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STRIFE ABOUT COMPLEMENTARITY (I) *

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UNTIL a few years ago only a few physicists questioned the usual interpretation of quantum theory. Their criticisms were doubtless useful, but remained mainly on the philosophical level; no consistent alternative interpretation of the successful mathematical formalism was offered. Now the situation has altered substantially: several realistic, rational, and deterministic interpretations of the same formalism have been advanced. As was to be expected, they are strongly opposed by the upholders of the official philosophy of quantum theory, which is essentially of a positivistic character. The purpose of the present paper is to examine a recent manifestation of this conservative standpoint, namely, the article in which Professor L. Rosenfeld [1] of Manchester, who is Bohr's best known pupil, criticises the new realistic, rationalistic, and deterministic trends.

1 *What is Complementary to What?*

The doctrine of complementarity is an interpretation of Heisenberg's uncertainty relations. In the case of mechanical systems, the latter state that it is impossible to know simultaneously, with an arbitrary accuracy, the values of any two conjugate variables, such as the position and the momentum of an electron; in the case of a radiation field, the uncertainty relations consist of similar statements regarding the electric and the magnetic field strengths. The doctrine of complementarity, far from interpreting such mathematical relations in terms of errors of measurements of objectively existent attributes

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[1] L. Rosenfeld, 'Strife about Complementarity' (referred to below as *SC*), *Science Progress*, July 1953, No. 163, 393, being a revised version of 'L'évidence de la complémentarité', in André George (Ed.), *Louis de Broglie, physicien et penseur*, Paris, 1953

(as is commonly believed), claims that it is meaningless to ascribe simultaneously an objective position and an objective momentum to an electron, or all of its components to a radiation field. Conjugate quantities were called by Bohr *complementary* to each other, in the sense that they are (*a*) both mutually exclusive, since the sharpening in the value of one of them results in a larger uncertainty regarding the complementary quantity; and (*b*) both needed to achieve a complete description of experimental results, which the present form of the quantum theory is assumed to yield, at least in the atomic realm.

Owing to the fact that complementary aspects are mutually exclusive, it is impossible—thus Bohr argues—to afford a single well-defined picture of atomic phenomena, being on the other hand indispensable to split the image of reality into two *complementary* models, or pictures, which can be applied in succession, never simultaneously in all rigour, and this simply because the aspects covered by each model are not simultaneously *observed*. In the particular case of entities endowed with mass (such as electrons), one group of variables (position and time) describes the corpuscular aspect, while the group of quantities complementary to these (momentum and energy respectively) describes—as can be seen by recalling de Broglie's relation between momentum and wave-length, and Planck-Einstein's relation between energy and frequency—the wave aspect. In this regard, the contention of the doctrine of complementarity is, that microsystems endowed with mass are neither particles, nor waves, nor wavicles, but that they simply *are* not in themselves, for nothing is supposed to exist apart from the means of observation. Hence, according to complementarity, the words 'particle' and 'wave' designate neither material objects nor properties of material objects; they have no ontological status, but solely an empirical one, for they are only entities entering the description of certain experiments.

Most people believe that the doctrine of complementarity merely expresses the obvious fact that we alter nature whenever we act in order to know it; in other words, that when we perform a measurement we establish an interaction between a piece of apparatus and the object under consideration whereby we unavoidably disturb the latter. This is a valid interpretation of Heisenberg's uncertainty relations, which the doctrine of complementarity attempts to interpret; but that conception is contradictory to the doctrine of complementarity, which is not centred in *things* that are to be observed and that exist

before and after the acts of observation, but which is centred in *observations*—because, it is argued, it would be ' metaphysical ' to assume that there *is* something beyond observational data. It is not merely that the doctrine of complementarity stresses the doubtless active rôle of the experimenter, the active side of knowledge ; it goes beyond this, asserting that observations are the alpha and the omega of knowledge, that there is nothing which is being observed, nothing beyond observation itself.

Bohr has carefully and untiringly explained, for almost a quarter of a century, that we cannot attribute an autonomous physical reality (i.e. a reality independent of the experimenter) to objects at the atomic scale.[1] Philipp Frank, an authorised spokesman of the same philosophical trend, has elucidated this point with his usual clarity, explaining that what we call electron is not a bit of matter but a set of symbols : ' The " electron " is a set of physical quantities which we introduce to state a system of principles from which we can logically derive the pointer readings on the instruments of measurements.'[2] Of course, the same is deemed to be valid for the qualities of things ; thus for instance the momentum of an electron ' has never existed except in so far as we have a set-up which allows the definition of a " momentum ".'[3] Things and qualities of things are said to exist only in so far as features of experimental set-ups and acts of observations in themselves.

Now that we are clear about the operational meaning of the concept of reality, we are in a position to understand what is complementary to what. According to Bohr[4] two things, experimental set-ups, and their corresponding descriptions can all be complementary. When we have an experimental set-up for determining (' defining ', in the positivistic jargon) one attribute, we destroy the possibility of setting

[1] N. Bohr, *La théorie atomique et la description des phénomènes* (referred to below as *TA*), transl. by A. Legros and L. Rosenfeld, Paris, Gauthier-Villars, 1932, p. 51 ; ' Licht und Leben ' (referred to below as *LL*), *Die Naturwissenschaften*, 1933, 21 245-50, p. 247 (see also ' Light and Life ', *Nature*, 1933, 131, 422, 457) ; ' Kausalität und Komplementarität ' (referred to below as *KK*), *Erkenntnis*, 1936, 6, 293-303, p. 295 ; ' Le problème causal en physique atomique ' (referred to below as *PCPA*), in the collective volume *Les nouvelles théories de la physique*, Paris, 1939, 11-32, p. 25 ; ' Newton's principles and modern atomic mechanics ' (referred to below as *NP*), in the collective volume ed. by the Royal Society, *Newton Tercentenary Celebrations*, Cambridge, 1947, 56-61, p. 59.

[2] Philipp Frank, *Foundations of Physics* (referred to below as *FP*), in *International Encyclopedia of Unified Science*, 1, No. 7, Chicago, 1946, p. 54

[3] Frank, *FP*, p. 55

[4] Bohr, *KK*

up the 'complementary' arrangement which would allow us to determine its 'conjugate' attribute.

Notice once again that it is not the numerical value of the attribute that is changed by the act of its measurement—since this would entail that it had a value before its measurement. In all this we have neither atomic objects nor their attributes considered as things-in-themselves: complementarists avowedly do not make statements about the real world, they maintain that quantum mechanics does not speak of real objects that are observed but only of experimental arrangements.[1]

On this purely epistemological ground, complementarists have criticised two very common notions. According to one of these, 'Heisenberg's relations say that it is impossible to measure simultaneously the position and the velocity of an electron'. This is wrong, explains Bohr, because it implies that position and velocity are well-defined attributes of the object, whereas the point is just that we are forced to give up the notion of 'autonomous attributes of the object' (*selbständige Attribute des Objektes*).[2] The second popular notion criticised by the complementarists is that 'The electron has no simultaneously determined velocity and position, these being actually indeterminate'. This interpretation is wrong, says Frank, because it assumes that there is something (the electron with indeterminate properties) that pertains to the real world.[3]

What is at stake in all this is not the structure of micro-objects, but the whole theory of knowledge with its old struggle between materialism and immaterialism: complementarity is not a physical but a philosophical doctrine, because it does not refer to matter in motion but to concepts and their verbalisations. As Frank says so amusingly, 'All the confusion is produced by speaking of an object instead of the way in which some words are used'.[4] This fact, that the doctrine of complementarity is of a philosophical, not of a scientific nature, is not willingly accepted by most complementarist physicists who, like Rosenfeld, regard it as 'the most direct expression of a fact'.[5] But what positivist physicists fail to see is granted by positivist philosophers. Thus Reichenbach in one of his last books wrote:

[1] Philipp Frank, 'Philosophische Deutungen und Missdeutungen der Quantentheorie' (referred to below as *PDM*), *Erkenntnis*, 1936, **6**, 303-317, p. 308. See also *Interpretations and Misinterpretations of Modern Physics*, Paris, 1938

[2] Bohr, *KK*, p. 297 [3] Frank, *PDM*, p. 308 [4] Frank, *FP*, p. 55

[5] Rosenfeld, *SC*, p. 396

> The duality of interpretations thus assumed its final form : the *and* of de Broglie's discovery does not have the direct meaning that both waves and corpuscles exist at the same time, but has the indirect meaning that the same physical reality admits of two possible interpretations, each of which is as true as the other, although the two cannot be combined into one picture. The logician would say : the *and* is not in the language of physics, but in the *metalanguage*, that is, in a language which speaks about the language of physics. Or, in another terminology, the *and* belongs, not in physics, but in the philosophy of physics ; it does not refer to physical objects, but to possible descriptions of physical objects, and thus falls into the realm of the philosopher.[1]

The philosophical nature of all this debate will become more apparent when going over to its central problem, which is also the central problem of philosophy, viz. the question of the relation of subject and object.

2 *Esse est Percipi*

In order to be classified as an idealist one does not need to speak the whole day long about the spirit, or to maintain that life is a dream ; it is enough to maintain that nothing exists or appears by itself, autonomously, independently from *some* mind. Berkeley explained it long ago in his straightforward way :

> The table I write on, I say, exists, that is, I see and feel it ; and if I were out of my study I should say it existed, meaning thereby that if I was in my study I might perceive it, or that some other spirit actually does perceive it ; [but] as to what is said of the absolute existence of unthinking things without any relation to their being perceived, that seems perfectly unintelligible. Their *esse* is *percipi* [their being is to be perceived], nor is it possible they should have any existence, out of the minds or thinking things which perceive them.[2]

Nowadays it is hard to maintain such a subjective idealism in ordinary life ; it is easier to maintain it for a domain accessible only to the specialist—for instance, atomic physics. Thus, we often find the amusing spectacle that subjective idealism is asserted with regard to microscopic events, whereas some sort of materialism is retained

[1] Hans Reichenbach, *The Rise of Scientific Philosophy*, Berkeley and Los Angeles, 1951, pp. 175-176

[2] Berkeley, *A Treatise concerning the Principles of Human Knowledge*, § 3

for the macroscopic level. The following is an example of this epistemological dualism :

> In classical physics it is possible to establish a sharp distinction between the system investigated and the means of observation, and therefore to ignore the latter in framing our conception of the phenomenon. The existence of the quantum of action makes such a distinction impossible because it imposes a limit upon the analysis of the interaction between the system and the apparatus which fixes the circumstances in which we observe it. It is therefore the indivisible whole formed by the system and the instruments of observation which now defines the ' phenomenon '.[1]

Bohr has sometimes adopted consistently the idealist point of view, extending it to the macroscopic level. He has argued that, since every observation entails a finite interaction with the instrument, ' one cannot attribute to the phenomena nor to the instrument of observation an autonomous physical reality in the ordinary sense of the word '.[2] He went so far as to approve Heisenberg's remark that ' ordinary (i.e. macroscopic) phenomena are in a way engendered by repeated observations '.[3] But usually he attributes validity to idealism at the atomic level only, a favourite statement being that in the analysis of quantum effects we are faced with the impossibility ' of drawing any sharp separation between an independent behaviour of atomic objects and their interaction with the measuring instruments which serve to define the conditions under which the phenomena occur '.[4] The central point is thus the negation of the *autonomous* existence of atomic objects.[5] Since atomism, that stronghold of traditional materialism, could no longer be rejected (as it was in Mach's days), it became advisable to denaturalise it : atoms are at last granted a right to existence, but only on the ideal plane, only as ' auxiliary concepts '.[6]

Once materialism has been disposed of, it is easy to dispense with the notion that everything comes from something else, that is, with causality. Bohr explained clearly, for once, that the rejection of causality was only *a consequence* of the rejection of materialism:

[1] Rosenfeld, *SC*, p. 395 [2] Bohr, *TA*, p. 51 [3] Bohr, *TA*, p. 64

[4] Bohr, ' Discussion with Einstein on epistemological problems in atomic physics ' (referred to below as *DE*), in P. A. Schilpp (Ed.), *Albert Einstein : Philosopher-Scientist*, Evanston, Ill., 1949, p. 218. See also *NP*, p. 59

[5] Bohr, *LL*, p. 247 and *KK*, pp. 294-296

[6] cf. Mario Bunge, ' Mach y la teoría atómica ', *Boletín del Químico Peruano*, 1951, No. 16, 12-16

> We have been forced to forego the ideal of causality in atomic physics solely because, as a consequence of the unavoidable interaction between the object of experiment and the measurement instruments—an interaction which cannot be corrected for if these instruments are to allow the unambiguous application of the concepts that are needed for the description of the experiments—we cannot speak any longer of an autonomous behaviour of the physical object.[1]

Thus, we see clearly that the celebrated crisis of causality is nothing but a consequence of the adoption of an idealist theory of knowledge : it is not a simple result of modern physics, it is a tenet of modern positivism.

3 *Sozein ta Phainomena*

The most important point in this controversy is that most scientists, at least when they are doing research, share the materialistic principle of the objective existence of a gradually knowable thing-in-itself, whereas positivism maintains that there is no such ' hidden ' reality behind appearance, since the object is exhausted by its perception (nowadays by its measurement). This positivistic axiom is very old, but in modern times it was first clearly stated by Berkeley,[2] who maintained that everything is such as it appears to be, there being no such contrast between appearance and reality, for everything is appearance. Hence the methodological prescription : *sozein ta phainomena*, *salvare apparentias*, to give account of phenomena (appearances).[3]

This phenomenalist attitude, typical of positivism since Comte, has been adopted by the upholders of the official philosophy of quantum mechanics, one of whose best representatives, Heisenberg, has explicitly stated that the quantum theory does not assume the existence of a *Ding an sich* behind the phenomena (or appearances).[4] In a more technical language this is expressed in the principle of observables, according to which physics, or at any rate atomic physics, is only concerned with observable properties—meaning the actually observed ones, with exclusion of all sorts of ' hidden parameters '. Thus,

[1] Bohr, *KK*, p. 298

[2] Berkeley, op. cit., §§ 87, 88

[3] For the early history of this rule, see Pierre Duhem, *ΣΩZEIN TA ΦAINOMENA, Essai sur la notion de théorie physique de Platon a Galilée*, Paris, Hermann, 1908

[4] Werner Heisenberg, *Wandlungen in den Grundlagen der Naturwissenschaften*, 7th ed., Zürich, 1947, p. 86

physics is not presented as the investigation of what Bacon called *natura libera* (such as it is without our intervention) through the *natura vexata* (such as it becomes when we subject it to our cognitive actions) —but as the examination of appearances, the latter being conceived (as we shall see) as unanalysable wholes.

For instance, Bohr [1] warns especially against the use of phrases such as ' disturbance of phenomena by observation ', i.e. against the use of the concept of vexed nature. The reason is plain : such phrases imply the assertion of the objective existence of a reality hidden, for the time being, behind the appearances ; of a *natura libera* existing while we are not acting upon it. That is why Bohr redefined the notion of phenomenon so as to eliminate from it every reference to observed things ; in fact, he repeatedly advocated the ' limitation of the use of the word *phenomenon* to refer exclusively to observations obtained under specific circumstances, including an account of the whole experiment '.[2] All this is admitted and elucidated by Weizsäcker, who suggests that one should not condemn causality as such but only the notion of *objective* causality and, in general, the notion of thing in itself in the sense of existing independently from the subject.[3] Being a learned theologian, he does not conclude from this the validity of materialism, as Rosenfeld does, but he confirms his mystic faith. He would never dream of saying that ' From the dialectical point of view it is almost self-evident to observe that the essential part played by the observer in the definition of the phenomena is perfectly consonant with the fundamentally materialistic character of science '.[4]

We have already observed the inconsistency of maintaining subjective idealism for the atomic realm and materialism for the macroscopic level (sec. 2). Atoms do not exist apart from instruments, maintain idealists. Now, the instruments have avowedly an atomic structure—so far not taken into account by the theory. So that, if one asserts that ' Only instruments exist ', then one is implicitly stating the proposition that is contradictory to that, namely, ' Atoms exist objectively as well '. This is why Bohr always insists that instruments must be treated in a classical (i.e. macroscopic) way—just in order to

[1] Bohr, *DE*, p. 237

[2] N. Bohr, ' On the Notions of Complementarity and Causality ', *Dialectica*, 1948, 2, 312-319, p. 317. See also *PCPA*, p. 24 and *DE*, pp. 237-238

[3] Carl Friedrich von Weizsäcker, *Zum Weltbild der Physik*, 5th ed., Stuttgart, 1951, pp. 30, 41-42, 76 and *passim*

[4] Rosenfeld, *SC*, p. 407

prevent a further analysis of the famous interaction, an analysis that would show what the contribution of each, object and subject, is to the phenomenon. Pauli avoids the mentioned inconsistency by taking a further step ; he declares that not only must we deal with observations without implying observed things, but we must not even deal with *actual* observations—only with possible ones : 'The actual observation appears as an event outside the range of a description by physical laws and brings forth, in general, a discontinuous selection out of the several possibilities foreseen by the statistical laws of the new theory.' [1] Thus, according to the representatives of the official philosophy of quantum mechanics, as for Berkeley, observations must be accepted at their face value and every attempt to analyse and understand them is forbidden forever.

It seemed as though, from now on, we could not be sure whether we are observing the object, or whether the object is observing us, or whether it is observing itself, or whether we are not doing physics but introspective psychology : the obsolete distinction between subject and object is no longer valid, complementarists say ; in its place we have an unanalysable muddle—not precisely a unity in which both terms interact in a determined way, but just a ' sealed unit ' which we are forbidden to look into. It is consistent to match such a stand with any sort of idealistic philosophy. But it is difficult to understand why Rosenfeld should advocate, in the name of materialism, the rejection of the distinction established by ' the narrow and antiquated brand of materialism ' between subject and object.[2]

4 *Not a Departure from Objectivity ?*

Is this not a departure from the ideal of objectivity ? Weizsäcker [3] admits it openly and with joy ; Rosenfeld denies it.[4] He argues on an analogy with the theory of relativity, whose objective content he sees in the invariance of the form of its equations, with respect to certain groups of transformations, or with respect to the choice of the mode of reference. (In this connection it is interesting to remark that Bohr,[5] on the other hand, thinks that relativity is just the recognition of the *essential* dependence of *every* physical phenomenon upon the observer.)

[1] Wolfgang Pauli, *Exclusion Principle and Quantum Mechanics*, Nobel Prize lecture, Neuchâtel, ed. du Griffon, 1947, p. 18

[2] Rosenfeld, *SC*, p. 405

[3] Weizsäcker, op. cit.

[4] Rosenfeld, *SC*, p. 405

[5] Bohr, *LL*, p. 247, and *KK*, p. 294

It seems to the author that Rosenfeld wrongly identifies *objective* (pertaining to or related to the object) with *absolute*, which in physics means independent from standards and frames of reference. Such an identification (and the correlative of subjective with relative) was held by Newton, but is now untenable. The Doppler effect is a classical example of an objective though relative phenomenon : objective, because it is produced independently of the existence of human beings, independently of the subject ; relative, because it is not the same for all material systems irrespective of their state of motion (it does not involve one object but a potential infinity of objects). The relativistic increase of mass with velocity is often presented as an apparent phenomenon depending on the observer—which is also false. It is certainly relative, but it is also objective, because it takes place independently of its being observed or not ; and, thanks to the convertibility of kinetic energy into radiation energy, by accelerating an electron in the betatron we are rewarded with X-rays that are as objective as the causes producing them. Thus not only invariant but also relative entities may be perfectly objective. On the other hand, absolute entities and relations may not have an objective meaning.

The theories of relativity work with objective facts—some of them relative and others absolute ; and, in giving account of reality, they make use of ideal entities, which in turn may be relative or absolute. Relativity, like any other branch of physical science, is concerned only with objective facts, never with facts essentially dependent upon the observer (i.e. subjective facts)—in spite of Bohr's statements. Relative entities are expressed in a non-invariant way, whereas absolute entities are expressed in an invariant way—with the proviso that the categories ' relative ' and ' absolute ' are in turn relative, for they refer always to a certain set of transformations ; whereas, on the other hand, the degree of objectivity of a theory is not dependent on the extent of its invariance, but on the extent of its agreement with the objects to which it refers. The observer, who plays such a central rôle in the positivistic presentations of relativity, is, as in the case of quantum mechanics, just *one* of the possible material systems entering into a relative phenomenon.

Contrary to Rosenfeld, I think that the character of objectivity of a set of symbols does not depend upon their properties of invariance (which, let us repeat, is relative to a given set of transformations), but only upon the *physical meaning* attached to them. That is, it does not depend upon the form of the equations but upon their *content*—upon what logical empiricists call the semantical rules. If, within the

context of a given theory, we say that ' The symbol x stands for the position of a mass-point ', this statement will form part of the objective content of that theory in so far as mass-points can be said to exist, and even if we are not able to measure the effective value of x. This statement will have an absolute meaning in so far as quality is concerned (since x will not cease to represent a position, it will not turn into a momentum, for example) ; and it will have a relative meaning as regards quantity, since the numerical value of x will depend on the system of reference (whether or not an actual measurement is performed). In a simple definition such as that we can understand how objectivity is not necessarily linked with invariance or absoluteness.

Mutatis mutandis, the same applies to quantum theory. Rosenfeld asserts that the objective content of this theory, ' the objective expression for the quantal laws of nature ', is represented by the equations connecting the operators among each other, because these equations (for example, the commutation rules) are invariant under the canonical transformations, ' which express the passage from one mode of observation to another '.[1] Now, the operator equations are susceptible to an infinity of representations which, when *explicit* reference to observational data is made, refer each to a ' mode of observation ', to a ' particular condition of observation '. The first point I wish to stress is that such statements amount to the assertion that the quantum laws *do* refer to objects existing independently from our acts of observation ; they imply that there is a *unique* reality *behind* the countless appearances, behind our representations of that reality. And this plainly contradicts Rosenfeld's basic contention that *no* such separation of the object from the subject is even conceivable. So that, without noticing it, he is telling us that we may retain scientific objectivity on condition that we do *not* accept the epistemological foundations of the usual interpretation of quantum theory—which is a fine piece of empiricist logic.

But there is more to it : once again Rosenfeld confuses, I believe, ' absolute ' and ' objective '. A choice of representation, contrary to his remark, does not necessarily involve subjectivity—the same as the choice of a frame of reference does not eliminate objectivity ; it only involves, from the mathematical point of view, a specialisation. The canonical invariance of certain basic equations do not provide the objective content of a theory. One might construct, and this is

[1] Rosenfeld, *SC*, p. 406

actually being done every day, theories that are invariant under a host of transformations, but which simply do not work, that is, which have no objective content—as happens with most meson field theories. On the other hand, we may limit ourselves to the choice of a special representation (in particular, to the choice of space and time as basic variables) and still obtain most if not all of the verified results of quantum mechanics. Moreover, what will happen to the mathematically beautiful framework of transformations in Hilbert space the day that the present basic equations (such as the wave equations) are recognised as just linear approximations to non-linear equations ? As has been pointed out by Bohm,[1] if we accept such a possibility, the whole framework breaks down and we are compelled to sacrifice *mathematical* generality and choose, for the benefit of *physical* generality, a special representation. And this is not idle speculation, for we know from experience in other fields of physics that linearity is not an absolute and ultimate quality of nature but only an approximation of our knowledge of it.

To sum up, Rosenfeld seems to be inconsistent when he identifies objectivity with absoluteness, or invariance, for he is then led to admit implicitly that matter exists independently of its being perceived—which runs counter to the official philosophy of quantum mechanics. Further, I think he is wrong in asserting that identity, because there are relative objectivities as well as absolute subjectivities.

[1] David Bohm, ' A Suggested Interpretation of the Quantum Theory in Terms of " Hidden Variables " ' (referred to below as *IQT*), *Physical Review*, 1952, **85**, 166, 180. See also ' Comments on an Article of Takabayasi concerning the Formulation of Quantum Mechanics with Classical Pictures ', *Progress of Theoretical Physics*, 1953, **9**, 273.

(To be concluded)