Laszlo Tisza's Contributions to Philosophy of Science

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I. Introduction

The purpose of this paper is to bring Laszlo Tisza's philosophical ideas to the attention of both philosophers and physicists. *Prima facie* it is surprising that advocacy for Tisza's philosophical contributions is needed, since he has great prestige as a theoretical physicist and since there is widespread interest in the opinions of philosopher-physicists, deplorations about walls between disciplines notwithstanding. An explanation is to be found in the fact that there are only a few written expositions of his philosophical ideas and these have mainly been given in the course of working out or commenting upon physical theories. [The longest and most comprehensive of the papers which directly address issues studied by professional philosophers is "The conceptual structure of physics," which first appeared in *Reviews of Modern Physics* 35:110–131 (1962); it was reprinted in *Generalized Thermodynamics* (abbreviated as *GT* in the references throughout the present paper). Much of the philosophical content of this paper is presented in a less technical manner in "The logical structure of physics," which first appeared in *Synthese* 14:110–131 (1962) and was also reprinted in *GT*. Two brief articles that appeared in philosophical collections and one unpublished philosophical paper are listed in the references.] This mode of presentation has constituted a formidable barrier to professional philosophers, while professional physicists have usually been insufficiently aware that something philosophical was happening in a discussion of such topics as critical points and structure functions.

The inseparability of Tisza's philosophical ideas from his scientific

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work, however, is one the characteristics that makes them extraordinarily interesting. His theses on concept analysis, methodology, and ontology are bolstered by detailed references to scientific results and could not even be stated intelligibly outside the context of physics. Conversely, a comprehensive philosophical viewpoint has provided the momentum and the organization of Tisza's scientific research. Furthermore, his philosophical viewpoint has been refined by feedback from the scientific research to which it was applied.

Modern science began with two marvelous paradigms of the interplay of philosophy and science—the dialogues of Galileo *Concerning Two New Sciences* and *Concerning the Two Principal World Systems*. The dialogue form was appropriate not just because of the dramatic conflict between scholasticism and the scientific renaissance, but also because of the reciprocity between organizing philosophical ideas and concrete scientific results. There have been regrettably few documented examples of such reciprocity, neither on Galileo's titanic scale nor on a smaller scale. All the examples that we possess deserve careful study because they are episodes in a continuing dialogue with nature, whether or not they are presented in the dialectical literary form. What I most want to bring to the attention of two professions is that Laszlo Tisza has provided a documented contemporary example of reciprocity between philosophy and physics. Unavoidably, this paper will be more a work of indication than of exposition, since the details and the concrete context are indispensable for the presentation of Tisza's point of view.

II. Philosophical Affinities

Tisza says that his method of analysis is "in agreement with the spirit and the underlying goals of the philosophical school that is alternately called analytic, positivist, or empirical" (*GT*, pp. 333 and 375). For several reasons, however, this statement is not entirely accurate and only roughly places him in the philosophical spectrum.

First of all, within the analytic school there is great diversity on a multitude of issues of logic, semantics, epistemology, methodology, and ontology. Tisza is obviously well acquainted with much of the literature of analytic philosophy of science up to 1950, for example, Mach, Poincaré, the Vienna circle, Bridgman, Popper, and Frank, and in some essential respects he is critical of it. He seems not to have paid much attention to the new wave in philosophy of science initiated by Hanson, Quine, Toulmin, Kuhn, Feyerabend, Putnam, and others in the late 1950s and early 1960s, even though some of their criticisms of earlier analytic philosophy parallel his own. From time to time in this paper I shall compare Tisza's departures from earlier analytic philosophy with theirs. On the whole, he is more conservative in his relations to his predecessors than they are, and, in my opinion, his departures are more controlled than theirs by precise analysis of past and present physics.

A second reason why the quotation above only roughly places Tisza is that philosophers not belonging to the modern analytic school have influenced his thinking. He acknowledges the precedent of Aristotle in his views on form (*morphe*), which plays a central role in his interpretation of quantum mechanics, and some of his ideas on the plurality of sciences and on the possibility of reliable induction from a small number of cases are strikingly Aristotelian. Tisza has stated in conversation, however, that Aristotle's natural philosophy must be tempered by Plato's insistence upon the importance of mathematical structures. He admires Zeno of Elea and has stated that the paradoxes of motion are not yet completely solved. Also, in conversations he has said that the general pattern of Hegelian dialectic is very illuminating in intellectual history, an example being the opposition of the principles of transformation and conservation in the early theories of heat and their synthesis in the thermodynamics of Clausius (*GT*, pp. 13–14).

Third, Tisza has been very sensitive to philosophical observations made, often in passing, by great scientists, an attentiveness which is to be expected in view of the interplay of his own scientific and philosophical work. In writing or in conversation he has cited philosophical opinions of Galileo, Newton, Euler, Hamilton, Maxwell, Boltzmann, Gibbs, Einstein, Bohr, Pauli, Hilbert, and Delbrück. Two examples have given him much pleasure, since they show the *force majeure* of nature over ideology in the thinking of dedicated men. The first is Boltzmann's warning, after a lifetime of study of classical mechanical models of thermodynamic processes, that these models rest upon unwarranted extrapolations and may have to be replaced by a finer conception of microscopic physical reality (Boltzmann, p. 52). The second is the final paragraph of the fifth (and last) edition of *The Meaning of Relativity*, where Einstein writes, "From the quantum phenomena it appears to follow with certainty that a finite system of finite energy can be completely described by a finite set of numbers (quantum numbers). This does not seem to be in accordance with a continuum theory, and must lead to an attempt to find a purely algebraic theory for the description of reality"

(Einstein, pp. 165–166). This was written, of course, after pursuing a monumental program of continuum physics.

III. The Analysis of Physical Concepts

Tisza's views on concept formation were largely the consequence of his reflections upon the relation between quantum physics and several branches of classical physics, which will be considered in section IV. For the purpose of exposition, however, it is useful to take Bridgman's operationalism as a point of reference. According to the initial thesis of operationalism (later modified), "The concept is synonymous with the corresponding set of operations" (Bridgman, p. 5). This is primarily a semantical thesis, prescribing how meanings are assigned to words. However, the requirement that concepts in scientific discourse be explicitly tied to laboratory operations also has methodological and epistemological consequences, which Tisza finds to be in conflict with the actual successful practices of physics: "The operational point of view considered as a sole criterion would always favor the low-level abstractions. However, the most spectacular advances in theory are connected with the discovery of abstractions of a very high level" (*GT*, p. 376). This critique is made particularly forceful by Tisza's demonstration that abstractions of a high level are indispensable even in thermodynamics, a part of physics that has been regarded by many physicists from Mach to Bridgman as the exemplary case of a phenomenological science. His treatment of the concepts of thermodynamic temperature and of thermodynamic equilibrium are especially illuminating.

Since we are endowed with a thermal sense that qualitatively parallels thermodynamic temperature, and since macroscopic bodies exhibit a multitude of temperature-sensitive properties, it is tempting to regard temperature as a concept that is easily made intuitive. Tisza warns that "absolute thermodynamic temperature and entropy are inextricably connected with each other. If someone claims to understand temperature while being mystified by entropy, then his statements may be presumed to be 50% accurate" (*GT*, p. 75). His point is that in order to relate the thermodynamic temperature T to an empirical temperature θ that is operationally defined in terms of some specified thermometric substance, one has to make use of thermodynamic theory. For example, if the empirical temperature is read from a constant-pressure gas thermometer, then a differential equation

$$\frac{1}{T}\frac{dT}{d\theta} = \alpha^*\left(\frac{\lambda^* C_p^*}{V} + 1\right)$$

can be derived, where α^*, λ^*, and C_p^* are, respectively, the expansion coefficient, the Joule-Thomson coefficient, and the constant-pressure specific heat, all expressed in terms of the empirical temperature θ and all measured by standard macroscopic operations. Integrating this equation yields the function $T(\theta)$, thereby anchoring T to operations. In deriving the differential equation, however, one uses some differential expression like

$$dH = V\,dP + T\,dS$$

(where H is the enthalpy $U + PV$; S is the entropy), and this expression is a special case of the first and second laws of thermodynamics in conjunction (*GT*, pp. 75–77). Theory is thus indispensable for the semantical analysis of thermodynamic temperature.

Thermodynamic equilibrium presents even greater subtleties. The gross empirical correlate of equilibrium is quiescence, but that is only a necessary and not a sufficient condition for true equilibrium: visible changes of a system may cease because of extremely slow transition rates, causing "frozen-in" nonequilibrium. Tisza suggests an extraordinary prescription for dealing with this difficulty. He makes use of the third law of thermodynamics (Nernst's postulate) in a strong form: that is, at the absolute zero of thermodynamic temperature the entropy of a system vanishes—a strong form, because it is not phrased in terms of entropy differences, for which fairly definite empirical procedures exist. The prescription is first to evaluate the entropy of the system of interest in the limit of the low-density highly dispersed gaseous state, where it is approximately the sum of the entropies of the individual molecules, the latter being calculated with precision from a quantum mechanical analysis of the individual molecule in the light of spectroscopic data. With the entropy at one point in thermodynamic space thus determined by means lying beyond conventional thermodynamics, an integration is then performed along a path of interest, using only standard thermodynamic data, down to the lowest temperature T_0 for which the specific heat of the system has been measured. If the entropy S_0 thus determined at T_0 is within experimental error equal to zero, then it is reasonable to assume that T_0 is close enough to absolute zero to permit an application of the third law in strong form. Furthermore, each item of the thermodynamic data employed in the integration can be inferred to have been gathered in near equilibrium, for were this not the case the specific heats would some of the time have been underestimated and S_0 would have been calculated to be greater than zero. Of this prescription Tisza remarks, "The clarification of the situation often requires a considerable ingenuity combining experimental and theoretical techniques. The method is far from trivial, but it works, and under no conditions are we led to doubt Nernst's postulate" (*GT*, p. 93).

Although Tisza speaks of "dovetailing of the experimental and theoretical procedures" (*GT*, p. 94) in applying thermodynamic concepts, it is significant that he never explicitly or implicitly conflates these procedures. He carefully distinguishes what can be measured directly from what can be measured indirectly, contrary to the thesis of Hanson, Kuhn, and Feyerabend that observations are theory laden (see Suppe, pp. 146–148, 152–156, 177, 196–198 for summaries, references, and discussion). For example, Tisza notes that the great utility of the Maxwell identities in thermodynamics is that they equate quantities that are difficult or impossible to measure directly to those that are directly measurable—for example, $(\partial S/\partial P)_T$ is equated to $-(\partial V/\partial T)_P$. The experimenter's "seeing" in a series of volume measurements is not changed by thermodynamic theory, but the first and second laws permit an inference to be made from observations. What Tisza does exhibit by his examples is that theory has a directive role in experimentation, not only in the commonly recognized sense of suggesting important tests between competing hypotheses, but in the sense of intimate involvement in the execution of experiments.

Despite Tisza's reservations about the restrictions that operationalism imposes upon concepts, he acknowledges that it does have an important constructive aspect: "If we have two theoretical systems, both of them confirmed by experiment but inconsistent with each other, we usually find that the inconsistencies are produced by nonoperational assumptions that can be dropped without losing the measure of experimental agreement already achieved. In fact, subsequent developments often result in an extraordinary expansion of the range of concordance" (*GT*, p. 376). This constructive use of operationalism is exhibited in Tisza's treatment of the interrelation of theories, to which I turn next.

IV. The Interrelation of Theories

Tisza has a program concerning the interrelation of physical theories, which consists in part of some general and methodological ideas and in part of proposals concerning the meshing of specific theories.

One of Tisza's characterizations of his program is "*dynamical logical analysis*, or the *dynamics of deductive systems*" (*GT*, p. 344): "In the present approach the basis is tentative and subject to change if this leads to an improvement of the system in accounting for experimental facts. . . . Instead of assuming that deductive systems have to be perfect in order not to collapse, the present method of analysis deals with imperfect systems. In fact, one of the tasks of the method is to locate and eliminate imperfections" (*idem*). The characterization of scientific theories as "dynamic" is fairly common among analytic philosophers of the last three decades, who have criticized the Vienna Circle and other early analytic philosophers for neglecting the history of science and science as it is practiced (see Suppe, p. 114, for a summary of these criticisms). Although Tisza concurs about the history of science, he does not share the opinion of the critics that formalization is incompatible with the dynamical view of theories or their rejection of the notion of "logical reconstruction" that Carnap and Reichenbach used to justify formalizations. Rather, he considers the rigorous formulation of deductive systems to be valuable for several reasons: defining concepts by postulation as a supplement to operational definition; knowing with precision what the experimental consequences of the theory are; and determining the compatibility or the clash with other theories.

The most original aspect of Tisza's program is called "*integrated* or *consistent pluralism*" (*GT*, pp. 334–335 and 345). He contrasts this type of pluralism with *monistic integration*, which consists in postulating one deductive system (e.g., mechanics of particles) as fundamental and by reducing all other theories to this one; and also to *eclectic, nonintegrated pluralism*, which deals with physical phenomena in a local and unsystematic manner (*GT*, pp. 345–346). Eclectic pluralism neglects the conception of a physical reality of which all phenomena are mutually compatible aspects (*GT*, p. 345), while monism errs by assuming that the fundamental character of physical reality is already known (*GT*, p. 346).

Integrated pluralism is illustrated by the historical example of the interrelation among classical mechanics, classical electrodynamics, and relativistic mechanics. The conflict between the first two, concerning the effect of motion of the frame of reference on optical phenomena, stimulated Einstein's operational analysis of spatiotemporal concepts in a constructive way (as suggested in the passage quoted at the end of section III). The relativistic mechanics that Einstein then proposed was consistent with classical electrodynamics and *dominant* to classical mechanics, which was then recognized as a *subordinate* theory. A dominant theory is strictly inconsistent with a subordinate theory, but since a range of validity of the latter is established, the inconsistency is said to be *under control*. The dominant-subordinate relation can typically be epitomized in terms of a limit of a crucial parameter; in this case, the velocity of light c goes to infinity. Clearly Tisza's conception of the dominant-subordinate relation has some affinity to Bohr's correspondence principle, but since Tisza is critical of Bohr's insistence upon the entrenchment of the concepts of classical physics (see section V), the conceptions of the two men should not be conflated. It may also be noted that the conception of controlled inconsistency has obvious implications for an issue that Tisza never mentions explicitly, though it is much debated in recent philosophy of science: that is, the *incommensurability* of concepts of different theories (see Suppe, pp. 173–174, 193, 206–207). By acknowledging that "primitive concepts have a definite meaning only *relative* to a particular *context* characterized with precision by a deductive system and its formula" (*GT*, p. 349), Tisza accepts one of the premises of the advocates of incommensurability. But he insists that in the metalanguage one can make illuminating comparisons of concepts formulated in different deductive systems. In particular, experimental reports can be expressed in a neutral manner in the metalanguage and can be used to assess the experimental predictions of conflicting deductive systems.

Tisza conceives that his integrated pluralism has a heuristic function. Although he does not rule out the possibility that the program of integrated pluralism will eventuate in a theoretical structure with one deductive system dominating all others, there still would remain a difference between integrated pluralism and monism as dynamical programs. "In a certain sense we are dealing with an *inverse deductive* method. Starting from the experimentally tested low-level abstractions, we search for the basis from which the former can be derived" (*GT*, p. 346). Once again there are parallels between Tisza's proposals and those of other recent philosophers of science. Hanson has criticized a commonly held views of analytic philosophers that the context of discovery must be sharply distinguished from the context of justification and that only the latter is susceptible to a logical treatment (Hanson, pp. 20–35, and discussions of his proposals by Cohen, Putnam, and Achinstein in Suppe, pp. 357–366); and Pólya has written a treatise on plausible reasoning in mathematics that contains some maxims transferable to the natural sciences (Polya, vol. 2, pp. 39–41). The program of Polya (but not of Hanson) is to some extent psychological, in that he attempts to formulate strategies that stimulate the investigator to see things from a new perspective or otherwise augment his native ingenuity. Tisza, by contrast, is suggesting ways of formulating physical theories in a way that makes ameliorations and extensions compelling. The dynamics, as Tisza conceives it, are in the theory rather than in the theorist. (A historian of ideas might suggest that here is another Hegelian element in Tisza's philosophy, but if so, it is kept under quite strict control.)

The crucial point in the heuristics is the exploitation of limitations manifested in a carefully formulated theory. The theory must be precise enough to permit unequivocal predictions, and attention must be given to possible conflicts with experimental results. The limitations of the theory may either take the form of *marginal breakdown*, occurring when there is unequivocal conflict with experiment or else a singularity or an anomaly within the theory itself. What is most suggestive, however, is the occurrence of discrepancies between two theories, each of which is strikingly successful in its respective domain. At this point Tisza recommends a constructive use of operationalism. It is often found that nonoperational assumptions in one or both of the conflicting theories are responsible for the disagreements. Careful attention to the connection between concepts and experiments at crucial junctures can provide the heuristics for formulating a successful theory that is dominant to one or both of the conflicting theories.

Needless to say, these heuristic recommendations are far from constituting an algorithm for scientific discovery, and Tisza has emphasized that the fruitful exploitation of a marginal breakdown or other limitations is a very difficult enterprise (*GT*, p. 351). Nevertheless, he is able to present a number of cases from the history of physics that can be construed as applications of his heuristics. What gives most weight to Tisza's heuristic program, however, is his putting it into práctice by formulating two subdisciplines of thermodynamics, MTE ("macroscopic thermodynamics of equilibrium") and STE ("statistical thermodynamics of equilibrium"), thereby providing a paradigm.

MTE is an axiomatization of Gibbs's version of thermodynamics, and it has the great virtue of exhibiting explicitly the occurrence of "singularities." Let $X_1, \ldots, X_n$ be the extensive variables of a thermodynamic system (e.g., volume, entropy, and mole numbers of chemical species). With this choice of the extensive variables an energy function $U(X_1,\ldots,X_n)$ is postulated, and then intensities conjugate to the X_i are defined by $P_i = \partial U/\partial X_i$. If the system is in contact with a reservoir with intensities $P_1^0, \ldots, P_n^0$ (which are, respectively, negative pressure, temperature, and chemical potentials), then MTE establishes as a condition for equilibrium that $P_i = P_i^0$ for $i = 1, \ldots, n$. A major result in MTE is the *principle of thermostatic determinism*, that the P_i uniquely determine the X_i, and conversely, when the Jacobian

$$\frac{\partial(P_1, \ldots, P_n)}{\partial(X_1, \ldots, X_n)}$$

is neither 0 nor ∞. At critical points, however, the Jacobian is 0 and at absolute zero it is ∞, and these singularities exhibit the limitations of MTE. The behavior of systems at critical points induces an extension of MTE to a statistical theory—not to Gibbsian statistical mechanics, which is tied to classical particle mechanics, but rather to a more phenomenological theory, which he calls statistical thermodynamics of equilibrium (STE): "Whereas in MTE the virtual states states compared with the actual state in applying the entropy maximum principle or the energy minimum principle have but a formal role, in the new theory they are assigned physical reality as fluctuation states. The free variables of a thermodynamic system are considered as random variables and the principle of thermostatic determinism is weakened to the extent that instead of the *values* of these variables, only their *probability distribution functions* ... are assumed to be fixed in equilibrium" (*GT*, p. 363).

Confirmation of this heuristic reasoning is provided by the phenomenon of opalescence, which indicates enormous fluctuations of the extensive quantities when the system is at a critical point. If, however, this example of the extension of MTE to STE is discounted as reconstruction in hindsight of a past discovery, then it is fair to recall that a similar argument led Tisza to make a new theoretical proposal with new experimental predictions: He argued from considerations internal to MTE that at least one of the partial derivatives $\partial P_i/\partial X_k$ cannot be an analytic function of the temperature in the neighborhood of a critical point (*GT*, pp. 208 and 101), and this argument of 1948 was one of the pioneering steps in the development of the microscopic theory of critical phenomena in the past three decades.

The singularity in MTE at absolute zero is bound up with the third law of thermodynamics. As mentioned in section III, quantum mechanical information must be invoked in order to determine reliably whether a quiescent state close to absolute zero is in fact a state of thermodynamic equilibrium: "Careful dovetailing of the experimental and theoretical procedures ... *takes the place of the traditional exclusion of microscopic* *considerations from thermodynamics*" (*GT*, p. 94). More relevant to the present discussion is that MTE together with the statistical concept of entropy in STE point almost unequivocally to some fundamental facts of microphysics: that the ground state energy of a finite system is either nondegenerate or has a very small degeneracy and that the low-lying states are few in number and well spaced. Tisza maintains that in contrast to classical mechanics, which breaks down in the small and is subordinated to quantum mechanics only by "controlled inconsistency," thermodynamics can be smoothly integrated with quantum mechanics. STE plays a crucial role in this integration, since it is a statistical theory that is free from dependence upon the concepts of classical particle mechanics.

A further test of the fruitfulness of Tisza's heuristic program, on which it is premature to report, is his current work on elementary particle theory. Again he suggests that phenomenological means permit intuitive access to the microworld if we know how to make use of them—notable examples being the polarization of light and the gyromagnetic precession of charged particles observed in magnetic resonance experiments.

V. The Nature of Physical Reality

In an unpublished lecture to the Metaphysical Society of America in 1979 Tisza said, "The physicists' rejection of metaphysics stems from the best of intentions: to avoid dogmatism and meaningless squabbles. Unfortunately such defects come naturally to all of us, and exorcising metaphysics may not be the most effective help" (*ONT*, p. 17). In the body of the lecture the questions whether physical theories should be interpreted realistically or instrumentally, and whether a metaphysical commitment to realism is meaningful, were not discussed in the abstract but rather in terms of his own ontology of microphysics, thereby exhibiting concretely that scientific considerations are relevant to metaphysical questions.

Tisza suggests that one of the main reasons for unwillingness to construe microphysics realistically is the tacit assumption that a realistic world picture must conform to the pattern of classical particle mechanics: permitting detailed spatiotemporal location of the fundamental physical entities, permitting in principle their individual trajectories to be followed, and governed by deterministic laws. Since the uncertainty principle and the stochastic transitions of quantum mechanics break this pattern, the fallacious conclusion is sometimes drawn that modern physics requires a renunciation of physical realism, as exemplified by the famous remark attributed to Bohr, "There is no quantum world" (Petersen, p. 12).

Classical particle mechanics, however, was distilled by Newton from astronomy, and its inapplicability to the microcosm does not imply the breakdown of the concept of object, but rather that microphysical objects have different properties from macrosocpic ones.

First of all, the intrinsic or noncontingent characteristics of all representatives of a microphysical class, such an electron or a U_{235} atom, are exactly the same. Associated with each of these classes is a set of pure states, each being a maximal specification of the contingencies accessible to a representative of the class. It follows that representatives of a class in the same pure state are absolutely indistinguishable. The impossibility, according to quantum mechanics, of following the trajectory of a particle is a necessary condition for absolute indistinguishability, but the concept of the object is not thereby lost, because *generic identity* takes the place of the classical *orbital identity* (*GT*, pp. 366–368). The determination of the pure states associated with a class of objects is one of the standard problems of quantum mechanics, the most familiar instrument being the time-independent Schrödinger equation (*GT*, p. 366). This may not be the most profound and general procedure, however, because it relies upon a quasi-classical characterization of structures in terms of positions of components and interactions among them. Tisza envisages more fundamental algebraic procedures that do not borrow from classical mechanics and may suffice not only to calculate the pure states of a specified class but to determine the classes themselves (*ONT*, pp. 14–15). The standard calculation of pure quantum states by means of the Schrödinger equation (e.g., the wave functions of the hydrogen atom) suffices to show that form or *morphe* is crucial to the ontology of microphysics, and the program of deriving states and classes of entities algebraically leads to the same conclusion even more emphatically. *Morphe* played a minor role in Newton's hypothesis that indestructible particles of various shapes and sizes were formed at the time of creation (Queries of *Opticks*), but this hypothesis is ad hoc, and Newton offers no explanation for it but God's fiat. Quantum mechanical *morphe*, by contrast, is intrinsic to the theory. In this way, Tisza claims, Aristotle's conception of the role of *morphe* in nature is vindicated in modern physics, though with an admixture of Platonism, since it can only be characterized by means of group theory and other mathematical methods.

A consequence of this role of *morphe* is a radical supplementation of the conceptions of causality and determinism, as they are understood in classical mechanics. "What the average man expects form determinism is an assurance that days and seasons will vary regularly, and that an apple seed will produce an apple tree. The former is mechanical determinism, the latter is chemical, and is the deeper of the two. Its principle was understood by Aristotle, but this was rejected by the mechanists. In the ontologically rejuvenated quantum mechanics chemical determinism is dominant to the mechanical one, as it should be" (*ONT*, p. 16). (To this passage is attached a reference to Max Delbrück's article, "How Aristotle Discovered DNA.")

Although Tisza is confident that the quantum mechanical revolution is irreversible, and nothing like a hidden variables theory will succeed in restoring mechanical determinism, he acknowledges that there are unsolved problems concerning the quantum mechanical treatment of dynamics. Two kinds of dynamics are postulated by quantum mechanics, *propagations* and *the occurrence of events*, and these are in tension (*GT*, pp. 372–373). Propagations occur in all processes governed by the time-dependent Schrödinger equation, which ensures that the wave function at time t is related to the wave function at an initial time by a unitary transformation, with complete memory of phase relations. Events occur in transitions from one stationary state to another and in interaction processes governed by the S matrix. (They also occur in certain types of measurements, but overstressing this fact distorts the objectivity and non-anthropocentric character of physical events, and it confuses the epistemological problems of interpreting measurements—to be discussed in section VI—with the ontological problem of dynamics.) It is characteristic of Tisza's insistence on the solidity of phenomenological physics that he regards both of these types of dynamics to be solidly entrenched (so that, for example, Everett's extrapolation of the time-dependent Schrödinger equation to the universe as a whole and his consequent denial of the occurrence of events is as doctrinaire as Laplace's universal mechanical determinism.)

The paramount problem is to ascertain the limits of validity of the time-dependent Schrödinger equation (*GT*, p. 373). Concerning this problem Tisza has made some intriguing suggestions, but to my knowledge has not worked them out in detail. One is that "wave functions corresponding to pure states have their natural space-time extension of coherence. Such intrinsically coherent units become basic entities of the suggested theory. They are to be joined to each other either incoherently or coherently" (*GT*, p. 374). He has also suggested that an adequate dynamical theory cannot be formulated until microphysics is liberated to some extent from the classical space-time framework. At least in the case of the simplest physical objects, he has a program for finding the appropriate space. For example, in dealing with the polarization of photons an appropriate space is the Poincaré sphere, which permits a simple representation of all pure and mixed polarization states (see Shurcliff and Ballard). This example shows that we are not condemned to operate abstractly as soon as we describe physical processes in other ways than in four-dimensional space-time, since the Poincaré sphere is both accessible to intuition and interpretable operationally. Tisza's ideas on integrating the internal space of an elementary particle with the four-dimensional space-time which is essential for field theory have not, however, been brought to a definitive form.

There is one important set of problems on the foundations of quantum mechanics on which Tisza and I have not agreed. I am preoccupied with the Einstein-Podolsky-Rosen argument, which concluded that quantum mechanical descriptions are incomplete, and with Bell's argument that no local hidden variables theory can agree with all the statistical predictions of quantum mechanics. Nonlocality in Bell's sense is related to action at a distance, though the exact character of this relation is a subject of debate in the literature. Einstein apparently did not anticipate Bell's theorem but surely would have found it troublesome, because he recognized that action at a distance would entail a drastic modification of the geometrical structure of space-time as conceived by either special or general relativity. Since Tisza is exploring novel theories of space-time structure in order to integrate the internal spaces of particles with the four-dimensional space of field theory, I have hoped that this integration might throw some light upon the nonlocality that results from Bell's theorem in conjunction with experiments (see Clauser and Shimony). So far, however, I have not been able to persuade Tisza that Bell's nonlocality represents a genuine "line of stress" (his phrase in *GT*, p. 353) between quantum mechanics and space-time theory. One reason why Tisza resists this line of thought is that he has an entirely different diagnosis from Bell's about the nature of the impasse between Einstein and Bohr: "We propose that the reason for this impasse is that both participants tacitly assumed that there is only one type of causality depending on the exhaustive specification of the initial conditions. In contrast, we have argued that most of the causal chains expressing the regularities in nature are of a second kind and are based on the selective specification of composite processes in composite systems" (*GT*, p. 374). It is true that Einstein had expressed skepticism in 1926–1927 about taking a stochastic theory to be fundamental, but there is no overt or tacit assumption of mechanical determinism in the paper of Einstein-Podolsky-Rosen in 1935. Rather, a very mild condition for the existence of an element of physical reality, conjoined with the assumption of no action at a distance, led rigorously to a local hidden variables theory. The experiments inspired by Bell's theorem refute not only deterministic but also stochastic hidden variables theories. Hence an assumption about the nature of causality is not at the heart of the Einstein-Bohr debate. What is crucial is that the experimental results require that one of the premisses of the Einstein-Podolsky-Rosen argument must be abandoned: either their mild criterion for reality or their assumption of locality. Either choice is philosophically momentous. Since in agreement with Tisza I believe that microphysics should be interpreted realistically, but with a new conception of reality, I am inclined to accept nonlocality as a permanent part of physics. This argument, incidentally, is an inference from phenomenological physics, in the manner that Tisza's methodology recommends, for the beauty of Bell's theorem is that it is not dependent upon any model and hence cannot be tinkered with. I continue to hope that some connection will be found between the nonlocality resulting from the work of Bell and the innovations in space-time theory implied by elementary particle phenomena.

VI. Induction

There have been advocates in recent years of the thesis that the principles of inductive inference are not entirely a priori, but depend in part upon factual assumptions about the constitution of the world. The obvious objection to this thesis is that induction seems to be required to justify these assumptions, but it has been argued in response that there is no vicious circularity in this procedure (e.g., by Black). Although Tisza has not given a comprehensive analysis of induction and has not addressed himself to the logical problems of basing inductive inference upon assumptions about the world, he has nevertheless made an important contribution by providing a concrete and fruitful example of such an assumption.

Tisza points out that a fundamental problem in experimental science is to identify an object on the basis of the response of its environment.

The point is that there is no satisfactory method for estimating the nature of an object from its observed responses without prior knowledge of the possible set of objects available for selection. In practice, such prior taxonomical information on possible objects is available by induction from past experience. However, neither the justification of induction nor an insight into its limitation was provided by classical physics. The whole question gradually lost respectability and it seemed to have escaped notice that the solution of the problems of the existence and observability of definite objects is implicit in the practical procedures of quantum physics. [*GT*, p. 366]

The essential ingredient that quantum mechanics provides is the ontological property discussed above: morphic invariance. Quantum mechanics has already established the discreteness of almost all the physically important quantum numbers (except those associated with translation in space-time), and different realizations of the same state are absolutely identical: "Since the same experiment can be repeated an indefinite number of times on identical replicas of the same class, it is, in general, possible to resolve the different predictions and eliminate all but one of the competing possibilities (*GT*, p. 367).

Elementary particle physics has not yet succeeded in inferring from first principles what classes of objects exist, but much progress has been made and more can be expected; and in any case, the phenomenological evidence is overwhelming that there is a discrete spectrum of classes of objects. In this way the stage is set for reliable identification of an object from observed environmental response.

Tisza's reliance upon morphic invariance is reminiscent of Keynes's postulate of limited variety (Keynes, pp. 258–260), but there are two important differences. Tisza's principle of morphic invariance is well founded in contemporary physics, whereas Keynes's postulate is an unsystematic distillation from natural history, which studies natural kinds among animals, plants, minerals, and so forth. A second difference is that Tisza seems to be suggesting a hierarchical organization of scientific inquiry, with somewhat different methodological principles governing the different stages. The inferences of ordinary life constitute one stage, and we assume morphic invariance in these inferences because of the enormous but diffuse background of experience of natural kinds. At a higher stage, the principles of quantum mechanics are confirmed by making precise tests of its predictions. Quantum mechanics, in turn, legitimates the belief in morphic invariance for a large class of classes of simple objects, and in favorable instances even permits the calculation of the invariant shapes from first principles. Finally, the physical theories of composite structures—especially molecular physics, solid state physics, and molecular biology—form a progressive research program (in Lakatos's phrase) for explaining the natural kinds that we take for granted in ordinary experience. The failure to pay attention to the hierarchical structure of scientific inquiry is one of the weaknesses of Keynes's theory of induction and of a number of other theories that take probability to be their central concept.

VII. Concluding Remark

Because of compression and selection, the foregoing summary inevitably fails to do justice to Tisza's philosophical views, and furthermore there may have been some distortion because of my failure to understand certain of his ideas or because of my own philosophical preoccupations. Also, I have not been able to give an adequate account of recent developments in Tisza's thinking, because our exchanges were not systematic and the spoken word is fleeting. My hope, therefore, is that the inadequacies of this summary will stimulate him to write a definitive exposition of his own.

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