The Feynman LECTURES ON PHYSICS

QUANTUM MECHANICS

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1–1 Atomic mechanics

"Quantum mechanics" is the description of the behavior of matter and light in all its details and, in particular, of the happenings on an atomic scale. Things on a very small scale behave like nothing that you have any direct experience about. They do not behave like waves, they do not behave like particles, they do not behave like clouds, or billiard balls, or weights on springs, or like anything that you have ever seen.

Newton thought that light was made up of particles, but then it was discovered that it behaves like a wave. Later, however (in the beginning of the twentieth century), it was found that light did indeed sometimes behave like a particle. Historically, the electron, for example, was thought to behave like a particle, and then it was found that in many respects it behaved like a wave. So it really behaves like neither. Now we have given up. We say: "It is like *neither*."

There is one lucky break, however—electrons behave just like light. The quantum behavior of atomic objects (electrons, protons, neutrons, photons, and so on) is the same for all, they are all "particle waves," or whatever you want to call them. So what we learn about the properties of electrons (which we shall use for our examples) will apply also to all "particles," including photons of light.

The gradual accumulation of information about atomic and small-scale behavior during the first quarter of this century, which gave some indications about how small things do behave, produced an increasing confusion which was finally resolved in 1926 and 1927 by Schrödinger, Heisenberg, and Born. They finally obtained a consistent description of the behavior of matter on a small scale. We take up the main features of that description in this chapter.

Because atomic behavior is so unlike ordinary experience, it is very difficult to get used to, and it appears peculiar and mysterious to everyone—both to the novice and to the experienced physicist. Even the experts do not understand it the way they would like to, and it is perfectly reasonable that they should not, because all of direct, human experience and of human intuition applies to large objects. We know how large objects will act, but things on a small scale just do not act that way. So we have to learn about them in a sort of abstract or imaginative fashion and not by connection with our direct experience.

In this chapter we shall tackle immediately the basic element of the mysterious behavior in its most strange form. We choose to examine a phenomenon which is impossible, *absolutely* impossible, to explain in any classical way, and which has in it the heart of quantum mechanics. In reality, it contains the *only* mystery. We cannot make the mystery go away by "explaining" how it works. We will just *tell* you how it works. In telling you how it works we will have told you about the basic peculiarities of all quantum mechanics.

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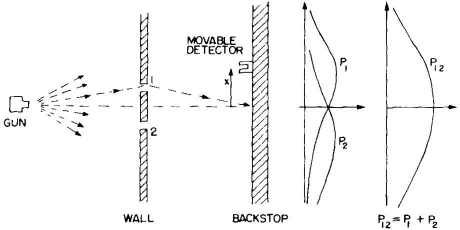
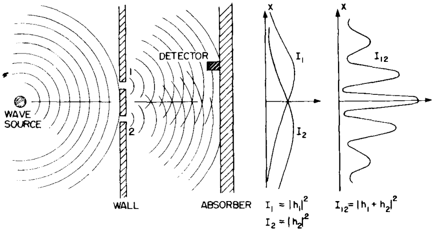


La doble rendija con balas



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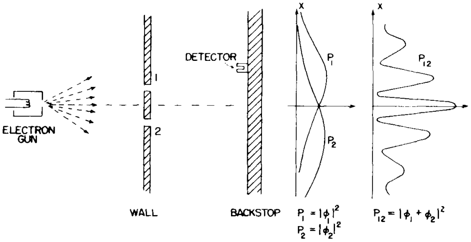
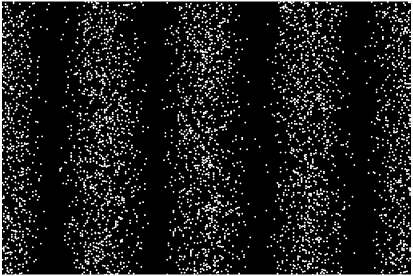
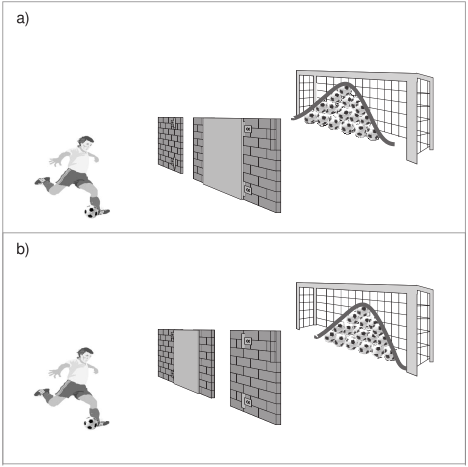


La doble rendija con electrones



Construcción del patrón de interferencia de a una partícula por vez


a)
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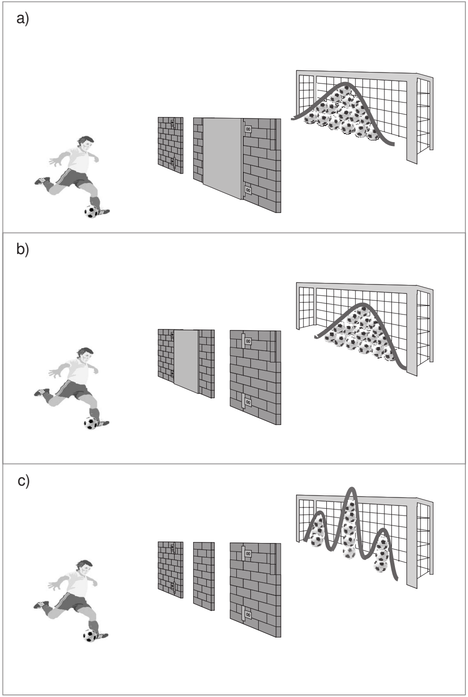
a)
b)
c)

Fig. 2. The fullerene molecule C_{60}, consisting of 60 carbon atoms arranged in a truncated icosahedral shape, is the smallest known natural soccer ball.

Quantum interference experiments with large molecules

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Wave–particle duality is frequently the first topic students encounter in elementary quantum physics. Although this phenomenon has been demonstrated with photons, electrons, neutrons, and atoms, the dual quantum character of the famous double-slit experiment can be best explained with the largest and most classical objects, which are currently the fullerene molecules. The soccer-ball-shaped carbon cages C_{60} are large, massive, and appealing objects for which it is clear that they must behave like particles under ordinary circumstances. We present the results of a multislit diffraction experiment with such objects to demonstrate their wave nature. The experiment serves as the basis for a discussion of several quantum concepts such as coherence, randomness, complementarity, and wave–particle duality. In particular, the effect of longitudinal (spectral) coherence can be demonstrated by a direct comparison of interferograms obtained with a thermal beam and a velocity selected beam in close analogy to the usual two-slit experiments using light.

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I. INTRODUCTION

At the beginning of the 20th century several important discoveries were made leading to a set of mind-boggling questions and experiments that seemed to escape any answers based on classical, pre-quantum physics. The first were the discoveries[1–3] that implied that optical radiation has to be composed of discrete energy packages that can be well localized in space and time. This localization was in marked contrast to the existing knowledge based on Maxwell's theory which successfully represented light as electromagnetic waves. The second and complementary breakthrough was the theoretical result by de Broglie,[4] and the experimental demonstration by Davisson and Germer[5] that massive particles also propagate in a wave-like manner.

Both statements were stunning at the time that they were proposed and both keep us busy thinking even today because we generally associate the notion of point-like locality with a particle while we attribute spatial extension to a wave. The observation of both phenomena in one and the same experiment leads us also to the concept of delocalization, which goes beyond the simple concept of ''being extended,'' because single quantum objects seem to be able to simultaneously explore regions in space–time that cannot be explored by a single object in any classical way.

To illustrate the wave–particle duality we shall briefly recall the double-slit experiment as sketched in Fig. 1 because it is both one of the simplest and most general quantum experiments used in introductory quantum physics and is the prototype for our studies with molecules.

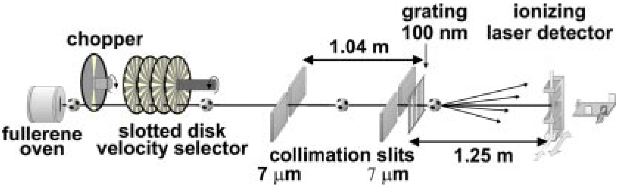
Let us first discuss an experiment that is usually performed in a ripple tank. If we excite surface waves in water and let them propagate through a small hole in a barrier (Fig. 1, left), we would observe a circular wavelet emerge behind the barrier in agreement with Huygens' principle. If we now open a second hole in the barrier, we could create regions where the water remains completely still (Fig. 1, center). This phenomenon is simply explained by the fact that the surface waves superpose on each other and the wave minima can be filled by wave maxima at well-determined places. We call this phenomenon interference. It can only be easily observed if the disturbances in the two slits are synchronized with each other, which means that they have a well-defined and constant phase relation, and may therefore be regarded as being coherent with respect to each other.

For water the picture appears intuitive because the wave is composed of many particles, each interacting with its neighbors. But the experiment turns into the mind-boggler mentioned above if we repeat it with an ensemble of isolated objects—photons or even massive particles—which we send through the double-slit one by one.

We shall present experimental results with, at present, the most massive particles that exhibit wave properties. The results confirm that under appropriate circumstances we still obtain interference patterns, the shape of which can be predicted with certainty. However, it is important to note that in such investigations a single particle always gives a single click at one detector position only, and we have no means of calculating the position of this event in advance because, as far as we can tell, it is governed by chance.

Therefore, the double-slit experiment with single particles leads us to the following questions: How can a single particle, which we observe both in the source and in the detector as being well-localized and much smaller than a single opening in the barrier, acquire information about the state (open/closed) of a very remote opening, if it were considered to pass only one through the openings? Why can't we track the particle position without destroying its wave nature? How can we understand the emergence of a well-defined interference pattern in contrast to the random hitting point of the single object if none of the particles can interact with the rest of the ensemble in any way that we know?[6]

We thus find many fundamental quantum concepts in the context of double-slit interferometry. First, we find the complementarity between our knowledge about the particle's position and the visibility of the interferogram. If we open one slit only, the particle must pass this opening and the interference pattern must disappear. Perfect interference contrast can be obtained only if we open the second slit and if we exclude all possibilities of detecting, even in principle, the path the object has taken. The wave–particle duality states that the description of one and the same physical ob-


grating
100 nm
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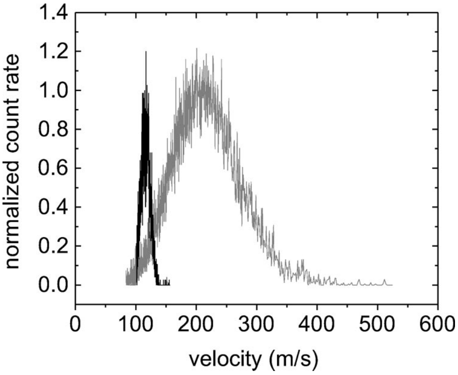


Fig. 5. Velocity distribution of the C_{60} molecules for a thermal and a velocity selected beam. The thermal beam (gray curve) is centered around $\overline{v} = 200$ m/s and has a width of $\Delta v/v \sim 0.6$, while the selected beam (black curve) is centered around $\overline{v} = 117$ m/s with a width of $\Delta v/v \sim 0.17$. We therefore expect the velocity selected interference pattern to be expanded by 70% on the screen and to show at least three times ($\simeq 0.6/0.17$) as many interference orders as the unselected pattern.

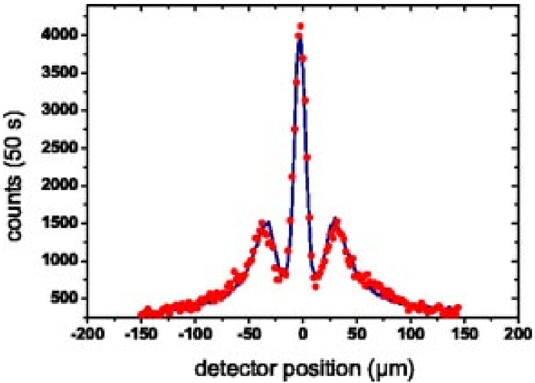


Fig. 6. Far-field diffraction of C_{60} using a thermal beam of $\overline{v} = 200$ m/s with a velocity spread of $\Delta v/v \sim 60\%$. The absence of higher order interference fringes is due to the poor spectral coherence.

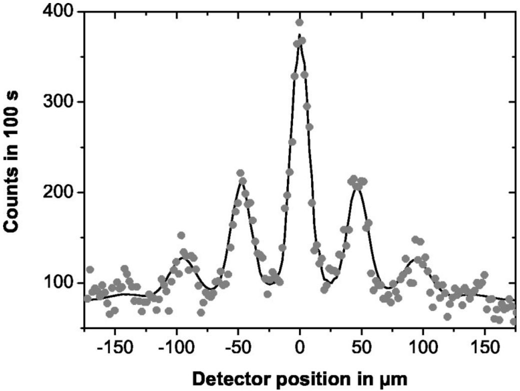
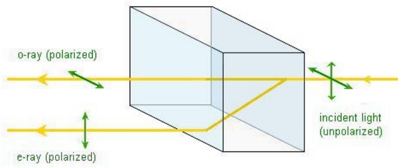


Fig. 7. Far-field diffraction of C_{60} using the slotted disk velocity selector. The mean velocity was $\overline{v} = 117$ m/s, and the width was $\Delta v/v \sim 17\%$. Full circles represent the experimental data. The full line is a numerical model based on Kirchhoff–Fresnel diffraction theory. The van der Waals interaction between the molecule and the grating wall is taken into account in form of a reduced slit width. Grating defects (holes) additionally contribute to the zeroth order.



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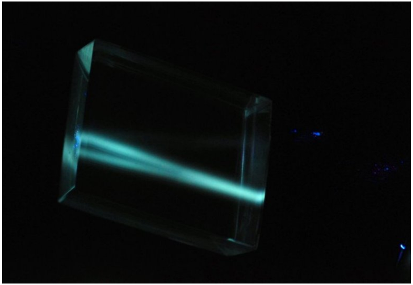

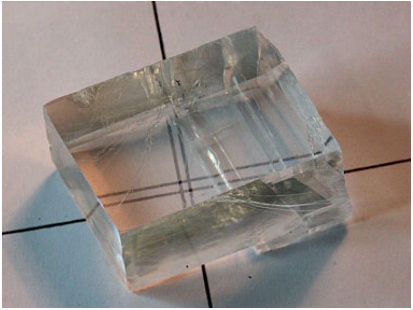


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