Jeremy Butterfield and Hans Halvorson, eds, **Quantum Entanglements: selected papers of Rob Clifton**, Oxford University Press, 2004

In his brief but extraordinary career, Rob Clifton (1964-2002) wrote some fifty first-rate papers on the foundations and interpretation of quantum theory. *Quantum Entanglements*, edited by Jeremy Butterfield and Hans Halvorson, collects fourteen of these, addressing a wide array of subjects: "modal" interpretations of quantum mechanics, the concept of a particle in relativistic quantum field theory, contextual hidden variables, quantum information theory, and much more. Reflecting Clifton's zeal for collaborative work, most of the papers in *Quantum Entanglements* are jointly authored (many with Halvorson, others with Jeffrey Bub, Michael Dickson, Sheldon Goldstein and Adrian Kent). Individually, these papers are excellent; several are certifiable *tours de force*. Collated, they are even better. For, despite their diversity of topic and of co-authorship, the papers in *Quantum Entanglements* display a considerable continuity of thought. Clifton's early work dealt with no-collapse interpretations of elementary quantum mechanics; later, he turned to the interpretational challenges posed by quantum field theory. Although the former evolved largely in reaction to the operationalist orthodoxies of the Copenhagen interpretation, Clifton's later work on algebraic quantum field theory tended to undercut some of the assumptions driving that reaction; and, indeed, the general drift of his work seems to have been towards a *realist* neo- Copenhagen interpretation.

No-Collapse Interpretations. Quantum states assign values to quantum observables only probabilistically. Realist interpretations of quantum mechanics (QM) nevertheless attempt to understand observables as *having* definite values, and to explain the results of quantum-mechanical measurements in terms of these values. *No-collapse* interpretation attempt to do so without appealing to non-unitary dynamics. Complicating this task is the fact (a consequence of Gleason's Theorem) that one can't consistently assign definite values to *all* quantum observables in a non-contextual way. Accordingly, a no-collapse interpretation must either embrace contextualism (at a steep price in non-locality), or, more conservatively, attempt to isolate a *subset* of the observables as carrying definite values. The Bub-Clifton Theorem (presented in various stages of refinement in the first three papers in *Quantum Entanglements*) classifies all (reasonable) interpretations of this latter sort. Call a set $\mathcal{D}$ of observables *definite* for a pure state e iff it supports sufficiently many non-contextual dispersion-free states to reproduce the statistical predictions of the state e, as they apply to observable in $\mathcal{D}$. The Theorem identifies, subject to a few normative requirements, the maximal definite set of observables for e containing a preferred determinate observable R. Different choices of R correspond to different interpretations: in the Bohm interpretation, R is position; in "modal" interpretations, it is (in effect) the reduced state of a composite system on one of the components. Interestingly, Bub and Clifton regard Bohr's complementarity interpretation as being a no-collapse interpretation, in which R is chosen pragmatically.

In charaterizing a class of interpretations of QM in a mathematically precise way, the Bub-Clifton theorem makes it possible to obtain precise and sweeping conclusions about this class. For example, in *Lorentz Invariance in Modal Interpretations*, Clifton and Michael Dickson show that modal interpretations, as described above, can't be made fully Lorentz-covariant, being tacitly committed to a preferred reference frame (though one that is empirically undetectable.)

Algebraic Quantum Field Theory. During the last five years of his life, Clifton (together with his student, Halvorson) devoted much of his attention to the interpretation of algebraic quantum field theory (AQFT). Here the fixed Hilbert space of QM gives way to an abstract C^*-algebra $\mathfrak{A}$, the self-adjoint elements of which represent bounded obervables. Physical states are represented by positive, normalized linear functionals on $\mathfrak{A}$, understood as assigning expected values to observables. In elementary QM, $\mathfrak{A} = \mathcal{B}(\mathbf{H})$, the algebra of all bounded linear operators on a Hilbert space $\mathbf{H}$. In this context, states are assumed to be normal, i.e., countably-additive over orthogonal projections. More generally, each state ω on a C^*-algebra $\mathfrak{A}$ yields a representation, $\pi_\omega : \mathfrak{A} \to \mathcal{B}(\mathbf{H}_\omega)$ of $\mathfrak{A}$ as an algebra of operators on a Hilbert space $\mathbf{H}_\omega$, and thus, a von Neumann algebra $\mathfrak{R}_\omega = \pi_\omega(\mathfrak{A})''$ supplying the rich projection lattice needed to sustain the theory's probabilistic interpretation. That this apparatus is in some measure state-dependent marks one difference between AQFT and ordinary QM. Another is that $\mathfrak{R}_\omega$ is typically of type III, and so, has neither atomic projections nor pure normal states. In *Open systems in algebraic quantum field theory*, Clifton and Halvorson discuss various ways in which this plays hob with received ideas concerning entanglement and the interpretation of mixed states.[1]

A third point at which AQFT differs from QM is the existence of physically inequivalent states (or representations). Call two states, α and β, physically equivalent iff there exists a $*$ isomorphism between $\mathfrak{R}_\alpha$ and $\mathfrak{R}_\beta$ intertwining the representations π_α and π_β. An example of *in*equivalent states are the Minkowski and Rindler vacuum states associated respectively with inertial and accelerated reference frames in Minkowski space-time: in the Minkowski vacuum state, accelerated observers will detect quanta unseen by inertial observers. In *Are Rindler quanta real?*, Clifton and Halvorson urge that the corresponding representations be understood as *complementary* – but in a realist sense:

> Rindler quanta get their status as such not because they are, *by definition*, the sort of thing that accelerated detectors detect. This gets things backwards. Rindler detectors display Rindler quanta in the Minkowski vacuum *because* they couple to *Rindler* observables of the field that are distinct from, and indeed complementary to, Minkowski observables. (p. 316)

This very interesting idea is further developed in *Complementarity between position and momentum as a consequence of Kochen-Specker arguments* and *Reconsidering Bohr's reply to EPR*, joint with Halvorson. [2]

[1]Indeed, as later argued by Ruetsche [2], it's not even clear how to formulate the measurement problem in this setting.

[2]See also [1], an important paper of Halvorson and Clifton that is much referenced, but

If, as the editors suggest in their introduction to *Quantum Entanglements*, Clifton never settled on an interpretation of quantum mechanics, he nevertheless produced, with Halvorson, a detailed sketch for a realist, neo-Copenhagen interpretation of quantum field theory. Whether it can be rendered more fully, remains to be seen; but on the evidence of this volume, the prospects seem good.

References:

[1] Halvorsen, H. and R. Clifton, *Maximal Beable Subalgebras of Quantum Mechanical Observables*, International Journal of Theoretical Physics **38** (1999), 2441-2484.

[2] Ruetsche, Laura, *Intrinsically Mixed States: an appreciation*, Studies in the History and Philosophy of Modern Physics **35** (2004), 221-239.

unfortunately not included, in *Quantum Entanglements*.