

The historical role of cloud chamber experiment

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Abstract: The aim of this study is to make a review of the interpretations of the cloud chamber experiment during the foundations of quantum mechanics as well as its subsequent influence. One can see how the analysis of the problem leads to reflect on the concept of measurement and collapse of the wave function.

Keywords: History of physics, cloud chamber, quantum mechanics, wave function collapse, Copenhagen interpretation, quantum decoherence

SDGs: SDG 4 – Quality Education

I. INTRODUCTION

During the foundational period of quantum mechanics, the cloud chamber experiment was presented by Albert Einstein (1927) as a challenge to the new theory. Based on the Copenhagen interpretation of the wave function, the alpha particle emerging from a disintegration process is associated with a spherically symmetric wave centred at the radioactive nucleus and propagating isotropically in space. Therefore, why do we observe a straight track instead of random ionizations? During the foundations of quantum theory, two main answers were proposed: one invoked the collapse of the wave function; the other offered an explanation based on the interaction of the particle with the environment trying to avoid the collapse.

For the purpose of this work, exhaustive historiographical research has been conducted, consulting primary sources such as the original articles by Neville Francis Mott [1], Sir Charles Galton Darwin [2], and Werner Heisenberg [3], as well as a thorough examination of secondary literature, among which *Quantum Theory at the Crossroads* by Guido Bacciagaluppi and Antony Valentini stands out [4]. Recent publications from authors such as Rodolfo Figari and Alessandro Teta [5] were also consulted.

Section II builds the historical framework, providing context for the first steps in quantum mechanics. Section III shows how, after Einstein formulation, the topic is openly discussed during the 1927 Solvay Conference by Max Born. Sections IV, V and VI present an analysis of the different publications written by Darwin, Mott and Heisenberg about the topic. Lastly, Section VII displays the conclusions and offers potential directions for future research.

II. HISTORICAL FRAMEWORK

Published between 1927–1930, the contributions analysed in the present study constitute a set of early derivations from the phase of consensus in quantum theory after the Fifth Solvay Conference.

The modern quantum mechanics was established during the 1920s and is characterized by the creation of a proper formalism. This and the subsequent developments are well described in [6]. One of the triggers of this new era was the article published by Heisenberg on the quantum-theoretical reinterpretation of kinematical and mechanical relationships (1925).

Afterwards, Heisenberg collaborated with Pascual Jordan and Max Born in the famous “three man paper” (1926). Together they developed the new “matrix mechanics.” They quickly started solving atomic problems via the new formalism, such as the calculation of the stationary states of the hydrogen atom, hydrogen fine structure, and the anomalous Zeeman effect. At the same time, Paul Dirac independently developed the method of q-numbers, a different scheme based on Heisenberg’s 1925 paper, also successful in various applications. In early 1926, Erwin Schrödinger introduced wave mechanics. From there, Born proposed to identify the wave function with the probability of finding the electron at each location. In March 1927, Heisenberg presented the uncertainty relations, which affected the simultaneous measurement of conjugate variables.

Finally, the emerging quantum mechanics was built upon Born’s probabilistic view of Schrödinger’s wave function, Heisenberg’s formulation of the uncertainty principle, and Niels Bohr’s concept of complementarity. These principles were discussed during the Fifth Solvay Conference in October 1927. This framework, which later came to be known as the “Copenhagen Interpretation”, brought a wide consensus within the scientific community. However, not everyone accepted it. Albert Einstein raised strong objections at the Solvay meeting of 1927 and later in his well-known 1935 EPR paper.

III. SOLVAY 1927

During one discussion about causality, determinism and probability, Born introduces the following paradox:

MR BORN. -Mr Einstein has considered the following problem: A radioactive sam-

ple emits α -particles in all directions; these are made visible by the method of the Wilson cloud [chamber]. Now, if one associates a spherical wave with each emission process, how can one understand that the track of each α particle appears as a (very nearly) straight line? [4, p. 437]

Born proposes two solutions. The first one invokes the reduction of the probability packet recently proposed by Heisenberg. Before the first ionization the wave associated to the α -particles is indeed a spherical wave. But when we observe that it ionizes the first atom we must reduce the packet into the vicinity of the drops. Through this process one obtains a wave packet in form of a ray.

The second explanation tries to develop a proposal by Pauli. The central idea is to avoid the reduction of wave packets by solving the problem in a multi-dimensional space that includes the atoms hit by the radiation. Due to the ambiguity between the interpretation of the wave function and probabilistic calculation during that time, Born performs a calculus based on probabilities. He considers a system formed by the α -particle and two atoms so as to verify the statement. Since it is not a proper quantum derivation, he arrives at the conclusion that both atoms can only be ionized if they are on the same side, aligned with the trajectory of the α -particle. Finally, he relates the change in probabilities as a result of observation to the reduction of the wave packet.

The discussion of the problem did not progress much further since the rest of those present at the congress do not seem to fully grasp Born's idea.

IV. DARWIN

Darwin was the first to revisit the Wilson chamber problem in 1929 after the fifth Solvay Conference and the theory of radioactive disintegration presented by Gamow. In his article, "A Collision Problem in the Wave Mechanics" [2], he criticizes the discontinuous changes of wave functions and explains the compatibility between the particle-like and wave-like properties of matter. Even though Darwin does not present a complete calculation of the cloud chamber problem, he outlines how it should be approached. When it comes to the tracks in the cloud chamber, we must include the vapour atoms as variables on our equation in order to conserve the energy.

Darwin points out how the apparent paradox of the traces is caused by an erroneous interpretation of the problem. Once we include the atoms in the system we no longer have a wave existing in ordinary three dimensional space, as it is usually pictured. Instead we are dealing with a wave in the multispace formed by the variables of all the atoms in the Wilson chamber and the α -particle. Before the first collision it can be expressed as the product of a spherical wave for the α -particle and a set of stationary wave for the atoms. After each collision the

function gets less intuitive and the different variables get entangled.

V. MOTT

Mott presents his article [1] as a continuation of the work started by Darwin.

As a reduction of the problem, he considers a system formed by the α -particle and only two atoms—for simplicity we shall consider that they are hydrogen atoms—. The position of both of them (a_1 and a_2) will be treated as a parameter so they stay effectively at rest while we ignore the possibility of a collision between the particle and the atoms. Each atom has an electron, with coordinates \vec{r}_1 and \vec{r}_2 , which will be the responsible of the interaction particle-atom. Let us consider the global wave equation of the system as a series over all the ground and excited states of the atoms (eigenfunctions, Ψ_{J_i}) and that the coefficient contains the information about the particle and states of the atoms:

$$F(R, r_1, r_2)^{(n)} = \sum_{J_1, J_2} f_{J_1, J_2}^{(n)}(R) \Psi_{J_1}^I(r_1) \Psi_{J_2}^{II}(r_2). \quad (1)$$

$J_i = 0$ is the ground state or non ionized atom, $J_i \neq 0$ represents the ionized atom and R the location where we study the function. Notice we have already introduced n as the order in perturbation theory. By interpreting the wave function, we see that $|f_{J_1, J_2}(R)|^2 dV$ is the probability at which we shall find the α -particle within a certain volume dV while the atoms are in the states J_1 and J_2 . Consequently, $f_{00}(R)$ will represent an outgoing spherical wave at any rate for R less than either a_1 or a_2 .

First of all we present the general wave equation as

$$\left\{ \frac{-\hbar^2}{2m_\alpha} \nabla_R^2 + \frac{-\hbar^2}{2m_H} (\nabla_{r_1}^2 + \nabla_{r_2}^2) - \frac{e^2}{|r_1 - a_1|} - \frac{e^2}{|r_2 - a_2|} - E \right\} F^{(n)} = - \left\{ \frac{2e^2}{|R - r_1|} - \frac{2e^2}{|R - r_2|} \right\} F^{(n-1)} \quad (2)$$

where the first terms refer to the kinetic energy of the α -particle and electrons, the following ones represent the interaction between each electron with his nucleus, E stands for the total energy of the system and, finally, the interaction between the α -particle and electrons. As Mott decides to use perturbation theory, the interaction of the atoms and the α -particle is considered as a perturbation of first order. At order zero of the theory

$$F^{(0)} = e^{ik|R|} / |R| \cdot \Psi_0^I(r_1) \Psi_0^{II}(r_2) \quad (3)$$

where $k = \sqrt{2m_\alpha(E - 2E_0)/\hbar^2}$, E_0 is the energy of the atoms at rest. If we insert (1) in (2) for first order, multiply by $\Psi_0^I(r_1) \Psi_0^{II}(r_2)$ and integrate over $dr_1 dr_2$:

$$\left\{ \frac{\hbar^2}{2m_\alpha} \nabla^2 + E - E_{J_1} - E_{J_2} \right\} f_{J_1 J_2}^{(1)}(R) = K(R) \quad (4)$$

where

$$K(R) = f_{00}^{(0)}(\delta_{J_2 0} V_{J_1 0} + \delta_{J_1 0} V_{J_2 0}) \quad (5)$$

$V_{J_i 0}$ contains the excitation of the atom i . We can identify this differential equation (4) as an inhomogeneous Helmholtz equation so it can be solved via Green's equation. Then the most general solution is

$$f_{J_1 J_2}^{(1)}(R) = \frac{1}{4\pi} \int \frac{2m_\alpha}{\hbar^2} K(R') \frac{e^{\pm i k' |R-R'|}}{|R-R'|} dR' + G(R) \quad (6)$$

$$k' = \sqrt{\frac{2m_\alpha}{\hbar^2} (E - E_{J_1} - E_{J_2})}$$

being $G(R)$ the solution of the homogeneous Helmholtz equation. Since both atoms are in the ground state before collision $G(R) = 0$, we see that at first order of the theory either one of the atoms is excited or none of them are. Given that they can't be both ionized, we take the case where J_2 is excited and J_1 remains in the ground state. Consequently, $K(R)$ vanishes but around a_2 . In order to interpret the shape of the function after the ionization, it is useful to introduce some approximations. The first one, which refers to the distance between the origin and point where we study the wave R , is much larger than the distance between the origin and the atom, a_2 , so $R \gg a_2$. Therefore,

$$f_{0J_2}^{(1)}(R) \sim \frac{e^{ik'|R-a_2|}}{|R-a_2|} \Im(1) \quad (7)$$

where

$$\Im(1) = \frac{m_\alpha}{2\pi\hbar^2} \int V_{0J_2}(R') \frac{e^{-i(k|R'-a_2|+k'uR')}}{|R'-a_2|} dR' \quad (8)$$

The term $u = \frac{(R-a_2)}{|R-a_2|}$ and the election of the positive value of ik' ensures that the direction of the propagator is diverging from a_2 . Considering that the particle has a high momentum and the collisions are almost elastic, the integral corresponds to a highly oscillatory integral that cancels outside a certain angle $\theta_c \approx 1/(k|y|)$.

The next step is to consider the second order term $F^{(2)}$ to find the probability that both atoms should be excited.

$$\left\{ \frac{-\hbar^2}{2m_\alpha} \nabla_R^2 - E + E_{J_1} + E_{J_2} \right\} f_{J_1 J_2}^{(2)}(R) = f_{0J_2}^{(1)} V_{0J_2}(R - a_2) \quad (9)$$

Now, because f_{0J_2} describes an emerging cone from a_1 , where the function vanishes outside this region, and

$V_{0J_2}(R - a_2)$ is non-zero only around a_2 , a second ionization requires that a_2 lies inside the cone emerging from a_1 . Therefore, if the point a_2 does not stand near the straight line joining the origin to a_1 , there is no probability of both atoms being excited. In the case that both atoms are aligned with the origin, we can obtain a new function describing a wave diverging from the point a_2 .

VI. HEISENBERG

In the transcription of his Chicago lectures (spring 1929), *The Physical Principles of the Quantum Theory* [3], Heisenberg presents the foundations of quantum theory on the framework of Copenhagen Interpretation. It was published in 1930, at a time when quantum theory was well established and there was a broad consensus within the physics community. Chapter V, *Discussion of Important Experiments*, displays an extensive analysis of how the Wilson Chamber experiment, among others, must be treated from the quantum point of view, emphasizing the inevitable use of the wave function collapse or as he calls it "...the discontinuous change of the probability packet...".

Heisenberg introduces the derivation pointing out the simplicity of the problem with the help of the classical corpuscular picture. Its quantum treatment is nonetheless of interest, as it raises the discussion of whether the molecules of the vapour should be included as part of the quantum system.

A. Quantum description with the α -particle alone

The system consists of a single α -particle which is observed through the ionization vapour that produces visible droplets. Its position is represented by the probability density amplitude $|\Psi(q)|^2$. Assuming ionization occurs at time $t = 0$ we can localize the particle at position \bar{q} , where \bar{q} is the most probable value of the coordinate at that time, and the uncertainty Δq corresponds to the molecular vapour's spatial resolution. Presuming we also have access to a previous ionization event, we are allowed to estimate the momentum of the particle at $t = 0$ as $\bar{p} = m_\alpha(\vec{x}_0 - \vec{x}_i)/(t_0 - t_i)$. The momentum's probable error is Δp and it can be found by the uncertainty relations assuming that $\Delta p \Delta q = \hbar/2$. Since this case is discussed previously in Chapter II §I. *The Uncertainty Relations*, Heisenberg introduces the wave function as

$$\Psi(x'_0) = e^{-(x'_0 - \bar{x})^2 / 2(\Delta x)^2 - \frac{2\pi i}{\hbar} \bar{p}(x' - \bar{x})} \quad (10)$$

because the Gaussian probability distribution causes the product $\Delta p \Delta q \geq \hbar/2$ to assume its minimum value for a free particle with momentum \bar{p} .

As no external force is applied, the particle will follow a straight trajectory defined by the classical relations of the uniformly linear motion.

Through a unitary transformation, the wave function at time t becomes, once again, another Gaussian packet with amplitude

$$|\Psi(q')|^2 = N e^{-(q' - p't/m)^2 / [2(\Delta q)^2 (1 + im\Delta q / \Delta p t)]} \quad (11)$$

Its most probable value, q' , follows a straight line, as expected from the classical theory, and the variance increases in time causing the wave to spread in the same direction. Bare in mind this result only applies between ionizations.

Here Heisenberg distinguishes between the ionization accompanied by observation and not.

Each successive ionization of water molecule transforms the packet [(11)] into an aggregate of such packets [...]. If the ionization is accompanied by an observation of the position, a smaller probability packet of the same form as [(11)] but with new parameters is separated out of the aggregate [...]. This forms the starting-point of a new orbit-and so one. [3, p. 69]

Finally, he concludes this first derivation by justifying that the angular deviation among consecutive ionizations is caused by the relative motion between the particle and the atomic electron with which it interacts, causing the differences through the paths of α -particles and β -particles.

B. Inclusion of vapour molecules

Similar to Mott's approach, Heisenberg provides an explanation that incorporates the vapour molecules into the quantum system. Subsequently, we will observe that the treatment is largely analogous with only a few, although important, modifications.

Just like in the previous case, Heisenberg assumes that the particle has already a known momentum \vec{p} , in which case the initial wave has not a spherical wave term as in Mott.

$$-\frac{\hbar^2}{8\pi^2 m_\alpha} \nabla^2 \Psi + H^0(q_1) \Psi + H^0(q_2) \Psi + \epsilon [H^{(I)}(1) \Psi + H^{(I)}(2) \Psi] + \frac{\hbar}{2\pi i} \frac{\partial \Psi}{\partial t} = 0 \quad (12)$$

where $H^0(q_i)$ is the energy operator of the molecule i and $H^{(I)}(i)$ is the energy interaction between the α -particle and the molecule i . The function is to be expanded in terms of the perturbation parameter ϵ : $\Psi = \Psi^{(0)} + \epsilon \Psi^{(1)} + \epsilon^2 \Psi^{(2)} \dots$ By solving the differential equation at order zero you get an initial wave product of the two eigenfunctions corresponding to each atom by a plane wave.

$$\Psi^{(0)} = e^{\frac{2\pi i}{\hbar} p \cdot x} \varphi_{n_1}(q_1) \varphi_{n_2}(q_2) e^{\frac{-2\pi i}{\hbar} E^{(0)} t} \quad (13)$$

At superior order it can be expanded in terms of the eigenfunctions (notice this is identical to what Mott does):

$$\Psi^{(i)} = \sum_{J_1 J_2} v_{J_1 J_2}^{(i)} \varphi_{J_1}(q_1) \varphi_{J_2}(q_2) \quad (14)$$

being $|\sum_i \epsilon^i v_{J_1 J_2}^{(i)}|^2$ the probability of observing the particle at a certain position while the molecules in the states J_1 and J_2 .

Substituting equation (14) in (12) for $i = 1$, we obtain

$$\left\{ -\frac{\hbar^2}{8\pi^2 m_\alpha} \nabla^2 + E_{n_1} + E_{n_2} + \frac{\hbar}{2\pi i} \frac{\partial}{\partial t} \right\} v_{J_1 J_2}^{(1)} = (h_{n_1 J_1}(1) \delta_{n_2 J_2} + h_{n_2 J_2}(2) \delta_{n_1 J_1}) e^{\frac{2\pi i}{\hbar} [p \cdot x - E^0 t]} \quad (15)$$

We can simplify the equation by considering

$$v_{J_1 J_2}^{(1)}(x, y, z, t) = w_{J_1 J_2}^{(1)}(x, y, z) e^{\frac{-2\pi i}{\hbar} E^0 t} \quad (16)$$

and defining

$$k^2 = \frac{8\pi^2 m_\alpha}{\hbar^2} (E_{n_1} + E_{n_2} + \frac{1}{2m_\alpha} p^2 - E_{J_1} - E_{J_2}) \quad (17)$$

so the final equation to solve is

$$(\nabla^2 + k^2) w_{J_1 J_2}^{(1)}(x, y, z) = \rho_{J_1 J_2}(x, y, z) \quad (18)$$

where $\rho_{J_1 J_2}(x, y, z)$ is the density of oscillators producing the wave. In order to solve the equation, Heisenberg appeals to Huygens' principle. Accordingly,

$$w_{J_1 J_2}^{(1)} = \iiint \rho_{J_1 J_2}(x', y', z') \frac{e^{-ikR}}{R} dx' dy' dz' \quad (19)$$

As a result of $\rho_{J_1 J_2} \propto (h_{n_1 J_1} \delta_{n_2 J_2} + h_{n_2 J_2} \delta_{n_1 J_1})$, $w_{J_1 J_2}$ is zero unless one of the two molecules is excited, $J_1 = n_1$ or $J_2 = n_2$. Once again we find that the probability of two collisions is of second order. Heisenberg interprets $\rho_{J_1 J_2}$ as the density of oscillators. They generate the wave and are located in a region around q_1 and q_2 in which h_{ij} is appreciably different from zero. According to the expression of $\rho_{J_1 J_2}$ they vibrate coherently with a phase determined by $e^{\frac{2\pi i}{\hbar} p \cdot x}$ and wave length λ_0 . The wave's amplitude is then only appreciable in a conic region emerging from the molecule ionized and in the direction of \vec{p} . Its angular opening depends on the Δq , being greater when Δq is smaller.

In second-order perturbation theory, both molecules must lie in a line parallel to the direction of motion of

the α -particle so that two ionizations occur. This is applicable to bigger systems where only the molecules in the path of the α -particle can be excited.

Heisenberg argues that it is not necessary to introduce a discontinuous change in the probability wave to demonstrate that the particle will ionize the atoms it encounters. However, the concept of collapse becomes relevant once again when we try to explain how the excitation of the molecule is actually observed.

VII. CONCLUSIONS

Once we have the full picture, some relations and questions arise. As Darwin points out, the problem is originated on the erroneous interpretation of it. In view of the fact that we introduce the vapour atoms in the wave function, it can not longer be interpreted as a spherical wave pictured in the 3D space. The natural following question is how this new wave can produce straight tracks, but Mott already solves this problem.

Drawing a comparison between Heisenberg's and Mott's analyses, we question whether the wave function collapse is truly necessary. Considering what we have learned, collapse is not essential to describe the form of the tracks, but it is crucial to explain which one we actually observe. In Mott's wave function, due to the symmetry of the problem, we are still unable to predict which atom will be ionized first —and thus determine the direction of the track—. We do not have multiple eigenstates in superposition, but rather a single one that is constrained by the information provided by the observation of several ionizations. From my point of view we have therefore not avoided the wave function collapse, we have instead reduced a problem based on multiple collapses to a single one. In this reasoning, the studied phenomenon more closely resembles an epistemic issue related to a lack of knowledge, as opposed to inherent

randomness.

This ongoing debate has led to the development of various alternative theories aiming to avoid the collapse, the most well-known being quantum decoherence. Recent authors [5] have related Mott's interpretation to this theory. Even though it seems that Mott's problem did not strongly influence the development of quantum decoherence, it was mentioned a few times. The most remarkable one being Erich Joos and Heinz-Dieter Zeh's [8]. Their intention was to develop a theory where all classical properties may be deduced using quantum mechanics but avoiding the discontinuous collapse. The interaction of systems with their environment causes the system to collapse locally in a continuous manner, leading to the emergence of classical properties. As an example of this, they point out the analysis made by Mott.

In parallel to these interpretations, I would like to highlight John Stewart Bell's observation in "Quantum Mechanics for Cosmologists" [7]. He notes that discovering the original publications often leads students to reflect on the concept of wave function collapse. Quantum theory divides the world into two parts: the observed system and the observer. The most disconcerting thing is how the theory offers no clear criteria to delimit this separation. As Heisenberg shows in his derivation, this line can be shifted. We could stick with the simplest explanation, but not doing it leads us to ask ourselves how far we can expand our system. Could we expand it to such levels that include cosmological systems?

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- [1] N. F. Mott, "The wave mechanics of α -ray tracks," *Proceedings of the Royal Society of London. Series A*, vol. 126, pp. 79–84, 1929. Reprinted in: J. A. Wheeler and W. H. Zurek (eds.), *Quantum Theory and Measurement*, Princeton University Press, 1983.
 - [2] C. G. Darwin, "A collision problem in the wave mechanics," *Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character*, vol. 124, pp. 375–394, 1929.
 - [3] Werner Heisenberg, *The Physical Principles of the Quantum Theory*, translated by Carl Eckart, reprint edition, Martino Fine Books, 2015. Originally published in 1930.
 - [4] Guido Bacciagaluppi and Antony Valentini, *Quantum Theory at the Crossroads: Reconsidering the 1927 Solvay Conference*, Cambridge University Press, 2009.
 - [5] R. Figari and A. Teta, "Emergence of classical trajectories in quantum systems: the cloud chamber problem in the analysis of Mott (1929)," *Archive for History of Exact Sciences*, vol. 67, no. 3, pp. 215–234, 2013.
 - [6] Heisenberg Gesellschaft, "The Development of Quantum Mechanics (1925–1927)," *heisenberg-gesellschaft.de*, [Online]. Available: <https://www.heisenberg-gesellschaft.de/3-the-development-of-quantum-mechanics-1925-ndash-1927.html>. [Accessed: 10-May-2025].
 - [7] J. S. Bell, "Quantum mechanics for cosmologists," in *Quantum Gravity 2: A Second Oxford Symposium*, C. J. Isham, R. Penrose, and D. W. Sciama (eds.), Clarendon Press, Oxford, 1981, pp. 611–637.
 - [8] E. Joos and H. D. Zeh, "The emergence of classical properties through interaction with the environment," *Zeitschrift für Physik B Condensed Matter*, vol. 59, no. 2, pp. 223–243, 1985.

El paper històric de l'experiment de cambra de boira

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Resum: L'objectiu d'aquest treball és fer un repàs històric de les interpretacions de l'experiment de la cambra de boira durant els anys fundacionals de la mecànica quàntica. Per tal de fer-ho, analitzem articles i llibres originals publicats entre els anys 1927-1930 on s'intenta demostrar mitjançant mecànica quàntica com es produeixen les traces rectilínies en l'experiment. L'estudi del problema ens porta a reflexionar sobre el concepte i paper del col·lapse de la funció d'ona. Concloem com aquest fenomen és inevitable i, alhora, té implicacions fonamentals en la manera d'entendre la física. Addicionalment, mostrem la influència d'aquestes interpretacions de l'experiment en autors posteriors i la teoria de decoherència quàntica.

Paraules clau: història de la física, cambra de boira, mecànica quàntica, col·lapse de la funció d'ona, interpretació de Copenhaguen, decoherència quàntica

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