ELECTROMAGNETIC INTERACTIONS OF HADRONS
VOLUME 2

Edited by A. Donnachie and G. Shaw

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Preface

While electromagnetic interactions were first used to probe the structure of elementary particles more than 20 years ago, their importance has only become fully evident in the last 10 years. In the resonance region, photoproduction experiments have provided clear evidence for simple quark model ideas, and confirmed the Melosh-transformed $SU(6)_W$ as a relevant symmetry classification. At higher energies, their most striking feature is their similarity to hadron-induced reactions, and they have provided fresh insight into the ideas developed to explain strong-interaction physics. New dimensions are added by taking the photon off mass shell, both in the spacelike region, where the development of high-energy electron and muon beams has led to the discovery and study of scaling and the introduction of "partons," and even more dramatically in the timelike region, where the development of high-energy electron–positron storage rings has led to the exciting discoveries of the last four years.

In view of the immense interest stimulated by these developments, an extensive review of our present state of knowledge is both timely and useful. Because of the very wide range of the subject, a cooperative venture presents itself as the most suitable format and is the one we have adopted here. The emphasis throughout is primarily, but not entirely, on phenomenology, concentrating on describing the main features of the experimental data and on the theoretical ideas used directly in their interpretation. As such we hope that it will be of interest and of use to all practicing physicists in the field of elementary particles, including graduate students.

The work is in two volumes. The first deals with photoproduction and electroproduction in the resonance region and at medium energy, treating mainly two-body and quasi-two-body final states. The present volume first considers multiparticle production and inclusive reactions, and then goes on to deep inelastic scattering and electron–positron annihilation. In addition, the relevant aspects of current algebra are covered, and photoprocesses on nuclei are discussed in depth.

We are deeply indebted to the many authors who have contributed to this work. Their adherence to the proposed guidelines greatly eased the problems of editing, and contributed significantly towards achieving a balanced presentation.

We would like to thank Mrs. S. A. Lowndes of Daresbury Laboratory for her invaluable assistance in the technical editing of the articles in both this and the companion volume.

Manchester, 1978

A. Donnachie
G. Shaw

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Many-Body Processes

G. Wolf
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P. Söding

1. Introduction

This chapter will be concerned with the many multibody channels induced by collisions of real and virtual photons with target nucleons. One would like to be able to trace in detail the way in which all the individual channels manage to arrange themselves into the striking pattern presented by the total cross section, particularly in the deep-inelastic region. Such a complete decomposition is not yet feasible, and we must restrict ourselves to a discussion of more global features like multiplicities, prong cross sections, and diffractive vs. nondiffractive processes. These can be compared with the corresponding features in completely hadronic reactions on the one hand, and those in other current-induced reactions like neutrino–nucleon and e^+e^- processes on the other. In addition we will discuss a few individual many-body channels that are of special interest, such as diffractive processes in electroproduction and channels with strong contact amplitudes. We start by recalling the most important properties of the total cross sections.

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2. Global Properties

2.1. σ_{tot} for Real Photons

Measurements of the total cross sections of photons on protons and deuterons have been made up to a photon laboratory energy $\nu = 38$ GeV. Compilations of the measured values are shown in Fig. 1. Above the s-channel resonance region the data can be fitted by (Caldwell *et al.*, 1973, Belousov *et al.*, 1975)

$$\begin{aligned} \sigma_{tot}(\gamma p) &= (99.8 \pm 1.6\mu b + (57.0 \pm 3.0)\nu^{-1/2}\mu b \, GeV^{1/2} \\ \sigma_{tot}(\gamma p) - \sigma_{tot}(\gamma n) &= (14.5 \pm 1.9)\nu^{-1/2}\mu b \, GeV^{1/2} \end{aligned} \tag{2.1}$$

These cross sections show a close similarity to those of purely hadronic processes, as expected in the simple vector-dominance picture. If we

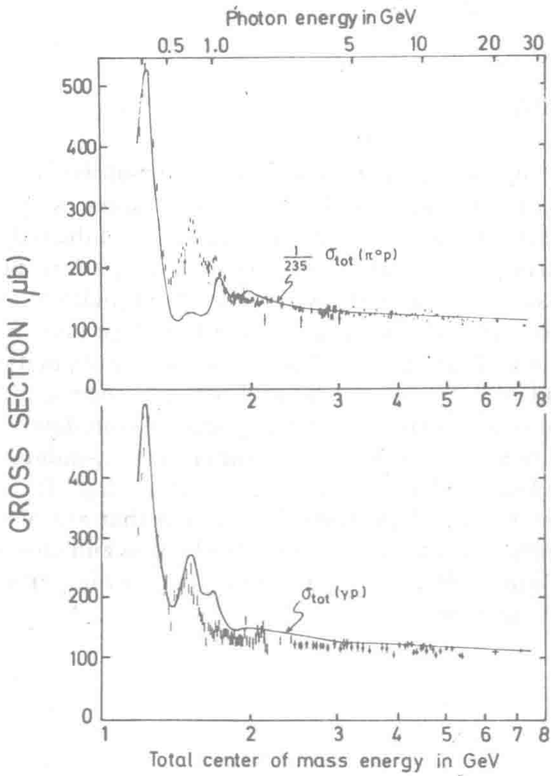

Fig. 1. Total γp (top) and γn (bottom) cross sections (as compiled by the Particle Data Group, 1974), compared with the cross section $\sigma_{tot}(\pi^0 p) = \frac{1}{2}[\sigma_{tot}(\pi^+ p) + \sigma_{tot}(\pi^- p)]$.

compare $\sigma_{tot}(\gamma p)$ with $\sigma_{tot}(\pi^0 p)$ (see the curve in Fig. 1) we find that after scaling by a factor 1/235 they are practically identical at all s out to the highest energies measured, except in the region near $(s)^{1/2} = 1.5$ GeV, to which we will return for a detailed discussion in Section 5.

In terms of the leading t-channel poles for forward Compton scattering we have

$$\frac{\nu}{4\pi}\sigma_{tot}(\gamma p) \sim \text{Im } T_P + \text{Im } T_f + \text{Im } T_{A_2} \tag{2.3}$$

$$\frac{\nu}{4\pi}\sigma_{tot}(\gamma n) \sim \text{Im } T_P + \text{Im } T_f - \text{Im } T_{A_2} \tag{2.4}$$

The determination of the A_2 term from the experimental data is strongly affected by corrections for shadowing and Fermi motion in the deuteron. The high-energy Serpukhov data agree with a vanishing A_2 term (Belousov *et al.*, 1975). Since in the vector-dominance framework the same t-channel amplitudes appear in Compton scattering and in forward vector meson photoproduction, one can turn to photoproduction for more information. In particular, ω production is sensitive to A_2 exchange since the A_2 couples to $\rho\omega$ but not to $\rho\rho$ (Barker *et al.*, 1974). We have

$$\text{Im } T_{A_2}(\gamma N \to \gamma N) = 2\left(\frac{\alpha}{f_\omega^2/4\pi}\right)^{1/2} \text{Im } T_{A_2}(\gamma N \to \omega N) \tag{2.5}$$

A_2 exchange is expected to be the dominant contribution to the energy-dependent part of the natural spin-parity exchange cross section for $\gamma p \to \omega p$, which can be measured using transversely polarized incident photons. One can also determine the A_2 exchange contribution from the proton–neutron difference of ω photoproduction, which gives the $I = 1$ exchange part in which the π and A_2 exchange contributions have then to be separated. This can be done either on the basis of the s dependence, or by observing the crossover in $d\sigma/dt$ that should occur at $-t \sim 0.3\ (\text{GeV}/c)^2$ as $T_P + T_f$ interferes with Im T_{A_2}, which presumably has a zero at $-t \sim 0.3\ (\text{GeV}/c)^2$ (Harari, 1971). High-energy measurements of ω production on protons and deuterons by the Cornell–Rochester group indicate an A_2 exchange forward amplitude of $(8 \pm 20)\%$ (Behrend *et al.*, 1971; Abramson *et al.*, 1973). At present, then, the A_2 exchange in ω production and in $\sigma_{tot}(\gamma N)$ is not well determined; measurements at higher energies will be necessary.

Although the main features of $\sigma_{tot}(\gamma N)$ look typically "hadronic," there are features that may be more peculiar and possibly are connected with the elementary local coupling of the photon. They are as follows:

(i) The enhancement in $\sigma_{tot}(\gamma p)$ in the region around $(s)^{1/2} = 1.5$ GeV. One might think that this indicates a resonance excited much more strongly by protons than by pions; note also that photons have an isoscalar part for which no analogy with pions exists. However, the enhancement actually comes from contact terms that arise from the usual Born graphs as a consequence of gauge invariance. We will discuss these in Section 5.

(ii) A possible fixed pole at $J = 0$. Let us consider the Kramers–Kronig dispersion relation for the spin-independent forward Compton scattering amplitude,

$$\mathrm{Re}\, f_1(\nu) = -\frac{\alpha}{m} + \frac{\nu^2}{2\pi^2} P \int_0^\infty d\nu' \frac{\sigma_{\mathrm{tot}}(\nu')}{\nu'^2 - \nu^2} \tag{2.6}$$

in which the low-energy Thomson term $-\alpha/m = f_1(0)$ occurs. In Regge language such a constant term is a fixed pole with angular momentum $J = 0$ in the complex angular momentum plane. There has been much discussion whether or not this fixed real pole term is cancelled at high energies by a corresponding contribution from the integral (see, for example, Tait and White, 1972). If the nucleon consists of elementary charged constituents then one expects a fixed pole to survive at high energies (although not necessarily of size $-\alpha/m$), arising from the local interaction of the photon with the constituents. If the measured $\sigma_{\mathrm{tot}}(\nu)$ can indeed be expressed as Pomeron + Regge contributions as it seems, then the fixed pole in the real part is *not* cancelled. This question is connected with the uncertainty of the A_2 exchange term and can only be decided by measurements of $\sigma_{\mathrm{tot}}(\gamma N)$ out to higher energies. The fixed pole may be related to the contact amplitudes mentioned before (Close *et al.*, 1975).

(iii) The possible incompleteness of the shadowing of the interactions of photons in nuclear matter. If real photons interact in nuclear matter like hadrons as the simple vector-dominance (ρ, ω, ϕ) picture supposes, then shadowing should be essentially complete if the longitudinal spread of the virtual vector meson "cloud" of the photon is

$$\langle \Delta z \rangle = \langle \Delta t \rangle = \frac{1}{\Delta E} = [(\nu^2 + m_h^2)^{1/2} - \nu]^{-1} \approx \frac{2\nu}{m_h^2} > 2\lambda_h \approx 4\ \mathrm{fm} \tag{2.7}$$

where $m_h \approx m_\rho$ is the typical vector meson mass and λ_h the mean free path of the vector mesons in nuclear matter. This is fulfilled for $\nu > 6$ GeV. Although shadowing has been clearly seen, there is a tendency to find it to be quantitatively less than the pure vector-dominance picture gives, both in $\sigma_{\mathrm{tot}}(\gamma A)$ and in $d\sigma(\gamma A \to \gamma A)/dt$. Results from forward Compton scattering are shown in Fig. 2 (Criegee *et al.*, 1975). Thus there may be some part of the interaction that lacks shadowing, perhaps owing to a more local nature of the interaction. Significant contributions from heavy vector states indeed reduce the longitudinal spread of the interaction, but it is not yet clear whether generalized vector dominance is able to describe the Q^2

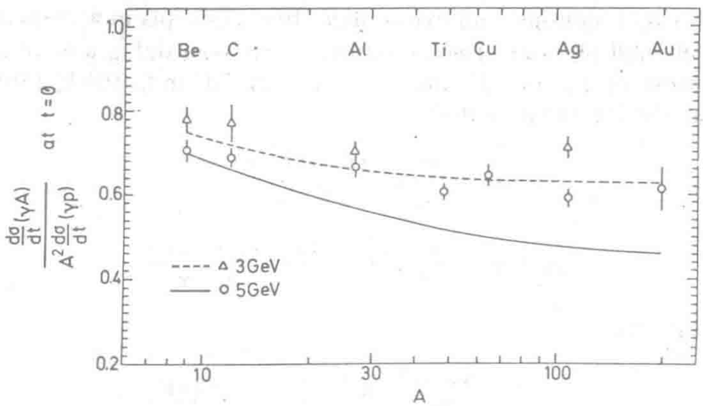

Fig. 2. Shadowing effect in forward Compton scattering on nuclei [Criegee *et al.*, 1975]. The error bars show statistical errors; there is an additional 7% normalization uncertainty. The curves show the shadowing expected in the vector dominance model.

dependence of shadowing in nuclei correctly (Schildknecht, 1973; Taylor, 1975; Ditsas *et al.*, 1975; Ditsas and Shaw, 1976).

2.2. σ_{tot} for Virtual Photons

We assume the validity of the one-photon exchange approximation, and restrict our discussion to unpolarized targets.

The total virtual-photon–nucleon cross sections are directly connected with the structure functions $F_1(Q^2, \nu) = mW_1(Q^2, \nu)$ and $F_2(Q^2, \nu) = \nu W_2(Q^2, \nu)$. This connection arises from writing the differential cross section for inclusive scattering of the lepton in the form

$$\frac{d^2\sigma}{dQ^2\, d\nu/\nu}(lN \to l + \cdots) = \frac{dN_T^\gamma}{dQ^2\, d\nu/\nu}[\sigma_T(Q^2, \nu) + \varepsilon\sigma_L(Q^2, \nu)] \tag{2.8}$$

where the first factor is the number of virtual transverse photons "radiated" by one lepton per Q^2 and ln ν interval, and

$$\varepsilon = \left[1 + \frac{2(\nu^2 + Q^2)}{4EE' - Q^2}\right]^{-1} = \left[1 + 2\left(1 + \frac{\nu^2}{Q^2}\right)\left(\tan\frac{\theta}{2}\right)^2\right]^{-1} \tag{2.9}$$

is the ratio of longitudinal to transverse photon intensity (see the article by Lyth in the companion volume). The subscripts L and T stand for longitudinal ($\lambda_\gamma = 0$) and transverse ($\lambda_\gamma = \pm 1$) photon polarization, respectively. Note that neither the number of virtual photons nor the cross section for a virtual projectile is an unambiguously defined concept; only their product is. One can only start from the definitions of a flux of real photons, and the cross