Elementary Particle Physics

An Introduction

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Preface

Elementary Particle Physics is a textbook for a graduate-level course for students some of whom will specialize in the study of matter and energy at the extremes of high energy and small distance. It is also intended to serve research workers who need a convenient reference book covering basic topics.

Both of us have worked in experimental particle physics and taught undergraduate and graduate physics courses for many years. One of us (GKO'N) has taught a graduate course in particle physics at Princeton University frequently over the 15-year period during which this manuscript was revised and refined. Thus, we owe much to the helpful comments of many students, colleagues, and reviewers.

Prior to the study of this book a student should have completed courses in quantum mechanics and electricity and magnetism. A knowledge of selected topics in nuclear physics and in mathematical methods in physics would also be helpful, but could be obtained concurrently.

We selected for inclusion concepts whose basic importance was attested either by long usage or by recent yet solid agreement with experiment. We found it particularly rewarding to return to original formulations of ideas, which were often more transparent than the detailed elaborations that had followed them. One aim was to present ideas that seemed nearly certain to remain valuable, and to choose approaches that would give a maximum of physical insight and understanding, if necessary at the expense of sophistication. To reach that goal we often included in derivations intermediate steps customarily omitted in communication between specialists. For the same reason we chose notation and mathematical treatment for ease of understanding, rather than for highest speed in routine repetitive computation.

In keeping with the trend toward deemphasis of the importance of specific particles and greater concentration on their group relationships, the book is organized along the lines of interaction types: strong, electromagnetic, and weak.

The Introduction begins by tracing the development of particle physics from its roots in the nineteenth century through nuclear physics to the still-continuing explosion of new-particle discoveries. It continues with a chapter on calculational techniques for relativistic collisions: Lorentz transforms of particle distributions; the Klein-Gordon and Dirac equations; Feynman diagrams; phase space; and the crossing relationships in s,t,u notation. On the other hand, a discussion of renormalization has been omitted because it proved impossible to treat adequately within reasonable length.

Part II, on electromagnetic interactions, makes use of the techniques developed in Part I to derive, among other results, Møller scattering with the use of gamma matrices, Bhabha scattering from it by crossing symmetry, and the Rosenbluth formula. We found Part II also the appropriate place to discuss nucleon structure, deep inelastic scattering, and electron-positron annihilation. The quark model, including color and charm, introduced in Part

I, reappears in Part II, though not forced beyond the area solidly established by experiment.

In Part III, on weak interactions, the $V-A$ current-current interaction theory is developed from its origins with Enrico Fermi in nuclear physics through the distinction between electron and muon neutrinos. The quark model reappears with its description of weak interactions, including changes of strangeness and charm. In our description of neutral kaon interactions, C, P, and T violations we close with the superweak model, and the section concludes with a comparison of theory and experiment for high-energy neutrino interactions, emphasizing the roles of an intermediate vector boson, neutral currents, and gauge theories.

Over the past decades the higher symmetries have been a continuing source of ferment and fruitful ideas; they are a particularly appropriate topic for this book because they can be handled by simple techniques, vivid and graphic. In that framework, Part IV, on strong interactions, focuses on special unitary symmetry schemes linked to the quark model, but also includes chapters on dispersion relations and Regge poles. In keeping with our preference for carrying through derivations not normally found in textbooks, SU_6 symmetry is used in Part IV to obtain the ratio of neutron and proton magnetic moments.

Experiments as such are described only in outline. Experimental techniques change continually, so it seems inappropriate to freeze them into a book of this type. Problems and exercises are given at the end of each major section. Their level is appropriate to a PH.D. qualifying examination; in some cases they are used to illustrate a relatively recent development. Over the course of three decades particle physics has remained a field of rapid development, rich in surprises and enormously challenging to both experimentalists and theoreticians. We hope that this book will encourage readers to seek out the key ideas in their original forms, and will facilitate the understanding of new results transmitted in colloquia and current journals.

We should like to record that this book owes its beginning to the encouragement and enthusiasm of Leonard Schiff, and its continuation to the sustaining interest of both Professor Schiff and Professor Donald Hamilton. We thank Professor Marvin Goldberger for his critical reading of one chapter and Drs. Alexander Grillo and Dennis Smith for their critical reading of the final manuscript. We assume responsibility for any errors that may remain and would appreciate having them called to our attention. We thank the Physics Department of Princeton University and the High Energy Physics Group at the University of California at Santa Cruz for their support and encouragement. We also thank especially Ms. Rose Rothfuss, Ms. Pam Csira, Ms. Deborah Johnson, and Ms. Brenda Miranda for their assistance in the preparation of the manuscript.

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Contents

PART 1

INTRODUCTION

CHAPTER 1

History and Terminology

Natural units ~ discovery of new particles ~ the strong, electromagnetic, and weak interactions ~ symmetry and conservation laws ~ particle classification ~ quarks

UNITS

In elementary particle physics, as in nuclear physics, the quantities often measured are energy, momentum, mass, distance, cross section, lifetime, rate, and spin. For elementary particles the magnitudes of these quantities are so small that special units are often employed. Energy is written in units of electron volts (eV) because the equipment used to accelerate and detect elementary particles can most easily be calibrated electrically. Metric notation, with 1 KeV = 10^3 eV, 1 MeV = 10^6 eV, 1 GeV = 10^9 eV, etc., is customary. Momentum is written in units of eV/c (c is the velocity of light) and mass is written in units of eV/c^2. Length is written in units of centimeters (cm) or fermis (1 F = 10^{-13} cm), and cross section is written in cm^2 or barns (1 b = 10^{-24} cm^2). Time is measured in seconds. Angular momentum, spin, and isospin are measured in units of $\hbar$ (Planck's constant divided by 2π).

Both quantum mechanics and relativity are essential to theories of elementary particles; the constants c and $\hbar$ occur in most calculations. It is convenient therefore to adopt "natural" units in which $\hbar = c = 1$. With that choice, the mass of an arbitrary particle is unity:

$$M_0 \equiv 1$$

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and unit energy is associated with that rest mass:

$$M_0c^2 \equiv 1$$

Unit length is the Compton wavelength of the M_0 particle:

$$\bar{\lambda}_0 = \frac{\hbar}{M_0c} \equiv 1$$

and unit time is the interval required for light to traverse the length $\bar{\lambda}_0$:

$$t_0 = \frac{\bar{\lambda}_0}{c} \equiv 1$$

The final expression of any calculation made in natural units can be converted to "normal" units by dimensional arguments. For the purpose of conversion, one must know that $\hbar \simeq 6.58 \times 10^{-22}$ MeV-sec, $c \simeq 3.00 \times 10^{10}$ cm/sec, and in rationalized units for the electric charge $\alpha \equiv e^2/4\pi\hbar c \simeq 1/137.036$. For example, the spin-averaged cross section for nonrelativistic electron–electron elastic scattering is given in the center-of-momentum system (CMS) in natural units by

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{CMS}} = \frac{\alpha^2m^2}{16|\mathbf{p}|^4}\left(\frac{1}{\sin^4\theta/2} + \frac{1}{\cos^4\theta/2} - \frac{1}{\sin^2\theta/2\,\cos^2\theta/2}\right) \tag{1-1}$$

To convert this expression to "normal" units, we note that the left-hand side of the expression is in units of (length)^2 and the right-hand side is in units of (energy)$^{-2}$. To convert the expression, we need only insert $(\hbar c)^2$ into the right-hand side, obtaining

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{CMS}} = \frac{\alpha^2(\hbar c)^2(mc^2)^2}{4(|\mathbf{p}|c)^4}\left(\frac{1}{\sin^4\theta/2} + \frac{1}{\cos^4\theta/2} - \frac{1}{\sin^2\theta/2\,\cos^2\theta/2}\right) \tag{1-2}$$

In the first chapter of this book, all quantities are written with $\hbar$ and c displayed explicitly, for the benefit of readers unfamiliar with natural units. In subsequent chapters, $\hbar$ and c are set equal to 1 except for cases in which the authors feel that the explicit display of $\hbar$ and c is helpful to the understanding of the subject.

HISTORY

The desire to identify the smallest possible constituents of matter, in the hope that they will turn out to be simple and understandable, is at least as old as the time of Democritus. The search for simplicity in the world of the very

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small, motivated by that desire, produced rich results in the nineteenth century with the formulation by Mendeleev of the periodic table. That table, in spite of its age, is still a most useful guide even to such a subtle phenomenon as superconductivity [1].

A case could perhaps be made for regarding the atoms of Mendeleev's table as the elementary particles of nineteenth century physics, but we choose to date the beginning of this topic at the discovery of x rays (photons) by Roentgen [2] in 1895. Soon after that time Becquerel detected the beta and alpha radiations [3] and J. J. Thomson [4] discovered the electron. To the best of our knowledge today, the electron is in fact elementary, that is, unbreakable into component parts; in contrast, the discovery of the electron was itself the indicator that the atoms of the periodic table were composite particles. Thomson postulated that an atom consisted of a number of discrete electrons embedded in a substance with a continuous positive charge distribution, with the total positive charge equal to the total number of electrons.

Not until 1900 were beta rays identified as electrons, and eight more years passed before Rutherford and Geiger determined the charge of alpha particles and showed that the alphas were identical to helium ions [5]. Calculations based on the Thomson model of the atom predicted a very small deflection for alpha particles that had undergone a single collision within the atom, because the negatively charged electrons were much lighter than the alpha particles and the positive charge was uniformly distributed within the atom. In this model, for alpha particles to emerge from the atom with large scattering angles they would have had to undergo a large number of scatterings within the target. If this had been true, the angular distribution of the scattered particles would have obeyed a Gaussian distribution with a small angular width, and the number of large deflections would have been proportional to the square root of the number of atoms along the collision path. Rutherford pointed out that neither one of these predictions agreed with experimental data. He suggested an alternative model in which the positive charge resided in a very small region at the center of the atom.

The Rutherford atomic model, which strongly implied the existence of the proton as a separate constituent of the atom [6], was confirmed by the alpha-particle scattering experiment [7] of Geiger and Marsden. A mystery remained: How could the atom postulated by Rutherford be stable? The problem was "solved" by Bohr's application of Planck's quantization idea to the angular momenta of atomic electron orbits [8]. Thus in 1913, with Bohr's description of atomic hydrogen, the existence of the proton was established. Some 18 years had therefore been required for the expansion of the list of elementary particles from one to three (the electron, the photon, and the proton). In the course of that expansion and the great increase of understanding that accompanied it, the alpha particle was recognized as very probably a composite particle. Over 60 years later, we suspect that on a still smaller scale of distance the proton too is composite.

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In 1919 the first observations of what we now call nuclear reactions were made [9]; they were continued by Rutherford and his co-workers during the 1920s. All of these reactions were of the type

$$^{A}_{Z}\mathrm{R} + \alpha \rightarrow {}^{A+3}_{Z+1}\mathrm{R} + p \tag{1-3}$$

induced by an incident alpha particle. They yielded a final-state proton and transmuted a nucleus $^{A}_{Z}\mathrm{R}$ to a higher place $^{A+3}_{Z+1}\mathrm{R}$ in the periodic table.

Although the 1920s were the seminal years of quantum mechanics, and left atomic spectroscopy as a subject solved "in principle," no new elementary particles were discovered until 1932, despite many attempts to detect neutrons. Then Chadwick [10], by a combination of skillful experimentation and close reasoning, disproved an erroneous interpretation by Curie and Joliot of their earlier experiment [11] on alpha-particle bombardment of beryllium, and showed that neutrons were produced in the reaction

$$^{9}_{4}\mathrm{Be} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{12}_{6}\mathrm{C} + {}^{1}_{0}n \tag{1-4}$$

With that proof, the last of the three constituents (electrons, protons, and neutrons) of ordinary matter was identified and the subject of nuclear physics began to separate from that of elementary particles. Within a year, Anderson gave the first decisive proof [12] of the existence of the positron.

MESONS

A continuing puzzle in nuclear physics during the 1930s was the apparent great strength and short range of the nuclear forces. In 1935 Yukawa [13] used one of the simplest consequences of quantum mechanics, the uncertainty principle, to relate the range R of those forces to the mass m_π of a hypothetical new particle, now called the π meson (pion).

Yukawa considered the possibility that a neutron or proton could emit and shortly afterward reabsorb a meson through the reactions

$$\begin{aligned} n &\leftrightarrow n + \pi^0 \\ n &\leftrightarrow p + \pi^- \\ p &\leftrightarrow p + \pi^0 \\ p &\leftrightarrow n + \pi^+ \end{aligned} \tag{1-5}$$

The π mesons were taken to be the carriers of momentum and energy that provided the n–n, n–p, and p–p interactions (the fundamental nuclear binding forces). Yukawa used the uncertainty principle in the form

$$(\text{momentum uncertainty})(\text{position uncertainty}) \sim \hbar$$

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identifying the momentum uncertainty as $m_\pi c$, with m_π the meson mass, and the position uncertainty as the range R of the nuclear force. Then

$$(m_\pi c)(R) \sim \hbar \tag{1-6}$$

These mesons, existing only for a time limited by the uncertainty principle, were called *virtual*. Yukawa's first estimate of R led to a mass of from 50 to 100 MeV/c^2 for the new particle. He was correct within a factor of 2.

Soon a meson (the μ or muon) was found in cosmic radiation by Anderson and Neddermeyer [14]. A classic experiment by Conversi, Pancini, and Piccioni [15], prepared under the difficult conditions of wartime Italy, showed, however, that the cosmic-ray muons did not interact strongly. The dilemma was resolved in 1947 by Powell [16] and his co-workers, who used a high sensitivity silver-halide-loaded photographic emulsion to detect and identify the decay of a π meson into products that included the weakly interacting muon. The conclusion that the π must be distinct from the μ was also inferred independently by Marshak and Bethe [17] from a number of pieces of experimental evidence. In 1948, pions were produced and observed at the Berkeley cyclotron.

NEUTRINOS

Discovery of the only other elementary particle known before 1950, the neutrino, shared with the pion an origin in nuclear physics. The neutrino, with zero mass and charge, spin $\frac{1}{2}$, and a small interaction strength, obeying Fermi statistics, was postulated by Pauli in 1930 and incorporated by Fermi [18] into a theory of beta decay developed in 1934. As an "invented" particle, it was originally brought forward as an alternative to the even more distasteful idea of energy nonconservation. Experiments in the 1920s had established that electrons from beta decay emerged with various energies up to a certain maximum. That maximum was equal to the energy release of the beta-decay nuclear transition. Pauli guessed that the missing energy was carried away by an unseen neutral massless particle. Although the neutrino ν was not detected directly [19] until 1953, the validity of the decay formulas

$$\pi^\pm \rightarrow \mu^\pm + \nu(\bar{\nu}) \tag{1-7}$$

for pions and

$$\mu^\pm \rightarrow e^\pm + \nu + \bar{\nu} \tag{1-8}$$

for muons had been accepted some time before. The inference that reaction (1-7) produced only one missing neutral particle and (1-8) at least two was drawn from the facts that π decay at rest led to a charged secondary of fixed energy, whereas μ decay at rest did not. We now make further distinctions,

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TABLE I A LIST OF ELEMENTARY PARTICLES AS OF 1950[a]

Particle name	Symbol	Lifetime (sec)	Particle mass (MeV/c^2)
Photon	γ	Stable	0
Positron and electron	e^+, e^-	Stable	0.511
Proton	p	Stable	938.3
Neutron	n	10^3	939.5
Pion	π^+, π^-	2.6×10^{-8}	π^+, π^-: 139.6
	π^0	0.8×10^{-16}	π^0: 135.0
Muon	μ^+, μ^-	2.2×10^{-6}	105.7
Neutrino (electron type)	$\nu, \bar{\nu}$	Stable	0 (< 60 eV)

[a] The π^0 had been measured only rather poorly at that time and the neutrinos ν and $\bar{\nu}$ had been inferred but not yet detected. Masses and lifetimes are based on more recent measurements.

discussed in later sections, among the neutrinos, all assumed to be massless, of reactions (1-7) and (1-8).

By mid-century the list of elementary particles had grown to 12 (Table I). Of these, all except the μ^+ and μ^- seemed to have some purpose in an economical scheme of the structure of matter. By now many properties of the muons are nearly as well measured as are corresponding numbers for electrons, but their role has not been greatly clarified even by more than a quarter century of subsequent research.

STRANGE PARTICLES

With the discovery in 1947 of the pion, which was assumed to provide the nuclear binding force, a relatively simple picture of elementary particles emerged. However, this simple interpretation did not go unchallenged for long. In the same year, two cloud-chamber pictures of cosmic rays, obtained by Rochester and Butler [20], indicated the existence of new particles. One of the pictures showed a "V-track," indicating the decay of a neutral particle into two charged particles. The other picture showed a track with a kink, indicating the decay of a charged particle into another charged particle and a neutral. Since 1947, many observations of these new particles have been made in cosmic-ray studies.

In 1953, the first machine capable of producing the new particles, the cosmotron, went into operation at the Brookhaven National Laboratory. This machine permitted a systematic study of the particle production and decay reactions. Both the cosmic-ray experiments and those done at accelerators showed the decay lifetimes of the new particles to be on the order of 10^{-10} sec, extremely long compared to the particle production time of 10^{-23} sec. To account for this discrepancy, Pais [21] suggested the concept of associated

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TABLE II A PARTIAL LIST OF THE STRANGE PARTICLES[a]

Particle name	Symbol	Lifetime (sec)	Mass (MeV/c^2)	Strangeness
Baryons				
Lambda	Λ^0	2.6×10^{-10}	1115.6	−1
	Σ^+	0.8×10^{-10}	1189.4	−1
Sigma	Σ^0	$< 1.0 \times 10^{-14}$	1192.5	−1
	Σ^-	1.5×10^{-10}	1197.4	−1
Xi	Ξ^0	3.0×10^{-10}	1314.9	−2
	Ξ^-	1.7×10^{-10}	1321.3	−2
Omega	Ω^-	1.3×10^{-10}	1672.2	−3
Mesons				
Kaon	K^+, K^-	1.2×10^{-8}	493.7	+1, −1
	K^0, $\overline{K^0}$	$0.89 \times 10^{-10} (K_S \rightarrow 2\pi)^b$ $5.2 \times 10^{-8} (K_L \rightarrow 3\pi)$	497.7	+1, −1

[a] Higher-mass resonance states are not listed.

[b] K_L and K_S are linear combinations of K^0, $\overline{K^0}$ states. The decay scheme of K^0 will be discussed in a later section.

production. This concept was formalized by Gell-Mann and Nishijima [22] with the introduction of a "strangeness" quantum number. The strangeness was taken to be conserved in strong nuclear interactions. That assumption implied that a particle produced with a certain strangeness would always be accompanied by a particle or particles totaling an equal but an opposite strangeness. If the strangeness quantum number were to be absolutely conserved, as is, for example, electric charge, the strange particle would be stable. The long decay lifetime of the newly observed particles indicated that strangeness is not conserved in weak interactions. A partial list of the strange particles is shown in Table II.

RESONANCES

The availability of high-energy accelerators allowed systematic searches for new particles. In pion–proton collisions (π^+–p and π^-–p), it was found that the total cross sections exhibited a sharp peak at a pion kinetic energy of about 190 MeV (see Fig. 1). Such a peak was consistent with the formation by the pion and proton of a short-lived excited state. The mass of the unstable particle was equal to the center-of-mass energy (invariant mass) of the π–p system at resonance, about 1240 MeV. The decay lifetime τ could be estimated from the width ΔE of the peak by the uncertainty principle, $\tau \cong \hbar/\Delta E$. In this case, $\tau \cong 6.8 \times 10^{-22}$ MeV-sec/140 MeV $\cong 5 \times 10^{-24}$ sec. Such a short decay lifetime was expected if the decay proceeded by the strong interaction. Of course, the observed peak could be interpreted as the decay of an

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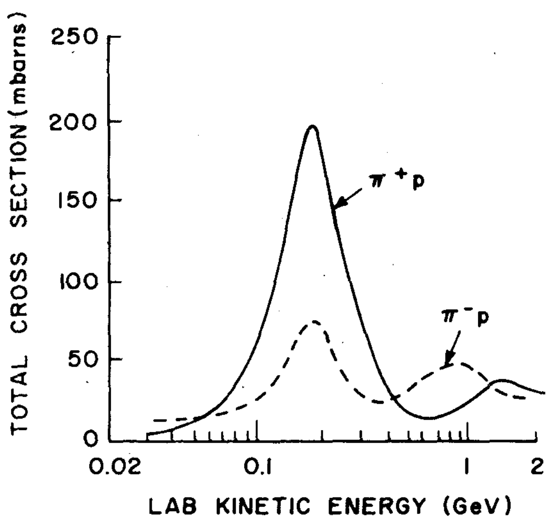

Figure 1-1 Total cross sections for the scattering of positive and negative pions by protons (from Ref. 23).

unstable particle only if that object had well-defined quantum numbers. Indeed, subsequent detailed analyses have verified that the π^+–p and π^-–p resonances are two of the four possible charged states of an unstable particle (Δ^{++}, Δ^+, Δ^0, Δ^-) with spin of $3\hbar/2$. Higher-mass states of this resonant channel produce similar peaks. The higher-mass states are generally more difficult to observe because the peaks are smaller and the background continuum is larger. In addition to the Δ resonances mentioned, a series of charge-doublet resonances (N^{*+}, N^{*0}) was also discovered. The proton and neutron are considered as the doublet of lowest mass within that family of N^* resonances.

When the protons were bombarded by strange particles, other resonances were produced. These resonances, with quantum numbers similar to those of the hyperons listed in Table II, are generally labeled by the names listed in Table II, with the mass in MeV of each resonance attached (e.g., Σ(1385) or Σ*(1385)).

Resonances were also found among clusters of pions in pion–nucleon collisions, and some of these were later found in proton–antiproton annihilation. For example, the two-pion final state in the reaction

$$\pi^- + p \rightarrow \pi^+ + \pi^- + n \qquad (1\text{-}9)$$

exhibited resonance peaks at invariant masses of 765 MeV/c^2 and 1264 MeV/c^2.

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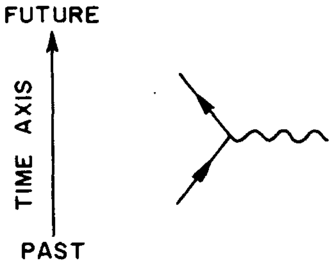

Figure 1-2 Fundamental vertex-diagram for electromagnetic interactions; the charged particle (solid line) emits a photon (wavy line) as it travels forward in time.

INTERACTION STRENGTHS

Among elementary particles, as in nuclear physics, three interaction types are observed. Of these, the electromagnetic interaction, which binds electrons and nuclei into atoms, is the best understood. Its strength is characterized by the coupling constant

$$\alpha = \frac{e^2}{4\pi\hbar c} \cong \frac{1}{137} \tag{1-10}$$

and the coupling constant can be interpreted, in a very rough but intuitive way, as the probability for emission or absorption of a photon (the exchanged boson of electromagnetism) from a charge (the conserved quantity of electromagnetism). All the electromagnetic interactions can then be thought of in terms of what are called Feynman diagrams, built from the fundamental vertex diagram of Fig. 2. The typical energy of a photon in such a diagram is limited by the necessity for momentum conservation, and in the case of a slow-moving charge is therefore roughly the rest energy of the charge carrier. For example, the binding energy of the hydrogen-atom ground state can be

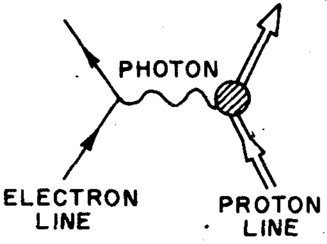

Figure 1-3 Lowest order graph for calculation of hydrogen-atom ground-state binding energy.

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