the Clifton-Halvorson-Kent argument to the case of algebras of local observables that are von Neumann algebras 'of infinite type'. (For the proof of the result, the essential property of these algebras is that they have infinitely many orthogonal projections that are pairwise 'equivalent'.) The infinite von Neumann algebras include the algebra of all bounded operators on an infinite-dimensional Hilbert space (which is used to represent elementary quantum systems whose observables can take infinitely many different values) as well as the type III von Neumann algebras. Thus, Clifton and Halvorson show that whenever local algebras of observables are of infinite type, then the Bell correlated states are dense. Although this generalized result still does not prove Malament's conjecture, it does show that the vacuum is approximated arbitrarily closely by nonlocal, i.e. Bell correlated, states.

So Clifton's work on nonlocality shows that there is a similarity between relativistic QFT and nonrelativistic quantum mechanics on infinite-dimensional Hilbert spaces — viz., in both cases there is a dense set of states that violate a Bell's inequality. But in his next major publication ('Entanglement and open systems in algebraic quantum field theory'; 2001, Chap. 7: again with Halvorson), Clifton shows that there is a sense in which nonlocality is *worse* in relativistic QFT than it is in nonrelativistic QM! In particular, in nonrelativistic QM, one can always disentangle (or 'isolate') a system by performing a measurement of a maximal observable — the resulting state will always be a product state, and so will have no correlations. But Clifton and Halvorson show that when the algebras of local observables are type III, then local observers cannot perform such disentangling operations. So, not only is the generic state of relativistic QFT nonlocally correlated: also, it is impossible to disentangle a local system from its environment.

However, this paper's central topic is not disentanglement or its impossibility, but rather the interpretation of one of the most fundamental results of rigorous quantum field theory: the Reeh-Schlieder theorem, proved in 1961.

## 2.2 The Reeh-Schlieder theorem

This theorem says, roughly speaking, that any state of the quantum field can be approximated arbitrarily closely by applying to the vacuum state operators from any fixed local algebra of observables (no matter how small the local region is). This is a very striking result. Indeed, many of the interesting features of the relativistic vacuum, and even of relativistic QFT in general, are closely related to it — or even derivable from it.

But there is also an interpretative danger. The theorem seems to suggest that actions in a spacetime region $O$ can have instantaneous effects in a distant, i.e. spacelike separated, region $O'$: viz., changing the state from the vacuum to another state, with expectation values for chosen observables associated with $O'$ that are arbitrarily close to prescribed values. If that were correct, then the Reeh-Schlieder theorem would suggest a serious conflict between relativistic QFT and the fundamental principles of special relativity. This suggestion has of course been addressed before; for example by Segal (1964) and Fleming (2000). But Clifton and Halvorson argue in Chapter 7 (especially Sec. 3) against the suggestion (cf. also Halvorson 2001). The main idea is to apply the distinction between *selective* and *nonselective* operations: a distinction which is also applied in discussion of elementary quantum mechanics, to reconcile nonlocal correlations with the no-signaling theorem. Thus in a selective operation (represented, e.g., by applying a projection operator to a state vector), an observer performs a measurement and then ignores, or destroys, the elements of the original ensemble that do not correspond to a certain set of results. And if we are concerned with an ensemble that is spread over two spacelike separated regions, then one can maintain that such a selection should not be thought of as a physical *action* occurring in just one region that has *effects* in the other (spacelike separated) region.

## 2.3 The modal interpretation of AQFT

One of Clifton's main goals in the period between 1999 and 2001 was to translate interpretive questions from the context of elementary quantum mechanics to the (more technically demanding) context of relativistic QFT. Of course, Clifton was not alone in this goal. For example, in a 2000 paper, Dennis Dieks put forward a proposal for extending the modal interpretation to relativistic QFT. As Dieks points out, making such an extension is not completely straightforward. In particular, the modal interpretation's rule for picking determinate observables makes use of the fact that there is a one-to-one correspondence between quantum states and a certain kind of operator on a Hilbert space (viz., density operators); but in QFT this correspondence between states and observables no longer holds (since type III algebras cannot contain density operators). To bypass this problem, Dieks proposes making use of the split property, according to which any local algebra of observables in QFT can be approximated by a type I algebra (i.e., the algebra of all bounded operators on a Hilbert space). Since the approximating type I algebra does contain density operators, Dieks proposes that we apply the standard KD rule to the approximating algebra in order to find an approximation of the set of definite-valued observables for the relevant spacetime region.

Clifton fired off a quick response to Dieks in his paper, 'The modal interpretation of algebraic quantum field theory' (2000; Chap. 5). In this paper, Clifton argues that Dieks' method of using the approximating type I algebra does not provide a non-arbitrary method for determining the definite-valued observables associated with a spacetime region. Clifton then goes on to supply a rule for picking the definite-valued observables within a general von Neumann algebra, and he proves that this rule is a generalization of the Kochen-Dieks rule for type I factors. However, Clifton also shows that this generalized rule entails that very frequently (viz., in all ergodic states, which form a dense subset of the state space), there will be no non-trivial definite-valued quantities associated with any given spacetime region. Thus, it seems very unlikely that the KD modal interpretation can be successfully extended to provide a solution of the measurement problem in the context of relativistic QFT.

## 3 The concept of a particle

One of the oldest debates in natural philosophy concerns the composition of matter: Is there a limit to the divisibility of matter ('particle ontology'), or is matter a continuum that can be subdivided *ad infinitum* ('field ontology'). Different attitudes toward this question have driven competing research programs in physics; and philosophers similarly have tried either to resolve the issue, or (like Kant in the Second Antinomy) to show that the issue cannot be resolved.

The debate over particle vs. field ontology becomes more interesting in the context of quantum mechanics, and even more so in relativistic quantum theory. First, it seems impossible to build a consistent relativistic quantum theory of particles; and, so it looks like relativity forces us to a quantum *field* theory. However, as Teller (1995, p. 93) points out, 'the subject matter of so-called 'quantum field theory' does not need to be presented as a field theory'. In fact, Fock showed in 1932 that the states of a quantum field have (in many important cases) a completely natural interpretation as particle states, and so it seems that QFT does not immediately settle the particle vs. field dispute.

However, there are a number of difficulties with the particle interpretation of QFT. Part III of this volume consists of two papers that each take up one of these difficulties. The first concerns the localization of particles, the second the appearance of particles in the vacuum.

In the first paper, 'No place for particles in relativistic quantum theories' (2002; Chap. 8), Clifton and Halvorson investigate arguments which purport to show that there can be no localized particles in any relativistic quantum theory.[1] The tensions between relativity and the notion of a localized quantum state have been known since at least the 1940s. They were then made precise in a series of results by Newton and Wigner, Hegerfeldt and others: results whose broad thrust is that localized quantum states would violate relativity's prohibition of superluminal velocities (e.g. Hegerfeldt 1974, Hegerfeldt & Ruijsenaars 1980).[2]

Clifton and Halvorson's point of departure is a theorem of Malament (1996), to the effect that if in a relativistic quantum theory there are no 'act-outcome' correlations at spacelike separation, then there are no localized particles. Although Malament bases his argument on a clearly valid mathematical proof, the soundness of his argument has been questioned by a number of researchers — including Barrett, Dickson, and Fleming. In 'No place for particles', Clifton and Halvorson defend Malament's arguments against these criticisms, and they supply variations of his mathematical proof to thwart potential further criticisms. In particular, Malament's proof is a *reductio ad absurdum* which derives a contradiction from the assumption that there is a 'standard' (i.e., self-adjoint) position operator that satisfies certain relativistic conditions. Clifton and Halvorson strengthen Malament's result by showing that the assumption of an 'unsharp' position operator leads to a contradic-

[1]The adjective 'localized' may seem redundant. However, we will suppose that 'particle' simply means an individual indivisible entity, whether or not that entity is spatially extended.

[2]Since superluminal velocities are consistent with Lorentz covariance, it is a separate issue whether there is a Lorentz covariant notion of localization. Extensive work has been done on this latter topic, most particularly by Fleming; see, e.g., Fleming (1989), Fleming & Butterfield (1999).

tion, and similarly that the assumption of a system of local number operators (which would quantify the number of particles in a local spacetime region) leads to a contradiction.

Aside from the project of clarifying the ontological commitments of relativistic quantum theories, there is an independent reason for being concerned about the existence of localized particles: namely, the simple fact that we seem to see localized objects. So, if our best theory entails that there are no such objects, then either our best theory is false, or our experience is radically misleading. But even if we can get past this first worry, there is a second worry about the empirical coherence of a physical theory which entails that there are no localized objects. Such a theory seems to preclude determinate perceptions, and hence its own confirmation. In Section 7 of 'No place for particles', Clifton and Halvorson deal with these issues by arguing that the *appearance* of localized objects, which is consistent with relativistic QFT (despite its entailing the nonexistence of strictly localized particles), is sufficient to provide an empirical basis against which we can test theories.

In 'Are Rindler quanta real?' (2001; Chap. 9) Clifton and Halvorson discuss a second difficulty about particles in relativistic QFT: namely, the effect discovered and analysed by Fulling, Unruh and others — and now usually called the 'Unruh effect'. An observer traveling at a constant (nonzero) acceleration in the Minkowski vacuum state will find that her particle detectors click wildly, as if she were immersed in a thermal bath of particles. (An observer traveling at a constant velocity will not detect any particles.) The question, then, is whether the clicks in the accelerating observer's detector should be taken at face value as indicating the presence of particles in the vacuum — which are called 'Rindler quanta' — or whether the response of the detector should be interpreted in some other way.

A number of different interpretations of the Unruh effect have been proposed. For example, Arageorgis (1995) argues that Rindler quanta do not qualify as genuine particles. On the other hand, Arageorgis et al. (2002) argue that the inertial and accelerating observers' different descriptions of the quantum field should be thought of as incommensurable theories, in the manner of Kuhn. Finally, Davies (1984) argues that the two observers' descriptions are complementary in exactly the same way that measurements of position and momentum are. From this, Davies goes on to draw the radical conclusion that there is no objective (i.e., observer-independent) fact about whether Rindler quanta exist in the vacuum.

Clifton and Halvorson argue that these three interpretations, and others, become much clearer — and their merits and demerits more visible — if one adopts the framework of algebraic QFT. They go on to adjudicate between the interpretations, proving several theorems *en route*. Their analysis begins by discussing how the two observers' descriptions correspond to distinct, and inequivalent, representations of the canonical commutation relations. Accordingly, the claim that Rindler quanta are not 'real' corresponds in some way to a claim that the Rindler representation is the 'wrong' representation (and the Minkowski representation is the 'right' representation). The claim of incommensurability amounts to claiming that the states in the two representations make incomparable predictions. And the claim that the Minkowski and Rindler pictures are complementary amounts to a claim that the corresponding representations are complementary.

Broadly speaking, Clifton and Halvorson argue that the complementarity interpretation is superior to its rivals, some of which are in any case incompatible with previously established results or with Clifton and Halvorson's theorems. But the complementarity involved is formally more sophisticated than usually envisaged. For usually, complementarity is formally expressed in terms of noncommuting operators on a single Hilbert space; but here the two inequivalent representations are defined on two different Hilbert spaces.

## 4 Complementarity, hidden variables, and entanglement

Niels Bohr struggled throughout his life to create a philosophical framework that would solve the conceptual puzzles of quantum theory. As is well known, at the root of Bohr's 'solution' is the idea of complementarity: quantum mechanical systems do not admit a single unified description, but instead require the use of mutually exclusive and jointly exhaustive descriptions. But Bohr also claimed that quantum mechanics is 'complete' in the sense that no future theory could resolve these complementary descriptions into a single unified description.

Bohr's idea of complementarity had a huge impact on the first generation of physicists working on quantum theory. However, professional philosophers — at least since the wane of logical positivism — have usually taken a dim view of Bohr's contribution to foundational issues. Early examples include the critiques by Bunge (1955*a*,*b*) and Popper (1967). More recent criticisms include Cushing (1994), Fine & Beller (1994) and Beller (1999). A common theme of these criticisms is that Bohr's views can only be defended, or even made sense of, by invoking some or other positivist doctrine.

As we noted earlier, sometime in the mid-1990s Clifton came to the conclusion that Bohr's interpretation is best thought of as a version of the modal interpretation. Since the modal interpretation is obviously consistent with the negation of positivism — indeed, it was developed by philosophers (such as van Fraassen and Dieks) who explicitly reject positivistic semantic principles — Clifton of course became bothered by claims that complementarity presupposes positivism. Some philosophers and historians had indeed taken a more favorable view of the complementarity interpretation. In particular, a series of papers by Howard (for example Howard (1994) and Howard (2003)) argue for the ongoing relevance of Bohr's complementarity interpretation for the project of interpreting quantum mechanics; and for this interpretation bearing little resemblance to the 'Copenhagen interpretation' — which was only constructed in the mid-1950s onwards, by people other than Bohr.[3] Clifton's work in this area, i.e., reviving the complementarity interpretation, yielded two papers (in addition to Chap. 9's interpreting Rindler quanta in terms of complementarity); both are reprinted in Part IV.

In 'Reconsidering Bohr's reply to EPR' (2002; Chap. 12), Clifton and Halvorson explicate and defend Bohr's reply to EPR's argument for the incompleteness of quantum mechanics. As is well known, EPR argue that Bohr is committed to saying that a measurement on one system can make a difference to 'what is real' at a distant location. The challenge for Bohr — and the challenge for contemporary interpreters of quantum theory — is to explain how this fact is consistent with the claim that physical causes operate locally.

[3] The 1980s also saw the appearance of three sympathetic expositions of Bohr's philosophy (Murdoch 1987, Folse 1985, Honner 1987). However, these books are not aimed at developing the complementarity interpretation within the technical foundations of quantum theory.

In his reply to EPR, Bohr famously agrees that 'there is … no question of a mechanical disturbance of the [distant] system'. But notoriously, he goes on:

> But … there is essentially the question of an influence on the very conditions that define the possible types of predictions regarding future behavior of the system.

It is of this passage that Bell (1987, p. 155) says, 'I have very little idea what it means', and which Fine (1981, pp. 34–5) interprets as an example of 'virtually textbook neopositivism', and as a sort of 'semantic disturbance' without a 'plausible or intuitive physical basis'.

However, Clifton and Halvorson claim that Bohr's statement makes sense as a claim about which quantities of the distant system can (without falling into a Kochen-Specker contradiction) possess values simultaneously with the quantity that is measured on the local system.

The general idea that Bohr's statement can be explicated via the modal interpretation had been floated earlier by Howard (1979), Bub (1989*a*), and by Clifton himself (in the 1996 paper with Bub). However, Clifton and Halvorson provide a number of novel results (such as Theorem 1, on page **??**), with special emphasis on using the tools of algebraic quantum theory to reconstruct Bohr's reply to the *original* EPR argument (which employs continuous spectrum observables).

As mentioned earlier, critics of the complementarity interpretation have claimed that it is based on invalid positivistic reasoning. Clifton, of course, agreed that deriving ontological conclusions from epistemic premises is generally invalid, and so cannot establish complementarity. In 'Complementarity between position and momentum as a consequence of Kochen-Specker arguments' (2000: Chap. 11), Clifton attempts to provide a more solid foundation for complementarity (specifically, between position and momentum) by means of a Kochen-Specker-type no-hidden-variables theorem. One should be clear, however, that Clifton's argument is not just another simplification of the original Kochen-Specker theorem. Rather, the original Kochen-Specker theorem (and the many simplified versions of it that have been proven over the years) does not establish position-momentum complementarity, since the assumption of the Kochen-Specker *reductio* is that *all* observables (and not just position and momentum) possess values. Clifton, however, shows that a contradiction can be derived from the weaker assumption that position and momentum possess values, at least for the case of two and three degrees of freedom. (It is still an open question whether the result holds for the case of a single degree of freedom.)

Though in Chapter 11, Clifton argues for a strengthened version of the Kochen-Specker theorem, in 'Simulating quantum mechanics by non-contextual hidden variables' (2000; Chap. 13), Clifton and Kent argue that Kochen-Specker-type theorems cannot decisively rule out an explanation of quantum statistics by means of hidden variables. More precisely, Clifton and Kent show that hidden variables can explain the results of a set of measurements that is dense in the 'space of measurements' (where each measurement is represented by a projection-valued resolution of the identity, or more generally by a positive operator-valued resolution of the identity); and, thus, that any quantum mechanical measurement can be 'simulated' by a measurement for which there is a hidden variable explanation. More precisely, the original Kochen-Specker theorem proceeds by choosing a (finite) set of measurements for which there is no explanation by a hidden variable theory. However, Clifton and Kent's result shows that the Kochen-Specker contradiction must always choose at least one measurement $M$ that falls outside of Clifton and Kent's set of classically explainable set of measurements. So, since our measurements are not infinitely precise, one can always maintain that instead of $M$, some classically explainable measurement $M'$ was performed.

In the final years of Clifton's career, he grew increasingly interested in the rapidly growing field of quantum information theory. Here, we have chosen 'The subtleties of entanglement and its role in quantum information theory' (2002; Chap. 14), which is especially helpful in setting out the new questions and research topics that this field offers philosophers of science. As the title suggests, the overarching theme of this paper is that entanglement is subtle. More specifically, it has theoretical features, and suggests experimental possibilities, which have not been addressed by the philosophical analysis of quantum nonlocality. In particular, these features and possibilities suggest various classifications of kinds of entanglement or nonlocality which are different from, and typically more fine-grained than, the traditional philosophical splitting of stochastic hidden variable models' main assumption of factorizability into parameter independence and outcome independence (i.e., into the prohibition of act-outcome correlations and of outcome-outcome correlations, respectively).

Clifton discusses two such experimental possibilities — dense coding and teleportation — and two theoretical features: hidden nonlocality and entanglement thermodynamics. We shall leave him to speak for himself about the experimental possibilities; but we will introduce the theoretical features.

'Hidden nonlocality' refers to the Werner states mentioned in Section 2.1 above: mixed non-separable states that obey Bell's inequality and indeed admit a local hidden variables model. It emerged in the mid-1990s through the work of Popescu, Peres and others that in general these states, despite admitting a local hidden variables model, had a hidden nonlocality, in the sense that a suitable sequence of local operations (including measurements) on the component systems $A$ and $B$, together with ordinary classical communication between the parties (always called 'Alice' and 'Bob'), could yield a Bell correlated state. In short: investigating Werner states engendered a new classification of different kinds of nonlocality.

Finally, Clifton discusses entanglement thermodynamics, in which one quantifies the amount of pure entangled states needed to 'form' a given (in general, mixed) state, and the amount of pure entangled states that can be 'distilled' from a given (in general, mixed) state. As Clifton points out, the measures of entanglement of formation and entanglement of distillation provides a finer-grained classification of nonlocality than the measure provided by Bell's inequality. Clifton concludes by exploring the analogy between entanglement thermodynamics and classical thermodynamics, with a view to shedding new light on the question of whether quantum theory needs to be underpinned by a more fundamental (i.e., hidden variable) theory.

# 5 Conclusion

If the reader was hoping that this Introduction might provide a picture of a unified 'philosophy of Rob Clifton', then we are afraid we must disappoint her. Clifton had a supreme talent for condensing a philosophical claim into a precise technical proposition — and then proving or refuting it. This talent, combined with the fact that he worked across the whole range of the philosophy and foundations of quantum theory, makes for a picture of great achievement — but also of diversity. For example, in some chapters Clifton develops the modal interpretation, while in others he defends complementarity. And in Chapter 13, he shows that hidden variables cannot be completely ruled out by Kochen-Specker arguments. So what was really Clifton's favored interpretation of quantum mechanics? In our opinion, it is not really helpful to try to pin Clifton down like this. It is almost as if Clifton was governed by the 'uncertainty principle for interpreters of quantum mechanics' stated some years ago by Jeff Bub (1989*b*, p. 191):

> … *as soon as you've found a position, you lose your momentum.*

Rob Clifton may never have found a definite position, but he never lost momentum.

## References


Albert, D. Z. & Loewer, B. (1990), Wanted dead or alive: Two attempts to solve Schrödinger's paradox, *in* A. Fine, M. Forbes & L. Wessels, eds, 'Proceedings of the 1990 biennial meeting of the Philosophy of Science Association', Philosophy of Science Association, East Lansing, MI, pp. 277–85.

Arageorgis, A. (1995), Fields, particles, and curvature: Foundations and philosophical aspects of quantum field theory on curved spacetime, PhD thesis, University of Pittsburgh.

Arageorgis, A., Earman, J. & Ruetsche, L. (2002), 'Weyling the time away: the non-unitary implementability of quantum field dynamics on curved spacetime', *Studies in History and Philosophy of Science. B. Studies in History and Philosophy of Modern Physics* **33**, 151–84.

Arntzenius, F. (1990), Kochen's interpretation of quantum mechanics, *in* A. Fine, M. Forbes & L. Wessels, eds, 'Proceedings of the 1990 biennial meeting of the Philosophy of Science Association', Philosophy of Science Association, East Lansing, MI, pp. 241–9.

Bacciagaluppi, G., Donald, M. J. & Vermaas, P. E. (1995), 'Continuity and discontinuity of definite properties in the modal interpretation', *Helv. Phys. Acta* **68**, 679–704.

Bacciagaluppi, G. & Hemmo, M. (1996), 'Modal interpretations, decoherence and measurements', *Stud. Hist. Philos. Sci. B Stud. Hist. Philos. Modern Phys.* **27**, 239–77.

Bell, J. (1964), 'On the Einstein-Podolsky-Rosen paradox', *Physics* **1**, 195–200.

Bell, J. S. (1987), *Speakable and unspeakable in quantum mechanics*, Cambridge University Press, Cambridge. Collected papers on quantum philosophy.

Beller, M. (1999), *Quantum Dialogue*, University of Chicago Press, Chicago.

Brown, H. R. & Harré, R. (1988), *Philosophical foundations of quantum field theory*, Clarendon Press, Oxford.

Bub, J. (1989*a*), 'On Bohr's response to EPR: A quantum logical analysis', *Foundations of physics* **19**, 793–805.

Bub, J. (1989*b*), 'The philosophy of quantum mechanics', *The British Journal for the Philosophy of Science* **40**, 191–211.

Bub, J. (1993), 'Measurement: it ain't over till it's over', *Foundations of Physics Letters* **6**, 21–35.

Bub, J. (1994), 'How to interpret quantum mechanics', *Erkenntnis* **41**, 253–73.

Bunge, M. (1955*a*), 'Strife about complementarity, part I', *The British Journal for the Philosophy of Science* **6**, 1–12.

Bunge, M. (1955*b*), 'Strife about complementarity, part II', *The British Journal for the Philosophy of Science* **6**, 141–54.

Cushing, J. T. (1994), *Quantum mechanics: Historical contingency and the Copenhagen hegemony*, University of Chicago Press, Chicago, IL.

Davies, P. C. W. (1984), Particles do not exist, *in* S. M. Christensen, ed., 'Quantum theory of gravity', Adam-Hilger, Bristol, pp. 66–77.

Dickson, W. M. (1994), Wavefunction tails in the modal interpretation, *in* 'PSA 1994', Philosophy of Science Assocation, East Lansing, MI, pp. 366–76.

Dieks, D. (1989), 'Quantum mechanics without the projection postulate and its realistic interpretation', *Foundations of Physics* **19**, 1397–423.

Dieks, D. (1993), 'The modal interpretation of quantum mechanics, measurements and macroscopic behavior', *Physical Review A* **49**, 439–46.

Dieks, D. (2000), 'Consistent histories and relativistic invariance in the modal interpretation of quantum mechanics', *Physics Letters A* **265**, 317–25.

Elby, A. (1993), 'Why "modal" interpretations of quantum mechanics don't solve the measurement problem', *Foundations of Physics Letters* **6**, 5–19.

Fine, A. (1981), Einstein's critique of quantum theory: The roots and significance of EPR, *in* P. Barker & C. G. Shugart, eds, 'After Einstein', Memphis State University Press, Memphis.

Fine, A. & Beller, M. (1994), Bohr's response to EPR, *in* J. Faye & H. Folse, eds, 'Niels Bohr and Contemporary Philosophy', Kluwer, NY, pp. 1–31.

Fleming, G. (2000), 'Reeh-Schlieder meets Newton-Wigner', *Philosophy of Science* **67**, S495–S515.

Fleming, G. N. (1989), Lorentz invariant state reduction, and localization, *in* A. Fine & J. Leplin, eds, 'Proceedings of the 1988 biennial meeting of the Philosophy of Science Assocation', Philosophy of Science Association, East Lansing, MI, pp. 112–26.

Fleming, G. N. & Butterfield, J. N. (1999), Strange positions, *in* J. Butterfield & C. Pagonis, eds, 'From physics to philosophy', Cambridge University Press, New York.

Folse, H. (1985), *The philosophy of Niels Bohr*, Elsevier Science, New York.

Halvorson, H. (2001), 'Reeh-Schlieder defeats Newton-Wigner: On alternative localization schemes in relativistic quantum field theory', *Philosophy of Science* **68**, 111–33.

Healey, R. (1989), *The philosophy of quantum mechanics: An interactive interpretation*, Cambridge University Press, Cambridge.

Healey, R. (1993), 'Why error-prone quantum measurements have outcomes', *Foundations of Physics Letters* **6**, 37–54.

Hegerfeldt, G. (1974), 'Remark on causality and particle localization', *Physical Review D* **10**, 3320.

Hegerfeldt, G. C. & Ruijsenaars, S. N. M. (1980), 'Remarks on causality, localization, and spreading of wave packets', *Physical Review D* **22**, 377–84.

Honner, J. (1987), *The description of nature: Niels Bohr and the philosophy of quantum physics*, Oxford University Press, New York.

Howard, D. (1979), Complementarity and ontology: Niels Bohr and the problem of scientific realism in quantum physics, PhD thesis, Boston University.

Howard, D. (1994), What makes a classical concept classical?, *in* J. Faye & H. Folse, eds, 'Niels Bohr and contemporary philosophy', Kluwer, NY, pp. 201–29.

Howard, D. (2003), 'Who invented the "Copenhagen interpretation"? a study in mythology', *Philosophy of Science* . Forthcoming.

Kochen, S. (1985), A new interpretation of quantum mechanics, *in* 'Symposium on the foundations of modern physics', World Sci. Publishing, Singapore, pp. 151–169.

Malament, D. B. (1996), In defense of dogma: Why there cannot be a relativistic quantum mechanics of (localizable) particles, *in* R. Clifton, ed., 'Perspectives on Quantum Reality', Kluwer, Dordrecht, pp. 1–10.

Mermin, N. D. (1996), Hidden quantum non-locality, *in* R. Clifton, ed., 'Perspectives on quantum reality', Vol. 57, Kluwer, Dordrecht, pp. 57–71.

Murdoch, D. (1987), *Niels Bohr's philosophy of physics*, Cambridge University Press, Cambridge.

Popescu, S. & Rohrlich, D. (1992), 'Generic quantum nonlocality', *Physics Letters A* **166**, 293–7.

Popper, K. R. (1967), Quantum mechanics without "the observer", *in* M. Bunge, ed., 'Quantum Theory and Reality', Springer, Berlin.

Redhead, M. L. G. (1982), Quantum field theory for philosophers, *in* 'Proceedings of the 1982 biennial meeting of the Philosophy of Science Assocation', Philosophy of Science Association, East Lansing, MI, pp. 57–99.

Redhead, M. L. G. (1995), 'More ado about nothing', *Foundations of Physics* **25**, 123–37.

Segal, I. E. (1964), Quantum fields and analysis in the solution manifolds of differential equations, *in* W. T. Martin & I. E. Segal, eds, 'Proceedings of a Conference on the Theory and Applications of Analysis in Function Space', MIT Press, Cambridge, MA, pp. 129–53.

Summers, S. J. & Werner, R. (1985), 'The vacuum violates Bell's inequalities', *Physics Letters. A* **110**, 257–9.

Summers, S. J. & Werner, R. (1987*a*), 'Bell's inequalities and quantum field theory. I. General setting', *Journal of Mathematical Physics* **28**, 2440–7.

Summers, S. J. & Werner, R. (1987*b*), 'Bell's inequalities and quantum field theory. II. Bell's inequalities are maximally violated in the vacuum', *Journal of Mathematical Physics* **28**, 2448–56.

Summers, S. J. & Werner, R. (1987*c*), 'Maximal violation of Bell's inequalities is generic in quantum field theory', *Communications in Mathematical Physics* **110**, 247–59.

Summers, S. J. & Werner, R. (1988), 'Maximal violation of Bell's inequalities for algebras of observables in tangent spacetime regions', *Annales de l'Institut Henri Poincaré. Physique Théorique* **49**, 215–43.

Summers, S. J. & Werner, R. F. (1995), 'On Bell's inequalities and algebraic invariants', *Letters in Mathematical Physics* **33**, 321–34.

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

Werner, R. F. (1989), 'Quantum states with Einstein-Podolsky-Rosen correlations admitting a hidden-variable model', *Physical Review A* **40**, 4277–81.