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Rejection of the Light Quantum: The Dark Side of Niels Bohr[1]

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Evidence is recalled of the strong opposition of Niels Bohr, at the time of the Old Quantum Theory 1913–1925, to the *Lichtquanten* hypothesis of Einstein. Some episodes with H. A. Kramers, J. C. Slater, and W. Heisenberg are recollected; Bohr's changing point of view is traced back to some philosophical antecedents and to his endeavor to deduce quantum results from the Correspondence Principle. Some consequences for the future interpretation of Quantum Mechanics, specially to the Complementarity Principle, are considered.

KEY WORDS: Niels Bohr; history of quantum theory; interpretation of quantum mechanics.

1. BOHR AND THE LIGHT QUANTUM

In the Trilogy (Bohr, 1913),[3] the famous 1913 paper *On the Constitution of Atoms and Molecules* in three parts by Niels Bohr (1885–1962), there are quite a few mentions to the Light Quantum Hypothesis (Einstein, 1905). For instance (Bohr, 1913, p. 6)

> . . . the energy radiation from an atomic system does not take place in the continuous way assumed in the ordinary electrodynamics but . . . , on the contrary, takes place in distinctly separated emissions . . .

Later in the same Trilogy Bohr describes the radiation emitted by the atom as (Bohr, 1913, p. 172)

> . . . emission of one of several quanta

which later turned to be mainly only one. Bohr, however, does not use Einstein's word *Lichtquanten* but Planck's energy quanta.

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[3] CW (Collected Works), Vol. II (*The Trilogy*).

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So at the very beginning Bohr embraced both the failure of classical electrodynamics to account for the atom's stability, and also the emission by discrete quanta. But very soon he changed the perspective: classical electrodynamics was to be maintained, indeed used as a guide, quantization limited to matter, and all references to discrete emission of (energy) quanta discarded. What brought about this change? We can trace back precisely the moment: when Bohr discovers, and tells Rutherford at once in a letter [N. Bohr, letter to E. Rutherford, 21-III-1913. CW (Collected Works), Vol. II (*The Trilogy*)], that for large quantum numbers the frequency of the emitted radiation coincides with the frequency of the revolution electron, as the classical theory would predict; Bohr had discovered (letter to Rutherford, 21-III-1913)

> . . . the most beautiful analogi [sic] between the old electrodynamics and the considerations used in my paper.

This was crucial for Bohr future view of quantum physics, and through Bohr's overwhelming influence to the whole of the physics community: the *Correspondence Principle* had germinated; indeed, it was cryptically expressed already in pp. 13–14 of the Trilogy. Henceforth Bohr takes it as the guiding principle to discoveries in the old quantum theory. Indeed, the original quantum conditions of Planck on oscillators, on which Bohr's first atom paper is based, are *rejected.* Heilbron and Kuhn (1969) already realized the contradictions between the July 1913 trilogy, and the December 1913 Copenhagen communication (Bohr, 1914).[4] In the latter, Bohr considers *misleading* the original derivation of the quantum rules (kinetic energy $T = nh/2$, the original quantum rule that Bohr borrows from Planck): the correspondence *criterion* is elevated to the correspondence *principle.*

In his writings in 1913–1920 Bohr steadily gets farther and farther away from the photon concept, and relying more and more on the classical radiation theory. A few quotations will suffice[5] :

> . . . the theory of spectra must be considered in a certain sense as the rational generalization of the ideas of the usual radiation theory [1918].
>
> On the other hand radiation had to be described by the classical electromagnetic theory [1921].
>
> [interference phenomena] cannot possibly be understood on the basis of a theory such as Newton's. In fact, the picture provided by Einstein . . . cannot more than give any sort of explanation of the interference phenomenon [1918].

There is no point in keeping quoting Bohr: all the authors agree on that Bohr rejected the corpuscular nature of light. Particularly detailed studies are in Pais (1991) and Murdoch (1987).

[4] CW, Vol. II, p. 303.
[5] CW Vols. II and III, pp. 229, 234.

There is some irony in Bohr's writings of the epoch; let us look at two cases. Sommerfeld in München was developing a quasiconsistent quantization system of rules for atomic systems, and was not happy with the correspondence principle, as . . . *etwas Fremdartigen* to the theory, a *magic wand, which operates only in Kobenhavn.* Bohr, of course, disliked Sommerfeld approach:

> . . . in every fine point that came up Sommerfeld was wrong. (Pais, 1991, pp. 178, 217).

The irony was, of course, that the difficult Sommerfeld *Feinstrucktuformel* was one of big successes of the Old Quantum Theory, an issue in which he, Bohr, failed (he did apply relativity to the *circular* orbits only). Sommerfeld never got the Nobel prize, to the surprise of many (including A. Pais, an admirer of Bohr). Actually, Bohr never recommended Sommerfeld to the Swedish Academy, whereas most of his recommendees did get the Prize (for a full list see (Pais, 1991, p. 210));[6] see also (Ne'eman and Kirsh, 1986)[7]

In a comment on Einstein's Lichtquantum, Bohr (1920) had this to say

> . . . the Light Quantum hypothesis is so formal, that even Einstein himself shrouded it of mysticism, talking about the *Gespensterfeld* to guide the *photons*

The irony here is double: first, Bohr himself, in the ill-fated BKS paper (which we shall comment later) introduced the *guiding field* in terms of virtual oscillators, although he borrows the idea from Slater; and secondly, Einstein's 1920 idea (unpublished, see (Pais, 1991, p. 287), was later, in the hands of Schrödinger, instrumental in founding the wave mechanics, which Bohr embraced! (see also later) because after all it came to the rescue of his beloved classical e.m. theory. The *Gespensterfeld,* in the hands of Max Born, became the basis for the probability interpretation, today universally accepted, also by Bohr, as part of *his* complementarity point of view. Of course, complementarity and the Born interpretation are at odds with each other. It had to be a philosopher (Popper),[8] coming from outside, who pointed out the contradiction.

[6] Most of Bohr's proposed people eventually got the Prize. The case of Sommefeld is flagrant. A. Pais again: *I belong to those who regret . . . that Sommerfeld's work was never sufficiently recognized by the Nobel Committee. He was nominated every year but one from 1917 until (at least) 1937* (Pais, 1991, p. 214).

[7] "En 1965 Feynman, Schwinger y Tomonaga compartieron el Premio Nobel de Física. Podrían haberlo recibido varios años antes, pero también Niels Bohr veía con recelo la nueva teoría y su actitud negativa disuadió al Comité Nobel de reconocer la obra de aquellos científicos. La decisión de otorgar el Premio Noble a los autores de la Q.E.D. fue adoptada solo despues de la muerte de Bohr (1962)."

[8] "La conexión que hizo Bohr del "principio de complementariedad" con el "dualismo de partículas y ondas" se vino abajo cuando se aceptó la interpretación de Born del cuadrado de la amplitud de onda como una probabilidad para hallar la partícula. Porque esto significaba, en realidad, la aceptación que la interpretación corpuscular era básica."

It was this very clear point of Popper which launched me into this historical revision [LJB].

2. KRAMERS VERSUS KRAMERS

It will be prophylactic to describe now the episodes in which Bohr clashed with people on the *photon* issue. The *first victim* was Hans A. Kramers (1894–1952), Bohr's first collaborator, and a *yes man* for Bohr, as Slater later put it. Now the historian-physicists A. Pais and M. Dresden speak (I resume from Pais (1991) and Dresden (1987)):

> [In Spring, 1921] The indications are that Kramers had obtained the conservation law description of the Compton effect, using the photon description explicitly . . . Bohr would object violently to the publication of these results. He and Kramers engaged immediately in a series of daily *no holds barred*[9] arguments about the photon . . . In these discussions . . . Kramers . . . was simply ground down by Bohr.
>
> After these discussions, which left Kramers exhausted, depressed, and let down, [he] got sick and spent some time in the hospital. During his stay in the hospital, Kramers gave up the photon notion . . . altogether. Instead, he soon became violently opposed to the photon notions, and never let an opportunity pass by to criticize or even ridiculize the concept. He disposed of most of his early calculations, but inadvertently left a few, early rough notes [which are extant, fortunately, in Kramers's family's hands. LJB]

The Bohr–Kramers discussions were in Spring, 1921. That year Bohr was overworked with building a new Ins., and had to renounce to participate in the Solvay meeting. But a glance of the spiritual turmoil is felt, I think, in the following revealing letter to Ehrenfest [N. Bohr, letter to P. Ehrenfest, 10-VII-21. CW, Vol III].

> You have no idea how much your friendship means to me. Specially at a time when I almost feel as a criminal in relation to all kinds of people here and elsewhere.

As the incident with Kramers is an important one, let us recall that already in his 1967 book, ter Haar said (ter Haar, 1967)

> Debye (1923) developed the theory of the Compton effect as did Kramers, who was persuaded by Bohr not to publish . . .

Further evidence comes from Jost, Pauli, O. Klein, Hugenholtz, Casimir, and others. It is interesting to read Kramers *abjuration*, which reminds me very much of the self-indicted declarations of the communists, in Russia or China:

> The theory of Light Quanta might be compared with a medicine which will cause the disease to vanish, but kills the patient. The fact must be emphasized that this theory in no way has sprung from Bohr theory, to say nothing of its being a necessary consequence of it. (Kramers and Holst (1923)).

Were it not because that title belongs to Leon Rosenfeld, one would call Kramers *Plus royalist que le Roi*[10] with respect to Bohr. One should also feel sorry

[9] The Spanish sentence *a calzón quitado* is more vivid.
[10] Again, the Spanish expression *Más papista que el Papa* is better.

for Kramers; the fact that he was a man with poor health alleviates the burden. His argument to reject the photon was, it seems, that it was not invented by God (*alias* Niels Bohr). The irony is that precisely it is in the Bohr atom that the photon concept enters in the most natural way. Many modern books describing the Bohr atom mention expressly the emission of a photon, when a valence electron makes a transition, as if it was part of the original hypothesis of Bohr!

Kramers left Bohr in 1926 to a distinguished career in his native Holland.

3. J. C. SLATER

The *next victim* is the brilliant American physicist John Clark Slater (1900–1976). I show here some evidence gathered from van der Wärden (1976), Pais again (Pais, 1991), and Slater *Recollections* (Slater, 1975). Slater conceived around November 1923 in England a theory to reconcile the apparent wavelike properties of light (interference and diffraction) with the corpuscular photon of Einstein. Slater had the excited atom to *communicate* with other atoms by virtue of some *virtual field* before emitting a photon:

> As soon as the atom reaches a stationary state the [virtual] field is set up . . . containing all the frequencies the atom can radiate. These fields determine the probability of emission of a quantum . . . Finally a quantum of someone of the frequencies will be emitted, [and] the radiation will cease. Meanwhile the quantum is traveling . . . until it is absorbed . . . As soon as I discussed [this] with Bohr and Kramers [Dec-1923] I found . . . to my consternation that they completely refused to admit the real existence of the photons.[11] It had never occurred to me that they would object to what seemed like so obvious a deduction from many types of experiments. They grudgingly allowed me to send a note to *Nature* indicating that my original idea had included the real existence of the photons, but that I had given that up at their instigation [Slater's abjuration, see soon below. LJB]

In a letter to van der Wärden (1976) Slater has this to say (1964)

> . . . Bohr and Kramers opposed this view [of the photon] so vigorously that I saw the only way to keep peace and get the main part of the suggestion [the virtual oscillators] published was to go along with them . . .

Before relating Slater's abjuration, let us comment briefly the ill-fated 1924 Bohr–Kramers–Slater paper. It was written entirely by Bohr and Kramers, while Slater was kept locked up in another room. The paper has 18 pages with a single formula, $E = h\nu$. Bohr gave up conservation of energy lest the photon survive. Einstein, Heisenberg, and Pauli opposed strongly; of course, energy conservation was vindicated in both sides of the Atlantic pretty soon (Bothe and Geiger, 1925; Compton and Simon, 1925). Did then Bohr accepted the photon? No! But let us first listen to Slater confession:

[11] Slater wrote this much later, when already the Lichtquantum of Einstein was universally called the photon, name due to G. N. Lewis (1926).

> it seems possible to build up a more adequate picture of optical phenomena than has previously existed, by associating the *essentially continuous* radiation field with the continuous existence of stationary states, and the discontinuous changes of energy and momentum with the discontinuous transitions from one state to another. [my italics. LJB]. Letter sent to Nature, 28-1-1924

In other words, Slater renounces to the photon. Some scattered comments convey more the spirit of the abdication:

> I have finally become convinced that the way they [Bohr and Kramers] want things, without the little lump carried along the waves . . . is better . . . I am going to have a chance at least to suggest changes. [J. C. Slater, letter to his mother, 18-1-1924; quoted in Pais (1991)].

Eventually Slater received an apology from Bohr: *I had bad conscience about you when in Copenhagen. . .* J. C. Slater went on to another distinguished career in physics in the East Cost, being instrumental in building the theoretical physics in the United States, as the *transition* person from the meteoric start of J. W. Gibbs to the preeminence with J. R. Oppenheimer, etc.

After the Compton–Simon and Bothe–Geiger experiments (Bothe and Geiger, 1925; Compton and Simon, 1925) (Spring, 1925), Bohr renounced to statistical-only conservation of energy and momentum), but he does *not* embrace the photon. Heisenberg says he believed around early 1925 Bohr was the only notorious physicist unbeliever about photons. Bohr's conclusion instead was: one should renounce to a space–time description of physical atomic phenomena; he took cold comfort in another enigma at the time, the discovery of the (Townsend-) Ramsauer effect (anomalous low energy scattering of electrons by noble gases), to delve in (meta-) physical thoughts about non-space–time descriptibility of microscopic phenomena; the irrationality so apparent in many of Bohr's statements in 1927–1930, somewhat corrected afterwards, takes its roots here.

4. SCHRÖDINGER AND HEISENBERG

In September 1926, E. Schrödinger (1887–1961) joined W. Heisenberg (1901–1976), and N. Bohr in Copenhagen. We shall learn more of the way Bohr dealt with opponents. The report is by Heisenberg (1969):[12]

> The discussions between Bohr and Schrödinger began already at the train station and were continued each day from early morning till late at night . . . And Bohr . . . now appeared to me almost as an unrelentic fanatic, who was not prepared to make a single concession to his discussion partner . . . So the discussion continued for many hours throughout day and night without a consensus being reached. After a couple of days, Schrödinger fell ill . . . He had to stay in bed with a feverish cold. Mrs. Bohr nursed him and brought tea and cakes, but Niels Bohr sat on the bedside and spoke earnestly to Schrödinger . . .

[12] Eng. tras. CW, Vol 6, pp. 11, 12.

At issue was the wave-like interpretation of the wave mechanics, no so much the photon; but I bring this incident to sharpen the reader's ideas on Bohr. Schrödinger later reported to a friend how was he [S.] astonished by Bohr's happy coexistence with contradictions bordering the irrational; also

> . . . There will hardly again be a man who . . . in his sphere of work is honored almost like a demigod by the whole world and who yet remains . . . rather shy and diffident like a theology student . . .
>
> [Bohr] talks often for minutes almost in a dreamlike, visionary and really quite unclear manner . . . [E. Schrödinger, letter to W. Wien, 21-X-26. See (Pais, 1991, p. 299)].

We are approaching the climax now. When Schrödinger left, the two men, Bohr and Heisenberg, embarked, through a Socratic dialogue, to set up the conceptual foundations of quantum mechanics, what soon will become the Copenhagen interpretation; but the starting points of them were very different: Bohr took the correspondence principle as a guide, and had already extracted the (unwarranted?) conclusion that

> Every description of natural processes must be based on ideas which have been introduced and defined by the classical theory. (1923; Pais, 1991, p. 300)

Bohr would take this phrase almost literally to *hold also in the new interpretation* (see later, Como conference report). As for Heisenberg,

> I dislike this [Bohr's] approach. I want to start from the fact that quantum mechanics [H. here means the Göttingen matrix theory as started by him, elaborated by Dirac and in the *Dreimannärbeit*, and sharpened in the transformation theory of Jordan and Dirac; he is more explicit in Heisenberg (1955)] . . . already imposed a unique physical interpretation . . . so . . . we no longer had any freedom with . . . interpretation. (Pais, 1991, p. 303)

In correspondence of H. with Pauli, which I shall not reproduce here, it is clear the main fighting point: Bohr wanted to include waves, and to make a blend of Schrödinger wave mechanics, but of course not his [S.] interpretation, whereas H. insisted in the particle point of view, with Max Born's probability interpretation for the matrix elements, in particular, for the wave function itself (von Neumann (1929) would definitely clarify this, stating that Heisenberg was using a *energy* representation, Schrödinger a *coordinate* representation, equally valid, and equivalent mathematically). That much is perfectly clear in Heisenberg's original writing of the *Umbestimmheit* paper (March 1927). When Bohr came back of his skiing holiday in Norway, he rightly corrected a small mistake in the paper of Heisenberg (he had made a similar error in his oral examination for the PhD, which nearly costed him the degree: Wien was reluctant, but Sommerfeld came to his rescue); then the fight between the two men was very acute, as witnessed by Oscar Klein; as described by Heisenberg,

> Bohr tried to explain [my paper] was not right and I shouldn't publish the paper. I . . . ended by my breaking out in tears because I just couldn't stand this pressure from Bohr . . . So it was very disagreeable [for] a short period of perhaps ten days or so in which we really disagreed rather strongly . . . [but after] we agreed that the paper could be published if it was improved on these points . . . (Pais, 1991, p. 308)

The published version of the uncertainty paper contains, as a *Nachtrag*, Heisenberg's abdication:

> After submission of this work, . . . Bohr has pointed out that I have overlooked essential features . . . The uncertainty in an observation depends not only on the occurrence of discontinuities, but also directly on the requirement that . . . measurements are to be made . . . as in particle theory or . . . as *in wave theory* . . . For permission to mention his new research . . . I was privileged to learn . . . at his genesis, I owe my heartfelt thanks to Professor Bohr. [(Duck and Sudarshan 2000) (my italics. LJB)]

The abdication of Heisenberg was a full *volte face*, same as Kramers had experienced 6 years before. The phrase *Kopenhagener Geist der Quantentheorie* is Heisenberg's own (Heisenberg, 1930).

To fully analyze how Bohr passed from Correspondence to Complementarity is beyond our purpose. In a nutshell, Bohr kept from the old principle about the survival of classical radiation theory (instead of, as I think it should be, deduce the classical wave behavior as statistical averaging of the individual quantum particles; but I shall not argue on this), the coexistence of particles and waves. Of course, an element of irrationality creeps in, but Bohr was happy with it,[13] as already Schrödinger noticed; see this other testimony, by Bohr:

> our endeavor is, by means of a suitably limited use of mechanical and electromagnetic concepts, to obtain a statistical description of the atomic phenomena that appears as a rational generalization of the classical physical theories, in spite of the fact that the quantum of action from their point of view must be considered as an irrationality. (Bohr, 1933)

Interpretation: Bohr invites us to study the quanta as a *rational* generalization of the classical theory, in spite of the fact that the quantum, from the very classical point of view, is seen as an *irrationality.* If this is intelligible, *que venga Dios y lo vea.*

I find this hard to swallow, to say the least, and I think Einstein, Schrödinger, Planck, and others, who opposed to the Copenhagen interpretation, did that because they were unable to digest this. Einstein is very explicit: *I never understood what Bohr means by the complementarity principle, in spite of a careful study of*

[13] There is a philosophical point involved here, in Bohr's insistence in using *only* classical concepts to describe phenomena. Since a child, Bohr was very much worried about using the right words to express himself; this is very well documented; in his insistence in limiting ourselves to classical concepts, he probably traded *concepts* by *words:* it is obvious, that for describing whatever *new* phenomenon, we have to use *known* words. See the Spanish introduction (in footnote 16) by M. Ferrero and also A. Peterman (Peterman, 1985).

it. If the first intelligence of the XX Century is unable to grasp the meaning of complementarity, the odds are . . . is un-understandable; and perhaps this is what Bohr really had in mind . . . *We must understand, that there is nothing to be understood.* Einstein did not *accept* the probability interpretation, but did not *understand* complementarity; there is a world of difference.

There some other episodes of rudeness of Bohr, with Landau and with Brioullin, for example, which would end to delineate the dark side of Bohr I'm showing; I just refer to the cartoon by G. Gamow with respect to Bohr's reaction to a paper by Landau and Peierls (1931).[14]

5. CONCLUSIONS

1. Bohr started using Planck's and Einstein's hypothesis to explain the atom and its radiation.
2. Very soon, before the first part of the Trilogy is published, he discovers that for large quantum number n the radiation and the rotation frequencies coincide; it acts like *a revelation* for him.
3. He next substitutes the quantum conditions by the *correspondence principle*, if dressed with the *adiabatic principle* of Ehrenfest (this is very clear in the *Tetralogy*).[15]
4. As a consequence, the *classical radiation* theory is set up as a *referent* for the new discoveries; the little original love for the energy quantum disappears completely. Later Bohr was the staunchest enemy of Einstein's photon concept, to the point of ridicule.
5. Part of the classical heritage is the necessity of speaking of all the concepts, *even the quantum ones*, with a classical language; at some point Bohr even said . . . *There is NO quantum world.*
6. There is strong competition between the München school of Sommerfeld and Bohr's in Copenhagen; *each spurns the other.*
7. After the Compton effect, he still is antiphoton, but starts to develop an irrational attitude towards the quantum, because coexistence of classical pictures, which he wants to maintain at any cost, and the hard reality of genuine quantum processes.
8. The advent of quantum mechanics (in matrix form; Heisenberg, July 1925) caught Bohr off guard; he always thought of making himself a contribution to its discovery.
9. He became a great fan of Heisenberg, to whom he considered as a kind of Messiah.

[14] Related by L. Rosenfeld in Heisenberg (1955).

[15] I refer here to four promised Bohr papers, but only three published, 1918-22. See the first reproduced in van der Wärden (1976, p. 95).

10. There is no evidence Bohr ever went through the intricacies of matrix mechanics; but he salutes the wave mechanics of Schrödinger (January 1926), and after the fall-26 discussions with Schr. and Hei., embarks himself in a crusade for THE right interpretation of Quantum Mechanics. He thinks he achieves this in the snow in Norway (February 1927).
11. He brainwashed Heisenberg, as had done with Kramers and Slater, forcing him to modify his paper; H. became thoroughly convinced.
12. His climax occurs at the time of the Como conference (Volta Death Centenary, 16 September 1927). I cannot refrain repeating some phrases, which reflect Bohr's fidelity to his concepts[16] :

> . . . nuestra interpretación de los datos experimentales se apoya de manera fundamental de los conceptos clásicos. (p. 98) Este postulado [the postulate Bohr calls quantum][17] *atribuye una . . . individualidad a todo proceso atómico* e implica la renuncia a una coordinación causal de los procesos atómicos en el espacio y en el tiempo. (p. 99)
>
> Por lo que se refiere a la luz, su propagación en el espacio y en el tiempo queda descrita de manera satisfactoria por la teoría electromagnética [read: Bohr does still not accept-in the fall 1927! the propagation of photons] . . . para llegar a una expresión exacta de la conservación de la energía . . . es preciso recurrir a la idea del fotón de Einstein [notice how reluctantly introduces Bohr the photon]. Esta situación muestra con claridad la imposibilidad de mantener una descripción causal y espacio-temporal de los fenómenos luminosos. . . . (p. 101)

13. The overwhelming personality of Bohr's wins everybody in the young generation (Pauli, Dirac, Landau, even Max Born) to his point of view. Heisenberg will be the new prophet:

> Since the conclusive studies of Bohr in 1927 there have been no essential changes in these [fundamental quantum] principles. (Heisenberg, 1930; Pref.)

14. Nevertheless, practitioners of Q. M. just *ignore* complementarity. Wigner was not impressed at all in Como. The books by Dirac and Lamdau do not mention it.

The degree of brainwashing by Bohr in all of us is remarkable (I learned the expression from Murray Gell-Mann). For example, in the *Welches Weg*? experiments,

[16] The Como lecture is reproduced in *Atomtheorie und Naturbeschreibung*; I'm using the Spanish. trasl., Alianza Universidad 1988.

[17] Bohr enunciated many *Principles* during his life, consequent to his somewhat dogmatic approach to science, and the *Quantum Postulate* here is just another one. First it was the Correspondence Principle, implicit already in the Trilogy (1913), as noted, but explicit in this *Tetralogy*, (1918). Then he extolled the Adiabatic Principle of Ehrenfest (since 1918). Then came the *Aufbauprinzip* (1921) in Atomic Physics, to be followed by the *Quantum Postulate* in his Como lecture, to culminate in the Complementarity Principle, divulgated after his Brussels Solvay Lecure (October 1927), but published in 1928 after many drafts, in which Pauli collaborated: Nature 121 (Supl.), 580 (1928).

either the two slit screens or Mach-Zehnder interferometer, people say (excuse me for not quoting!) that there is *complementarity* between waves or particles bzw. according the photon runs through both paths (that is, we maintain coherence) or only by one (incoherence, meaning we know which path). But this is as saying that interferences are undulatory, but diffraction is corpuscular!! The photon, a particle, is quantic, so its path does not exist if it is not observed. The Feynman's path integral formalism is just perfect to explain the *propensity* of the particle (photons or Mack trucks!) to explore *all* paths.

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