

# Why Bohr was wrong in his response to EPR

AURÉLIEN DREZET<sup>(1)</sup>

(1) Univ. Grenoble Alpes, CNRS, Institut Néel  
F-38000 Grenoble, France

**ABSTRACT.** We assess the analysis made by Bohr in 1935 of the Einstein Podolsky Rosen paradox/theorem. We explicitly describe Bohr's gedanken experiment involving a double-slit moving diaphragm interacting with two independent particles and show that the analysis provided by Bohr was flawed. We propose a different protocol correcting Bohr's version that confirms EPR dilemma: Quantum mechanics is either incomplete or non-local.

## 1 Préambule [hommage à Georges Lochak]

Georges Lochak était un physicien passionné et un écrivain remarquable vulgarisateur magnifique de la physique. Je pense avoir lu tous ses livres mais au moins trois ont marqué ma mémoire: il s'agit i) de *Quanta, Grains et Champs* [22] coécrit avec Andrade e Silva qui se focalise sur la pensée de de Broglie et la double solution, ii) sa remarquable biographie de Louis de Broglie intitulée simplement *Louis de Broglie-Un prince de la science* [18], livre merveilleux que je conseille à toute personne curieuse voulant comprendre l'oeuvre de Broglie (un physicien avec une âme d'historien, un chercheur du XIX<sup>ème</sup> siècle exilé au XX<sup>ème</sup> <sup>1</sup>), et finalement iii) *La géométrisation de la physique* [19] qui parle de la beauté des lois et symétries en physique. Cependant, Lochak fut avant tout le dernier grand collaborateur de de Broglie (avec Andrade e Silva) et il défendait sa (libre) pensée dès qu'il le pouvait contre les critiques qui lui reprochait son retour aux variables cachées (au grand dam des

---

<sup>1</sup>et cette remarque n'a rien de négative

physiciens nombreux en France qui considéraient et considèrent encore cela comme rétrograde voire même comme une hérésie). Je voudrais cependant mentionner un livre qu'il n'a pas écrit mais coédité (avec Simon Diner et Daniel Fargue). Intitulé *Les incertitudes d'Heisenberg et l'interprétation probabiliste de la mécanique ondulatoire* [12] il s'agit en fait d'un cours inédit de Louis de Broglie réalisé en 1950-1951. Comme Lochak l'explique dans la préface, de Broglie ne l'a jamais publié (contrairement à son habitude) car:

Il l'a désavoué, en effet, peu après l'avoir écrit, car il y exposait, pour la dernière fois sans critique et d'une manière particulièrement brillante et convaincante, l'interprétation de la mécanique ondulatoire selon les idées de l'école de Copenhague auxquelles il adhérait encore à l'époque mais dont il commença, justement, de douter en relisant son propre texte.[12]

Le livre contient entre autre des commentaires de de Broglie et Lochak suite au revirement progressif de la pensée de de Broglie; revirement qui se cristalisa lorsque celui ci reçut en 1951 un manuscrit de David Bohm [10] où l'auteur reprenait en l'étendant un peu la vieille théorie de l'onde pilote de 1927 [11] (qui devint par la suite la mécanique 'Bohmienne').

Pour le présent article ce qui fondamental c'est que cet ouvrage contient une description magistrale de la théorie de la mesure quantique de l'époque et tout particulièrement une analyse des expériences de pensée proposées par Heisenberg, Einstein et Bohr dans les années 1926-1935. Le célèbre débat Einstein-Bohr qui fit suite aux 5-6<sup>ème</sup> congrès Solvay, qui eurent lieu en 1927 et 1930, est analysé techniquement en détail par Louis de Broglie. Ce texte est donc précieux pour celles et ceux qui ne connaîtraient que la perspective de Bohr souvent semi-quantitative et très difficile à suivre. Cependant ce qui nous intéressera tout particulièrement ici c'est la discussion précise du fameux paradoxe d'Einstein Podolsky et Rosen (EPR) publié en 1935 [13]. Ce paradoxe fut analysé et critiqué par Niels Bohr dès 1935 dans le même journal [6] mais sa critique est réputée difficile à lire. Tellement en fait que John Bell lui même affirma qu'il ne comprenait pas ce que Bohr veut dire dans sa réponse à EPR ([3], chap. 16). Cela motive le présent travail qui portera sur une analyse plus poussée qu'à l'usuelle du fameux paradoxe EPR, ou plutôt théorème EPR car c'est bien d'un théorème dont il s'agit. C'est la réponse de Bohr qui est ici considérée et critiquée en

s'inspirant de l'analyse faite par de Broglie d'une expérience de pensée proposée par Bohr en 1935 et qui était censée corriger une erreur d'appréciation et d'analyse des auteurs EPR. Ce travail complète un peu je pense l'admirable analyse historique faite par de Broglie mais aussi Mara Beller et Arthur Fine [4]. Pour des raisons d'universalité du propos, et en trahissant un peu ici le souhait de Lochak de préserver l'usage de la langue française, le reste du présent article sera rédigé en anglais.

## 2 EPR: 'Einstein attacks quantum theory' (New York Times, May 4 1935)

It is (un)famously said that Bohr was victorious in the Einstein-Bohr battle; the EPR debate being the culminating point of the fight revealing the grandiose victory of the Copenhagen prophet <sup>2</sup> and the last defeat of Einstein 'naive' realism. Nothing can be further away of this unfortunate claim repeated again and again in the literature and popular press (especially with the 2022 Nobel prize of physics attributed to Clauser, Aspect and Zeilinger). To understand this curious issue it is first useful to briefly remind the content of the debate.

The EPR paradox/theorem concerns nonlocality and completeness in quantum mechanics. The goal of the EPR article [13] was to show that if we assume the principle of 'Einstein locality' or EPR-locality (that can be precisely defined) then quantum mechanics (supposed valid) must be incomplete. More precisely, EPR shows that either quantum mechanics is incomplete or quantum mechanics is nonlocal i.e., it violates Einstein's locality principle. Moreover, Bohm in his 1952 work [10] showed that his own hidden-variables theory able to complete quantum mechanics and based on the pilot-wave theory of de Broglie is explicitly non-local. While this doesn't contradict the EPR results seen as a theorem Bohm approach was certainly the option 'which Einstein would have liked least' ([3], chap. 1). Of course this was just the beginning of the story: In 1964 John Bell, based on EPR work, discovered his famous theorem ([3], chap. 2) firmly establishing that quantum mechanics (irrespective of being complete or incomplete) must be nonlocal.

The original EPR article focused on the position and momentum ob-

---

<sup>2</sup>Einstein famously, in private letters, ironically named Bohr a 'talmudic' or 'mystic' philosopher and accused him to behave as a 'prophet' preaching complementarity (identified to a 'tranquilizing-pill'). De Broglie later assimilated Bohr to a 'Rembrandt of physics' because of his use of clair-obscur.

servables for two entangled particles but it is common to use instead the example proposed by Bohm in 1951 of two spin- $\frac{1}{2}$  particles 1 and 2 entangled in the singlet state [9]. This is not the strategy that we will follow here and we will stick to the original EPR configuration. We remind that the original EPR paper used the two-particle wave function

$$\begin{aligned} \Psi(x_1, x_2) &= \delta(x_1 - x_2 - d) \\ &= \iint dk_1 dk_2 \delta(k_1 + k_2) \frac{e^{i(k_1 + k_2 x_2 + k_2 d)}}{2\pi} \end{aligned} \quad (1)$$

in the configuration and momentum spaces showing that we have the strong correlation  $x_1 = x_2 + d$  and  $k_1 = -k_2$ . First, I'd like to give the 'symmetrical' reading of the EPR paradox: It's not the one historically presented by EPR or Einstein, but it's the one I prefer because of its simplicity. In the following I will do as if EPR used this version. Therefore, in this symmetrical reading EPR argued (correctly) that if we measure the spatial coordinate  $x_1$  of the first particle we know counterfactually the spatial coordinate  $x_2$  of the second particle. All the same we could measure the momentum  $k_2$  of the second particle and deduce counterfactually the momentum  $k_1$  of the first particle. As a consequence explained EPR we have precise knowledge of complementary observables  $x_1, x_2, k_1$  and  $k_2$  but this is forbidden in the usual complete quantum mechanical interpretation. Therefore, assuming locality and the validity of quantum mechanics EPR deduced quantum mechanics must be incomplete!

The previous reading of the EPR 'paradox' is not exactly Einstein's way of explaining it, as he doesn't actually consider the 'symmetrical' problem of two observers crossing their measurements. Einstein's reasoning is based on the point of view of a single observer, and in terms of locality, observer B is not essential. So, if A (Alice) measures, say, momentum  $k_1$ , then she knows that if B (Bob) measured  $k_2$ , he would actually measure  $k_2 = -k_1$ . So, using locality, Einstein deduces that what happens in B cannot depend on the choice of measurement made in A, and so the value of  $k_2 = -k_1$  must 'exist' independently of whether or not the measurement was made in B. If A now measures  $x_1$  instead, she knows that if B measured  $x_2$ , he would obtain  $x_2 = x_1 - d$ . Once again, A deduces from locality that B's possible measurement cannot depend on what A decides to do, and so B's possible result 'pre-exists' the possible measurement. What this implies is that A applying locality is obliged to deduce that there exist in B (independently of whether the measurement is actually made in B) values  $k_2$  and  $x_2$  that are determined

in advance (this is the meaning of the word pre-existed used here). In an interesting letter written to Schödinger in June 1935 Einstein explained:

The only essential point here is that [the wave functions] are different. I assert that this difference is incompatible with the assumption that the  $\Psi$  description is one-to-one coordinated with physical reality (the real state). Indeed, after the collision, the real state of (AB) is composed of the real state of A and the real state of B, which have nothing to do with each other. The real state of B cannot depend on the measurement I undertake on A (see the separation hypothesis above). However, there are two  $\Psi_2$ , two (or as many as you like) equally legitimate candidates for the same state of B, in contradiction with the assumption of a one-to-one, complete description. [14]

What Einstein means in fact is that locality and his reasoning allow more information to be attributed to B than quantum mechanics can: Assuming locality, quantum mechanics is therefore incomplete!

It is central to understand that for EPR the counterfactual deduction is developed from Einstein's locality assumption and not from realism which is not imposed but better deduced. More precisely, EPR starts with the Einstein-locality assumption based on natural features of the classical realist World picture concerning correlations and relativistic causality. The main idea is that a local operation made by Alice on particle 1 at space-time point  $x_1$  should not influence what is happening to the second particle recorded by Bob at space-time point  $x_2$  if the two events are space-like separated (so that no-signal could propagate between the two points). As Einstein wrote in 1949 :

But on one supposition we should, in my opinion, absolutely hold fast: the real factual situation of the system  $S_2$  is independent of what is done with the system  $S_1$  which is spatially separated from the former.[15], p. 85

The crux of EPR is thus to assume that locality or local-causality is such a natural assumption that we can use it even independently of realistic presuppositions (i.e., without involving hidden variables completing quantum mechanics). This justifies the famous introduction of counterfactual 'elements of reality' by EPR:

If, without in any way disturbing a system, we can predict with certainty (i.e., with probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity.[13]

Of course EPR understood perfectly well that a counterfactual reasoning is in general forbidden in the usual approach to quantum mechanics for a single particle. This is because for a single particle one could invoke Heisenberg's principle to impose a strong form of complementarity and contextuality: It is impossible to record in one single experiment the position  $x$  and momentum  $k$  because the operators  $\hat{x}$  and  $\hat{k}$  don't commute. Therefore, one must choose between one experiment or the other and if one is doing sequential experiments (like measuring  $x$ , then  $k$  and finally again  $x$ ) it is known that dispersion will occur in agreement with Heisenberg's principle. However, with Einstein-locality EPR found a clean way to somehow circumvent Heisenberg's principle limitations. Assuming locality we can know counterfactually the complementary variables of the two particles even though we only recorded  $x_1$  and  $k_2$ . Therefore assuming locality we get more information that is usually accepted. In other words, assuming that quantum is local (QM-L) and complete (QM-C) we deduce quantum mechanics must be incomplete (QM-IC)! This is a wonderful logical contradiction that can be formally written:

$$\text{QM-L} \Rightarrow \text{QM-IC}, \text{ i.e., } \text{QM-C} \Rightarrow \text{QM-NL}. \quad (2)$$

where QM-NL (quantum mechanics nonlocal) is the negation of QM-L (i.e.,  $\neg$  QM-L). Importantly, EPR leads to three physical alternatives:

$$\begin{aligned} & (i) \text{QM-L} \& \text{QM-IC} \\ & (ii) \text{QM-NL} \& \text{QM-IC} \\ & (iii) \text{QM-NL} \& \text{QM-C} \end{aligned} \quad (3)$$

where (i) was favored by Einstein, (ii) by Bohm (with the pilot wave interpretation), and (iii) correspond to the orthodox interpretation of quantum mechanics assumed by Bohr and followers (even if we will see Bohr didn't clearly get the point). Also it is important to note that in EPR incompleteness was obtained through the logical deduction of determinism meaning that we actually have:  $\text{QM-L} \Rightarrow \text{QM-D}$ , i.e., quantum mechanics is deterministic <sup>3</sup> (assuming locality), and from that QM-D

---

<sup>3</sup>determinism results from the perfect correlations  $x_1 = x_2 + d$  and  $k_1 = -k_2$

$\Rightarrow$  QM-IC. The beauty and logic of the EPR deduction/theorem is often underappreciated and the fact that counterfactuality and determinism are actually derived and not presupposed by EPR are still nowadays misunderstood.

### 3 Bohr's response

The detailed answer of Bohr was rather cryptic and lengthy (Einstein in a letter to Schrödinger compared Bohr to a talmudic philosopher). Forgetting the cryptic part, and the long reminiscence concerning the previous battles he won against Einstein, we see that actually Bohr presented an explicit double-slit example. This involves two initially independent particles impinging with normal incidence on a rigid but translatable diaphragm with two narrow parallel slits separated by the distance  $d$ . In his analysis Bohr required the diaphragm to be treated using quantum mechanics so that we actually have a 3-body quantum system. Bohr didn't give the mathematical details for his device to work but this can be reconstructed a posteriori from his article (see also [1, 4, 12, 17, 23, 24]). He actually assumed that just after the 3-body interaction the quantum state of the whole entangled system reads:

$$|\Psi\rangle = \iiint dx_1 dx_2 da \delta(x_1 - a) \delta(x_2 + d - a) \Phi_1(x_1) \Phi_2(x_2) \frac{e^{iK_0 a}}{\sqrt{2\pi}} |x_1, x_2, a\rangle \quad (4)$$

where  $a$  is the coordinate of the quantum mechanical diaphragm with initial momentum  $K_0$ .  $\Phi_i(x_i)$  are the transversal wave functions of the two incident particles: These being irrelevant we now write  $\Phi_i(x_i) = 1$  in the following. Bohr supposes that the '*momentum of this diaphragm is measured accurately before as well as after the passing of the particles*'. This pre and postselection could in principle be easily done using a Compton-like interaction between the massive diaphragm and a long-wavelength photon in order to measure the Doppler effect on the photon frequency (see the Appendix). Moreover, this implies to consider the final wave-functions (written in different representations):

$$\langle x_1, x_2, K | \Psi \rangle = \frac{\delta(x_2 + d - x_1) e^{i(K_0 - K)x_1}}{2\pi} \quad (5)$$

$$\langle k_1, k_2, K | \Psi \rangle = \frac{\delta(K_0 - K - k_1 - k_2) e^{ik_2 d}}{2\pi} \quad (6)$$

where  $K$  is the postselected diaphragm momentum<sup>4</sup>. From Eqs. 5,6 we again find the perfect EPR correlation  $x_1 = x_2 + d$ <sup>5</sup> and  $k_2 = K_0 - K - k_1$  which reduces to Eq. 1 if  $K_0 = K$ . These conditions actually mean that if we subsequently measure the coordinates or momentum of the two particles 1 and 2 we obtain the EPR perfect correlations.

At that stage everything would be OK with Bohr's analysis: He provided a mechanical realization of the EPR state starting from a 3-body entangled system and considering a postselection on the momentum  $K$  of the diaphragm. However, in a subsequent step he considered that in order to measure the position of particle 1 it would require

[...] to establish a correlation between its behavior and some instrument rigidly fixed to the support which defines the space frame of reference. Under the experimental conditions described such a measurement will therefore also provide us with the knowledge of the location, otherwise completely unknown, of the diaphragm with respect to this space frame when the particles passed through the slits.

In other words, by projecting on a position state  $|X\rangle$  of the mechanical diaphragm we would instead get

$$\langle x_1, x_2, X | \Psi \rangle = \delta(x_1 - X) \delta(x_2 + d - X) \frac{e^{iK_0 X}}{\sqrt{2\pi}} \quad (7)$$

$$\langle k_1, k_2, X | \Psi \rangle = \frac{e^{i(K_0 - k_1 - k_2)X}}{(2\pi)^{3/2}} e^{ik_2 d} \quad (8)$$

where now we have clearly  $x_1 = X = x_2 + d$ . Therefore, measuring  $X$  (and not  $K$ ) leads to the perfect knowledge of  $x_1$  and  $x_2$ . In turn the price to pay is that we strongly interfered with the postselection procedure leading originally to Eqs. 5,6, i.e., to the EPR state (this is not surprising since the operators  $\hat{X}$  and  $\hat{K}$  do not commute:  $[\hat{X}, \hat{K}] = i$ ). From Eq. 8 we see that the momentum distribution of particles 1 and 2 is very broad and homogeneous, i.e.,  $|\langle k_1, k_2, X | \Psi \rangle|^2$  is a constant (compare with Eq. 6). A measure of particle-momentum would not lead

---

<sup>4</sup>We have  $|K\rangle = \int da \frac{e^{iKa}}{\sqrt{2\pi}} |a\rangle$ ,  $|K_0\rangle = \int da \frac{e^{iK_0 a}}{\sqrt{2\pi}} |a\rangle$  (we use a convention where  $\hbar = c = 1$ ).

<sup>5</sup>We stress that from Eq. 4 we directly get  $(\hat{x}_1 - \hat{x}_2)|\Psi\rangle = d|\Psi\rangle$  i.e.,  $d$  is an eigenvalue of  $\hat{x}_1 - \hat{x}_2$  implying the perfect correlation  $x_1 = X = x_2 + d$ . However,  $|\Psi\rangle$  is not an eigenstate of  $\hat{k}_1 + \hat{k}_2$ .

to any correlation! Therefore, the new post-selection on the ‘pointer’  $|X\rangle$  actually precludes the EPR analysis. As Bohr wrote:

By allowing an essentially uncontrollable momentum to pass from the first particle into the mentioned support, however, we have by this procedure cut ourselves off from any future possibility of applying the law of conservation of momentum to the system consisting of the diaphragm and the two particles and **therefore have lost our only basis for an unambiguous application of the idea of momentum in predictions regarding the behavior of the second particle.**

Bohr’s proposal, immobilizing the diaphragm, actually implies that a measurement of  $x_1$  precludes a measurement of  $k_2$  without disturbance. But this is certainly not what must occur with independent and local measurements of  $x_1$  and  $k_2$  advocated by EPR! Therefore, Bohr’s example is actually not a fair realization of the EPR scenario. Clearly, Bohr wanted to show that it is not possible to realize the EPR scenario with independent measurements of  $x_1$  and  $k_2$  but he was actually mistaken as we show below.

The rigidity of the diaphragm is a central problem in Bohr analysis. The transfer of momentum is instantaneously transmitted to all parts of the diaphragm even if the slits separation  $d$  is supposed very large<sup>6</sup>. But for EPR that was the key point of locality: Avoiding any faster than light communication and influence between **independent** measurements done on particles 1 and 2. The device of Bohr cannot properly do the job. The problem is that by projecting on the diaphragm state  $|X\rangle$  (i.e., complementary of the momentum state  $|K\rangle$ ) Bohr didn’t play the EPR game: He destroyed the initial EPR state by mixing the postselection and the measurement procedure and therefore precluded the independence of the measurements for  $x_1$  and  $k_2$ . Famously Bohr explained that EPR contains ‘*an ambiguity as regards the meaning of the expression without in any way disturbing a system*’. He also wrote that there

---

<sup>6</sup>Note that based on this analysis we get  $\langle x_1, k_2, K | \Psi \rangle = \frac{e^{i(K_0 - K - k_2)x_1}}{2\pi} e^{ik_2 d}$ , whereas with the Bohr modified state we would instead obtain  $\langle x_1, k_2, X | \Psi \rangle = \delta(x_1 - X) \frac{e^{i(K_0 - k_2)X}}{2\pi} e^{ik_2 d}$ . Bob recording conditional probabilities  $P(k_2|K)$  (associated with the first protocol) and  $P(k_2|X)$  (associated with the second protocol), i.e., averaged on all results of Alice, would still see a quantitative difference showing the disturbance and invasiveness of Bohr’s procedure.

is ‘*no question of a mechanical disturbance*’ in the experiment protocol but better ‘*an influence of the very conditions which define the possible types of predictions*’. All this is not self-consistent since actually Bohr’s proposal for realizing the EPR experiment with a rigid diaphragm clearly contradicts the independence and locality/separation condition required in EPR!

Moreover, Bohr could have done a correct analysis based on comple-

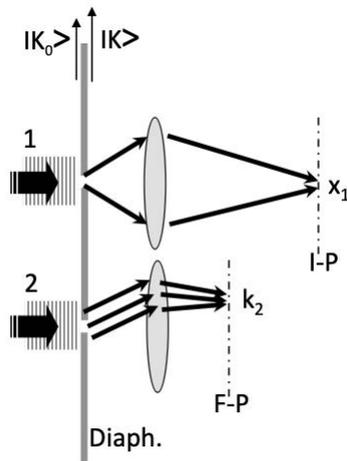


Figure 1: Principle of a gedanken EPR-experiment correcting the proposal of Bohr [6]. Two independent photons 1 and 2 are impinging on a freely moving double-slit diaphragm. The momenta  $K_0$  and  $K$  of this massive diaphragm are measured before and after the interaction with the two beams using Compton/Doppler effects with additional photons (not shown). The transverse particle position  $x_1$  of photon 1 is imaged using an objective microscope (I-P is the image plane). The transverse momentum  $k_2$  of the second photon is recorded in the back focal plane (Fourier plane : F-P) of a microscope objective (note that in principle only one microscope could be used for both particles).

mentarity with his device if he would have preserved the postselection by the diaphragm momentum state  $|K\rangle$  leading to the good EPR state. This however requires not fixing the position of the diaphragm (i.e., not projecting or postselecting on the state  $|X\rangle$ ). For example, consider that

particles 1 and 2 are independent photons transmitted by the moving slits: By using (see Fig. 1) two optical microscope objectives focused on the diaphragm plane Alice and Bob could decide to image independently the position  $x_1$  of the particle 1 (i.e., by recording photons 1 in the image plane of the microscope objective) and the momentum  $k_2$  of the particle 2 (i.e., by recording photons 2 in the back-focal plane of the microscope objective). This procedure would not interfere with the post selection leading to the EPR state, i.e., Eqs. 5, 6. The EPR diagnostic concerning locality and completeness in quantum mechanics is rigorously valid in this amended gedanken experiment and the deduction of the authors cannot be said to be faulty contrarily to Bohr's claims.

## 4 Conclusion

In his later analysis [7, 8] Bohr's emphasized the indivisibility of quantum phenomena, i.e., 'the quantum wholeness' without invoking the details of his 1935 EPR refutation and it has been said that he somehow modified or corrected his first view about complementarity based mostly on local disturbance and the Heisenberg principle (this has been claimed in [4]). It is however not very clear that he fully appreciated the real content of the EPR paradox in his writings [17, 4, 16]. Clearly, that was not so in 1935. Interestingly, the best argumentation that Bohr could have given was already in the EPR paper where it is written at the end:

One could object to this conclusion on the grounds that our criterion of reality is not sufficiently restrictive. Indeed, one would not arrive at our conclusion if one insisted that two or more physical quantities can be regarded as simultaneous elements of reality only when can be simultaneously measured or predicted.

This is actually alternative (iii) of Eq. 3 that EPR disliked very much since '*No reasonable definition of reality could be expected to permit this*'. It must be observed that Bohr article was not the first response to EPR appearing in print in the physical review. Arthur E. Ruark in a very short paper focused on the previous quotation of EPR and developed the strongly positivist conclusion (iii):

This [EPR] conclusion is directly opposed to the view held by many theoreticians, that a physical property of a given system has reality only when it is actually measured, and

that wave mechanics gives a faithful and complete description of all that we can learn from measurements.

Bohr wished a better response: He wanted to convince Einstein the realist of the inevitability of complementarity. Bohr's positivism was a pragmatic one and his goal was to explain why experimental/theoretical considerations tied to the '*finite interaction between object and measuring agencies*' actually impose his complementarity approach of quantum mechanics that '*fulfill, within its scope, all rational demand on completeness*'. However, the particular gedanken experiment he provided was flawed and couldn't be used to demonstrate a contradiction. It is also interesting to point out that Bohr didn't explicitly speak of non-seperability or nonlocality. For Bohr the key feature was indivisibility or impossibility to analyze the quantum system without taking into account the whole experimental setup. Bohr refuted the mere possibility to understand or analyze quantum phenomena within a single causal and spatio-temporal representation that would contradict the spirit of complementarity. However, this issue was not in conflict with the EPR result since alternative (iii) -considered by Einstein as non plausible- was clearly discussed in [13].

Retrospectively can we say that Einstein won the debate against Bohr? Alas, this is not so simple because actually the alternative (i) that Einstein favored was later shown to be untenable by Bell in 1964: Quantum mechanics must be nonlocal irrespectively of being complete or incomplete. Still, it must be said that locality or more precisely local-causality is a compound principle merging locality and causality, parameter setting and outcome independence. There are several possible loopholes that can be used in order to built up hidden-variables theories agreeing with the results of Bell's theorem and give sense to the spooky nonlocality. The author has for example recently proposed a new version of de Broglie's double solution involving retrocausality and superdeterminism [25, 26, 27]. In this theory non-locality à la Bohm is just an effective description: The Universe is fundamentally local as required by Einstein.

In the end, what we can conclude is that the EPR theorem is true, and therefore Einstein's argument is valid. However, Einstein's choice i) to preserve locality is untenable if we respect the results of quantum mechanics (i.e., according to Bell's theorem). This does not necessarily mean that Bohr was right in saying that mechanics is incomplete and cannot be made complete. It is therefore dangerous to repeat that "Ein-

stein was wrong and Bohr was right.” No, Einstein was not completely wrong, and it could very well be that quantum mechanics is incomplete, which would prove Bohr and the Copenhagen school wrong. In fact, de Broglie Bohm’s interpretation of the pilot wave, which corresponds to alternative ii), is a good way of denying that quantum mechanics is empirically equivalent to the orthodox approach and completing the theory with non-local hidden variables.

I would particularly like to thank Philippe Gachet, who did his M1 internship with me in 2024 and worked on the EPR paradox. It’s thanks to him that my understanding of the historical paradox of 1935 was clarified. I would also like to thank Arthur Fine and Vladimir Hnizdo for interesting discussions on the subject.

## 5 Appendix

In his book *Les incertitudes d’Heisenberg et l’interprétation probabiliste de la mécanique ondulatoire* [12] de Broglie discussed the measurement of the velocity of an electron using the Doppler effect. The idea is to consider a photon-electron collision. If  $\omega$ ,  $\omega'$  (respectively  $v$ ,  $v'$ ) denote the photon energy (respectively electron velocity) before and after the collision we have

$$\begin{aligned} \omega + \frac{1}{2}mv^2 &= \omega' + \frac{1}{2}mv'^2 \\ mv - \omega &= mv' + \omega'. \end{aligned} \quad (9)$$

From this we deduce

$$\omega - \omega' = \frac{1}{2m}[(\omega + \omega')^2 - 2mv(\omega + \omega')] \simeq 2\frac{\omega^2}{m} - 2v\omega \quad (10)$$

containing a Compton and Doppler recoil. In the limit where the electron mass is very large we obtain  $\omega - \omega' \simeq -2mv\omega$  which is Doppler formula. The result is left unchanged if we replace the electron by the diaphragm with very large mass  $M$ . Therefore, measuring the photon frequency shift while illuminating the quantum diaphragm we can deduce its momentum  $K_0$  and  $K'$  before and after the interaction with the two particles 1 and 2.

## References

- [1] T. Bai, J. Stachel, Bohr's diaphragms in Quantum structural studies, eds. R. Kastner and G. Jaroszkiewicz, pp. 23-52 (World Scientific, 2017).
- [2] G. Bacciagaluppi, Did Bohr understand EPR? in One Hundred Years of the Bohr Atom, eds. F. Aaserud and H. Kragh, Scientia Danica. Series M, Mathematica et physica, Vol. 1, pp. 377-396 (Royal Danish Academy of Sciences and Letters, Copenhagen, 2005).
- [3] J. S. Bell, Speakable and unspeakable in quantum mechanics, second edition, Cambridge University Press, Cambridge (2004).
- [4] M. Beller, Quantum dialogue (University of Chicago Press, Chicago, 1999); M. Beller and A. Fine Bohr's response to EPR in Niels Bohr and contemporary philosophy, eds. J. Faye and H.J. Folse, pp. 1-31 (Kluwer, Dordrecht, 1994).
- [5] N. Bohr, The quantum postulate and the recent development of atomic theory, Supplement to Nature, 580-590 (april 14, 1928).
- [6] N. Bohr, Can quantum-mechanical description of physical reality be considered complete?, Phys. Rev. **48**, 696-702 (1935); Quantum mechanics and physical reality, Nature (London) **136**, 65 (1935).
- [7] N. Bohr, Causality and complementarity, Philosophy of Science **4**, 289-298 (1937).
- [8] N. Bohr, Discussion with Einstein on epistemological problems in Atomic Physics, in Albert Einstein Philosopher scientist, edited by P.A. Schilpp, Open Court; 3rd edition (1998).
- [9] D. Bohm, Quantum Theory (Prentice-Hall, New York, 1951).
- [10] D. Bohm, A suggested interpretation of the quantum theory in terms of hidden variables-I and II, Phys. Rev. **85**, 166-179; 180-193 (1952).
- [11] L. de Broglie, La mécanique ondulatoire et la structure atomique de la matière et du rayonnement, J. Phys. Radium **8**, 225-241 (1927).
- [12] L. de Broglie, Les incertitudes d'Heisenberg et l'interprétation probabiliste de la mécanique ondulatoire, eds. S. Diner, D. Fargue, G. Lochak (Gauthier-Villars, Paris, 1982).
- [13] A. Einstein, B. Podolsky, N. Rosen, Can quantum-mechanical description of physical reality be considered complete?, Phys. Rev. **47**, 777-780 (1935).
- [14] A. Einstein, Letter to E. Schrödinger dated 19<sup>th</sup> June 1935. Reproduced (in french) in F. Balibar, O. Darrigol, B. Jech, Albert Einstein: Quanta, mécanique statistique et physique quantique (CNRS Editions, Paris, 1989). This is my own translation of the letter.
- [15] A. Einstein, Autobiographical notes, in Albert Einstein Philosopher scientist, edited by P.A. Schilpp, Open Court; 3rd edition (1998).

- [16] Don Howard, Nicht sein kann was nicht sein darf, or the prehistory of EPR, 1909-1935: Einstein's early worries about the quantum mechanics of composite systems, in *Sixty-two years of Uncertainty*, ed. A.I. Miller, pp. 61-111 (Plenum Press, New York, 1990); *Revisiting the Einstein-Bohr dialogue*, *Iyyun: The Jerusalem philosophical quarterly* **56**, 57-90 (2007).
- [17] M. Jammer, *The philosophy of quantum mechanics* (Wiley, New York, 1974).
- [18] G. Lochak, *Louis de Broglie - un prince de la science* (Flammarion, Paris, 1999).
- [19] G. Lochak, *La géométrisation de la physique* (Flammarion, Paris, 2013).
- [20] M. Paty, The nature of Einstein's objections to the Copenhagen interpretation of quantum mechanics, *Found. Phys.* **25**, 183-204 (1995).
- [21] A. E. Ruark, Is the quantum-mechanical description of physical reality complete? *Phys. Rev.* **48** (Letters to the editor) 466-467 (1935).
- [22] J. L. Andrade e Silva, G. Lochak, *Quanta, Grains et Champs* (Hachette, Paris, 1969).
- [23] S. M. Tan and D. F. Walls, Loss of coherence in interferometry, *Phys. Rev. A.* **47**, 4663-4676 (1993).
- [24] W. K. Wothers, W. H. Zurek, Complementarity in the double-slit experiment: Quantum nonseparability and a quantitative statement of Bohr's principle, *Phys. Rev. D.* **19**, 473-484 (1979). (1993).
- [25] A. Drezet, A time-symmetric soliton dynamics à la de Broglie. *Found. Phys.* **53**, 72 (2023).
- [26] A. Drezet, Whence nonlocality? Removing spooky action-at-a-distance from the de Broglie Bohm pilot-wave theory using a time-symmetric version of the de Broglie double solution, *Symmetry* **16**, 8 (2024).
- [27] P. Jamet, A. Drezet, A time-(anti)symmetric approach to the double solution, *Foundations* **5**, 1 (2025).

*(Manuscrit reçu le 17 mars 2025)*