The Theory of Fundamental Processes

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Richard P. Feynman

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Editor's Foreword

Addison-Wesley's *Frontiers in Physics* series has, since 1961, made it possible for leading physicists to communicate in coherent fashion their views of recent developments in the most exciting and active fields of physics—without having to devote the time and energy required to prepare a formal review or monograph. Indeed, throughout its nearly forty-year existence, the series has emphasized informality in both style and content, as well as pedagogical clarity. Over time, it was expected that these informal accounts would be replaced by more formal counterparts—textbooks or monographs—as the cutting-edge topics they treated gradually became integrated into the body of physics knowledge and reader interest dwindled. However, this has not proven to be the case for a number of the volumes in the series: Many works have remained in print on an on-demand basis, while others have such intrinsic value that the physics community has urged us to extend their life span.

The *Advanced Book Classics* series has been designed to meet this demand. It will keep in print those volumes in *Frontiers in Physics* or its sister series, *Lecture Notes and Supplements in Physics*, that continue to provide a unique account of a topic of lasting interest. And through a sizable printing, these classics will be made available at a comparatively modest cost to the reader.

These notes on Richard Feynman's lectures at Cornell on the Theory of Fundamental Processes were first published in 1961 as part of the first group of lecture note volumes to be included in the *Frontiers in Physics* series. As is the case with all of the Feynman lecture note volumes, the presentation in this work reflects his deep physical insight, the freshness and originality of his approach to understanding high energy physics, and the overall pedagogical wizardry of Richard Feynman. The notes provide both beginning students and experienced researchers with an invaluable introduction to fundamental processes in particle physics, and to Feynman's highly original approach to the topic.

David Pines
Urbana, Illinois
December 1997

Preface

These are notes on a special series of lectures given during a visit to Cornell University in 1958. When lecturing to a student body different from the one at your own institution there is an irresistible temptation to cut corners, omit difficult details, and experiment with teaching methods. Any wounds to the students' development caused by the peculiar point of view will be left behind as someone else's responsibility to heal.

That part of physics that we do understand today (electrodynamics, β decay, isotopic spin rules, strangeness) has a kind of simplicity which is often lost in the complex formulations believed to be necessary to ultimately understand the dynamics of strong interactions. To prepare oneself to be the theoretical physicist who will some day find the key to these strong interactions, it might be thought that a full knowledge of all these complicated formulations would be necessary. That may be so, but the exact opposite may also be so; it may be necessary to stay away from the corners where everyone else has already worked unsuccessfully. In any event, it is always a good idea to try to see how much or how little of our theoretical knowledge actually goes into the analysis of those situations which have been experimentally checked. This is necessary to get a clearer idea of what is essential in our present knowledge and what can be changed without serious conflict with experiments.

The theory of all those phenomena for which a more or less complete quantitative theory exists is described. There is one exception; the partial successes of dispersion theory in analyzing pion-nucleon scattering are omitted. This is mainly due to a lack of time; the course was given in 1959–1960 at Cal Tech, for which these notes were used as a partial reference. There, dispersion theory and the estimation of cross sections by dominant poles were additional topics for which, unfortunately, no notes were made.

These notes were made directly from the lectures at Cornell university by P. A. Carruthers and M. Nauenberg. Lectures 6 to 14 were originally written as a report for the Second Conference on Peaceful Uses of Atomic Energy, Geneva, 1958. They have been edited and corrected by H. T. Yura.

R. P. Feynman
Pasadena, California
November 1961

Contents

The Theory of Fundamental Processes

1 Review of the Principles of Quantum Mechanics

These lectures will cover all of physics. Since we believe that the behavior of systems of many particles can be understood in terms of the interactions of a small number of particles, we shall be concerned primarily with the latter. Bearing in mind that the present theories need modifications or revision to account for observed phenomena, we shall want to consider the foundation of quantum mechanics in their most general form. This is so we can get some idea of the minimum assumptions (and their character) which we use to formulate those parts of the theory we use in dealing with the new phenomena of the strange particles.

A rough outline of the book follows: First, we discuss the ideas of quantum mechanics, mainly the concept of amplitudes, emphasizing that other things such as the combination laws of angular momenta are largely consequences of this concept. Next, briefly, relativity and the idea of antiparticles. Following this, we give a complete qualitative description of all the known particles and all that is known about the couplings between them. After that, we return to a detailed quantitative study of the two couplings for which calculations can be carried out today; namely, the β-decay coupling and the electromagnetic coupling. The study of the latter is called quantum electrodynamics, and we shall spend most of our time with it.

Accordingly, we begin with a review of the principles of quantum mechanics. It has been found that all processes so far observed can be understood in terms of the following prescription: To every *process* there corresponds an *amplitude*†; with proper normalization the probability of the process is equal to the absolute square of this amplitude. The precise meaning of terms will become more clear from the examples that follow. Later we shall find rules for calculating amplitudes.

First, we consider in detail the double-slit experiment for electrons. A uniform beam of electrons of momentum p is incident on the double slit. To be more precise, we consider successive electrons, randomly distributed in the vertical direction (we prepare each electron with $p = p_x$, $p_y = p_z = 0$). (*Feynman:* They should come from a hole, at definite energy.)

†A complex number.

When the electron hits the screen we record the position of the hit. The process considered is *thus:* An electron with well-defined momentum somehow goes through the slit system and makes its way to the screen (Fig. 1-1). Now we are not allowed to ask which slit the electron went through unless

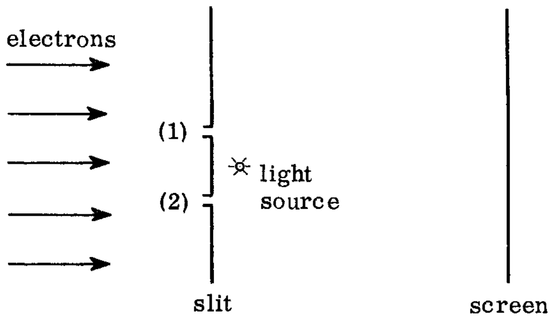

FIG. 1-1

we actually set up a device to determine whether or not it did. *But then we would be considering a different process!* However we can relate the amplitude of the considered process to the *separate amplitudes* for the electron to have gone through slit (1), (a_1), and through slit (2), (a_2). [For example, when slit (2) is closed the amplitude for the electron to hit the screen is a_1 (prob. $|a_1|^2$) etc.] Nature gives the following simple rule: $a = a_1 + a_2$. This is a special case of the principle of superposition in quantum mechanics (cf. reference 1). Thus the probability of an electron reaching the screen is $P_a = |a|^2 = |a_1 + a_2|^2$. Clearly, in general we have $P_a \neq P_{a_1} + P_{a_2}(P_{a_1} = |a_1|^2$, $P_{a_2} = |a_2|^2$), as distinguished from the classical case. We speak of "interference" between the probabilities (see reference 2). The actual form of P_a is familiar from optics.

Now suppose we place a light source between slits 1 and 2 (see Fig. 1-1) to find out which slit the electron "really" did go through (we observe the scattered photon). In this case the interference pattern becomes identical to that of the two slits considered independently. One way of interpreting this situation is to say that the act of measurement, of the position of the electron imparts an uncertainty in the momentum (ΔP_y), at the same time changing the phase of the amplitude in an uncontrollable way, so that the average over many electrons yields zero for the "interference" terms, owing to the randomness of the uncontrollable phases (see Bohm[3] for details of this view). However, we prefer the following viewpoint: By looking at the electrons we have actually changed the process under consideration. Now we must consider the photon and its interaction with the electron. So we consider the following amplitudes:

a_{11} = amplitude that electron came through slit 1 and the photon was scattered behind slit 1

a_{21} = amplitude that electron came through slit 2 and the photon was scattered behind slit 1

a_{12} = amplitude that electron came through slit 1 and the photon was scattered behind slit 2

a_{22} = amplitude that electron came through slit 2 and the photon was scattered behind slit 2

The amplitude that an electron seen at slit 1 arrives at the screen is therefore $a' = a_{11} + a_{21}$; for an electron seen at slit 2, $a'' = a_{12} + a_{22}$. Evidently for a properly designed experiment $a_{12} \cong 0 \cong a_{21}$ so that $a_{11} \cong a_1$, $a_{22} \cong a_2$ of the previous experiment. Now the amplitudes a' and a'' correspond to different processes, so the probability of an electron arriving at the screen is $P_a' = |a'|^2 + |a''|^2 = |a_1|^2 + |a_2|^2$.

Another example is neutron scattering from crystals.

(1) Ignore spin: At the observation point the total amplitude equals the sum of the amplitudes for scattering from each atom. One gets the usual Bragg pattern.

(2) Spin effects: Suppose all atoms have spin up, the neutrons spin down (assume the atom spins are localized): (a) no spin flip—as before, (b) spin flip—no diffraction pattern shown even though the energy and wavelengths of the scattered waves are the same as in case a. The reason for this is simply that the atom which did the scattering has its spin flipped down; in principle we can distinguish it from the other atoms. In this case the scattering from atom i is a *different process* from the scattering by atom $j \neq i$.

If instead of (localized) spin flip of the atom we excite (unlocalized) spin waves with wavenumber $k = k_{inc} - k_{scatt}$, we can again expect some partial diffraction effects.

Consider scattering at 90° in the c.m. system [see Fig. 1-2 (a to d)]:

(a) Two identical spinless particles: There are two indistinguishable ways for scatter to occur. Here, total amplitude = 2a and $P = 4|a|^2$, which is twice what we expected classically.

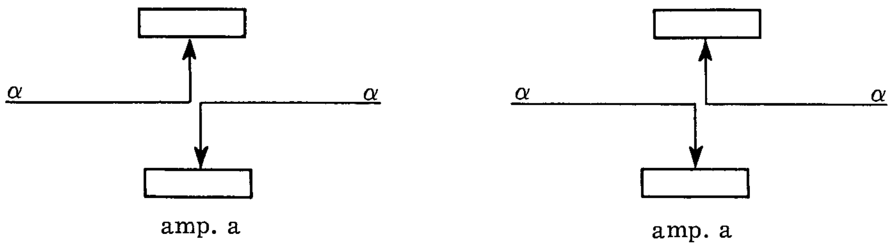

FIG. 1-2a

(b) Two distinguishable spinless particles. Here these processes are distinguishable, so that $P = |a|^2 + |a|^2 = 2|a|^2$.

(c) Two electrons with spin. Here these processes are distinguishable, so that $P = |a|^2 + |a|^2 = 2|a|^2$.

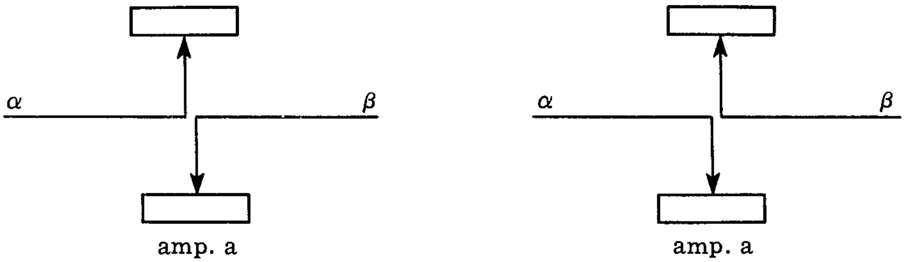

FIG. 1-2b

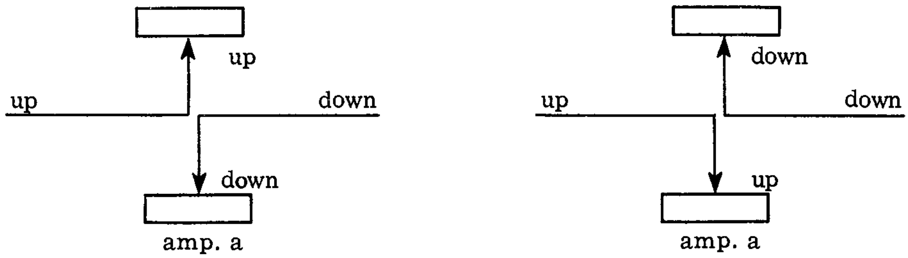

FIG. 1-2c

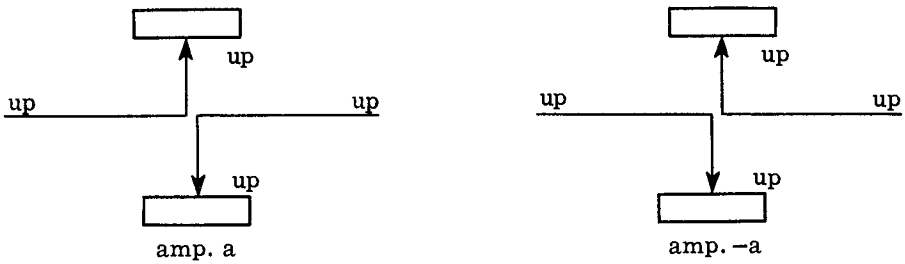

FIG. 1-2d

(d) But if both the incident electrons have spin up, the processes are indistinguishable. The total amplitude = a − a = 0. So here we have a new feature. We discuss this further in the next lecture.

Problem 1-1: Suppose we have two sources of radio waves (e.g., radio stars) and need to know how far apart they are. We measure this intensity in two receivers at the same time and record the product of the intensities as a function of their relative position. This measurement of the correlation permits the required distance to be computed. With one receiver there is no pattern on the average, because the relative phase of A and B sources is random and fluctuating. For example, in Fig. 1-3 we have put the receivers at a separation corresponding to that of two maxima of the pattern if the relative phase is 0 (Table 1-1). If L and R are at separation between a maximum and a minimum we have Table 1-2. Thus find the probability of reception of photon coincidence in the counters. Examine the effect of changing the separation between the receivers. Consider the process from the point of view of quantum mechanics.

FIG. 1-3

TABLE 1-1

Relative phases of sources	L (common)	R (max)	Product
0°	2	2	4
180°	0	0	0
90°	1	1	1
270°	1	1	1
			Av. = 1.5

TABLE 1-2

Relative phases of sources	L (common)	R (max)	Product
0°	2	0	0
180°	0	2	0
90°	1	1	1
270°	1	1	1
			Av. = 0.5

Discussion of Problem 1-1. There are four ways in which we can have photon coincidences:

(1) Both photons come from A: amp. a_1.

(2) Both photons come from B: amp. a_2.

(3) Receiver L receives photon from A, R from B: amp. a_3.

(4) Receiver L receives photon from B, R from A: amp. a_4.

Processes (1) and (2) are distinguishable from each other and from (3) and (4). However, (3) and (4) are indistinguishable. [For instance, we could, in principle, measure the energy content of the emitters to find which had emitted the photon in case (1) and (2).]

Thus, $P = |a_1|^2 + |a_2|^2 + |a_3 + a_4|^2$. The term $|a_3 + a_4|^2$ contains the interference effects. Note that if we were examining electrons instead of photons the latter term would be $|a_3 - a_4|^2$.