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Franck Laloë and Geneviève Tastevin

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The outcomes of measurements in the de Broglie–Bohm theory II

Les résultats de mesure dans la théorie de de Broglie et Bohm II

Franck Laloë ^a and Geneviève Tastevin ^a

^a Laboratoire Kastler Brossel, ENS-Université PSL, CNRS, Sorbonne Université, Collège de France,
24 rue Lhomond 75005 Paris, France
E-mails: laloe@lkb.ens.fr, tastevin@lkb.ens.fr

Abstract. Part I of this article discussed the quantum measurement process within the de Broglie–Bohm theory. In the experiment considered, the outcome of the measurements was primarily determined by the initial Bohmian positions within the measurement apparatus. This is nevertheless not always the case. Part II is a short addendum with a more general discussion: cases where the measurement results reveal the values of the positions attached to the measured system, the measurement apparatus, or both, are considered.

Résumé. La partie I de cet article contenait une discussion du processus de mesure dans le cadre de la théorie de de Broglie et Bohm. Dans l'expérience étudiée, les résultats de mesure étaient principalement déterminés par les positions bohmienne des particules au sein de l'appareil de mesure. Ce n'est cependant pas toujours le cas. La partie II est un court addendum qui propose une discussion plus générale, et envisage les cas dans lesquels les résultats de mesure révèlent les positions du système quantique mesuré, de l'appareil de mesure, ou des deux.

Keywords. Quantum measurement, de Broglie theory, Bohmian theory, Additional quantum variables.

Mots-clés. Mesure quantique, Théorie de de Broglie, Théorie bohmienne, Variables supplémentaires.

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In [1], we discussed the quantum measurement process within the de Broglie–Bohm (dBB) theory in order to emphasize that, in some cases, the outcome of the measurements was primarily determined by the initial Bohmian positions within the measurement apparatus M ; contrary to what intuition suggests, the positions attached to the measured system S then play no role in the determination of the outcome. This is nevertheless not always the case: in other conditions, the opposite is true, and what determines the results of measurement are the positions of S , not those of M ; as in classical physics, performing a measurement then reveals a pre-existing property (within the dBB theory) of S . See also for instance the discussion in [2]. The present text is an addendum to [1] containing a more general discussion of the measurement problem, and distinguishing between cases where the measurement results are determined by the Bohmian positions of S , or M , or both. This can be seen as a discussion of the mechanism of contextuality within the dBB theory.

1. A first, very simple, example is illustrated in Figure 1: a beam splitter separates the quantum wave of a single particle into two components, which are then directed towards two detectors D_1 and D_2 . The particles may be for instance metastable Helium atoms detected with microchannel

plates [3], while the atomic beam splitter can be obtained optically with near-resonant lasers [4]. When a metastable atom reaches the entrance of a microchannel, an electron is ejected from the solid surface which, under the effect of an applied electric field, triggers an electronic cascade inside the channel. This amplification effect eventually leads to a macroscopic electric current, and to a click of the detector. If the atoms are sent one by one into the system, in each realization of the experiment only one of the detectors clicks, while the other remains silent.

In this simple experiment, which detector clicks is determined by the trajectory of the particle in the optical device. This is because the Bohmian trajectory is continuous and cannot jump from one path to the other; when it reaches one of the detectors, the single particle trajectory determines which component of the many particle state vector is active and contains the cascade process, and which remains an “empty wave”. Mathematically, the state vector describing the whole system of the atom and the two detectors contains no component where the atom is in one arm while the variables of the detector in the other arm are subject to the cascade effect; the Bohmian positions cannot explore regions of the configuration space where the wave function vanishes. As a consequence, in this case, and as one could naively expect, the outcome of the measurement is indeed determined by the trajectory of the measured atom, that is by its position within its wave packet just after the crossing of the beam splitter.

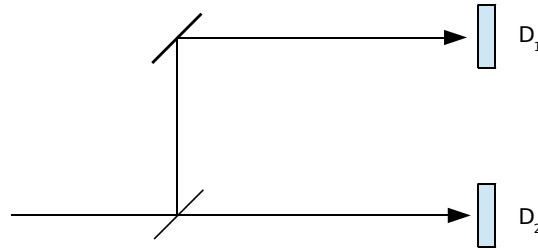


Figure 1. A very simple experiment where the Schrödinger wave of a single particle is split into two components, which are then sent on two detectors D_1 and D_2 .

A similar situation occurs when a beam of particles is sent onto a cloud chamber in order to detect the trajectories of particles. When the wave packet of a particle enters the cloud chamber and initiates a track by a cascade of condensation effects, it is the Bohmian position of the particle that determines the location of the start of the track, and therefore its continuation in the chamber, as discussed for instance by Darwin and Mott [5]. Again, in this case the result of measurement gives an information on the position of the particle before measurement; the Bohmian positions of the particles in the cloud play no essential role.

2. Maybe the example of quantum measurement most frequently discussed in textbooks remains the Stern–Gerlach experiment – even if in practice this category experiment is rarely performed in laboratories. This case is special since no cascade or amplification effect is involved, so that no single particle detection really occurs; what is done is to repeat the experiment a very large number of times, until visible spots of atoms are created on the detection plate. This allows the observation of the quantization of the spin of the Ag atoms, without any individual observation.

Reference [6] provides an interesting discussion of the Stern–Gerlach experiment within dBB theory. It emphasizes the fact that the trajectory of each atom deviates upwards if its initial position is initially in the upper part of the wave packet, downwards if it is initially in the lower

part¹. The surprising result is that this situation does not change when the direction of the gradient of the magnetic field is inverted, so that the relation between values of the spin and trajectory deviations is swapped. As a consequence, in an experimental situation a given initial position of the atom determines a value $+\hbar/2$ of the spin, in another situation an opposite value $-\hbar/2$. In other words, the initial atomic position determines the result of measurement (the value of one component of its spin), but in a way that depends on the design of the apparatus; the result is contextual.

3. Reference [1] discusses another experiment, an “optical version of the Stern–Gerlach experiment”, where two light beams with opposite circular polarizations create spin dependent recoil effects on the atoms. In this case, the two spin states of the atom occupy initially the same region of space; they start to separate only under the effect of the interaction with the measurement system. Two competing effects then take place: on one hand, the overlap between the two wave functions of the atom associated with the two spin directions decreases as a function of time, but on the other hand the overlap between the wave functions of the measurement apparatus associated with the two results also starts to decrease. Because the measurement apparatus contains a large number N of particles which, each, contribute to the decrease of the overlap, the N -particle wave functions become much more rapidly orthogonal in the configuration space of the apparatus than those of the atom. At the end, the choice of the result of measurement depends only on the initial positions of the particles inside the measurement apparatus, while the Bohmian position of the atom itself is practically irrelevant. It is the measurement apparatus that determines the result, and then drives the evolution of the position of the atom accordingly. The conclusion is therefore the exact opposite of that of the preceding paragraph, which is not contradictory since the experiment is different.

One may notice that the Gordon term was not included in the calculations in [1], which simplifies the equations. The discussion relies mostly on the motion of wave packets (not affected by perturbations of the Bohmian trajectories) and on the trajectories of the Bohmian positions of the measurement apparatus (which are not subject to a Gordon term). The conclusions of [1] should therefore remain almost unchanged when this term is included.

4. One can also have intermediate situations, for instance if the system S first interacts with an intermediate quantum system S' containing N' particles, which eventually interacts with a macroscopic measurement apparatus containing a very large number of particles. Depending on the dynamics of the interaction between S and S' and on the value of N' , the information carried by S' to the measurement apparatus may depend primarily on the position of the Bohmian variables of S , or of those of S' ; the dynamics of interaction between S' and the measurement apparatus also plays a role. Therefore, in such an indirect measurement using an ancilla quantum system S' , depending on the conditions the result of measurement may be determined by the initial positions of either S , S' , or M , or be a compromise between different Bohmian variables.

In conclusion, what matters is the spatial extent (before the measurement) of the parts of the total wave function that, under the effect of the interaction with the measurement apparatus M , will become entangled with orthogonal wave functions of S that are situated in different regions (of its configuration space). In other words, what matters is the spatial extent of the wave functions associated with the eigenvectors of the measured observable of S . If these eigenfunctions are already spatially separated, the result of measurement is determined by the Bohmian position of S ; if they overlap spatially, the Bohmian position of M may play an important role, or even determine the measurement result as in [1].

¹ Relativistic considerations show that the Bohmian velocity includes a rotational spin-dependent term (Gordon term) [7–9] that is not taken into account in this discussion. The Gordon term slightly modifies the trajectories [7], but does not change the main conclusions concerning the strong contextuality of the measurement results.

In experiments where the position of a particle is directly measured, the result of measurement (the place at which the particle materializes, for instance in a cloud chamber) is indeed determined by the Bohmian trajectory of the position of the particle. This is what intuition predicts; it remains true when the correlations between the positions of several particles are measured, for example as in [10]. By contrast, in experiment where another observable is measured, such as an internal variable of the particle (spin), the situation may be the opposite. In this case, the result of measurement may be a consequence of the initial state of the measurement apparatus (as defined by the initial position of its Bohmian positions).

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Declaration of interests

The authors do not work for, advise, own shares in, or receive funds from any organization that could benefit from this article, and have declared no affiliations other than their research organizations.

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