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CORRECTION TO

SLAC PUB 816, Electromagnetic Interactions, by W.K.H.Panofsky

Page 4, third line from bottom, change 10^{-31} to 10^{-32}

and change the second line from the bottom to read as follows:

This is of the same order of magnitude as the "point" cross section for the reaction

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(TH) & (EXP)

ELECTROMAGNETIC INTERACTIONS*

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CONTRIBUTIONS TO "COMMENTS ON NUCLEAR AND PARTICLE PHYSICS"

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Only a very small part of the Kiev conference was dedicated to electromagnetic interactions — less than the impact of recent work on current thought deserves. This note rests to a large part on the thorough experimental and theoretical summaries of R. Wilson and L. D. Soloviev. Even these could not do justice to the important new material introduced at Kiev, and these remarks can do even less.

Traditionally, the subject has been divided into Quantum Electrodynamics (QED), photoinduced processes at high energies, and lepton-hadron interaction. This conference may have been the last conference where this discussion retains some logic: All significant discrepancies in QED have disappeared and the subject may lose interest to high energy physicists until new problems arise; photon induced processes at high energies have lost their distinction from the corresponding all-hadronic processes; only lepton hadron interactions have retained their unique feature of exploring unknown structures with known forces.

No remaining discrepancies between theory and "pure" QED experiments remained at the time of the Kiev meeting. The discrepancies at low energies had been removed by the calculations of Brodsky and collaborators which corrected the errors in the theoretical Lamb shift values and reduced the discrepancy between theory and the CERN measurement of g - 2 of the muon to one standard deviation. A beautiful experiment of Telegdi's measured <u>both</u> the $m_F = +1$ to $m_F = 0$ transition of the F = 1 state in muonium <u>and</u> the $m_F = -1$ transition to the $m_F = F = 0$ state; both measurements were made at the "magic" magnetic field of 11.4 kG at which the dependence of the transition frequencies on the magnetic field vanish to first order. The sum of the two transition frequencies gives the usual hyperfine splitting $\Delta\nu$, while the difference gives a measurement of the muon mass which does not depend on any chemical effects as do the ordinary measurements based on the observation of the precession frequency of the muon in a magnetic field. With this measurement the values of the fine structure constant, the muon moment, and the muon mass form a set of data consistent to a few parts per million with the other natural atomic constants.

At high energies the limits of QED validity have been pushed further by the Frascati colliding beam experiments. Measurements on the annihilation process $e^+ + e^- \longrightarrow \gamma + \gamma$ has set a new limit for processes involving a virtual electron propagator and observation of Bhabha scattering of positrons and electrons and of the process $e^+ + e^- \longrightarrow \mu^+ + \mu^-$ have set new limits on the validity of QED for processes involving time-like and space-like photon propagators as well as checking muon-electron universality. Generally speaking, these experiments have extended the lower limit of the conventionally defined cut-off parameters to about 3 GeV at a 95% confidence level.

Reports were also given on new monopole searches and on violation of Fermi-Dirac statistics in the final state of "trident" production — all with negative results.

So all is well with QED over an enormous range of distances, and it is very unlikely that this situation will be changed unless the parameters are greatly extended.

The new experimental data at Kiev of greatest interest to electromagnetic interactions, (and probably to the entire conference) were (a) the new results on hadron production in the $e^- - e^+$ colliding beam experiments at Frascati, and (b) the new results on "deep inelastic" electron scattering from SLAC; the question is of course whether these two groups of results have the same physical origin.

These groups from Frascati reported hadron production cross sections in the energy range of about $1.6 \text{ GeV} < E_+ + E_- < 2.0 \text{ GeV}$; both "colinear," i.e., presumably two-body and "multibody" events are under investigation. Charged hadrons are separated from muons and electrons by range and the absence of shower production, respectively. Since there is a large excess of elastic e^-e^+ events, "colinear" hadron events are only credible if they are well in excess of electron pairs which "happen not to shower." This excess definitely is significant excepting possibly at the highest energies and shows that the number of pion pairs is nonresonant itself and is well above that extrapolated as the Breit-Wigner tail of the ρ-meson resonance — a prediction which would follow from a strict vector dominance model.

Even more spectacular is the number of multihadronic events produced in e^+-e^- collisions. The observations of three independent groups — Conversi-Grilli, Zichichi, and Silvestrini agree on the essential features which are the following:

a) The observed hadron prong distributions can be fitted by a variety of numbers of charged and neutral pions. However a best fit results if three quarters of the final states are composed of two charged (π^+ and π^-) and two neutral pions with the balance going to other multihadron channels; the production angles are too large to permit most noncolinear events to be interpreted as simple two charged hadron events (π^+ and π^- only) accompanied by bremsstrahlung.

b) The energy dependence of the cross section for production of visible charged prongs is flat — about 3×10^{-32} cm^2 within better than a factor of two.

c) The total cross section for production of more than two (charged and noncharged) hadrons is somewhat above 10^{-32} cm^2 at Frascati energies. This is of the same order of magnitude as the "point" cross section for the reaction $e^+ + e^- \rightarrow \mu^+ + \mu^-$.

What then is the meaning of these large cross sections? A valiant effort by theorists to find "pedestrian" explanations appears unsuccessful. The leading candidate in this category (Brodsky, Konoshita, and Terazawa; Budneev and collaborators) is the process of considering small angle virtual photons from both the e^- and the e^+ to produce the observed final state via annihilation of the two γ's. Such a process is two orders in the fine structure constant α below the usual channel proceeding via one photon annihilation of the electron and positron. However, the E^{-2} denominator stemming from the off-the-mass-shell photon in the latter process is absent and two substantial logarithmic factors are present in the two photon processes from the small angle (Weizacker-Williams) virtual photons. Numerically, at Frascati energies the calculated two photon yields appear to fall below the observations by at least an order of magnitude; at larger energies (perhaps 2 GeV per ring) the two photon process may predominate. In principle experimental techniques are available to distinguish these two likely hadron production processes, both of which are of interest in themselves: (a) the two photon annihilation process should occur equally both in $e^- - e^-$ and $e^- - e^+$ collisions; (b) final energetic electrons at small angles can be detected from the two photon reactions and (c) larger transverse hadron momenta are expected from the one photon process. The third criterion, together with the large value of the cross section, constitutes "hard" evidence that most of the Frascati data originates from a one photon process. Therefore the unexpectedly large Frascati colliding beam multihadron yield adds to the evidence that are seeing the products of interaction of the photon with "granular" or point-like constituents of the hadrons. Initial evidence in that direction originated from the early inelastic electron scattering data reported from SLAC at Vienna two years ago; let us now turn to the status and interpretation of this work as presented at Kiev.

The following new information on the SLAC deep inelastic scattering appeared at Kiev: (a) more data on the scattering from the proton at large angles (up to 34°) to permit separation of the W_1 and W_2 function (or the longitudinal and transverse cross sections σ_0 and σ_T) for energies up to W = 4 GeV in the center-of-mass system of the hadrons; (b) increase in the range of parameters to permit examination of the validity of "scaling," i.e., dependence of the function W_1 and W_2 on the single parameter $\omega = 2M\nu/q^2$ up to a value of $\omega = 20$, here $\nu = E - E'$ is the difference in initial and final electron energy which is proportional to the scalar product of the four-momentum transfer q and the four-momentum of the initial nucleon of mass M; (c) the first partially analyzed data on the deuteron became available. Out of this mass of information the following facts emerge: (a) the ratio $R = \sigma_0/\sigma_T$ is small (possibly even zero) and varies slowly, if at all, with the kinematic parameters; this result definitely contradicts the behavior predicted by strict vector dominance calculations; (b) "scaling" is not contradicted by the behavior of cross sections over the larger range of parameters accessible from the proton work, and also may be satisfied for the neutron. However, the validity of scaling for the large values of ω cannot be experimentally verified unless it is assumed that the ratio $R = \sigma_0/\sigma_T$ continues to be small even beyond the range in ω where this fact can be experimentally verified; (c) the ratio of neutron to proton deep inelastic scattering approaches unity for large values of ω but is considerably below unity for smaller values of ω; at low ω it may in fact be equal to the ratio of square of the static magnetic moments of the neutron to that of the proton; this prediction originates from a conjecture which introduces $\omega' = (2M\nu + M^2)/q^2$ as the "scaling" variable which permits the elastic scattering data to be consistently included with the inelastic data. A simple quark calculation predicts 2/3 for this ratio while a diffraction model would, of course, give unity.

(d) if one assumes that the ratio $R = \sigma_S/\sigma_T$ does not radically depart at high ω from the low values measured for low ω and that scaling remains valid for large values of ω also (although neither the R value nor the validity of scaling can be experimentally verified) then the function $\nu W_2(\omega)$ exhibits a statistically significant maximum as a function of ω, i.e., $\nu W_2(\omega)$ decreases for large values of ω.

What does all this mean? The principal casualties from the data given at Kiev are the many theories which try to account for the facts by not too radical assumptions. Vector dominance is clearly in trouble here; also an explanation of the results by purely diffractive processes is contradicted by the unequal neutron and proton cross sections; unsuccessful attempts were made at Kiev to account for the deep inelastic data (in which only the scattered electron is observed) by ordinary electrodynamic processes such as trident production. Both the large hadron yields from Frascati and the deep inelastic electron scattering work point toward a point-like substructure of the hadrons; should the maximum of the $\nu W_2(\omega)$ function be confirmed this constitutes important evidence in this direction.

During the next years we hope to see progress in deep inelastic lepton scattering in coincidence with final hadron states; some preliminary results from Cornell reported at Kiev on electron nucleon coincidences identifying the missing mass in the reaction $e + p \rightarrow e' + p + M.M.$ led to an anomalously large peak at a missing mass of zero in addition to the ρ-meson peak. Much work remains to be done in this field before the tantalizing questions dealing with the reality of a point-like substructure of the hadron will have a clearer answer.