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ELECTROMAGNETIC EXPERIMENTS AT NAL

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ABSTRACT

A number of possibilities for studying electromagnetic interactions at NAL are considered. In this report the scope of these studies is given, and some of the proposed experiments are discussed. Other experiments as well as questions concerning the electron-photon beam are considered in accompanying reports. We believe that a number of these experiments warrant early scheduling, and we recommend that NAL plan for the small but important modifications required for electron use of a high-intensity beam.

I. INTRODUCTION

The photon, muon, electron, and K beams which can be made at NAL will provide the opportunity to cover a wide range of real and virtual photon physics. We note in particular that the tagged-photon beams which can be built[1] will have fluxes at energies up to 80 GeV comparable to those available at electron synchrotrons, and with a significantly better duty cycle. The combination of known incident energy and high duty cycle will make experiments like the photon total cross section and vector-meson production relatively straightforward. The electron fluxes are comparable to the expected muon-beam intensity so that deep-inelastic electron-scattering experiments are feasible over the same kinematic range as the proposed muon experiments (described in SS-188 and SS-190). Under NAL conditions, inelastic Compton scattering should be possible as a complementary experiment in the deep-inelastic region. In addition, the high-energy π and K beams at NAL can be used with stationary electron targets to measure the charge radii of these particles. The studies which we have made fall under the following categories:

A. Measurement of the charge radii of the pion and kaon

The form factor for the pion has been well measured in the time-like, but not in the space-like, region. Pions of incident energies ~80 GeV can give momentum transfers $q^2 \leq 1.5\ f^{-2}$ to a stationary-electron target. The radius can then be measured to a precision of ~0.03 f with cross-section measurements of 1% absolute accuracy. Compared with the possibilities at Serpukhov the q^2 range is larger at NAL and the systematic errors can be more carefully studied since pion beams of both charges will be available. Comments concerning these experiments are given in SS-165 and SS-169.

B. Photon interactions in the diffractive region

At least qualitatively it has become evident that photon scattering behaves much like pion scattering in the diffractive region. This is demonstrated by the behavior of elastic photon scattering, the photon total cross section, and vector-meson photoproduction. The phenomena are described qualitatively by the model of vector-meson dominance which is described in Section II. The relevant NAL experiments are also described in that section. The goal of these experiments is to test the region of validity of the model and to see if the rho-like behavior of the photon persists at high energy.

C. Deep-inelastic scattering

The deep-inelastic electron scattering results from SLAC[2] have stimulated a great deal of interest and may lead to a better understanding of the structure of the nucleon. The SLAC work can be extended at NAL with muons as described in other reports or with electrons. In addition, the energy available at NAL and the high duty cycle will make possible the study of deep-inelastic Compton scattering, a process which has not yet been observed due to experimental problems at the lower-energy machines. This process and the proposed experiment are described in Section III.

D. New-particle searches

An experiment has been proposed by W. Lee et al.,[3] to search for the production of pairs of heavy leptons and intermediate mesons using high-energy photon interactions with nuclei. Since the cross sections have been calculated,[4] the experiment can demonstrate conclusively the existence or nonexistence of these particles, and from the rates available it is estimated that masses up to 7 GeV/c^2 will be observed.

E. More complex experiments

The possibilities for performing multibody photoproduction experiments at NAL are considered in SS-168 by D. Yount. In addition, the problems involved in producing polarized photons by the method of coherent bremsstrahlung from a crystal are considered by P. Patel in SS-205.

F. Electron-photon beam

It has been pointed out in previous Summer Studies that a normal beam transport can be easily adapted for electron use.[1] The essential features required are:

1. low Z target
2. magnetic sweeping between the primary target and the photon-to-electron converter. This converter must precede the normal beam transport.

We would like to point out that the electron and photon experiments need the highest possible flux. The experiments which we anticipate at NAL could all use more flux than will be available. Several proposals, for example, the inelastic Compton scattering (Proposal 24) and the heavy lepton search (Proposal 87) would be of more limited physics interest if the flux were much below expectation. We therefore recommend that NAL plan for the use of the highest-intensity beams for electrons.

The specific details involved in using the 3.5-mrad beam are considered in SS-195 and, in addition, the expected electron intensities are given. In addition, the expected fluxes for incident 400-GeV protons are given in SS-171.

II. DIFFRACTIVE PROCESSES

J. S. Trefil, F. Pipkin, and R. J. Morrison

A. Vector-Meson Dominance at High Energy

The most powerful theoretical tool which has been developed to study the hadronic interactions of photons is the vector-meson dominance (VMD) model in which the electromagnetic current is represented as the sum over the three vector fields

$$ej^{\mu} = \sum m_V^{\,2} f_V d_V^{\,\mu}, \qquad (1)$$

and the coupling constants f_V are taken from some other theoretical model, such as SU_3, a symmetry-breaking quark model, or directly from colliding-beam experiments.

In terms of reaction amplitudes, we can write

$$A(\gamma + T \rightarrow X) = \sum_{v} f_{v} A(v + T \rightarrow X), \tag{2}$$

where $A(\gamma + T \rightarrow x)$ represents the amplitude for a photon to produce a final state X from the target T, and $A(v + T \rightarrow X)$ represents the amplitude for one of the vector mesons to do the same.

An especially sensitive test of this idea can be made if one considers particular photon-induced reactions, namely

$$\gamma + p \rightarrow \gamma + p \tag{3}$$

$$\gamma + p \rightarrow v + p \tag{4}$$

$$\gamma + p \rightarrow \overline{\underline{X}} \tag{5}$$

and

$$\gamma + A \rightarrow \rho + A, \tag{6}$$

where A is a nucleus. [Note that the optical theorem connects Eq. (3) and Eq. (5) at $t = 0$ so that two experiments are, in a sense, equivalent for our purposes.] For the sake of simplicity of development, let us consider only the ρ meson in the sum over vector mesons above (the other mesons could, of course, be included in a more realistic discussion). Then, by the hypothesis of vector dominance, we write

$$\begin{aligned} A(\gamma + p \rightarrow \gamma + p) &= f_{v}^{2} A(\rho + p \rightarrow \rho + p) \\ &= f_{v}^{2}(i + \alpha_{\rho}) \frac{k}{4\pi} \sigma_{\rho N}, \end{aligned} \tag{7}$$

where the last equality holds at $t = 0$, and $\sigma_{\rho N}$ is the ρ-nucleon total cross section. Similarly,

$$\begin{aligned} A(\gamma + p \rightarrow \rho + p) &= f_{v} A(\rho + p \rightarrow \rho + p) \\ &= f_{v}(i + \alpha_{\rho}) \frac{k}{4\pi} \sigma_{\rho N}, \end{aligned} \tag{8}$$

where, again, the last equality holds at $t = 0$. Finally, from the production of ρ mesons on nuclei, one can, by well-known techniques, extract $\sigma_{\rho N}$.

Taking the imaginary part of Eq. (8) at $t = 0$, we get

$$\operatorname{Im} A(\gamma + p \rightarrow \gamma + p) = f_{v} \frac{k}{4\pi} \sigma_{\rho N} = \frac{k}{4\pi} \sigma_{\gamma p}, \tag{9}$$

where $\sigma_{\gamma p}$ is the total photon-nucleon cross section. Thus, we see that if experimental data on any three of the equations (3-6) are available, Eqs. (7-9) are overdetermined, and a sensitive test of vector dominance can be made. In addition, since an NAL photon beam would presumably exist at a wide range of energies up to more than 100 GeV/c, it becomes possible to make this type of test as a function of energy. This is particularly useful in the evaluation of Eq. (6), since the systematic errors which occur in the extraction of $\sigma_{\rho N}$ from nuclear production data (due, for example, to uncertainties in the handling of the nuclear wave functions) are not energy dependent, so that the energy dependence of $\sigma_{\rho N}$ can probably be determined much more accurately than the precise value of $\sigma_{\rho N}$ at a given energy. This comment would apply to the other reactions as well so that the possibility of really testing vector dominance over a wide range of energies and comparing the energy dependence of the above reactions (a comparison which does not depend critically on comparing normalizations between different experiments) offers a program of photon physics at NAL which is not available at other facilities.

Finally, we note that the measurement of the photoproduction of the ρ and the ϕ meson at high energies will test the accepted explanation of one of the great puzzles in photoproduction, namely, the question of why the production of the ϕ meson is so small compared to the ρ, when the coupling constants in the SU(3) limit are in the ratio

$$f_\rho^2 : f_\phi^2 = 9:2.$$

From Eq. (8), neglecting the real parts of the photoproduction amplitudes, we see that at t = 0,

$$R = \frac{\frac{d\sigma}{dt}(\gamma + p \rightarrow \phi + p)}{\frac{d\sigma}{dt}(\gamma + p \rightarrow \rho + p)} = \frac{2}{9}\left(\frac{\sigma_{\phi N}}{\sigma_{\rho N}}\right)^2$$

so that if $\sigma_{\rho N} = \sigma_{\phi N}$, the ϕ cross section should be 2/9 that of the rho, whereas in fact, the ratio is more like 0.03. The explanation for this lies in predicting the ratio $\sigma_{\phi N}/\sigma_{\rho N}$ from the quark model, where the rho and phi differ in that the former contains only nonstrange quarks, while the latter contains only strange ones. Using the additive quark model, one can then relate $\sigma_{\phi N}$ and $\sigma_{\rho N}$ to $\sigma_{\pi N}$ and σ_{KN}, since the pion also contains only nonstrange quarks, and the kaon has a mixture of strange and nonstrange. The prediction then becomes

$$R = \frac{2\left(\sigma_{K^-n} + \sigma_{K^+p} - \sigma_{\pi^+p}\right)^2}{9\left(\frac{\sigma_{\pi^+p} + \sigma_{\pi^-p}}{2}\right)^2}$$

Thus, when the π and K cross sections are known, the energy dependence of the ratio of ϕ to ρ photoproduction should constitute a good test of this symmetry-breaking model, and, coupled with measurements of $\sigma_{\phi N}$ and $\sigma_{\rho N}$ directly from nuclei, should provide another interesting test of VDM.

It is interesting to note that if the π and K cross sections approach each other at high energies [as one would expect from SU(3)], then one would predict that the ϕ-production cross section should rise as the energy is increased.

B. Experiments Relevant to Vector Dominance

There are several photoproduction experiments which can be used to test vector dominance at the higher energies available at NAL. It is important to do these experiments and see if the situation simplifies at higher energies. These experiments are the measurement of the total photon cross section as a function of energy, the photoproduction of vector mesons and elastic Compton scattering. Evidence concerning the validity of vector dominance can also be obtained from electroproduction and muoproduction experiments. Here we shall only discuss the electroproduction experiments:

1. Measurement of the total photon cross section.

There is a proposal by the Santa Barbara group (Proposal 25) to measure $\sigma_{\gamma p}$ and $\sigma_{\gamma D}$ over the energy range from 26 to 125 GeV. This experiment is a direct extension of their SLAC experiment to higher energies. They propose to obtain a statistical accuracy of ±1% in photon energy bins of 5 GeV or less. Systematic errors should be less than ±0.5% at all energies. In addition, they propose to measure the A dependence at 32 and 65 GeV with errors of approximately 2%.

This experiment should be much easier at NAL because of the factor of 500 improvement in the duty cycle. The data rate will be higher by a factor of 50 at energies below 60 GeV, and the systematic checks can be made in this region. In addition, the accidental rates will be less because of lower instantaneous rates in the counters. Their ability to separate the hadronic final states from the 200 times more predominant electron-positron pairs should be at least as good as at the lower energy.

2. Photoproduction of vector mesons.

There is no proposal to study the photoproduction of vector mesons. There is, however, a Summer Study report (SS-172) by M. Tannenbaum which explores the feasibility of measuring rho photoproduction with a tagged photon beam. There is also a letter of intent from a Santa Cruz - Berkeley group. The apparatus used in the Tannenbaum study is the same as that employed in the Harvard - SLAC muon proposal (Proposal 29). It is, in fact, pointed out that the two experiments could be done in sequence if an electron and a muon beam were available along the same beam line. The report shows that in a modest amount of time a high-statistics study of rho photoproduction can be made. The same apparatus can be used to study the rho photoproduction from hydrogen and from complex nuclei. At the same time, a search can be made for higher-mass vector mesons and the density-matrix elements for the rho could be measured as a function of energy and momentum transfer. This would give a test of helicity conservation in the production reaction:

3. Elastic Compton scattering.

There is no proposal to do this experiment. There is, however, a letter of intent from a Santa Cruz-Berkeley group to study elastic Compton scattering. The details of this experiment are not given. It is presumed, however, that it is similar to the experiment outlined in the 1969 Summer Study (SS-80). The reader is referred to these reports for further details. This is a very important but difficult experiment.

III. DEEP-INELASTIC COMPTON SCATTERING

E. A. Paschos and R. J. Morrison

A. Theoretical Motivation

Recent experiments have shown that lepton-induced processes at large momentum transfers have point-like cross sections. This is true for the SLAC electroproduction experiment[5] where

$$\frac{d\sigma}{dQ^2 d\nu} = \frac{4\pi\alpha^2}{Q^2} W_2(Q^2, \nu) \quad \text{(at small angles)},$$

with $\nu W_2(Q^2, \nu) \simeq 0.33$ in the deep-inelastic limit. Similarly, the CERN neutrino experiment[6] shows that the total neutrino cross section rises linearly with energy, with a slope very close to the slope predicted for a point cross section:

$$\sigma_{tot} = (0.6 \pm 0.15) \frac{G^2 M^2}{2\pi} \left(\frac{E}{M}\right).$$

There are further indications that point cross sections may also have been observed in other interactions:

1. There are indications that massive lepton-pair production in proton proton[7] collisions has a point-like cross section. The process is given by

$$p + p \to \mu^+ + \mu^- + \Gamma,$$

and it is consistent with a model calculation that gives[8]

$$\frac{d\sigma}{dQ^2} \cdot \frac{4\pi\alpha^2}{3Q^4} \rho(Q^2/S),$$

where Q^2 is the invariant mass of the muon pair, S is the square of the center-of-mass energy, and ρ is a form factor of order unity in the interesting kinematic region.

2. Preliminary results on the electron-positron ring at Frascati[9] suggest the abundant production of hadrons in the range of $2.5\ (\mathrm{GeV})^2 \leq S \leq 4\ (\mathrm{GeV})^2$. All these observations suggest that these cross sections arise from the interaction of massive electromagnetic (weak) currents with a point-like structure within the proton. It is very important to obtain additional evidence for the presence of point-like cross sections in other processes.

It has been suggested that inelastic Compton scattering at high energies and large momentum transfers proceeds through the incoherent scattering from point-like constituents.[10] The process has been analyzed in detail, and it was found that it can be predicted from the existing electroproduction data through the relation:

$$\left(\frac{d\sigma}{d\Omega dE'}\right)_{\gamma p} = \frac{\nu^2}{EE'} \left(\frac{d\sigma}{d\Omega dE'}\right)_{ep} \frac{\langle Q^4 \rangle}{\langle Q^2 \rangle} .$$

This relation is sensitive to the ratio of the mean value of the fourth power of charge to the mean square charge. The most formidable difficulty in such an experiment is the background from the decay of π^0's. Studies of the background contributions to such an experiment indicate that performing this experiment at SLAC at presently available energies will very likely be inconclusive. This is shown in Fig. 1, taken from Ref. 10, where the photon spectrum from the decay of π^0's from 20-GeV bremsstrahlung is shown. The predicted inelastic Compton scattering is also shown under the assumption $\langle Q^4 \rangle / \langle Q^2 \rangle = 1$. The situation changes dramatically at NAL energies, however, as shown in Fig. 2, taken from Proposal 24, where the comparable spectra are shown with 40-GeV incident bremsstrahlung. In this case the sum of the two contributions shows a clear break at a cross section

$$\frac{d^2\sigma}{d\Omega dE} \sim 10^{-32}\ \mathrm{cm}^2/\mathrm{sr} \cdot \mathrm{GeV}.$$

A variation of this experiment where a muon pair is produced has also been studied in detail.[11] The main background now comes from the Bethe-Heitler diagrams. Estimates of the events for these two experiments at the Cornell Synchrotron[12] indicate that the rates are small and the Bethe-Heitler is comparable to inelastic Compton. Such terms could perhaps be investigated in the W. Lee, et al., proposal.[3]

B. The Proposed Experiment (Proposal 24)

In this proposal scattered photons are detected in a lead-glass stack at an angle of 6°. The experiment is designed to cover the range of q^2 from 6-10 $(\mathrm{GeV}/c)^2$ and a range of $\nu = E - E'$ from 16-24 (GeV). The lead-glass array contains at least 40 counters (presently existing equipment) and would subtend an angle of 6×10^{-3} steradians. In order to maximize the data rate, the beam is adjusted for 40-GeV electrons incident upon a radiator of thickness 0.2 r.l. Tagged photons are definitely preferred, although not essential. The trigger would be a tagging signal, plus the indication of reaction products emerging from the target and a sizeable pulse in the lead-glass stack.

In front of the lead-glass stack is a lead converter followed by proportional planes. With this setup the π^o background is measured by the observation of both photons from the decay and to some extent this background is suppressed. The background suppression is difficult, however, because most of the photons in any interval of the yield curve (Fig. 2) come from π^o's of only slightly higher energy which means that a very low energy photon must also be detected. Assuming that the background is suppressed by a factor of five, the data rate in the region where the signal-to-noise ratio is about one is ~7/hour · GeV).

We note that a different setup was described in the 1969 Summer Study[13] and that these authors have submitted a letter of intent to NAL.

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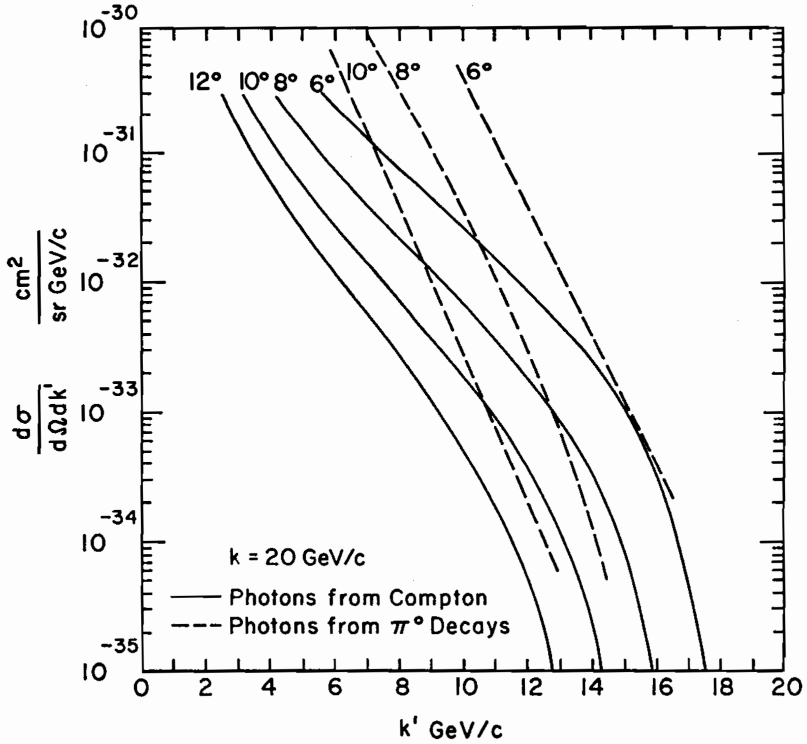

Fig. 1. Photon yields per equivalent quantum expected with an incident bremsstrahlung spectrum of end-point energy 20 GeV. The background from π^0 decays is seen to be at least comparable to the inelastic Compton yield which has been estimated under the assumption $<Q^2> / <Q^4> = 1$.

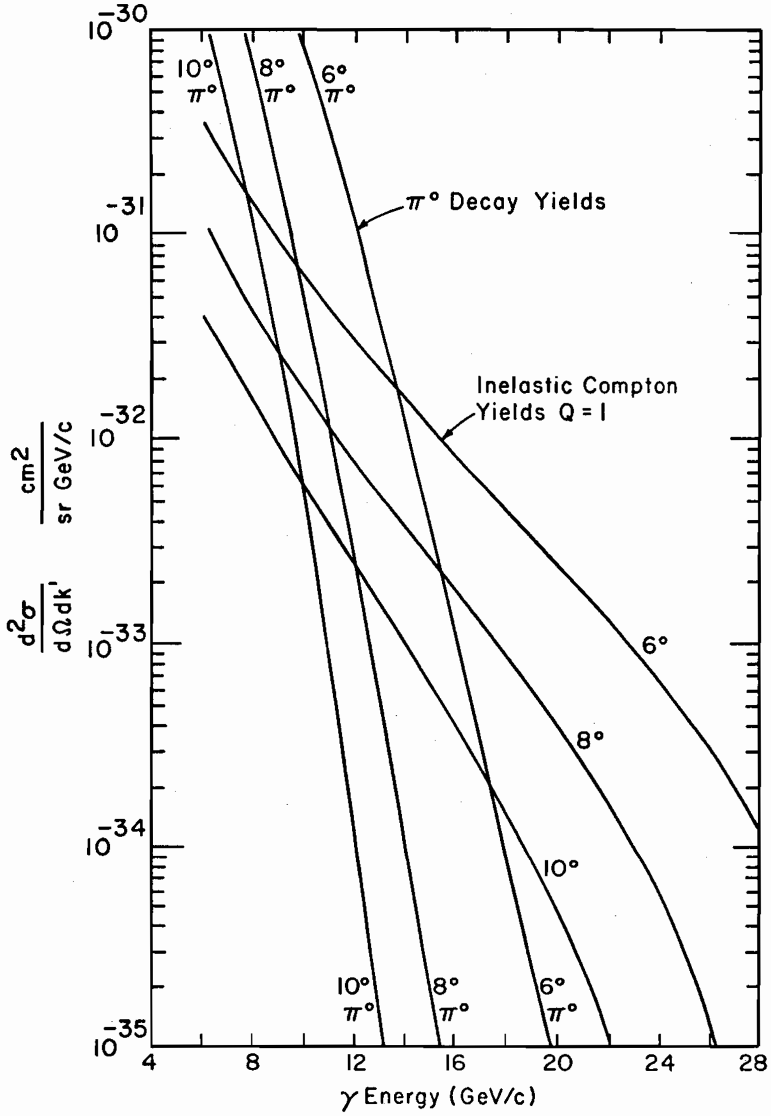

Fig. 2. Photon yields per equivalent quantum with an incident bremsstrahlung spectrum of end-point energy 40 GeV. At this energy there is a large kinematic region in which the estimated background of photons from π^0 decays is small compared with the inelastic Compton yield.