BASIC AXIOMS OF MICROPHYSICS

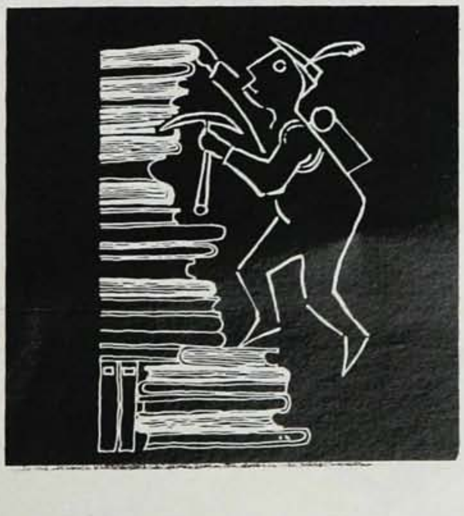
NEW FOUNDATIONS OF QUANTUM MECHANICS. By Alfred Landé. 171 pp. Cambridge University Press, London, 1965. $7.50.

by Abner Shimony

Professor Landé's aim is the *demystification* of quantum mechanics. He does not modify the usual formalism of the theory, but he gives it an interpretation which dispenses with such counterintuitive concepts as wave-particle dualism. Moreover, he claims to derive quantum mechanics from a few general nonquantal principles. Discussions and reviews of Landé's earlier books, *Foundations of Quantum Theory* (Yale U. Press, New Haven, 1955) and *From Dualism to Unity in Quantum Physics* (Cambridge U. Press, London, 1960), in which essentially the same arguments were presented as in the present work, have largely been concerned with his interpretation, and none that I have read has been sufficiently critical in assessing his derivations. Several reviewers and commentators have stated (sometimes with astonishment) that all or several of his derivations of quantum mechanical laws from very weak assumptions are correct.[1] I find, however, that this is not so, and that there are ambiguities in his premises and errors in his arguments.

First of all, Landé maintains, "Unpredictability, denoted as acausality of individual events, must be accepted as an irreducible feature of natural science" (page 37), and he asserts his agreement with the statement by C. S. Peirce, "You think that all the arbitrary specifications of the universe were introduced in one dose in the beginning, if there was a beginning. But I for my part think that the diversification, the specification has been continually taking place" (quoted on page 36). This doctrine of absolute chance is logically consistent and in some ways is attractive, but Landé's argument that it can be inferred from such macroscopic phenomena as games of chance is very weak. It is true that ergodic theory is far from complete, and yet there is a large class of systems for which it is known that the physically significant quantities have the same statistical distributions along almost all trajectories, thereby providing an explanation of statistical behavior without postulating "a *deus ex machina* who at one remote time has introduced statistical disorder which then is passed on deterministically" (page 36.) Also, it is possible to base games of chance upon the decimal expansion of irrational numbers, in spite of the fact that the "events" (that is, the digits in the expansion) are determined once the "initial condition" (choice of the number) has been specified. Landé's position on acausality is obscured, moreover, by his proposition that "Unpredictability of future events does not preclude the *reconstruction* of individual causes on the grounds of deterministic theory" (page 37).

Next, Landé postulates a principle of *cause-effect continuity*, or, rather (because of his commitment to acausality), a statistical principle that an infinitesimal change of initial conditions cannot produce a finite change in resulting statistical distributions. This seems to be a reasonable heuristic principle, which could conceivably be abandoned on account of



adverse evidence but not without regret, and it certainly is interesting to see what consequences can be drawn from it. Landé attempts to derive from it a recognizably quantum mechanical proposition about atomic states. He supposes the existence of a filter which permits all atoms of a given species in state A to pass while rejecting atoms of this species in other states $\overline{A}$, and he then says

> "It could have been expected from the continuity principle, and it is indeed confirmed by experience, that there is a third class of states intermediate between A and $\overline{A}$, between always passed and never passed, namely states B which are sometimes passed and at other times are repelled by the A-passing filter. . . . The states B then can neither be regarded as equal to A, nor as entirely unequal, that is as 100 per cent separable from A" (page 41).

This argument is unclear, however, unless the relation between the terms "state" and "filter" is made unambiguous. In view of Landé's discussion of separators (page 53) and of his intention to develop the full formalism of quantum mechanics, it is reasonable to assume that he would accept a statement like the following: the A-passing filter defines a state A if the filter is constructible by blocking all but one component of a *maximal separator*—a separator being an instrument through some component of which any atom of a given species will pass, and with the property that an atom which passes through one component will again pass through it and through no other, and a maximal separator being one which loses the property of being a separator if any of its components are subdivided. By assuming the existence of the state A, Landé is in effect assuming the existence of at least one maximal separator, and then he uses the principle of continuity to infer that there exists more than one. But an alternative way of satisfying the continuity principle would be to deny the existence of any maximal separator—to suppose, for example, that once a particle passed through a given component it would indeed have very small probability on a second trial of passing through a component which is remote (in some suitable ordering) from the first one, but a large probability of passing through one of those components close to it. Were it not for quantum theory and the empirical evidence for the superposition of states, the alternative way of satisfying the continuity principle would be overwhelmingly more plausible than Landé's way.

Landé then attempts to justify the symmetry postulate $P(A \rightarrow B) = P(B \rightarrow A)$, where $P(A \rightarrow B)$ is the fraction of atoms in the state A which pass through a B-filter, and $P(B \rightarrow A)$ is analogous. Four arguments are given. The first is that

> "we define the *fractional degree of equality* between A and B as the statistical *passing fraction* of B-state atoms through an A-filter. However, since the equality concept is mutual . . . , this definition of fractional equality makes sense only when B-state atoms pass through an A-filter with the same probability as A-state atoms pass through a B-filter" (page 41).

But in this argument the use of the term "fractional equality" clearly begs the question. The second argument is that the symmetry postulate "is the statistical counterpart to the reversibility of processes in classical mechanics" (page 41). The analogy is dubious because reversibility in classical mechanics depends upon the dynamics, and at this point Landé has not yet developed quantum dynamics; and also because classical reversibility holds only for an entire isolated system, whereas in the present situation the atoms interact with the filters, the modifications of which (though small on a macroscopic scale) are not taken into account. Even if the analogy were apt, however, reliance upon it would not be justified since classical mechanics is, strictly speaking, a false theory. A third argument, "Without P-symmetry there could not be any statistical equilibrium" (page 151), is too elliptical to evaluate with assurance. However, he may mean by "statistical equilibrium" a distribution among the states separated by one separator such that if all the atoms are passed through any second separator and then again through the first, the initial distribution is recovered; if so, then equilibrium can be maintained by a suitable global system of transition probabilities, without P-symmetry. The fourth argument is based on the evaluation of the entropy produced when a gas of N atoms in state A and occupying volume V and a gas of N atoms in state B and occupying volume V are allowed to diffuse into a common volume $2V$. Landé proposes to evaluate the entropy in one way by separating the mixture adiabatically and isothermally using an A filter as a semipermeable membrane, and in another way by similarly using a B-filter. The entropies of the separated systems in the two cases are equal only if $P(A \rightarrow B) = P(B \rightarrow A)$. From this Landé concludes that the symmetry principle is necessary "in order to render a univalent diffusion entropy irrespective of whether its value is determined by means of A- or B-filters" (page 68). But since in general the separation process increases entropy, as he later notes, this argument is inconclusive unless supplemented by an argument that the entropy changes caused by A-filtering and B-filtering are equal (an equality which he assumes without proof on page 20 of *Foundations of Quantum Theory* but does not mention at all in the present work).

The most important step in Landé's entire derivation is his attempt to exhibit the necessity for probability amplitudes, thereby explaining the interference phenomena of quantum mechanics. He postulates that there must be a law of interdependence "which determines, or at least restricts" the matrix of transition probabilities P_{AC} when P_{AB} and P_{BC} are given, where A, B, and C, now denote maximal separators, and the ijth element of P_{AB} is the transition probability $P(A_i \rightarrow B_j)$ from the ith state associated with A to the jth state associated with B, etc. He expresses the law governing the matrices of transition probabilities by "$F(P_{AB}, P_{BC}, P_{AC}) = 0$, or still shorter as $f(A, B, C) = 0$," and he imposes the two requirements of *symmetry* and *transitivity*: that is, "the same connection ought to hold also for any permutation of the letters A,B,C" (page 79), and "The interdependence ought to hold for *all* letter combinations so that from $f(A, B, C)$, $f(A, B, D)$, $f(A, C, D) = 0$ should *follow* $f(B, C, D) = 0$ by elimination of A" (pages 79-80). I find the second of these requirements puzzling, since I do not see how it can be construed so as to be satisfied by the transition probability matrices of quantum mechanics (although the matrices of probability amplitudes are easily seen to satisfy it). Landé then claims that the only law of interdependence among matrices of transition probabilities (the elements of which must be nonnegative real numbers such that the sum along any row or column is 1) which satisfies these requirements and which also is compatible with $P(A_i \rightarrow B_j) = P(B_j \rightarrow A_i)$ and with $P(A_j \rightarrow A_k) = \delta_{jk}$ is the familiar quantum mechanical relation: that the transition probabilities are the absolute squares of amplitudes $\alpha(A_i, B_j)$ constituting unitary matrices α_{AB}, etc., for which $\alpha_{AC} = \alpha_{AB}\,\alpha_{BC}$ is valid. The proof (Appendix I) rests upon an assumption which is not among Landé's explicit postulates and for which I can see no justification: that P_{AB}, P_{BC}, P_{AC} are determined by a set of matrices which satisfy some polynomial matrix equation. It is easy to give a set of transition probability matrices which satisfy a nonquantum mechanical law of interdependence and also seem to satisfy all of Landé's explicit postulates (so far as I understand them). For instance, if $0 \leq r < 2\pi/n$. let the separator A^r distribute particles confined to the circumference of a circle into n "states", the "state" $A_k{}^r$ being that of lying in the angular interval $[r + 2\pi(k-1)/n,\ r + 2\pi k/n]$, and let $P(A_i{}^r \rightarrow A_j{}^s)$ be $\pi/2$ times the magnitude of the intersection of the two angular intervals involved. This example has the virtue that the matrices $P_{A^r A^s}$, $P_{A^s A^t}$ determine $P_{A^r A^t}$, whereas in quantum mechanics the matrices of transition probabilities P_{AB} and P_{BC} only restricts P_{AC}. The matrices in this example do not satisfy a polynomial

matrix equation nor are they determined by matrices which satisfy one.

In order to derive the quantum mechanical commutation relations and the Schrödinger equation, Landé argues from invariance considerations:

"It is characteristic of mechanics that, whenever it deals with a coordinate value q, this value is meant with respect to a certain zero point. Hence, when one has to do with two values q and q', only their difference is of physical significance, and the arbitrary zero point cancels out in $q-q'$. The same holds for the momentum p, as well as for energy E and time t. In short, mechanics is Galileo invariant. Transferring this invariance from classical to quantum mechanics, we now introduce the postulate:

"(c) Any observable $T(q)$ has matrix elements (= transition values) $T_{pp'}$ which depend on the difference $p-p'$ only. Similarly, any observable $S(p)$ has matrix elements $S_{qq'}$ depending on $q-q'$ only. Analogous results hold for E and t" (page 96).

From postulate c he is able to show that the transition probability amplitude from the state in which the particle has momentum p to that in which it has position q has the desired form const·exp[ipq·real const]. However, even though the first two sentences of c are quantum-mechanically correct, it is hard to see how Landé has obtained them from invariance principles together with the general laws of quantum mechanics which he has developed up to this point. Even if the principle of translation invariance can be understood to imply that some observables S should have the property that $S_{qq'}$ are functions only of $q-q'$, why should these observables be identified as functions of the momentum? What reason has been given that $S_{qq'}$ should depend on $q-q'$ (as it in fact does) when q is not a Cartesian coördinate, in which case it is not true that only the difference between two values of the coördinate has physical significance? And why should Galilean invariance permit one to select observables $T(q)$, rather than some other observables, to have the property that T_{pp}' depends only on $p-p'$? I see no way of obtaining the commutation relations between the operators representing the position and momentum observables without making an explicit assumption about their kinematical relationship, the most straightforward being that a momentum operator p_j is the infinitesimal generator of the group of shifts $U_j(a)\psi(q_1,\dots,q_{3n}) = \psi(q_1,\dots,q_{j-1},q_j-a,q_{j+1},\dots,q_{3n})$ associated with the jth position observable. The momentum observable may simply be defined this way, but then an assumption is needed to relate it to the corresponding velocity observable. (Compare George W. Mackey, *Mathematical Foundations of Quantum Mechanics*, W. A. Benjamin, New York, 1963, pages 88 and 89.)

The last sentence of postulate c is especially obscure, since time is not an observable in ordinary formulations of quantum mechanics, and if Landé chooses to treat it as an observable he is obliged to explain what formalism he would use and to elucidate his conception of dynamics. It is indeed possible to obtain the Schrödinger equation from quite general assumptions (ibid., pages 81-4 and 89-90), but the analysis required is not implicit in Landé's remarks.

The leading ideas in Landé's interpretation of quantum mechanics are closely connected with his claim to derive its formalism from nonquantal postulates. "Elementary quantum mechanics of matter has to do with material bodies composed of particles with coordinates and momenta, q and p, . . . " (page 150). According to his "realistic view," the coëxistence of exact values of position and momentum is compatible with quantum mechanics, and it is often possible to reconstruct to an arbitrary degree of accuracy the simultaneous position and momentum of a particle at an earlier time and even to reconstruct the trajectory of a particle between two position measurements (pages 118-28). It thus seems correct to say that Landé accepts the characterization of the state of a particle given by classical mechanics, though his attitude towards classical dynamics is unclear, since, on the one hand, he rejects causality, and, on the other hand, it is classical dynamics which permits the reconstruction of trajectories. He does clearly maintain, however, that there is a limitation upon the use of classical dynamics for the purpose of predicting, since "p and q cannot be exactly prepared and predicted simultaneously" (page 124). The formalism of quantum mechanics governs the predictions that can be made on the basis of data from macroscopic instruments concerning subsequent data from macroscopic instruments (page 133 and (7) on page 140).

If the ambiguity concerning the correctness of classical dynamics is disregarded, this interpretation is attractive, for it permits the physicist to retain the conceptually straightforward classical characterization of the state of a system and yet to use the machinery of quantum mechanics for making predictions. The difficulty, however, is that physical systems behave consistently *as if* the set of probability amplitudes, which this interpretation construes only as devices for relating the data of instruments, intrinsically characterize the systems, and *as if* the simultaneous values of p and q are irrelevant to their intrinsic states. Thus, extraordinarily good explanations of chemical properties, specific heats, magnetic resonances, conductivities, etc. can be given in terms of the probability amplitudes, even though the observation of these properties does not involve the determination of the positions and momenta of the constituent particles. In several passages Landé seems to recognize the intrinsic role of the probability amplitudes. For example, in commenting on the tunnel effect he says, "We cannot accept the statistical meaning of ψ outside the tunnel where it has been confirmed experimentally and forsake it inside the tunnel" (page 127). And he admits that in this case the assumption of the simultaneous existence of position and momentum leads to difficulties (page 128). In this passage (and also on pages 138-9) he inclines towards accepting the quantum mechanical characterization of the state of a physical system, but how this is to be reconciled with the essentially classical characterization espoused elsewhere in his work is utterly obscure.

Landé's tone in discussing various

versions of the Copenhagen interpretation of quantum mechanics is extremely polemical, though it must be admitted that among the passages which he criticizes are some that are undoubtedly obscure. Actually, in spite of violent dissent regarding wave-particle dualism, Landé agrees with some fundamental elements in Bohr's position, particularly his insistence that quantum mechanics is concerned with the results obtained by different experimental arrangements, and his comment "There is no quantum world."[2] Perhaps both Landé, in his program of demystification, and his opponents, who maintain that the key to the mystery is complementarity, have underestimated the strangeness of microscopic reality which quantum mechanics has revealed.

I am grateful to Howard Stein for discussions of a number of the crucial points in this review.

References

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2. Quoted on page 12 of "The Philosophy of Neils Bohr" by A. Petersen, Bulletin of the Atomic Scientists **19**, 8 (1963).

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Molecular interactions

MOLECULAR BEAMS, Vol. X of Advances in Chemical Physics. John Ross, ed. 419 pp. Interscience, New York, 1966.

by Kurt E. Shuler

The present volume of Advances in Chemical Physics is devoted entirely to the subject of molecular beams. This idea of focusing a given volume of these series variously entitled: Advances in, Progress in, Studies in, Reviews of, etc., on a particular subject is an excellent one which deserves a much wider practice. What is particularly important in producing a successful focused review volume is the careful choice of an editor and his careful choice of authors with the concomitant selection of live topics in the forefront of research.

Molecular Beams is a success on all counts. The editor, Professor John Ross of Brown University, is one of the pioneer workers in the field of molecular beams and has made important contributions to the subject. The authors are all active and productive workers in the area of their contribution and must certainly be counted among the real experts in their specialty. The subject matters of the individual articles are well chosen for their importance and timeliness. Finally, the articles are well written; they are informative, detailed and authoritative.

The articles in this volume deal with current molecular-beam research in the general area of chemical physics. As mentioned in the preface, the common theme throughout the volume is *molecular interactions*. In principle, molecular-beam experiments involving such interactions provide one of the best, and certainly one of the most direct means for measuring molecular properties including cross sections for chemical reactions. In practice, as can be seen from a study of the articles in this volume, we are now firmly on the road of carrying out such measurements and converting what were once only Gedanken-experiments into data and graphs.

The menu of this delectable and nourishing meal is as follows: As an appetizer, B. Bederson and E. J. Robinson of New York University discuss the use of molecular beams in the measurement of atomic polarizabilities. I. Amdur and J. E. Jordan of MIT present a critically evaluated review of the work on elastic scattering of high-energy neutral beams for the determination of interaction potentials at small internuclear separation. This is followed by a chapter on quantum effects in elastic molecular scattering by R. Bernstein of the University of Wisconsin, which gives a detailed comparison between the classical and quantum results for various cases of inelastic scattering. Scattering in chemically reactive systems is discussed by Greene, Moursand and Ross of Brown University who show how their and other workers' results on the elastic scattering of chemically reactive species can be used to obtain information on inelastic reactive cross sections. E. E. Muschlitz of the University of Florida discusses the production and detection of molecular beams of electronically excited species and the measurement of elastic and inelastic cross sections of electronically excited metastable species in interactions with various neutral molecules. R. F. Stebbings of General Atomic, San Diego, presents a selective review of recent work on charge transfer, that is, elementary interactions involving the transfer of an electron between an ion and a neutral particle. This theme is continued and carried forward by C. F. Giese of the University of Chicago who discusses low-energy charge-transfer reactions and ion-molecular reactions in beams with particular reference to mass-spectroscopic measurements. As