Explaining cloud chamber tracks

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The operation of many detection devices is usually explained in terms of the ionization tracks produced by particles despite the fact that the corresponding incident wave functions extend over the entire sensitive regions of the detectors. The mechanism by which the wave function appears to collapse to a track is analyzed here.

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Let us consider the wave function Ψ that would represent a system composed of an incident alpha particle (a wave emitted by a single nuclear transition) and an activated Wilson cloud chamber. Of course, the calculation of a precise wave function for such a many-body problem would be prohibitively difficult. An understanding of its approximate form can be obtained, however, by means of the following analysis.

We shall first write the alpha particle wave function in the form of a superposition of packets ψ_j of minimum size, that is, a size such that the sum of the squares of the diameters of the packet, when it enters the cloud chamber and when it has travelled to a point 0.9 of the way toward the end of its cloud chamber track, is a minimum. Since the Schrödinger equation for this entire system is linear, it can be solved separately for the wave function of the system produced by each one of these minimum alpha particle packets by itself. These resulting components can then be added together to construct the wave function produced by the entire alpha particle wave. The wave function for the system can then be written as a superposition of terms, each composed of a packet and a wave function χ_j representing the state of the cloud chamber produced by the Coulomb field of the packet ψ_j . It is, at some instant of time,

$$\Psi = \sum_i \psi_i \chi_i + \sum_j \psi_j \chi_j \quad (1)$$

where the first sum is over terms involving the packets that have not yet reached the cloud chamber, and the second one is over terms with packets that have passed into the cloud chamber.

In the first sum, all of the χ_i 's are identical since they represent the undisturbed state of the cloud chamber χ_0 . The packets in this term are coherent and can be combined to produce an incident wave ψ_0 so that the first sum reduces to $\psi_0 \chi_0$.

We would like to combine the packets in the second sum as we did in the first,

but, unfortunately, this is not possible because the χ_j 's are not identical. This is because the Coulomb field from each packet disturbs different atoms and each one in a different way [1]. The best that we can do is to remove a common part from all of the χ_j 's and combine the ψ_j 's multiplying this part. For this purpose, we select one of the packets near the middle of its track in the cloud chamber and assign $j = 1$ to it. Each of the χ_j 's can then be separated into two parts, one being proportional to χ_1 and the rest orthogonal to χ_1 and represented by χ_{1j} . Thus the disturbed wave function of the cloud chamber produced by the j^{th} minimum packet can be written in the form,

$$\chi_j = a_{1j}\chi_1 + \chi_{1j} . \quad (2)$$

Of course, $a_{11} = 1$, and $\chi_{11} = 0$. In addition, a_{1j} decreases with increasing separation of the 1 and j atoms and must be determined by an averaging procedure over the positions of the atoms. These equations can be combined to write Eq. (1) in the form,

$$\Psi = \psi_0\chi_0 + \psi'_1\chi_1 + \sum_j \psi_j\chi_{1j} \quad (3)$$

where

$$\psi'_1 = \sum_j a_{1j}\psi_j . \quad (4)$$

The ψ'_1 has an extent of the order of the range of disturbance of the saturated vapor by the minimum packet ψ_1 . Thus its size is determined by energies required to alter the cloud chamber atoms as well as their transition times [1].

Instead of the minimum packets used in Eq. (1) for the alpha particle wave function, we now expand it (approximately) [2, 3] in terms of packets of the size of ψ'_1 in Eq. (4). If the size of such a packet is large compared with the wave length of the incident alpha particle wave function, it will maintain its shape and size through most of its moving time in the cloud chamber. Each of these new packets will produce a

track of ionized atoms as it progresses in the cloud chamber and vapor will condense on this track. The wave functions associated with these tracks are approximately orthogonal so that the packets in each term cannot be added together. These packets of the size of ψ'_1 replace the "particles" so often used in the explanation of cloud chamber tracks, counter activity, and scintillations on a screen.

Tracks covering the entire cloud chamber are represented in Eq. (3), but we see only one track. In order to understand why this is so, we include a human observer in the system. He interacts with the cloud chamber by observing light scattered from the condensed vapor. Again, since the Schrödinger equation for this entire system is linear, it can be solved separately for the wave function of the system produced by each one of the alpha particle packets by itself. Adding these terms together then gives

$$\Psi' \approx \psi_0 \chi_0 \phi_0 + \sum_j \psi'_j \chi'_j \phi_j, \quad (5)$$

where χ'_j represents the state of the cloud chamber after it has been disturbed by packet ψ'_j , and ϕ_j is the wave function of the observer that remembers the cloud chamber track in χ'_j . This form of the wave function was first suggested by von Neumann and later used by London and Bauer and by Wigner [3, 4]. Because each observer-state is the result of only one track, it can remember only that track.

This explains why we see only one track in a cloud chamber for one nuclear transition. In actual cloud chamber demonstrations, a number of tracks are seen. This is because a large number of nuclei in the radioactive source are undergoing transitions, each producing an alpha particle wave.

The above analysis can be applied to explain the operation of other detection devices that involve ionized tracks such as Rutherford's scintillations on a screen, bubble chambers, and proportional and Geiger counters. Up until now, the description of the

operation of each of these detectors has involved a particle. These have been taken by Heisenberg [5] as evidence of a particle nature of the fundamental entities of quantum mechanics. Although Heisenberg mentions, in addition, some other atomic and electronic phenomena such as the Compton effect as requiring a particle origin, these have already been explained in quantum electrodynamics as wave effects. Although many physicists will prefer to keep the wave-particle duality in their interpretation of quantum mechanics, the arguments that Heisenberg makes for the necessity of the particle concept appear to be no longer convincing.

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