

assume this responsibility, either individually or through our organizations. It does no good to complain about poor preparation of our incoming students if we do not try to change the situation.

There is a common rejoinder to these admonitions. Why bother? Some college teachers claim that it makes no difference whether their students have had a prior physics course. Most high school teachers observe that their students appear never to have studied science before, and certainly never have studied math. Considering that the earlier texts are so inaccurate and misleading, perhaps it's just as well. What if the students really remembered all the wrong things they were taught? The only thing that saves our whole educational enterprise is its terrible inefficiency.

I think we should care. I think there's a lot to worry about. When I look over the school texts, or many of the college texts, I'm not so much concerned with the factual mistakes. Instead, I worry that in many of them the style and spirit of science is missing. I worry that the eagerness of children to learn science soon turns into a widespread loathing of the subject.

All of us here, at whatever level of research or teaching,

have many things in common. We share a view of the universe and our relationship to that universe that is very different from the understanding of most of the people on our planet. We know in elaborate detail how grand and mysterious that universe is. We know the probability that humans on the earth are the only ones who are comprehending their situation. Maybe that's the proper role of humans, if we have a role.

If so, our business is to learn all we can about this universe. In optimizing our research base, we have an obligation, and it is in our self interest, to inform others—to spread the word. We are like missionaries on a crowded planet where most people are going about their daily business of propagating themselves and killing each other. But here we are, looking out at an unearthly drama and saying, "Look, look! Something very marvelous and very mysterious is going on and we humans may be part of it."

At every level of teaching and research we have special talents to contribute to this enterprise and to our common cause. We need each other and we need all the strong interactions we can get.

Resource letter IQM-2: Foundations of quantum mechanics since the Bell inequalities

L. E. Ballentine

Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada V5A 1S6

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This Resource Letter provides a guide to the literature on the foundations of quantum mechanics over approximately the past 20 years. Topics covered include Bell's theorem, interpretation of the quantum state concept, the theory of measurement, and experimental tests of fundamental aspects of the quantum theory of matter and the electromagnetic field. The letter E after an item indicates elementary level of material of general interest to persons becoming informed in the field. The letter I, for intermediate level, indicates material of somewhat more specialized nature; and the letter A indicates rather specialized or advanced material. An asterisk (*) indicates those articles to be included in an accompanying Reprint Book.

I. INTRODUCTION

The purpose of this Resource Letter is to review the developments in the foundations of quantum mechanics that have taken place during approximately the past 20 years, a period in which Bell's theorem has been the most spectacular development although by no means the only one. Another convenient reference point is the Resource Letter IQM-1 by DeWitt and Graham (Ref. 14) published in 1971. For the most part I shall not include papers that are listed in that earlier Resource Letter.

A glance at IQM-1 reveals that the Copenhagen interpretation was the dominant interpretation during that earlier period. It is doubtful whether that is true any longer.

But in order to make such a statement it is necessary to specify what is meant by the "Copenhagen interpretation." I shall use the term in its popular, but not necessarily historically accurate sense, as including the following propositions:

(a) The state vector provides a complete description of an individual system (that is, the views of Bohr rather than of Einstein in their famous controversy);

(b) The state vector evolves according to the Schrödinger equation while the system is isolated, but changes discontinuously during measurement to an eigenstate of the observable that is measured (Von Neumann's "projection postulate"). Of course this does not fully characterize the Copenhagen interpretation. In particular, Born's sta-

tistical interpretation of the wavefunction is also an essential ingredient, but it is either a postulate or a consequence of almost every interpretation, so it does not distinguish one from another. Some will not like my terminology. L. Rosenfeld has said (quoted in Ref. 21), "We in Copenhagen do not like (the phrase Copenhagen interpretation) at all. Indeed, this expression was invented, and is used by people wishing to suggest that there may be other interpretations . . . , namely their own muddled ones." Thus not only is the interpretation of QM controversial, but the existence of a controversy (which requires at least two interpretations) is controversial! There is no point in arguing about labels, and I shall employ the label "Copenhagen interpretation" to refer to the well-known ideas listed above.

One of the most interesting features of the newer interpretations is, in spite of their apparent diversity, a convergence on certain tenets that contradict the old Copenhagen interpretation. Ballentine (Ref. 18, *Statistical ensemble interpretation*) draws his philosophical inspiration from Einstein, criticizes the "Copenhagen interpretation," and rejects (a) and the projection postulate of (b). Stapp (Ref. 21) draws his philosophical inspiration from Bohr and calls his paper "The Copenhagen Interpretation," but he rejects several of Heisenberg's ideas, as well as the interpretation of which (b) is the corner stone (which, however, he calls "Absolute Ψ "). Moreover, it appears that Ballentine and Stapp are in substantial agreement about the concept of "state" (see Ref. 36). In order to distinguish it from the old Copenhagen interpretation above, I refer to Stapp's views as the "neo-Copenhagen interpretation."

None of the principal modern interpretations (Sec. V A) accept the consequence of Von Neumann's projection postulate, the so-called "reduction" or "collapse" of the state vector, as a real physical process. This rejection is necessary because the result of a consistent inclusion of the measurement apparatus in the system has been proved to be strictly incompatible with the result of the projection postulate (Sec. V D). The projection postulate is at best an approximation, valid under limited circumstances, and so has no place as an axiom.

Bell's theorem is regarded by many people as one of the most profound and startling developments in modern physics, affecting not only the interpretation of QM, but ultimately our whole world view. But the awareness of its significance was slow to develop, as may be seen from the graph (Fig. 1) of citations of Bell's original paper.

Bell's work is a continuation, after nearly 30 years, of the

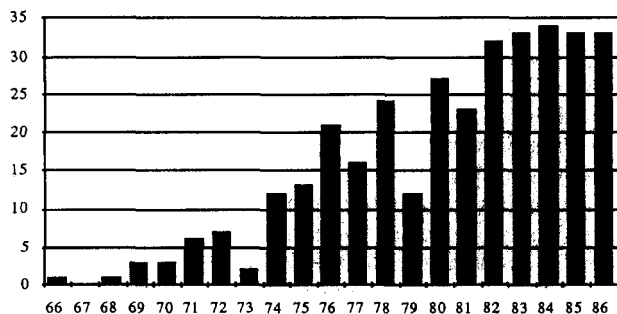


Fig. 1. Annual citations in *Science Citation Index* of Bell's paper (Ref. 53).

famous paper by Einstein, Podolsky, and Rosen. The essence of their argument was to consider a pair of particles which have been prepared in an eigenstate of total momentum $p_1 + p_2$ and relative position $q_1 - q_2$. If one measures p_1 , one can deduce the value of p_2 ; if one measures q_1 , one can deduce the value of q_2 . Invoking a postulate of *locality*, of a type suggested by special relativity, that there is no action-at-a-distance between the particles, EPR inferred that the values of p_2 and q_2 could not have been created by the measurement, but must have been preexistent *elements of reality*. Since no quantum state can describe simultaneous values for noncommuting variables like position and momentum, EPR concluded that the description of reality by QM states is incomplete.

Most of the published responses to EPR are only of historical interest. I mention only that of Margenau (Ref. 51), who pointed out that the EPR paradox highlights the need to eliminate Von Neumann's projection postulate. That conclusion, which has subsequently been reinforced by more powerful arguments, was relevant to the original form of the EPR argument. But the EPR argument can be reformulated without the projection postulate, as is done above, and it still retains its content. Any paradoxical aspects of the conclusions of the EPR and Bell arguments do not depend upon the notion of state-vector-reduction.

Bell's inequalities, in their most general form, are restrictions on the degree of correlation between two separated detectors, and are derivable from a locality postulate similar to that of EPR. Bell's theorem is that some predictions of QM violate these inequalities, even though there may be *no apparent mechanism* for action-at-a-distance. There is some confusion about the relation of Bell's theorem to the EPR argument, it being sometimes said that Bell's conclusion contradicts that of EPR. In fact Bell's argument is fully compatible with that of EPR, of which it is an extension. This can most easily be seen in the simplified presentation of Mermin (Ref. 70). One considers a source of pairs of spin $\frac{1}{2}$ particles in the singlet ($J = 0$) state. For each particle one chooses to measure the spin component in one of three directions, which form angles of 120° . A contradiction of Bell's inequality can be obtained from the combination of two predictions of QM: (i) For those pairs whose spins are measured along the same direction the results will be perfectly (oppositely) correlated; (ii) If one averages over all nine possible choices for the pair of directions then the average correlation for all pairs of particles is zero. EPR in effect used only the information (i), and hence Bell's result are more powerful. Although Bell's theorem casts serious doubt about the validity of the locality postulate used by EPR, it does not falsify their conclusion that QM is *incomplete* (in their technical sense of the word). Moreover, that conclusion seems to be confirmed by an independent argument (Ref. 115).

Many papers have been written about the significance and interpretation of Bell's theorem. What is the precise nature of the *locality* postulate that must be used in the derivation? Are more assumptions needed than merely *locality*? If indeed we must give up *locality*, what kind of nonlocality must we have, and how will this affect our world view? It is easy enough to invent an interpretation that admits nonlocality (allowing causality to propagate in both the forward and backward light cones is perhaps the easiest), but so far such attempts have not been very illuminating. Perhaps what is needed is not an explanation of nonlocality, but an explanation of locality. Why, if locality

is not true, does it work so well in so many different contexts?

The greatest change since the publication of Resource Letter IQM-1 is the increase in the number of *experiments* which test or illustrate the fundamental aspects of QM. IQM-1 lists only two experiments, one of which is only a proposal. Now the list includes: tests of the Bell inequalities; measurement of the electron momentum distribution in atomic hydrogen; interference experiments in which neutron beams are split, separated by centimeters, spin-flipped, and recombined coherently (confirming the superposition principle and contradicting "collapse" of the state vector); electron holography to make wavefunction phase fronts visible; observation of the Kapitza-Dirac effect (diffraction of matter by light, instead of the familiar diffraction of light by matter); and photon correlation measurements which are able to distinguish between quantum electrodynamics and semiclassical radiation theories. No longer can it be claimed that the interpretation of QM is a dull subject for endless debate by philosophers and arm-chair physicists. The foundations of QM has become what it always should have been, an exciting subject at the heart of mainstream physics.

II. CONFERENCE PROCEEDINGS

1. **Proceedings of the International School of Physics "Enrico Fermi,"** Course 49 (Varenna, 29 June-11 July 1970), "Foundations of Quantum Mechanics," edited by B. d'Espagnat (Academic, New York, 1971). (A)
2. **Les Implications Conceptuelles de la Physique Quantique,** J. Phys. (Paris) Coll. C-2 (March 1981). In French, except for the article by Bell. (A)
3. **Foundations of Quantum Mechanics in the Light of New Technology,** proceedings of an international symposium held at the Central Research Laboratory of Hitachi, Ltd., Tokyo, 29-31 Aug. 1983. Edited by S. Kamefuchi (Physical Society of Japan, Tokyo, 1984). (A)
4. **Open Questions in Quantum Physics,** proceedings of a workshop held in Bari, Italy, May 1983. Edited by G. Tarozzi and A. van der Merwe (Reidel, Dordrecht, 1985). (A)
5. **Fundamental Questions in Quantum Mechanics,** proceedings of a conference at Albany, NY, 12-14 April 1984. Edited by L. M. Roth and A. Inomata (Gordon and Breach, London, 1986). (I,A)
6. **Symposium on the Foundations of Modern Physics: 50 years of the Einstein-Podolsky-Rosen Gedankenexperiment,** proceedings of a conference at Joensuu, Finland, 16-20 June 1985, edited by P. Lahti and P. Mittelstaedt (World Scientific Publishing Co., Singapore, 1985). (I,A)
7. **New Techniques and Ideas in Quantum Measurement Theory,** edited by D. M. Greenberger, *Annals NY Acad. Sci.* **480** (1986). Proceedings of a conference at New York, 21-24 Jan. 1986. (I,A)

III. TEXTBOOKS AND EXPOSITIONS

Few textbooks deal adequately with the problems of interpretation of QM. Many give a perfunctory rehash of ideas circa 1930; others remain silent. A notable exception is the following book.

8. **Modern Quantum Mechanics,** J. J. Sakurai (Benjamin/Cummings, Menlo Park, California, 1985). This is the only textbook that discusses Bell's inequalities. (I)

There are some specialized expositions that deal with these problems.

9. **A survey of Hidden-Variable Theories,** F. J. Belinfante (Pergamon, Oxford, 1973). The scope of this book is wider than the title would suggest. A "hidden-variable model" is broadly interpreted as any dynamical or statistical model that is intended to illustrate some or all of the features of QM. Belinfante discusses the content of various theo-

rems that pertain to such models, often in terms much clearer than those of the original authors. The general theorems are illustrated by detailed studies of specific models. Part III of the book is devoted to the derivation and explanation of Bell's inequalities, and to detailed examination of their relation to specific models and to experiments. (I)

10. **The Philosophy of Quantum Mechanics: The Interpretations of Quantum Mechanics in Historical Perspective,** M. Jammer (Wiley, New York, 1974). A good account of the historical development of various interpretations of QM (mainly the older ones, but Bell's theorem is included). However, the reader should be aware that this is primarily a *history* of ideas, which are faithfully represented even when fallacious, and little criticism is provided beyond that which already exists in the literature. (I)
11. **Measurements and Time Reversal in Objective Quantum Theory,** F. J. Belinfante (Pergamon, Oxford, 1975). The purpose of this book is "primarily to give a reply to scientific papers written by a large number of authors," consequently it is not a self-contained introduction to the subjects of its title. But the author's personal views of those subjects are interesting and often helpful. (A)
12. **Conceptual Foundations of Quantum Mechanics,** B. d'Espagnat (Benjamin, Reading, MA, 1976). The topics include: a summary of relevant aspects of the formalism of QM; nonseparability (the EPR-Bell problem); measurement theories; and a discussion of philosophical views. (A)
13. **Chemistry, Quantum Mechanics and Reductionism,** H. Primas (Springer, Berlin, 1981). This book contains a remarkable combination of correct and contestable statements. It is *not* recommended for teaching, but readers who can exercise independent critical judgement may find it both interesting and challenging. In addition to a wealth of references, it contains good descriptive summaries and critiques of many interpretations. Ensemble interpretations receive little attention because of the author's prior belief that only an individual interpretation can supply his desiderata. He apparently believes that the "insoluble problem of measurement" (discussed under items 43 and 49), which bedevils all individual interpretations, can be resolved by means of superselection rules in the W^* -algebra formalism. That belief (or hope) is not well founded. (A)

IV. PREVIOUS REVIEWS

14. **Resource Letter IQM-1 on the Interpretation of Quantum Mechanics,** B. S. Dewitt and R. N. Graham, *Am. J. Phys.* **39**, 724-738 (1971). (E,I,A)
15. **"Quantum Mechanics Reality and Separability,"** F. Selleri and G. Tarozzi, *Riv. Nuovo Cimento* **4**, (2) 1-53 (1981). (I)
16. **Quantum Theory and Measurement,** edited by J. A. Wheeler and W. H. Zurek (Princeton U.P., Princeton, NJ, 1983). A reprint collection with a large supplementary bibliography. (E,I,A)
17. **"Bell's theorem: Experimental Test and Implications,"** J. F. Clauser and A. Shimony, *Rep. Prog. Phys.* **41**, 1881-1927 (1978). This is an excellent review of all subjects related to Bell's inequalities up to that date. (I,A)

V. CURRENT RESEARCH TOPICS

A. The principal interpretations of quantum mechanics

1. Statistical ensemble interpretation

- * 18. **"The Statistical Interpretation of Quantum Mechanics,"** L. E. Ballentine, *Rev. Mod. Phys.* **42**, 358-381 (1970). It is argued that the quantum state function should be regarded as a description of a conceptual ensemble of similarly prepared systems, rather than as the complete description of an individual system. The opposite assumption is untenable because it leads to unsolvable difficulties in the theory of measurement. (I,A)
19. **"Einstein's Interpretation of Quantum Mechanics,"** L. E. Ballentine, *Am. J. Phys.* **40**, 1763-1771 (1972). Einstein's view of QM and the nature of his critical arguments are reviewed. Certain widespread misconceptions about his views are corrected. (I)

2. Neo-Copenhagen interpretation

20. "S-Matrix Interpretation of Quantum Theory," H. P. Stapp, *Phys. Rev. D* **3**, 1303–20 (1971). Described by its author as "an elaboration upon the Copenhagen interpretation," this paper includes among its basic precepts: that the physical world must be separated into two parts, called the observed and the observing system (Stapp has subsequently come to view this as a serious limitation of the CI); and that the probabilities in the theory are probabilities of response of the measuring devices. "Collapse of the wave function" does not occur as a physical process, but only corresponds to a "change in the set of specifications on the preparation of the observed system." This paper is the first of many in which Stapp attempts to develop an interpretation of QM that is satisfactory in light of Bell's theorem. The appeal of this approach is limited by the unnaturalness of conceiving all processes as being essentially scattering processes. (A)
- * 21. "The Copenhagen Interpretation," H. P. Stapp, *Am. J. Phys.* **40**, 1098–1116 (1972). In attempting to save "the Copenhagen interpretation" the author radically revises what is often, rightly or wrongly, understood by that term. That interpretation in which Von Neumann's "reduction" of the state vector in measurement forms the core is rejected, as are Heisenberg's subjectivistic statements. The very "pragmatic" (one could also say "instrumentalist") aspect of the interpretation is strongly emphasized. Readers will be divided as to whether this is a virtue or a fault. (I)

3. Consistent histories interpretation

22. "Consistent Histories and the Interpretation of Quantum Mechanics," R. B. Griffiths, *J. Stat. Phys.* **36**, 219–272 (1984). The usual formula for probabilities of single events is generalized to yield conditional probabilities for selected sequences of events at several different times. A sequence of events must satisfy certain conditions, which are well defined within the formalism but are rather difficult to grasp intuitively, in order to qualify as a "consistent history" to which a probability may be assigned. The state function plays a much less prominent role than in other interpretations and there is no physical process of "collapse." There is no need to distinguish conceptually between the observed and the observing parts of the system. (A)
23. "Quantum Interpretation Using Consistent Histories," R. B. Griffiths, in Ref. 5, pp. 211–223 (1986). A less technical account of the concepts and results of the previous paper. (I)

4. Many worlds interpretation

This bizarre interpretation was motivated by the problem of quantum cosmology. The Copenhagen interpretation requires that there be an "observer" outside of the system who performs "measurements" on the system, and so it cannot be applied to the universe as a whole. The Statistical ensemble interpretation has no such limitation, and if applied to the whole universe could, in principle, yield a result such as, "The probability of a cosmos like ours developing out of the initial Big Bang is 42%." Such a prediction is not very useful, since it could be tested only by repeating the Big Bang a large number of times. The MWI postulates that the universe is described by a unique state vector. There is no "reduction" of the state vector, in measurement or at any other time, but whenever the state vector takes the form of a sum of orthogonal state vectors then each term is assumed to correspond to a separate world, or branch, of the universe. Appearances are saved because it is shown that an observer in one branch cannot detect any of the other branches. It was even claimed that "The mathematical formalism of quantum theory is capable of yielding its own interpretation." (That claim is refuted in Refs. 25 and 26.) Although the evolution of the universal state vector is deterministic, there is in principle no way to account for the particular combination of branches that con-

stitutes ones personal history. Thus the predictive power of the MWI is the same as that of the Statistical ensemble interpretation.

24. "The Many-Worlds Interpretation of Quantum Mechanics," edited by B. S. DeWitt and N. Graham (Princeton U.P., Princeton, NJ, 1973). Reprints of the original papers by H. Everett, J. A. Wheeler, B. S. DeWitt, L. N. Cooper, D. vanVechten, and N. Graham. (A)
25. "Can the Statistical Postulate of Quantum Theory Be Derived?—A Critique of the Many-Universes Interpretation," L. E. Ballentine, *Found. Phys.* **3**, 229–240 (1973). (The MWI was originally called the "Many-Universes" interpretation, before being more appropriately renamed by its proponents.) The author points out that the definition of the "branches" of the universe in the MWI is dependent upon the choice of representation, and is therefore ambiguous. He also argues that the bizarre assumptions of the MWI are neither necessary nor sufficient to derive the Born statistical formula of QM. (A)
26. "Quantum Theory and Cosmology," C. J. S. Clarke, *Philos. Sci.* **41**, 317–332 (1974). This author also shows that "some additional structures" must be added to the theory in order to determine which states will determine the "branching." (A)
27. "How Many Worlds?," R. A. Healey, *Nous* **18**, 591–616 (1984). A critical discussion of several versions of the MWI (A)

5. The quantum potential

When the Schrödinger equation is written in terms of the real amplitude and phase of the complex wavefunction Ψ , the phase equation has the form of the Hamilton–Jacobi equation with an additional "quantum potential." This H–J equation generates an ensemble of particle trajectories that reproduce the QM probability distribution $|\Psi|^2$. The quantum potential does not necessarily become small in regions where the wavefunction is very small, and it can give rise to an effective interaction between particles that do not tend to zero at large separations. Because of this apparent nonlocality, the quantum potential model was often regarded as a mathematical curiosity that lacked any physical significance. But it has acquired a new lease on life since Bell's theorem has shown that some kind of nonlocality must be a feature of all interpretations of QM.

28. "Quantum Interference and the Quantum Potential," C. Philippidis, C. Dewdney, and B. J. Hiley, *Nuovo Cimento* **52**, 15–28 (1979). The quantum potential and the ensemble of particle trajectories are computed and illustrated for the two-slit interference pattern. (I)
29. "On the Impossible Pilot Wave," J. S. Bell, *Found. Phys.* **12**, 989–999 (1982). In this perceptive and provocative paper Bell asks why so many prominent people took seriously Von Neumann's "proof" that QM is incompatible with a more detailed deterministic description, and why similar "proofs" have been advanced by other authors, when an explicit counterexample to all such "proofs" was published by Bohm in 1952, and the essential idea for Bohm's model was introduced by deBroglie in 1927. Among the morals of the story is, "Always test your general reasoning against simple models." (I)
30. "Unbroken Quantum Realism, from Microscopic to Macroscopic Levels," D. Bohm and B. J. Hiley, *Phys. Rev. Lett.* **55**, 2511–4 (1985). The quantum potential interpretation is put forward as a counterexample to recent claims that QM implies any denial of physical realism. (I)
31. "An Ontological Basis for the Quantum Theory," D. Bohm, B. J. Hiley, and P. N. Kaloyerou, *Phys. Rep.* **144**, 321–375 (1987). A quite complete account of the quantum potential theory, applied to both particles and fields. (I)

B. Nature of quantum state functions

32. "On Explaining the Meaning of the Wave Function," G. D. Hoyt, *Am. J. Phys.* **36**, 368–9 (1968). Stresses that $|\Psi|^2$ is a probability density for the *system*, and is not a matter wave for the electron. In the example of the hydrogen atom it gives as much information about the proton as about the electron. (E)

33. "Quantum Fact and Fiction: Clarifying Lande's Pseudo-paradox," J. M. Levy-Leblond, *Am. J. Phys.* **44**, 1130-2 (1976). A. Lande had objected that deBroglie's relation $p = h/\lambda$ violates Galilean invariance, since the wavelength λ of a wave is the same in two frames of reference with relative velocity v , but the momentum p of a particle transforms as $p' = p + mv$. Levy-Leblond points out that, unlike a classical wave, the wavefunction in QM undergoes a phase transformation in addition to the transformation of coordinates ($x' = x + vt$, $t' = t$), and that this causes the deBroglie wavelength λ to transform just so as to maintain the relation $p = h/\lambda$. He stresses that the notion of "wave-particle duality" can be misleading because the wavefunction of QM is not a real wave. (I)
34. "Probability Interpretation of Quantum Mechanics," R. G. Newton, *Am. J. Phys.* **48**, 1029-34 (1980). The author rejects the interpretation of the wavefunction as a real object in space, or as an expression of subjective knowledge, in favor of an objective statistical interpretation. He emphasizes that an ensemble interpretation is required for both pure and mixed states. (I)
- *35. "Solution to Two Paradoxes in the Quantum Theory of Unstable Systems," M. Bunge and A. J. Kalnay, *Nuovo Cimento* **77B**, 1-9 (1983). According to some people, all decay processes should be exponential. According to others, an unstable system under constant observation will never decay. Both of these incorrect conclusions are shown to be consequences of an incorrect interpretation of quantum states. (I)
36. "What is a State Vector?," A. Peres, *Am. J. Phys.* **52**, 644-650 (1984). A state vector is not a property of a single system, but rather of a *preparation procedure*. He quotes Ballentine (Ref. 18, "Statistical ensemble interpretation") and Stapp (Ref. 21, "Copenhagen interpretation") to show that both agree on this point. (I)

C. State preparation and state determination

- *37. "An Operational Interpretation of Nonrelativistic Quantum Mechanics," W. E. Lamb, Jr., *Phys. Today* **22**, (4) 23-28 (1969). Methods are described by means of which an arbitrary quantum state could, in principle, be prepared. Preparation is clearly distinguished from measurement. (I)
38. "The Empirical Determination of Quantum States," W. Band and J. L. Park, *Found. Phys.* **1**, 133-144 (1970). (I)
39. "A General Method of Empirical State Determination in Quantum Physics: Part II," W. Band and J. L. Park, *Found. Phys.* **1**, 339-343 (1971). Given a definite preparation procedure, how can one determine what state is actually being prepared? These two papers show how it can be done by measuring the averages, on an ensemble of similarly prepared systems, of a "quorum" of noncommuting observables. (I)
40. "The Physics and the Semantics of Quantum Measurement," H. Margenau and J. L. Park, *Found. Phys.* **3**, 19-28 (1973). In the course of criticizing another paper, the authors provide a clear distinction between *state preparation* and *measurement*. (I)
41. "Measurement of the Wigner Function," A. Royer, *Phys. Rev. Lett.* **55**, 2745-8 (1985). The Wigner function provides a phase space representation of a quantum state. Since it is not a probability, its operational significance has been unclear. Royer shows how, in principle, the Wigner function (and hence the state) can be experimentally determined for an ensemble of particles. (I)

D. Theory of measurement

Only papers that use the theory of measurement for the purpose of clarifying the interpretation of QM are included in this selection. Some papers on other aspects of the subject, such as the ultimate limits of measurements, are contained in Ref. 16. Reference to older works may be found in Ref. 14.

42. "Alternative to the Orthodox Interpretation of Quantum Theory," P. Pearle, *Am. J. Phys.* **35**, 742-753 (1967). Descriptions of the measurement process are given, according to two interpretations (the "old Copenhagen" and "Statistical ensemble" interpretations, in the terminology of this Resource Letter). Possible (but not yet practical) experiments to distinguish between the two are described. (I)

43. "Insolubility of the Quantum Measurement Problem," A. I. Fine, *Phys. Rev. D* **2**, 2783-7 (1970). The "problem" is whether a measurement interaction can leave the system (object + apparatus) in a mixed state, each component of the mixture displaying a definite value for the apparatus's indicator observable. It is shown that this is not possible. (Thus the "problem" is really not insoluble, as stated in the title, but rather it is answered negatively.) (A)
44. "Is there a Quantum Measurement Problem?," P. A. Moldauer, *Phys. Rev. D* **5**, 1028-32 (1972). It is argued that the state vector, *without* Von Neumann's "reduction" hypothesis, correctly describes the results of measurements, including correlations between successive measurements. Hence there is no "measurement problem." (A)
45. "There is a Measurement Problem: A Comment," A. I. Fine, *Phys. Rev. D* **5**, 1033 (1972). Fine agrees with the content of Moldauer's paper (Ref. 44), but points out that it involves a change from what had been the usual interpretation of QM. (A)
46. "Approximate Measurement in Quantum Mechanics," A. Shimony, *Phys. Rev. D* **9**, 2321-3 (1974). The theorem of Ref. 43 is extended to include approximate measurements, and a technical defect in that proof is remedied. (A)
47. "Quantum Measurements are Reversible," A. Peres, *Am. J. Phys.* **42**, 886-891 (1974). A simple example is given to show that the state of the total system, object plus measuring apparatus, does not change from a pure to a mixed state during the measurement process. But if one ignores the correlation of the apparatus to the object and attempts to describe the object alone, then it will appear to have a mixed state. (E)
48. "Quantum Theory of Measurement Without Wave Packet Collapse," M. Cini, *Nuovo Cimento* **73B**, 27-56 (1983). The main points of this paper are the "projection postulate" should not be part of the theory and "wave packet collapse" does not exist as a separate physical process. However, the loss of coherence predicted by the "collapse" postulate is often an approximate consequence of the macroscopic nature of the measuring apparatus. This need not involve irreversibility. (A)
- *49. "What is the Point of the Quantum Theory of Measurement?," L. E. Ballentine, in Ref. 5, pp. 65-75 (1986). Proves, under very general conditions, that the interaction of the measured object and the measuring apparatus must yield a final state of the system (object + apparatus) that is a *coherent superposition of macroscopically distinct* "pointer position" eigenvectors. Thus any interpretation of QM which requires a "reduction" of the state to an incoherent mixture of "pointer position" states (or to a single such state) is untenable. In particular, the old idea that "disturbances" during the measurement process cause such a "reduction" is proved false. (I)

E. Bell's theorem and its consequences

1. Before Bell's theorem

50. "Can Quantum-Mechanical Description of Physical Reality be considered Complete?," A. Einstein, B. Podolsky, and N. Rosen, *Phys. Rev.* **47**, 777-80 (1935). Reprinted in Ref. 16. (E,A)
51. "Quantum-Mechanical Description," H. Margenau, *Phys. Rev.* **49**, 240-2 (1936). Points out that many of the paradoxical features in the situation described by EPR cease to be paradoxical when one drops the assumption that a measurement projects that state of the measured system onto an eigenstate of the observable that is measured. (I,A)
52. "Discussion of Experimental Proof for the Paradox of Einstein, Podolsky and Rosen," D. Bohm and Y. Aharonov, *Phys. Rev.* **108**, 1070-6 (1957). Reformulation of the argument in terms of the correlated spins, thus making experimental tests more feasible. (I,A)

2. Bell's inequality

- *53. "On the Einstein Podolsky Rosen Paradox," J. S. Bell, *Physics* **1**, 195-200 (1964). The derivation of the inequality in this seminal paper is appropriate only for the case of *deterministic* hidden variables. The volume did not actually appear until 1965, and so this paper is sometimes referenced as 1965. (I,A)
54. "Introduction to the Hidden-Variable Question," J. S. Bell, in Ref. 1, pp. 171-181 (1971). A derivation of the inequality is given in Sec. 4, (entitled "A difficulty," one of the great understatements of the cen-

tury!). The generalization from *deterministic* to *stochastic* hidden variables is made here, but so briefly that it is easily overlooked. (I,A)

55. "Atomic-cascade Photons and Quantum-mechanical Nonlocality," J. S. Bell, *Com. At. Molec. Phys.* **9**, 121–6 (1980). A clear and entertaining discussion of Bell's theorem, the experimental results, and their implications. (E)

3. From Gedankenexperiment to real experiments

56. "Proposed Experiment to test Local Hidden-Variable Theories," J. F. Clauser, M. A. Horne, A. Shimony, and R. A. Holt, *Phys. Rev. Lett.* **23**, 880–4 (1969). (A)
- *57. "Experimental Test of Local Hidden-Variable Theories," S. J. Freedman and J. F. Clauser, *Phys. Rev. Lett.* **28**, 938–941 (1972). The experiment involves the correlation between the polarizations of two photons emitted in a $J = 0 \rightarrow J = 1 \rightarrow J = 0$ atomic cascade. (A)
58. "Experimental Investigation of a Polarization Correlation Anomaly," J. F. Clauser, *Phys. Rev. Lett.* **36**, 1223–6 (1976). Repeat of an experiment (by Holt and Pipkin) that had contradicted QM; the new results agree with QM. (A)
59. "Experimental Test of Local Hidden-Variable Theories," E. S. Fry and R. C. Thompson, *Phys. Rev. Lett.* **37**, 465–8 (1976). (A)
60. "Proposed Molecular Test of Local Hidden-Variables Theories," T. K. Lo and A. Shimony, *Phys. Rev. A* **23**, 3003–12 (1981). Analysis of the feasibility of measuring the spin correlations of a pair of Na atoms from the decay of an unstable singlet excited state of Na_2 . (A)
61. "Experimental Tests of Realistic Local Theories via Bell's Theorem," A. Aspect, P. Grangier, and G. Roger, *Phys. Rev. Lett.* **47**, 460–3 (1981). (A)
62. "Experimental Realization of Einstein–Podolsky–Rosen–Bohm Gedankenexperiment: A New Violation of Bell's Inequalities," A. Aspect, P. Grangier, and G. Roger, *Phys. Rev. Lett.* **49**, 91–4 (1982). (A)
- *63. "Experimental Test Bell's Inequalities Using Time-Varying Analyzers," A. Aspect, J. Dalibard, and G. Roger, *Phys. Rev. Lett.* **49**, 1804–7 (1982). The above three papers report a sequence of experiments on polarization correlations in pairs of atomic cascade photons, of increasing accuracy and sophistication, all of which confirm QM and contradict the Bell inequality. In the final experiment the polarizer directions are effectively switched between two orientations in a time shorter than the transit time for a light signal between them. (A)
64. "Experimental Tests of Bell's Inequalities," A. Aspect, pp. 377–390, in *The Wave-Particle Duality*, edited by S. Diner, D. Fargue, G. Lochak, and F. Selleri (Reidel, Dordrecht, 1984). A review of the experiments (Refs. 61, 62, and 63) and their implications. (I)

4. Simplifying the derivation

65. "On Hidden Variables and Quantum Mechanical Probabilities," E. P. Wigner, *Am. J. Phys.* **38**, 1005–9 (1970). This is the first paper to relate Bell's theorem to the nonexistence of a non-negative joint probability distribution for the results of several experiments, not all of which can be performed together. (E)
- *66. "Cryptographic Approach to Hidden Variables," N. Herbert, *Am. J. Phys.* **43**, 315–6 (1975). A very simple derivation of a simplified version of Bell's inequality. (E)
- *67. "Upperformed Experiments have no Results," A. Peres, *Am. J. Phys.* **46**, 745–7 (1978). (E)
68. "The Quantum Theory and Reality," B. d'Espagnat, *Sci. Am.* **241**, (5), 158–181 (Nov. 1979). An elementary account of Bell's inequality and its experimental tests. It is marred by an abstract stating, "The doctrine that the world is made up of objects whose existence is independent of human consciousness turns out to be in conflict with quantum mechanics and with facts established by experiment." That statement is devoid of any foundation because no assumption about the role of consciousness is made in the derivation of Bell's inequality. (E)
69. "Bringing Home the Atomic World: Quantum Mysteries for Anyone," N. D. Mermin, *Am. J. Phys.* **49**, 940–3 (1981). (E)
70. "Is the Moon there when Nobody looks? Reality and the Quantum Theory," N. D. Mermin, *Phys. Today* **38**, (4) 38–47 (1985). (E)
71. "A Lecture Demonstration of the Incompatibility of Quantum Predictions with those of a Local Realistic Theory," G. E. Stedman, *Am. J.*

Phys. **53**, 1143–9 (1985). A logic circuit is made to light bulbs in accordance with the QM predictions, in violation of any local theory. The device is essentially a realization of the imaginary device described by Mermin (Ref. 70). (E)

5. Strengthening and generalizing the inequality

- *72. "Experimental Consequences of Objective Local Theories," J. F. Clauser and M. A. Horne, *Phys. Rev. D* **10**, 526–535 (1974). This analysis treats stochastic, as well as deterministic, hidden-variable models, and treats in detail the limitations imposed by detector and polarizer efficiencies. (A)
73. "On the Consequences of Einstein Locality," F. Selleri, *Found. Phys.* **8**, 103–116 (1978). Systematic derivation of several Bell-type inequalities. (A)
74. "Generalized Inequalities Following from Einstein Locality," A. Garuccio, *Lett. Nuovo Cimento* **23**, 559–565 (1978). (A)
75. "Systematic Derivation of all the Inequalities of Einstein Locality," A. Garuccio and F. Selleri, *Found. Phys.* **10**, 209–216 (1980). (A)
76. "Joint Distributions and Local Realism in the Higher-Spin Einstein–Podolsky–Rosen Experiment," N. D. Mermin and G. M. Schwartz, *Found Phys.* **12**, 101–135 (1982). (A)
- *77. "Bell Inequalities with a Range of Violation that does not Diminish as the Spin Becomes Arbitrarily Large," A. Garg and N. D. Mermin, *Phys. Rev. Lett.* **49**, 901–4 (1982). (A) Erratum: *Phys. Rev. Lett.* **49**, 1294 (1982).
78. "Local Realism and Measured Correlations in the Spin- s Einstein–Podolsky–Rosen Experiment," A. Garg and N. D. Mermin, *Phys. Rev. D* **27**, 339–348 (1983). (A)
79. "Some Evaluations of Bell's Inequality for Particles of Arbitrary Spin," M. Ogren, *Phys. Rev. D* **27**, 1766–1773 (1983). Some results for higher spin are derived by a different method from that used by Mermin *et al.* (I)
80. "Farkas's Lemma and the Nature of Reality: Statistical Implications of Quantum Correlations," A. Garg and N. D. Mermin, *Found. Phys.* **14**, 1–39 (1984). A general method is given for determining whether a set of pair distributions are consistent with the existence of higher-order distributions, of which they are marginal. The method is applied to quantum spin correlations, yielding generalized Bell-type inequalities. (A)
81. "Generalizations of Bell's Theorem to Higher Spins and Higher Correlations," N. D. Mermin, in Ref. 5, pp. 7–20 (1986). Derivation of Bell-type inequalities that are violated by QM for every finite value of spin. A discussion is given of how these violations may disappear in the classical ($s \rightarrow \infty$) limit. (I)

6. Loopholes, real and imaginary

82. "Hidden-Variable Example Based upon Data Rejection," P. M. Pearle, *Phys. Rev. D* **2**, 1418–25 (1970). A deterministic HV model is constructed in which some fraction of the particles go undetected. On the assumption that the experimenter will reject events in which only one (or zero) particles is detected, the remaining coincidence data can agree with the predictions of QM. (A)
83. "On Hidden-Variable Theories and Bell's Inequality," L. de la Pena, A. M. Cetto, and T. Brody, *Lett. Nuovo Cimento* **5**, 177–181 (1972). It is claimed that the derivation of Bell's inequality is implicitly based on the postulate that "the measuring process has no discernable influence on the system subjected to it." This claim seems hard to sustain for the many careful derivations that have followed. (A)
84. "Resolution of the Einstein–Podolsky–Rosen and Bell Paradoxes," I. Pitowsky, *Phys. Rev. Lett.* **48**, 1299 (1982). It is claimed that a local hidden-variable model which agrees with QM and violates the Bell inequalities can be constructed by means of nonmeasurable sets. The following two comments point out that contradictions between such models and QM can be derived without any assumption of measurability. (A)
85. "Comment on 'Resolution ...'," N. D. Mermin, *Phys. Rev. Lett.* **49**, 1214 (1982).
86. "Comment on 'Resolution ...'," A. L. Macdonald, *Phys. Rev. Lett.* **49**, 1215 (1982).

87. "Pitowsky Responds," *Phys. Rev. Lett.* **49**, 1216 (1982).
88. "Local Realism has not been Refuted by Atomic Cascade Experiments," T. W. Marshall, E. Santos, and F. Selleri, *Phys. Lett.* **98A**, 5-9 (1983). A local hidden-variable model is constructed which fits experimental data as well as does the prediction of QM. However, it is only the low efficiency of the present detectors that makes this possible (see Ref. 96). More accurate measurements could discriminate between such local models and QM. (A)
89. "Bell's Theorem: Does the Caluser-Horne Inequality Hold for All Local Theories?," T. D. Angelidis, *Phys. Rev. Lett.* **51**, 1819-22 (1983). The negative answer given to the question in the title is based upon an error, as was pointed out by several authors.
90. "Comment on 'Bell's Theorem: Does ...?'," A. Garg and A. J. Leggett, *Phys. Rev. Lett.* **53**, 1019-20 (1984). (E)
91. "Rotational Invariance, Locality, and Einstein-Podolsky-Rosen Experiments," A. O. Barut and P. Meystre, *Phys. Rev. Lett.* **53**, 1021 (1984). (E)
92. "Angelidis Responds," *Phys. Rev.* **53**, 1022-3 (1984).
93. "Comment on 'Bell's Theorem: Does ...?'," M. A. Horne and A. Shimony, *Phys. Rev. Lett.* **53**, 1296 (1984). (E)
94. "Angelidis Responds," *Phys. Rev.* **53**, 1297 (1984).
95. "Comment on Angelidis's Universality Claim," J. T. Cushing, *Phys. Rev. Lett.* **54**, 2059 (1985). (E)
96. "The EPR Experiment—Thoughts about the 'Loophole,'" N. D. Mermin, in Ref. 7. Although the correlations predicted by QM definitely violate the Bell inequalities, it is possible to exploit the low efficiency (15%-20%) of current photon detectors to devise models such that the "real" correlations would obey the Bell inequalities (locality) but the observed data would appear to agree with QM. Papers 82, 72, and 88 contain examples of such models. This paper shows that the loophole for such models can be closed if and only if the detector efficiency exceeds 83%. (A)

7. Interpretation and significance of the results

97. "Comments on Stapp's 'Copenhagen Interpretation' and the Significance of Bell's Theorem," L. E. Ballentine, *Am. J. Phys.* **42**, 81-3 (1974). Argues that since the assumptions of "local causality" which leads to Bell's inequality is violated in experiments, we should give up the "local" restriction, rather than "causality"; also argues that it is incorrect to claim that the experimental contradiction of Bell's inequality supports the Copenhagen interpretation. (A)
98. "Reply to Ballentine's Comments," H. P. Stapp, *Am. J. Phys.* **42**, 83-5 (1974). (A)
99. "Bell's Theorem without Hidden Variables," P. H. Eberhard, *Nuovo Cimento* **38B**, 75-9 (1977). A Bell inequality is derived without using the concepts of hidden variables or determinism. (A)
100. "Bell's Theorem and the Different Concepts of Locality," P. H. Eberhard, *Nuovo Cimento* **46B**, 392-418 (1978). The logical relations among four different formalized notions of locality are discussed. Part of the results of Ref. 110 are anticipated in this paper. (A)
101. "Determinism and Locality in Quantum Mechanics," I. Nordin, *Synthese* **42**, 71-90 (1979). Argues that Bell's inequalities can be derived without any assumption of determinism, and that the observed violation of them indicates an essential nonlocality of QM and does not support any particular interpretation of QM. (A)
102. "Hidden Variables, Joint probability, and the Bell Inequalities," A. Fine, *Phys. Rev. Lett.* **48**, 291-5 (1982). Claims a far-reaching equivalence among the concepts mentioned in the title. The results seems to be correct up to a point, but the scope of their validity is disputed in the following comment and response. (A)
103. "Comment on 'Hidden Variables, Joint probability, and the Bell Inequalities,'" A. Garg and N. D. Mermin, *Phys. Rev. Lett.* **49**, 242 (1982).
104. "Fine Responds," *Phys. Rev. Lett.* **49**, 243 (1982). (A)
105. "Correlation Inequalities and Hidden Variables," A. Garg and N. D. Mermin, *Phys. Rev. Lett.* **49**, 1220-3 (1982). The controversy with Fine is settled with a counterexample to some of his claims. (A)
106. "Bell's Theorem as a Nonlocality Property of Quantum Theory," H. P. Stapp, *Phys. Rev. Lett.* **49**, 1470-4 (1982). This paper and the fol-

- lowing two seek to correct and/or clarify some of the points raised in Ref. 102. (A)
107. "Constraints of Determinism and of Bell's Inequalities are not Equivalent," P. H. Eberhard, *Phys. Rev. Lett.* **49**, 1474-7 (1982). (A)
108. "Comments on the Significance of Bell's Theorem," A. Fine, *Phys. Rev. Lett.* **49**, 1536 (1982). (A)
109. "Nonseparability and the Tentative Descriptions of Reality," B. d'Espagnat, *Phys. Rep.* **110**, 201-264 (1984). An extended discussion of the subject and its ramifications. The author's philosophical interpretations are not entirely convincing, however the appendix, "Some disproved objections to the Bell theorem," is quite useful. (A)
110. "On the Physical Significance of the Locality Conditions in the Bell Arguments," J. P. Jarrett, *Nous* **18**, 569-589 (1984). The *strong locality* condition that is used to derive the Bell inequalities is shown to be equivalent to the conjunction of *relativistic locality* and another condition which has to do with the "completeness" of the state descriptions of the theory. It is only the latter that fails in QM. (A)
- *111. "An Exchange on Local Beables," J. S. Bell; A. Shimony, M. A. Horne, and J. F. Clauser, *Dialectica* **39**, 85-110 (1985), reprinted from *Epistemological Letters*: no. 9 (1976), no. 13 (1976), no. 15 (1977), no. 18 (1978). (The hideous neologism in the title should be spelled "be-able" to indicate its pronunciation and etymology. It is intended to refer to that which exists, in contradistinction to that which can be measured, an "observable.") Bell attempts to formulate a notion of "local causality" that is independent of and weaker than determinism. He concludes that QM is not compatible with local causality. SHC object that Bell's conclusion does not follow without further assumptions. Bell concedes this point, emphasizing in response that the experimenters' ability to freely choose the settings of their instruments must be assumed, and that if those choices were predetermined by a suitable conspiracy the proof would not be valid. (A)
112. "Bell's Theorem and the Foundations of Quantum Physics," H. P. Stapp, *Am. J. Phys.* **53**, 306-317 (1985). The author derives a Bell-type inequality that is violated by QM, and carefully argues that no assumption of *realism* or *determinism* is involved, therefore, the contradiction is strictly between *locality* and QM. (See Ref. 17, Sec. 3.8, for an account of a controversy about the possibility of eliminating all traces of determinism from the proof.) (A)
113. "Comments on 'Locality, Bell's Theorem, and Quantum Mechanics,'" H. P. Stapp, *Found. Phys.* **15**, 973-6 (1985). A distinction is made between two ideas of locality: (1) No signal can travel faster than light; (2) The course of events in one space-time region can be *in no way disturbed* by what is done in a space-time region that is spatially separated from the first. (1) is involved in relativity, whereas (2) was used by EPR and Bell. (A)
114. "EPR: What has it taught us?" H. P. Stapp, in Ref. 6, pp. 637-652 (1985). A discussion of the significance for future work of the concepts introduced by EPR (Ref. 50). (I,A)
115. "Bell's Theorem: Does Quantum Mechanics Contradict Relativity?," L. E. Ballentine and J. P. Jarrett, *Am. J. Phys.* **55**, 696 (1987). Expanding on the ideas introduced in Ref. 110, the authors answer the question in the title negatively. *Strong locality* (needed to derive the Bell inequalities) is equivalent to *relativistic locality* plus *predictive completeness* of the state description. Violation of the latter condition by QM is responsible for the violation of the Bell inequalities. It has the additional consequence that QM is indeed *incomplete* in the EPR sense, notwithstanding any failure of the EPR locality condition. (I,A)

F. Experiments (other than for Bell inequalities)

116. "On the Statistical Aspect of Electron Interference Phenomena," P. G. Merli, G. F. Missiroli, and G. Pozzi, *Am. J. Phys.* **44**, 306-7 (1976). A demonstration experiment shows the buildup of an electron diffraction pattern from the pointlike flashes of individual electrons. The developing pattern can be shown in the classroom on a TV screen. (E)
117. "Coherence Effects in Neutron Diffraction and Gravity Experiments," D. M. Greenberger and A. W. Overhauser, *Rev. Mod. Phys.* **51**, 43-78 (1979). A detailed theoretical analysis of the neutron interferometer and the effects of gravity and acceleration. (A)
118. "Gravity and Inertia in Quantum Mechanics," J.-L. Staudenmann, S. A. Werner, R. Colella, and A. W. Overhauser, *Phys. Rev. A* **21**,

- 1419–38 (1980). Sensitive neutron interferometer experiments are able to measure the effects of gravity and the Earth's rotation of the phase of the neutron wavefunction. (I)
119. "Search for a Nonlinear Variant of the Schrödinger Equation by Neutron Interferometry," C. G. Shull, D. K. Atwood, J. Arthur, and M. A. Horne, *Phys. Rev. Lett.* **44**, 765–8 (1980). A plausible nonlinear variant of the Schrödinger equation, which preserves Galilean invariance and the usual probability interpretation but possesses stable nonspreading wave-packet solutions, is subjected to experimental test. An upper bound of 3.4×10^{-13} eV is obtained for the magnitude of the nonlinear term. (I)
120. "Neutron Optical Tests of Nonlinear Wave Mechanics," R. Gähler, A. G. Klein, and A. Zeilinger, *Phys. Rev. A* **23**, 1611–7 (1981). The upper bound for the nonlinear term is reduced to 3.3×10^{-15} eV by means of precise Fresnel diffraction measurements. (I)
- *121. "Explicit Experimental Verification of Quantum Spin-State Superposition," J. Summhammer, G. Badurek, H. Rauch, and U. Kischko, *Phys. Lett.* **90A**, 110–112 (1982). The single-crystal interferometer is used to split a polarized neutron beam into two parts, which separate by a few centimeters before being recombined. The initial spin state is polarized in the $+z$ direction. A spin flipper is inserted into one of the separated beams, so that upon recombination one has a superposition of $|+\rangle$ and $|-\rangle$ spin states, which is mathematically equivalent to a spin state polarized in the xy plane. This prediction of the superposition principle is confirmed. (I)
122. "The Neutron Interferometer as a Device for illustrating the Strange Behavior of Quantum Systems," D. M. Greenberger, *Rev. Mod. Phys.* **55**, 875–905 (1983). An interesting account of how many *Gedankenexperiments* are now capable of realization by means of the neutron interferometer. In an appendix he analyzes the weak equivalence principle (the motion of a particle in a gravitational field is independent of the mass of the particle) in the classical limit, and shows why the applicability of the Schrödinger equation to a particle in a gravitational potential should not have been regarded as a forgone conclusion before its experimental confirmation (Ref. 118). (I)
123. "Time-Dependent Superposition of Spinors," G. Badurek, H. Rauch, and J. Summhammer, *Phys. Rev. Lett.* **51**, 1015–18 (1983). An experiment similar to Ref. 121, except that a radio-frequency spin flipper is used, instead of a static spin flipper. This causes the energies (frequencies) of the partial beams to be different. Upon recombination of the beams one has a nonstationary state, and oscillations of the spin polarization at the beat frequency is observed. (I)
124. "A Real 'Thought' Experiment for the Hydrogen Atom," I. E. McCarthy and E. Weigold, *Am. J. Phys.* **51**, 152–5 (1983). The momentum probability distribution for the electron on a hydrogen atom is measured and found to agree with the square of the momentum representation wavefunction. (I)
125. "Experimental Confirmation of the Aharonov–Bohm Effect by Electron Holography," A. Tomomura, in Ref. 5, pp. 169–176 (1986). Very striking confirmation of the relative phase shift of two electron beams that have passed through field-free regions separated by a region of magnetic flux. The nonquantization of flux is also clearly demonstrated. (I)
126. "Neutron Interferometric Double-Resonance Experiment," G. Badurek, H. Rauch, and D. Tuppinger, *Phys. Rev. A* **34**, 2600–8 (1986). An experiment similar to Ref. 123, except that rf spin flippers are placed in both beams of the interferometer. Coherence of the beams persists in spite of the spin-flip and energy transfer to every neutron. (I)
127. "Diffraction of Atoms by Light: The Near-Resonance Kapitza–Dirac Effect," P. L. Gould, G. A. Ruff, and D. E. Princhard, *Phys. Rev. Lett.* **56**, 827–330 (1986). The diffraction of an atomic beam by an electromagnetic standing wave, predicted by Kapitza and Dirac in 1933, has been observed. (A)

G. Quantization of the electromagnetic field

128. "The Concept of the Photon," M. O. Scully and M. Sargent, *Phys. Today* **25** (3), 38–47 (1972). Many phenomena (including the photo-

electric effect and much of quantum optics) that are commonly thought to require the photon concept for their explanation, can in fact be explained by semiclassical methods that apply QM only to matter but not to radiation. Quantum electrodynamics is needed to explain certain field fluctuation phenomena, but the "fuzzy ball" picture of the photon often leads to unnecessary confusion. (I)

Further correspondence on this subject is contained in the Aug., Dec. 1972, and Feb. 1973 issues.

129. "Experimental Limitations to the Validity of Semiclassical Radiation Theories," J. F. Clauser, *Phys. Rev. A* **6**, 49–54 (1972). It is pointed out that some polarization correlation measurements by Koshner and Commins in 1967 are able to exclude theories which treat the electromagnetic field classically and use QM only for matter. (A)
- *130. "Experimental Distinction between the Quantum and Classical Field-Theoretic Predictions for the Photoelectric Effect," J. F. Clauser, *Phys. Rev. D* **9**, 853–860 (1974). A demonstration that a photon, unlike a wave packet, cannot be split by a half-silvered mirror. (I)
131. "Non-Classical Effects in the Statistical Properties of Light," R. Loudon, *Rep. Prog. Phys.* **43**, 913–949 (1980). The classical and quantum theories of second-order coherence are reviewed. Three inequalities are derived which are satisfied by the classical theory but may be violated by the quantum theory. Experimental violations of two of these inequalities are described. (A)
132. "Violations of Bell's Inequality in Cooperative States," P. D. Drummond, *Phys. Rev. Lett.* **50**, 1407–1410 (1983). Bell's inequality is applied to a cooperative state (analogous to the superfluorescent state) of N photon pairs. [The experiments of Aspect *et al.* (Refs. 61–63) correspond to $N = 1$.] As N becomes large the low-order correlation functions of the field cease to violate Bell's inequality, but violations always exist in sufficiently high-order correlations. (A)
133. "Evidence for the Quantum Nature of Light," D. F. Walls, *Nature* **280**, 451–4 (1979). The "antibunching" of photons in resonance fluorescence is one of the few known phenomena which cannot be explained by any classical field theory of radiation. (I)
134. "Nonclassical Radiation of a Single Stored Ion," F. Diedrich and H. Walther, *Phys. Rev. Lett.* **58**, 203–6 (1987). Radiation from a single atom exhibits antibunching. (I)
135. "Photons in Introductory Quantum Physics," J. Strnad, *Am. J. Phys.* **54**, 650–2 (1986). Analogies between photons and electrons can be misleading. A photon wavefunction cannot be introduced except under very limited circumstances. (I)

H. Miscellaneous papers

136. "Test of the Non-Separability of the $K^0\bar{K}^0$ System," J. Six, pp. 391–6, in *Quantum Mechanics a Half Century Later*, edited by J. L. Lopes and M. Paty (Reidel, Dordrecht, 1977). Proposes a test for EPR-type correlations in the decay of the $K^0\bar{K}^0$ system. (A)
137. "Theory of Reality," H. P. Stapp, *Found. Phys.* **7**, 313–323 (1977). "Bell's theorem is used to guide the formulation of a unified theory of reality that incorporates the basic principles of relativistic quantum theory," (quoted from author's abstract). (A)
138. "Locality and Reality," H. P. Stapp, *Found. Phys.* **10**, 767–795 (1980). An attempt to formulate an interpretation of QM that is compatible with the ideas of both Bohr and Einstein, and with Bell's theorem. (A)
139. "Probability Theory in Quantum Mechanics," L. E. Ballentine, *Am. J. Phys.* **54**, 883–9 (1986). It is demonstrated that the formalism of QM satisfies the axioms of probability theory. Some erroneous claims that QM violates classical probability theory are examined and refuted. (E)
140. "Microphysical Reality," W. Duch and D. Aerts, *Phys. Today* **39**, (6), 13–5 (1986). A humorous poll of physicists regarding their beliefs about locality and QM. (E)