Photon-Hadron Interactions

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EDITOR'S FOREWORD

The problem of communicating in a coherent fashion the recent developments in the most exciting and active fields of physics seems particularly pressing today. The enormous growth in the number of physicists has tended to make the familiar channels of communication considerably less effective. I has become increasingly difficult for experts in a given field to keep up with the current literature; the novice can only be confused. What is neede is both a consistent account of a field and the presentation of a definite "point of view" concerning it. Formal monographs cannot meet such a need in a rapidly developing field, and, perhaps more important, the review article seems to have fallen into disfavor. Indeed, it would seem that the people most actively engaged in developing a given field are the people least likely to write at length about it.

FRONTIERS IN PHYSICS has been conceived in an effort to improve the situation in several ways. One of these is to take advantage of the fact tha the leading physicists today frequently give a series of lectures, a graduate seminar, or a graduate course in the special fields of interest. Such lectures serve to summarize the present status of a rapidly developing field and may well constitute the only coherent account available at the time. Often, notes on lectures exist (prepared by the lecturer himself, by graduate students, or by postdoctoral fellows) and have been distributed in mimeographed form on a limited basis. One of the principal purposes of the FRONTIERS IN PHYSICS Series is to make such notes available to a wider audience of physicists.

It should be emphasized that lecture notes are necessarily rough and informal, both in style and content, and those in the series will prove no exception. This is as it should be. The point of the series is to offer ne

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rapid, more informal, and it is hoped, more effective ways for physicists to teach one another. The point is lost if only elegant notes qualify.

A second way to improve communication in very active fields of physics is by the publication of collections of reprints of recent articles. Such collections are themselves useful to people working in the field. The value of the reprints would, however, seem much enhanced if the collection would be accompanied by an introduction of moderate length, which would serve to tie the collection tog ther and, necessarily, constitute a brief survey of the present status of the field. Again, it is appropriate that such an introduction be informal, in keeping with the active character of the field.

A third possibility for the series might be called an informal monograph, to connote the the fact that it represents an intermediate step between lecture notes and formal monographs. It would offer the author an opportunity to present his views of a field that has developed to the point at which a summation might prove extraordinarily fruitful, but for which a formal monograph might not be feasible or desirable.

Fourth, there are the contemporary classics--papers or lectures which constitute a particularly valuable approach to the teaching and learning of physics today. Here one thinks of fields that lie at the heart of much of present-day research, but whose essentials are by now well understood, such as quantum electrodynamics or magnetic resonance. In such fields some of the best pedagogical material is not readily available, either because it consists of papers long out of print or lectures that have never been published.

The above words, written in August, 1961, seem equally applicable today (which may tell us something about developments in communication in physics during the past decade). Richard Feynman contributed two lecture note volumes ("Quantum Electrodynamics" and "The Theory of Fundamental Processes") to the first group of books published in this series, and, with the publication of the present volume and "Statistical Mechanics," it gives me special pleasure to welcome him back as a major contributor to FRONTIERS IN PHYSICS.

DAVID PINES

Urbana, Illinois

Summer 1972

PREFACE

The most advanced course in graduate theoretical physics at Caltech is "Special Topics in Theoretical Physics." Each year the professor chooses the topic with which he will deal. This year, (1971-72), having just come back from the 1971 International Symposium on Electron and Photon Interactions at High Energies, held at Cornell University, my own interest in the subject was aroused, and I chose to analyze the various theoretical questions related to that conference. The lectures themselves became so extensive that the decision was made to put them into book form, with the thought that other people might also be interested. Thus, the report of the Cornell conference should be considered as a companion volume to these lecture notes. The references given here are far from complete, but a full list of references is given in the Proceedings of the Symposium, published by the Laboratory of Nuclear Studies, Cornell University, January 1972.

The material is dealt with on an advanced level; for instance, knowledge of the theory of hadron-hadron interactions is assumed. I have tried to analyze in detail where we stand theoretically today. The treatment is somewhat uneven; for example, I should have liked to study the theory of the decay of the η in more detail than I was able to do. On the other hand, there are long discussions of vector meson dominance and of deep inelastic scattering. The possible consequences of the parton model are fully discussed.

Time did not permit me to complete the original plan which was to include the theory of weak interaction currents which are so closely related to electromagnetic currents.

Many thanks must go to Arturo Cisneros who edited, corrected, and extended the lectures from my class notes. Without his effort, this book would not have been possible. I also wish to thank Mrs. Helen Tuck for typing the lecture notes.

RICHARD P. FEYNMAN

Pasadena, California

Summer 1972

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General Theoretical Background

Lecture 1

One very powerful way of experimentally investigating the strongly interacting particles (hadrons) is to look at them, to probe them with a known particle; in particular the photon (no other is known as well). This permits a much finer control of variables, and probably decreases the theoretical complexity of the interactions. For example in an ordinary hadron-hadron collision like $\pi p \to \pi p$ we are hitting two unknowns together, and further, we can only vary the energy, we cannot vary the q^2 of the pion which must be m_π^2. In fact a "pion far off its mass shell" may be a meaningless - or at least highly complicated idea. On the other hand in $\gamma + p \to p + \pi$ we know the γ is single and definite, and we can vary the q^2 of the γ by using virtual γ's via, for example, electron scattering $e + p \to e + p + \pi$.

We are assuming that we do know the photon. QED has been checked so closely that we know that if the photon propagator were off by a factor of the form $(1 - q^2/\Lambda^2)^{-1}$ then Λ exceeds 4 or 5 GeV. The amplitudes are known to about 5% for q^2 as high as $(1\ \text{GeV})^2$. For the rest of this course we shall assume QED is exact. There is already evidence, as we shall see, that in virtual photon-hadron collisions the photon acts normally (i.e., obeys QED expectations) up to Λ of 6 to 8 GeV.

At any rate we shall suppose QED exact - where we mean by QED the standard interaction theory for electrons, muons and photons. Exact, but incomplete - for hadrons are charged and interact also with the QED system. We discuss first how we shall assume we can describe this interaction.

Since e^2 is small it is natural to describe their interaction in a series of orders in e. One photon exchange, two photon exchange, etc. (It might be thought that to describe this coupling we shall have to have some detailed dynamical theory of the hadrons - ultimately, of course, yes - but some things can be said in general restricting the matrix elements whatever the underlying hadron dynamics - and it is these restrictions we seek in this lecture.)

The no coupling case presents no problem. The factor giving the amplitude that a hadron system goes from an incoming state $|n, in\rangle$, to an outgoing state $\langle m, out|$ is:

$$S_{mn} = \langle m, out \mid n, in\rangle \tag{1.1}$$

The S matrix is the transformation matrix from the "in" representation to the "out" representation

$$\sum_n S_{mn} \langle n, in| = \langle m, out| \tag{1.2}$$

The state $|n, in\rangle$ means a state which far in the past is asymptotically free stable hadrons (stable in strong interactions only, e.g. π^0 is "stable") described by momenta, and helicities all contained via the index n. The state m, out has the set of indices m with the same space of indices, but represents a state which in the future is asymptotically in situation m.

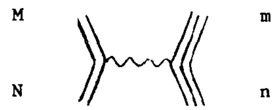
Thus the S matrix is really the unit matrix but in a mixed representation, a different labeling for incoming and outgoing states. Supposing these states are all there are, conservation of probability requires

$$S^+S = 1. \quad (\text{i.e., } \sum_m (S_{mn'})^* S_{mn} = \delta_{nn'}) \tag{1.3}$$

(In the special case that the state n represents a single stable particle the in and out states are the same).

First Order Coupling.

The general coupling of electrons and hadrons is represented by the diagram:



The electron-photon system goes from state N to M, the hadrons from n in to m out. We suppose the only interaction possible is by the exchange of a photon - and this photon is characterized by a polarization μ, momentum q:

$$\text{amp} = \langle M| j_\mu(q) \,|\, N\rangle \; \frac{4\pi e^2 i}{q^2} \; \langle m, \text{out}|J_\mu(q)|n, \text{in}\rangle \; . \tag{1.4}$$

That is to say (supposing we could measure the amplitude) we define in a given experiment the quantity

$$\mathcal{J}_\mu(q)_{mn} = \langle m, \text{out}|J_\mu(q)|n, \text{in}\rangle \tag{1.5}$$

This is done by removing from the measured amplitude the known (by QED theory) factors

$$\langle M|j_\mu(q)|N\rangle \bullet 4\pi e^2 i/q^2 .$$

It is then our first supposition that this quantity $\mathcal{J}_\mu(q)_{mn}$ depends only on the states m, n of the hadron system and only the virtual momentum q and polarization μ of the virtual photon. $\mathcal{J}_\mu$ depends in no way on how the photon was made (eg. whether by μ's or electrons or on the angles and energies of the electron for fixed q and photon polarization).

This is a strong assumption. It has been verified most completely for the case of proton form factor measurements, but is often assumed in checking equipment, comparing results from one lab to another etc. We assume it.

We emphasize then that $\mathcal{J}_\mu(q)$ is an experimentally defined quantity - definable in principle for all q.

We find it convenient to define a new matrix $J_\mu(q)_{kn}$ defined in a non-mixed representation as

$$J_\mu(q)_{kn} = \langle k, \text{in}|J_\mu(q)|n, \text{in}\rangle \tag{1.6}$$

so we now write