VECTOR-MESON AND MISSING-MASS PHOTOPRODUCTION USING A TAGGED-PHOTON BEAM AT NAL

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ABSTRACT

This note discusses in detail how the detector proposed for muon inelastic scattering could also be used to perform a significant photoproduction experiment.

It is proposed to study vector-meson photoproduction and search for other bosons via missing mass in the energy range 30-100 GeV using a tagged-photon beam of 10^5/pulse with ±1% resolution. The detector is a large-aperture magnetic spectrometer in the forward direction and two wide-angle, proton-recoil, pulse-height spectrometers. Wire spark chambers are used throughout. The counting rate is 250,000 detected ρ^o mesons and an estimated 60,000 events in the missing-mass range 1.2-4.0 GeV per day. Since the apparatus described is essentially identical to the Harvard muon proposal (29), it could be used for both experiments with minor modifications if a tagged-photon beam and a muon beam could both be brought down the same beam line.

I. INTRODUCTION AND DISCUSSION OF METHOD

An experiment to measure photoproduction of any neutral meson regardless of the decay mode via the reaction:

$$\gamma + p \rightarrow p + X^o,$$

using the missing-mass technique, has recently been completed in the ±1% resolution tagged-photon beam at the Cambridge Electron Accelerator. In a 60-cm H_2 target with a proton spectrometer covering 1/20 of the azimuth, ±10° of polar angle and a recoil proton kinetic energy range of 50 to 400 MeV, the number of mesons detected was about $1/10^6$ equivalent quanta and the triggering rate about 5 times this much. A missing-mass spectrum obtained in the $\rho\omega$ region is shown in Fig. 1. The ω peak on top of the ρ illustrates the ±25 MeV or ±3% mass resolution obtained. The missing-mass kinematics are extremely favorable in the high-energy range (energy much greater than the proton mass) so that it is relatively easy to do missing-mass studies on the recoil proton even at NAL energies.

If T is the kinetic energy and p is the momentum of a proton of mass M recoiling from elastic scattering by a massless particle of energy ν, then the angle of the recoil proton is:

$$\cos \phi_{EL} = \frac{T}{p} \left(1 + \frac{M}{\nu}\right).$$

Clearly as $\nu \to \infty$ the recoil angle ϕ becomes independent of energy. (See Fig. 2.)

$$\cos \phi_{EL} = \frac{T}{p}.$$

$$\tan \phi_{EL} = \sqrt{\frac{2M}{T}}.$$

The four-momentum transferred to the proton is $t = 2MT$.

For the same four-momentum transfer, the production of a particle of mass m results in a recoil proton of kinetic energy T and angle ϕ given by:

$$m^2 = 2T(\nu + M)\left(\frac{\cos\phi}{\cos\phi_{EL}} - 1\right).$$

Again for $\nu >> M$ it can be shown that:

$$m^2 = 2\nu\sqrt{2MT}\,(\phi_{EL} - \phi),$$

or

$$m^2 = 2\nu\sqrt{t}\,(\phi_{EL} - \phi).$$

Thus, the missing-mass resolution if given by:

$$\frac{\Delta m}{m} = \frac{1}{2}\frac{d\nu}{\nu} + \frac{1}{4}\frac{dt}{t} - \frac{1}{2}\frac{d\phi}{\phi_{EL} - \phi}.$$

Hence, for a fixed t, and given angular resolution, and fixed percent energy resolution of the incident beam, all missing-mass experiments at a given value of m^2/ν should have the same mass resolution at low t. Scaling from our 3% mass resolution (for missing masses in the range 0.5-1.2 GeV) obtained in a real experiment with 5 GeV (±1%) γ rays, we expect at 50 GeV (±1%) photon energy, a mass resolution of 3% for missing masses in the range 1.6-4 GeV.

In the mass range 0.7-1.6 GeV where the known vector mesons (ρ, ω, and ϕ) are found, the missing-mass technique by itself does not give adequate mass resolution. Fortunately, these mesons have characteristic decay modes:

$$\rho \to \pi^+\pi^-$$

$$\omega \to \pi^+\pi^-\pi^0$$

$$\omega \to \pi^0\gamma$$

$$\phi \to K^+K^-,$$

which can easily be detected by a high-resolution forward spectrometer. The forward spectrometer can also be used to analyze the decay products of any new particles which might be uncovered in the 1.6-4 GeV missing-mass range.

II. THE EXPERIMENT PROPOSED AND PHYSICS JUSTIFICATION

We propose to study the photoproduction of the known vector mesons in the energy range of 20-100 GeV and in addition look for new particles of mass 1.2-4 GeV which may also be photoproduced. A tagged-photon beam with momentum resolution ±1% will be used as a source of photons. The mesons will be detected with a recoil proton spectrometer at roughly 60° from a liquid-hydrogen target in combination with a large-aperture magnetic spectrometer in the forward direction (0°). To study coherent photoproduction of the known vector mesons in heavy elements, the forward spectrometer alone is used.

Over the past several years the study of vector-meson photoproduction in the energy range 1-10 GeV has greatly elucidated our knowledge of the hadronic interactions of photons and of diffraction phenomena in general. If vector mesons are diffractively produced, their cross sections should remain constant with energy. Furthermore, vector-meson photoproduction in hydrogen and in heavy elements is an extremely clean way to study diffraction scattering. Hence, this should be a very useful reaction to study Regge effects and shrinkage of diffraction peaks at high energies.

After the great success of the CEA, DESY, and Cornell vector-meson photoproduction experiments and the Orsay and Novosibirsk colliding-beam experiments, it looked like the hadronic interaction of photons was well understood. Vector dominance was in vogue. However, the deeply inelastic ep scattering results from SLAC, and the preliminary results of the high-energy storage rings at Frascati seem to indicate that photons really like to interact with hadrons. This is much to everyone's surprise.

The new energy range available at NAL can not help but clean up these unsolved problems in the hadronic interaction of photons and will probably also reveal some totally unexpected phenomena.

III. DETAILS OF THE DETECTOR

The recoil-proton spectrometer is made up of magnetostrictive wire spark chambers with 2-meter × 2-meter active area. These chambers measure the angle of the recoil proton. Scintillation counters of 1-mm thickness near the hydrogen target and 50-cm thickness behind the wire chambers measure the energy and dE/dx of the recoil particles by pulse height and the velocity by time-of-flight. One such spectrometer is put on each side of the liquid-hydrogen target at roughly 60°. The magnetostrictive spark chambers have already been built and are now being used in an experiment at Brookhaven. [See Fig. 3 (a).]

The forward spectrometer is based on the Jolly Green Giant magnet owned by the CEA and proposed to be moved to NAL by Proposals 29 and 30. The useful aperture of the magnet is 1.5-m wide by 0.75-m high by 2-m deep, and the magnet can give a transverse momentum deflection of up to 0.9 GeV/c. The large magnet sits 5-8 m downstream of a 2-m liquid-hydrogen (or heavy-element) target, straddling the beam line. Wire spark chambers in front of and behind the magnet define the trajectories of particles emerging from the target.

Lead-glass Cerenkov counters behind the rear spark chambers measure any neutral particles emerging from the target while scintillation hodoscopes on either side of the magnet roughly delineate charged-particle trajectories.

For the liquid-hydrogen target, the trigger is either a pair of charged particles emerging from the target, or a recoil proton emerging from the target. For the heavy-element target, the recoil proton trigger is eliminated. Because the hydrogen target is 1/4 of a radiation length, there may be a problem with the γ rays converting in the target and the resulting electron pairs being swept into the forward apparatus by the magnet. If this proves troublesome, a small round plug of lead 4 cm in diameter and 20 cm thick can be put downstream of the H_2 target to stop the beam and the converted pairs.

Note that this detector is virtually identical to that proposed for the Harvard muon-scattering experiment (Proposal 29). The compatibility of these experiments will be discussed in Section VII.

The resolution of the recoil-proton arm has been discussed in the introduction. The forward spectrometer will detect vector-meson events, e.g., $\rho^o \rightarrow \pi^+\pi^-$ as illustrated in Fig. 3(b). The mass of the pion pair is given to a good approximation by

$$M^2 = E_1 E_2 \theta^2,$$

where E_1 and E_2 are the energies of the two pions and θ is the opening angle. The mass resolution is given by

$$\frac{\Delta m}{m} = \left[\left(\frac{\Delta E}{E}\right)^2 + \left(\frac{\Delta\theta}{\theta}\right)^2 \right]^{\frac{1}{2}}.$$

Our wire spark chambers have spatial resolution of ±1/4 mm and have a 5-meter lever arm which gives $\Delta\theta = \pm 0.05$ mrad. For a 50-GeV ρ, $\theta = 30$ mrad, $E_1 = E_2 = 25$ GeV, and the pions bend 36 mrad in passing the magnet

$$\frac{\Delta\theta}{\theta} = \frac{\pm 0.07}{30},$$

$$\frac{\Delta E}{E} = \frac{\pm 0.07}{36},$$

$$\frac{\Delta m}{m} \simeq \pm 0.3\% = \pm 2.5 \text{ MeV}.$$

IV. TAGGED-PHOTON BEAM

We propose to use a beam of 10^5 tagged photons per pulse with a resolution of ±1% in 10-30 tagging channels. This requires an electron beam of $\approx 10^7$/pulse with ±0.5% resolution with a spot size of 1 by 2 cm. This seems feasible either with the 3.5 mrad HEHI beam in Area 2 or the 0° γ beam in Area 1, both proposed by R. Morrison. The tagging radiator would be 0.03 radiation lengths.

The tagging system at the CEA uses a C magnet roughly 10-cm high × 30-cm wide × 200-cm long and a field strength of ~ 20 kG-m. It can tag the upper 3 GeV of the bremsstrahlung spectrum in 50 channels. This magnet can deflect a 100-GeV electron beam by 6 mrad (6 cm in 10 meters) so that 20 meters after the tagging magnet the primary electron beam is separated by 12 cm from the photon beam. A lead collimator with a 2-cm square hole and 50-cm thick will stop the electron beam and allow the tagged-photon beam to strike the liquid-hydrogen target. As shown in Fig. 4, the present CEA tagging system could be easily extended to tag the top 6 GeV of the bremsstrahlung spectrum at any incident electron energy up to 100 GeV. A stronger tagging magnet would improve the system but would certainly not be required for first-round experiments.

It is important to note that any incident electron energy can be used with the same tagging system. An incident electron which radiates a high-energy photon becomes a low-energy electron and is analyzed by the tagging system. At NAL the dominant source of momentum uncertainty in the tagged photon will be the energy spread of the incident beam.

V. TRIGGERING RATE

Detection of ρ mesons in the forward spectrometer is roughly 100% efficient so the counting rate can be computed from the 15-μb cross section. For 2 meters of liquid hydrogen the event rate per incident particle is $8.4 \times 10^{-6} \times 15 = 12.6 \times 10^{-5}$ ρ mesons per tagged photon. For 10^5 tagged γ rays per pulse, this gives 12.6 events per pulse or about 12 000 ρ mesons per hour. Clearly, a definitive experiment could be completed in a day or two.

For the recoil-proton trigger, which runs simultaneously with the vector-meson trigger, the detection efficiency is not 100%. The proton aperture is defined by a 2-foot high counter, 4 feet from the beam axis, giving 8% of the azimuth on each side of the H_2 target. This is 3 times the azimuth of the CEA photoproduction experiment. If the photoproduction cross section is constant with energy, then we can scale up the triggering rate of $1/10^6$ equivalent quanta observed in the CEA experiment by a factor of 3 for the azimuth, by a factor of 3.3 because we use a 2-m H_2 target, and by another factor of 3.3 because the m interval is increased by the factor of 10 increase in incident energy. Thus, we expect an event rate in the recoil-proton spectrometer of three detected recoil proton per 10^5 real photons. The recoil-proton triggering rate is thus about 1/4 of the vector-meson rate so that we expect about 3000 high-mass events per hour in addition to the vector mesons.

VI. DATA REDUCTION

With the data rates just discussed, on-line data analysis is a necessity. Fortunately, we have a complete, working on-line data analysis system for wire-chamber magnetic spectrometers, based on a 360/65 or an XDS Sigma 7 as a central computer. The programs are entirely in Fortran and thus can easily be modified for any other computer. We would expect NAL to supply a PDP-15 type small computer connected up in some way for limited access to a larger central computer.

We should be able to complete the off-line analysis of a 10^6 event experiment in about 6 months utilizing the equivalent of about 100 hours of 360/65 CPU time.

VII. COMPARISON AND COMPATIBILITY WITH MUON-SCATTERING EXPERIMENTS

Electrons are stable and are easily collimated by a few inches of lead. Hence, we expect the electron and photon beams to be quite clean and well collimated. This is in contrast to muon beams which have at least as many particles far outside the beam as inside it. Photon beams have one extra advantage over muon or electron beams. The incident particle is neutral and so does not leave stray tracks in apparatus placed directly in the beam. Because of problems of beam loading of detectors in charged beams and halo around muon beams, the maximum useable intensity of a muon beam will be 10^6 per pulse.

For studying deeply inelastic muon-proton scattering, nothing beats a muon beam. However, to learn about the hadronic electromagnetic interaction, a real photon beam is 2 to 3 orders of magnitude (!) superior to muons. Each incident muon is worth about 2.5×10^{-3} virtual photons so that a beam of 10^6 muons gives a total of 2.5×10^3 virtual photons. Hence, the proposed photoproduction experiment using only 10^5 photons per pulse gives 40 times the triggering rate. Furthermore the 10^5 per pulse incident photon-beam intensity is set by what the accelerator can produce and not by what the detector can accommodate. The proposed detector could easily accommodate a factor of 10 increase in photon flux.

In the photon experiment, the only particles appearing in the detector are hadrons which result from photons interacting in the target and walls. Triggering is easy and clean. In the muon experiment the entire apparatus is flooded with muons, $\sim 10^5/m^2$ over the whole detector. Triggering is much more difficult and has not even been mentioned in most of the proposals. Hence, we expect this photon experiment to be considerably simpler than any of the proposed muon experiments.

The apparatus proposed for this experiment is essentially identical to the Harvard muon-scattering proposal (29). The tagging system substitutes for the incident-muon spectrometer and the thick hadron filter required in the muon experiment is not used. It would, therefore, be greatly advantageous to have the tagged-photon beam and the muon beam come down the same beam line and into the same apparatus. The filter in the muon beam would be removed for photon running.

The muon experiment requires 800 hours to obtain 4×10^5 counts, while the tagged-photon experiment obtains 10^6 counts in 80 hours. This means that many high-statistics tagged-photon runs could be interspersed during an extended muon run. Presumably the photoproduction experiment would come first since it requires so little running time. The muon experiment could then tune up and run and when the data from the first photoproduction experiment had been digested; the muon experiment could be turned off for a few days and the second-round photoproduction could be performed.

VIII. CONCLUSION

It seems that a significant knowledge of the hadronic interactions of photons and vector-meson photoproduction at 50-100 GeV could be gained in a few days using a tagged-photon beam of intensity 10^5 per pulse derived from an electron beam of 10^7 per pulse with momentum resolution of $\pm 1/2\%$. Most of the magnets, scintillation counters, and wire chambers required for this experiment already exist and had been in use at the CEA. The apparatus for this experiment is nearly identical to the Harvard muon proposal and could be used for both experiments if a tagged-photon beam and a muon beam could be both brought down the same beam line.

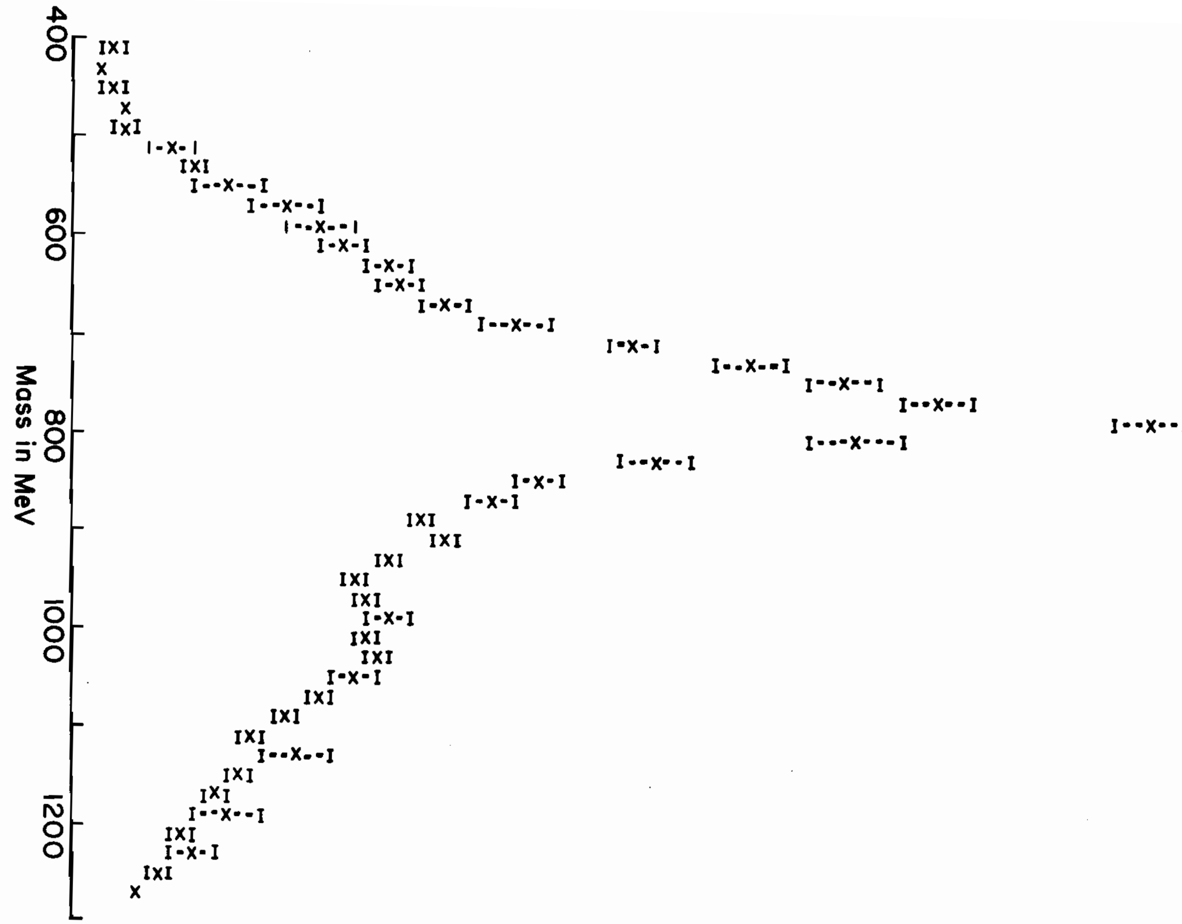

Fig. 1. Recoil proton missing-mass spectrum obtained by G. Gladding, J. J. Russell, M. J. Tannenbaum, G. Thomson, and J. M. Weiss in the CEA tagged-photon beam.

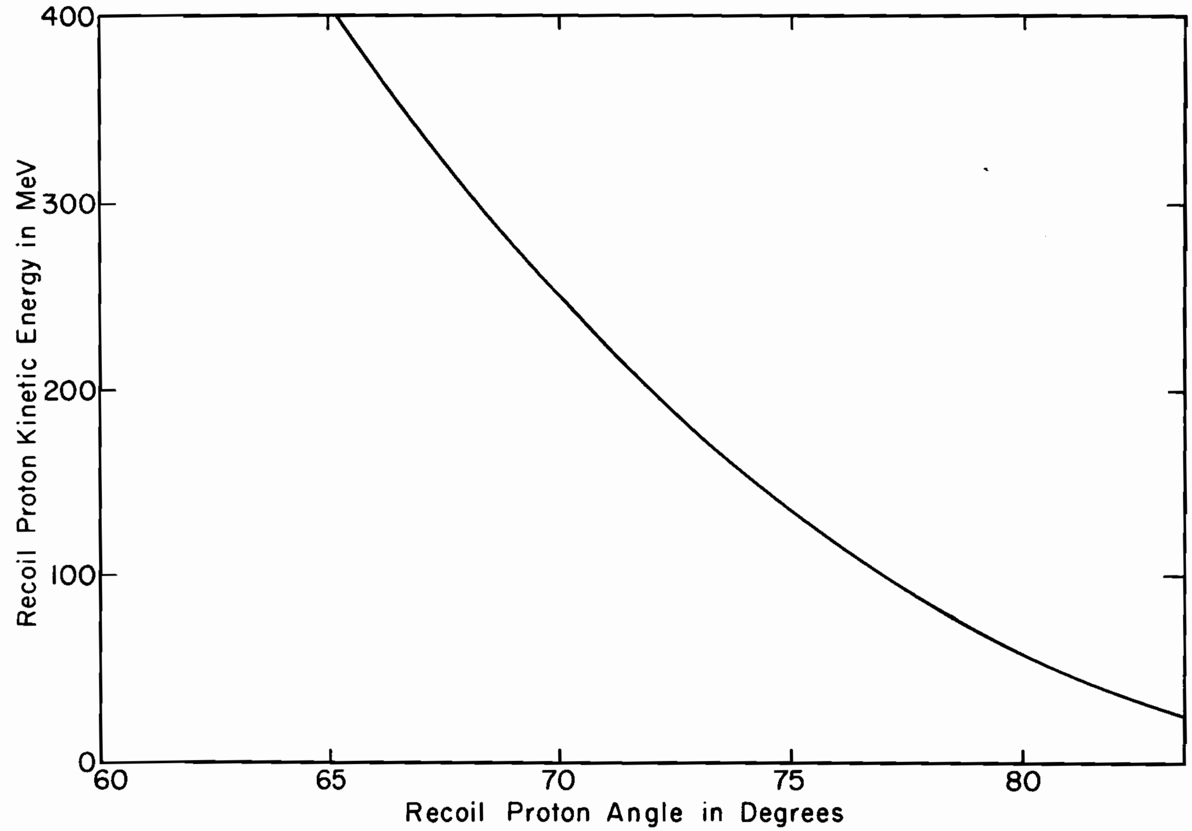

Fig. 2. Kinematics of the recoil proton for the scattering of an infinite-momentum particle on hydrogen.

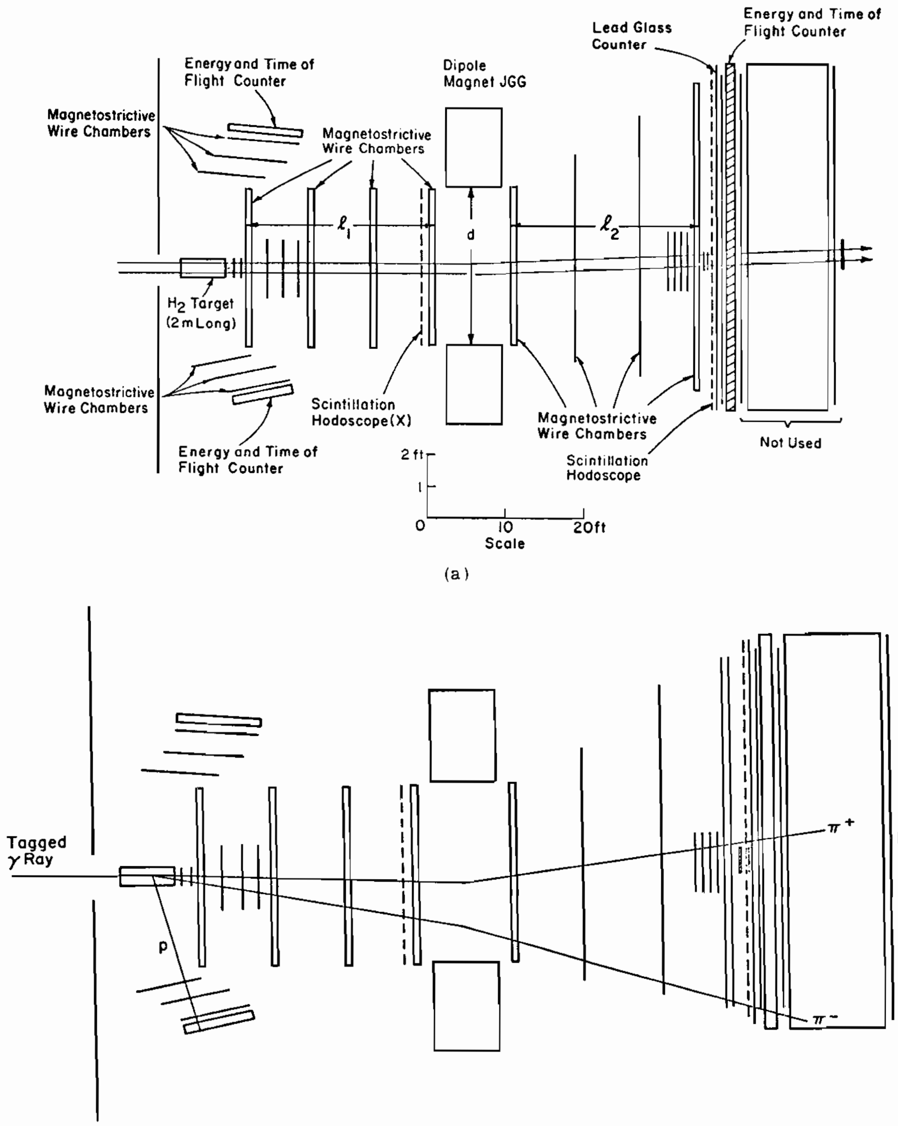

Fig. 3(a). Plan view of the Harvard muon scattering apparatus (Proposal 29), which could be used for photoproduction experiments. The hadron absorber at the end is not used. (b) Illustration of a 50 GeV ρ^0 meson in the detector.

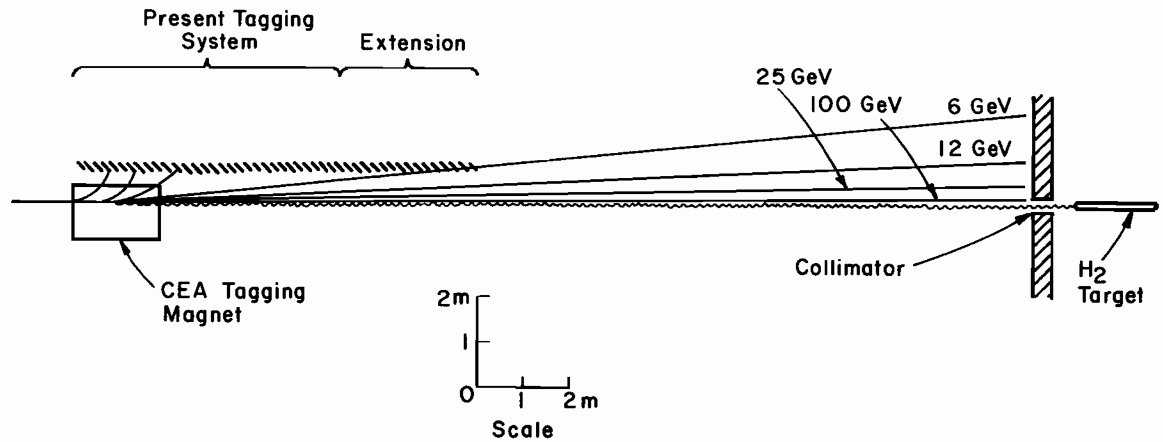

Fig. 4. Tagged-photon beam using the presently existing CEA "C" tagging magnet.