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LETTERS TO THE EDITORS

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Quantum mechanics in the experimenter's eyes
(comment on the article by M B Menskiĭ)

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1. Introduction

In the context of the renewed discussion about the foundations of quantum mechanics (see, for example, Refs [1 – 5]), we would like to defend the well-established experimenter's outlook, which ought to be credited primarily to Feynman [6], who does not always get his deserts in this discussion. The term 'experimenter' here means 'materialist' — vulgar rather than dialectical.

So, particles are the particles — they are corpuscles but not waves [7, p. 35]. It is true that an amplitude (alias the wave function) of the particle bears a resemblance (purely mathematically) to the wave, but this (one and the same) mathematics describes a different physics (which is often the case with mathematics). The wave function is not something material (possessing energy), but is only responsible for the probability of, say, the particle position.

Quantum mechanics is a statistical theory: it only predicts the probabilities of various final states of the objects under investigation, and this statement does not yet contain anything surprising for the experimenter, unless there is an implication that the amplitude (i.e. the probability!) behaves in a deterministic fashion.

The surprise comes only when it turns out that the probability theory does not always hold in quantum mechanics (see papers [8, 9] and the monograph [10, 1st paragraph]). If a process may take different paths that lead to one and the same final state of all the participants in the process (and the Universe on the whole), then we must add the probability amplitudes of different paths (and not the probabilities by themselves).

If the final states are different, then the classical probability theory is good — we add up the probabilities and not their amplitudes, and there is nothing interesting to observe.

Of course, we are not speaking of refuting the axiomatic probability theory which certainly is an entirely self-consistent chapter of pure mathematics. This mathematics, however, bears no relation to the experiment: here the mathematical term 'probability' does not mean the relative rate of occurrence of a given event. However, the probability theory applied to the experiment (if only for calculating the experimental errors) — that is, aspiring to describe the experimental data — must certainly admit the possibility of experimental refutation (the principle of falsifiability, see Ref. [9]).

Apart from the outlook, the experimenter also has the professional duty that obliges him almost always to measure simultaneously the momenta and the coordinates of the particles. Of course, this is done within an accuracy of measurement that does not contradict the uncertainty relations. The experimenter deals with approximate measurements [11, p. 396].

2. Schrödinger's cat

"Never add up the amplitudes of different final states, states that are not the same" [6, Section 3.2]. For example, one must not add up the amplitudes of the entire atom and the decayed atom or, which is the same, of the alive and dead cats. Superposition of amplitudes may only exist while the two states occur *simultaneously* — for example, if the atom continually disintegrates and rejoins again — which is probably what it keeps on doing virtually before decaying irreversibly.

For example, a K^0 meson may decay into π mesons that means transforming into a $\bar{K}^0$ meson (and returning back) through virtual decay into π mesons and their subsequent fusion. This leads to the emergence of two other states — K_S^0 and K_L^0 mesons which are the superpositions of the former [6, Section 11.5]. After the actual decay into free π mesons, however, the K meson disappears. The disappearance of the K meson (like the disappearance of the nondisintegrating atom) is the *cause* of the appearance of the decay products. These states are incompatible.

To be on the safe side, let us add that the superposition of the entire and the decayed atoms implies the superposition of the one-particle (entire atom) and the many-particle (free particles resulting from the atomic decay) states. This is a superposition of Feynman diagrams, where even the *number* of outgoing lines is not the same. An ampule with poison and cat cannot make this 'paradox' more paradoxical!

According to a more elegant approach to quantum mechanics, we have to add up the amplitudes of all the final states, square this sum, and diligently write out all the interference terms. Then it should be declared that the amplitudes of the different final states are orthogonal, and therefore their interference terms vanish. Here we also are left with a sum of probabilities, but the use of the mathematical term 'orthogonal' adds convincingness to the argument.

One can further complicate the treatment by saying that the amplitudes must be added up for the atom, and the probabilities for the cat, since the cat is a macroscopic object and is described by classical mechanics. The interference

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(superposition) in the atom will break down only when the measuring instrument is tripped that determines the atomic state. An example of such an instrument may be the macroscopic cat that dies when the atom disintegrates.

Further sophistication is also curious: the amplitudes must be added up for the cat as well, and the interference will disappear when the experimenter looks at the cat. Yet another improvement of the theory with the aid of the many-world interpretation is so far beyond the imagination of the experimenter that we dare not discuss it.

"Repeat: do not add up the amplitudes of different final states" [6, Section 3.2].

3. Macroscopic behavior of the device

Various interpretations of quantum mechanics often state that the breaking of superposition requires a macroscopic device that has the property of instability or amplification sufficient for converting the fact of the particle interaction with the device into a macroscopic event which either falls beyond the domain of quantum mechanics, or is within the reach of the experimenter senses. For instance, a macroscopic ball must fall as a result of such interaction. Or an electron avalanche must develop in the photomultiplier (gas-filled detector), producing a loud sound (click).

It turns out that the change of the state of a photon having knocked out an electron from the photocathode of a photomultiplier (or from the gas atom) depends on whether the voltage is applied to the photomultiplier (spark chamber). And that the test photon cares whether it has knocked out an electron from the cathode or from the stand under the photomultiplier. It would seem quite sufficient that a change has occurred in the world — an electron has escaped — whereupon it is no longer possible to add the amplitude (the wave function) of the photon, and of the whole world for that matter, to their amplitudes that do not contain this electron.

For example, in the case of Bragg neutron scattering by a crystal one must add up the *amplitudes* for neutron scattering from each atomic nucleus if the neutron scattering has taken place without spin flipping. If, however, the spin has flipped, then the interference disappears — one has to add up the *probabilities* of scattering by each nucleus, since the spin exchange in scattering takes place with some particular nucleus whose state (spin) ought to have changed [6, Section 3.3]. And even though this spectator is almost impossible to be identified even in a 'gedanken experiment', it is sufficient that it has to exist.

When the scattering occurs without the spin flipping, the absence of such a spectator is related to the rigid fixation of atoms in the crystal — the momentum exchange takes place instantaneously with the entire crystal rather than with a single nucleus [12].

In the experiment on the interference of electrons in two slits, the interference disappears when the electrons behind the screen are illuminated with photons whose wavelength is shorter than the distance between the slits [6, Section 3.2]. The presence of photon detectors is completely unnecessary.

It is true that the experimenter requires the amplification of the detector for studying the microscopic phenomena, but this is entirely human fault. A very low sound from the avalanche is sufficient for the cat. And it is quite possible that a cat is capable of seeing a single photon (the human threshold measures several photons). But this has nothing to do with the Nature of Things.

4. Wave function reduction

The term 'reduction' was quite apt in the early Schrödinger interpretation of quantum mechanics, in which the electron was truly endowed with wave properties, i.e. it could spread out to infinity together with its wave packet, with which it was actually identified. Or, which is essentially the same, the electron could be disintegrated in two to pass through two holes at once. When detected, however, it turned out to be a small corpuscle (corpuscle – wave dualism) localized at one point. In such an event, its mass and charge, smeared out all over the space, immediately contracted into that point. This wonderful property certainly called for the introduction of the new term — the wave packet reduction.

With the advent of Born's statistical interpretation of quantum mechanics, the wave function (amplitude) lost its materiality, and the term 'reduction' its esoteric meaning. It simply became synonymous to the word 'detection'. If someone is sighted in Moscow, then the chance for him to be seen in Leningrad is immediately reduced to zero [11, p. 372].

The classical probability theory and the quantum theory of probability amplitudes give different predictions for the *probability* of detection. Let us assume that a classical particle escapes from a fixed source in an unknown direction. The probability of a certain take-off angle is realized when this particle is detected, for example, upon collision with another particle. Assume that the surrounding space is filled with a very dilute gas of another particles. The probability of collision of our particle with the gas particle will propagate outside at a certain speed (not exceeding the speed of light) until it reaches the gas particle located at the angle at which our particle had taken off the source.

For a quantum particle, before it is detected, there is no probability of a certain take-off angle. In this case the probability amplitude will spread out (see Fig. 9 in the review [9]) and soon reach the nearest gas particle, with which our particle will interact with a certain probability. The gas particles that are farther away stand a poorer chance of detecting the take-off angle. In other words, the quantum particle with the highest probability will be detected in the direction of the nearest detector.

Now about the partial reduction in the case of entangled states. Let us imagine that two classical billiard balls collide in space (in their center-of-mass system, and with a random impact parameter). Each of them has some probability to fly after the collision in any direction. If, however, after a long long time one of them is found at the distance of 1 parsec exactly to the left from the collision point, then the other at the same time will be found undoubtedly at the same distance to the right.

If, owing to the interaction being not completely elastic, one of the balls is found spinning, then the other will, of course, be rotating with the same speed in the opposite direction. In quantum mechanics, where the laws of conservation are also valid, such correlations of particles are known as quantum correlations, the state of these particles is 'entangled', and the possibility of inferring the state of one particle from the state of the other is referred to as quantum nonlocality or teleportation.

Each of these correlated quantum particles cannot have an amplitude that is independent of the other particle, which is a superposition of the probability amplitudes of different take-off angles or spin projections, because they lead to

different final states of the second 'spectator particle', which in our case has equal in magnitude and oppositely directed momentum and spin projection.

However, both these particles together are still described by the superposition of probability amplitudes of different take-off angles and spin projections. The superposition of different angles is broken down when one of the particles interacts with a third particle. The superposition of spin projections vanishes if this interaction depends on the spin projection, for example, in the event of spin exchange with a third particle.

The classical probability theory and quantum theory of probability amplitudes give different predictions for the *numerical value* of spin correlations. The experiments on the validation of the Einstein–Podolsky–Rosen gedanken experiment in Bohm's formulation, and various versions of Bell's inequalities confirm the quantum theory [13].

5. Interference of π mesons

Many experiments concerned with measuring the generation volume of π mesons make use of the phenomenon that is sometimes referred to as the intensity interference, although in quantum mechanics it is only the amplitudes that can interfere, and the interference can only be observed through the probabilities (intensities).

In the case of interaction, for instance, of two nuclei, when the energy of interaction is large, π^- mesons, i.e. bosons with spin zero, escape from the collision region among other particles. These pions are generated practically independently of one another by different 'sources' — that is, in different nucleon–nucleon reactions — in different space–time points of the nuclear collision region.

The probability amplitude for a random pion to have the 4-momentum $p = (E, \mathbf{p})$ and be emitted from 4-point $r = (t, \mathbf{r})$ is $\varphi(\mathbf{p}) \exp(-\mathrm{i}pr)$ [14], where $\varphi(\mathbf{p})$ is the amplitude of probability that the momentum equals $\mathbf{p}$, and $\exp(-\mathrm{i}pr)$ is the amplitude of the conditional probability that if the momentum is $\mathbf{p}$, then at the moment of time t the pion was located at the point $\mathbf{r}$ [10, Section 5.1].

The probability density for the pion to have the momentum $\mathbf{p}$ is equal to the modulus squared of this amplitude: $W(\mathbf{p}) = \varphi^*(\mathbf{p})\,\varphi(\mathbf{p})$.

The amplitude of probability that of the two random pions the first one (with the momentum $\mathbf{p}_1$) is emitted at the point r_a, and the second (with the momentum $\mathbf{p}_2$) is emitted at the point r_b, is equal to the product of one-particle amplitudes, since by assumption the *pions are generated independently from one another:*

$$A_{ab} = \varphi(\mathbf{p}_1)\,\varphi(\mathbf{p}_2) \exp\left[-\mathrm{i}(p_1 r_a + p_2 r_b)\right]. \tag{1}$$

Similarly, the amplitude of probability that the first pion is emitted at r_b , and the second at r_a, is given by

$$A_{ba} = \varphi(\mathbf{p}_1)\,\varphi(\mathbf{p}_2) \exp\left[-\mathrm{i}(p_1 r_b + p_2 r_a)\right]. \tag{2}$$

If these two possibilities are indistinguishable — that is, lead to the same final state of all the particles participating in the reaction — then the probability density of selecting two π^- mesons with momenta $\mathbf{p}_1$ and $\mathbf{p}_2$, being emitted by these sources, is found as (see Ref. [14]):

$$2W(p_1, p_2) = |A_{ab} + A_{ba}|^2 = |A_{ab}|^2 + |A_{ba}|^2 + 2\mathrm{Re}\,(A^*_{ab} A_{ba}). \tag{3}$$

A similar result is obtained in the case of scattering of *one* electron by two holes [10, Section 1.1] or atoms [15, Section XIX.25]. In the same way, if these two possibilities are for some reason distinguishable, we must add up the probabilities rather than the amplitudes:

$$2W^{\mathrm{off}}(p_1, p_2) = |A_{ab}|^2 + |A_{ba}|^2. \tag{4}$$

Such a background spectrum with the switched-off correlations is usually obtained in the experiment from mixed pairs of pions, each of which is randomly selected from different nuclear collisions. Constructed in a similar way is the background in the case of one-particle interference, when only one of the holes is opened alternately [10, Section 1.1].

The correlation function for our two pions is equal to the ratio between probabilities (3) and (4):

$$C_{ab}(p_1, p_2) = 1 + \cos\left[(p_1 - p_2)(r_a - r_b)\right]. \tag{5}$$

This correlation function is not equal to 1, although it has been obtained under the assumption of independent emission of pions. The quantum probability theory is non-Laplacian [10, paragraph 1], and non-Kolmogorovian [9].

In the description of the Brown–Twiss experiment on the measurement of angular dimensions of stars, it is sufficient to replace the words about emission of two pions from the sources located at the points r_a and r_b by the words about absorption of two photons by the detectors located at r_a and r_b (see Ref. [14] and references cited therein).

The correlation function for the scattering of one electron by two holes (atoms) located at $\mathbf{r}_a$ and $\mathbf{r}_b$ looks similar:

$$C_{ab}(\mathbf{k}', \mathbf{k}) = 1 + \cos\left[(\mathbf{k}' - \mathbf{k})(\mathbf{r}_a - \mathbf{r}_b)\right], \tag{6}$$

where $\mathbf{k}$ and $\mathbf{k}'$ are the initial and final electron momenta [15, Section XIX.25].

Let us average the function (5) over the shape of the generation volume $\rho(r)$ — that is, over all positions of the sources of pions ($q \equiv p_1 - p_2$):

$$C(q) = 1 + \iint \rho(r_a)\rho(r_b) \cos\left[q(r_a - r_b)\right] \mathrm{d}^4 r_a\, \mathrm{d}^4 r_b. \tag{7}$$

This procedure, i.e. the averaging of probabilities rather than amplitudes, assumes that different positions of the point r_a (and/or r_b) lead to *different* final states of the particles that participate in the reaction.

Given that

$$\cos\left[q(r_a - r_b)\right] = \mathrm{Re}\left[\exp(\mathrm{i}qr_a)\exp(-\mathrm{i}qr_b)\right],$$

we arrive at

$$C(q) = 1 + \left|\int \rho(r) \exp(\mathrm{i}qr)\, \mathrm{d}^4 r\right|^2. \tag{8}$$

Specifying some form of the function $\rho(r)$, and fitting the experimental correlation function with its Fourier transform (8), we can find the free parameters of the function $\rho(r)$: the size of the pion generation volume, the duration of their emission, and the speed of movement of this volume. The result exhibits little dependence on the particular form of $\rho(r)$.

6. Clarification

In formula (3) we added up the amplitudes of two possible ways of emitting a pair of pions on the assumption that these ways are indistinguishable. However, apart from the two selected π^- mesons, many other free spectator particles are emitted from different points of the collision region. Measuring their coordinates and momenta immediately after their escaping, we may try to find out which of the ways has been realized in this particular case without disturbing our chosen pions. Of course, this can only be done with the accuracy permitted by the uncertainty relation.

It is not necessary, however, to actually perform these measurements — the spectator particles themselves are detectors which after the permutation of pions may occur in a different quantum state.

A striking example which does not differ from ours in any substantial respect is the case when the two pions are emitted not from the distinct regions of one collision, but from two different collisions of nuclei. If the distance in space or time between the collisions is large, then the momentum conservation law holds separately for each collision, which precludes the possibility of pion permutation (for $p_1 \neq p_2$). If, however, this distance is small enough ($\sim \hbar/(p_1 - p_2)$), then only the sum of momenta for the two collisions is conserved.

A qualitative estimate can be obtained using the concept of a quantum state for the system occurring in the continuous part of the momentum spectrum [10, Section 4.3]. The quantum state of the free particle (system of particles) of any kind corresponds to the elementary cell in the phase space with the dimension of $2\pi\hbar$ per each degree of freedom, which is "equivalent to one discrete state" [16, Section 62] and [17, Section 7].

When the pions are permuted, the recoil moment is redistributed between the spectator particles. Those that leave the collision region near the point r_a increase their momentum by $q \equiv p_1 - p_2$, and those that leave near r_b decrease their momentum by the same amount. In other words, the change takes place in the system of all spectator particles: the 4-momentum q is transferred to the 4-vector $s \equiv r_a - r_b$. The position of this system in the phase space with respect to each coordinate (i) is also changed by $q_i s_i$. If this change is considerably greater than $2\pi\hbar$, then the system of spectator particles moves to a different quantum state.

This means that the direct and the crossover paths of the reaction are indistinguishable only if $q_i s_i < 2\pi\hbar$. Then, however, our two pions must be emitted in the same state $q_i s_i < 2\pi\hbar$, and the entire effect becomes equivalent to the phenomenon of induced radiation [6, Sections 4.4, 4.5].

In the intermediate case of $q_i s_i \sim 2\pi\hbar$, amplitudes (1) and (2) must obviously be averaged in Eqn (3) with different weights, which is analogous to the case of one-particle interference, when the electrons beyond the screen are illuminated with photons whose wavelength is of the same order as the distance between the slits [6, Section 3.2]. This leads to smearing of the boundaries of elementary cells.

Thus, the indistinguishability of the paths can only be guaranteed within one cosine period (5). This distinguishes our case from the cosine (6) for the one-particle interference. As a matter of fact, the condition of applicability of formula (6) is the infinite mass or, which is the same, the rigid fixation of the two atoms [15, Section XIX.24], the mirrors [16, Section 3], or the holes [12], which precludes the possibility of finding out (by the recoil momentum) which of the two targets has participated in the scattering. If the electrons are scattered by free atoms or by the unfixed halves of the screen with holes, then only the central interference peak of the cosine (6) will be also left.

This clarification does not lead to any considerable corrections when formula (8) is used in the experiment. However, it makes the assumption about the absence of recoil of the spectator particles superfluous, and may also serve as the basis for supposing the distinguishability of different points when the probabilities are averaged in formula (7).

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