Photoproduction of Mesons and Gluonic Excitations
Using 6 to 12 GeV Photons

The Hall D Project

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Abstract

Data on the photoproduction of mesons with masses below charm threshold ($\approx 3\ \mathrm{GeV}$) are sorely needed to understand the spectrum of QCD mesons: conventional $q\bar{q}$ states, glueballs, hybrids and four-quark states. Data from hadroproduction (mainly with π beams), $\bar{p}p$ annihilations, J/ψ radiative decays and e^+e^- and $\gamma\gamma$ collisions have revealed richness in the meson spectrum but at the same time leave open questions as well. Photoproduction provides crucial complementary information to close the gap. The photon wears a number of hats: an electromagnetic probe, a virtual vector meson or an $s\bar{s}$ fluctuation. It is expected to be a rich source of spin-1 exotic hybrids and states with hidden strangeness. There is a woeful paucity of photoproduction data on mesons in the mass regime below $\approx 3\ \mathrm{GeV}$. In order to remedy this, photon beams are needed with ultimate energies in the range 10 to 12 GeV, with fluxes of $3 \times 10^8\ \gamma\text{'s}/\mathrm{sec}$ and duty factor close to one, with small spot size. A state-of-the-art hermetic 4π detector with excellent momentum and energy resolution and particle identification capabilities is required as well. A group of experimentalists and theorists (the so-called *8+ Group*) has held a series of four workshops during the last year to define the open questions and requirements of beam and detectors. A tentative plan is now in place to mount a first-stage detector to use photon beams of energies between 6 to 8 GeV likely to be available within the next few years. The goal of this detector will be to explore the meson mass range up to about 2 GeV. The detector will be upgraded as the available photon energies grow beyond 8 GeV to 12 GeV, to span a higher region of meson masses with more complete sensitivity to decay modes. More workshops are planned for the future. This report is a “snapshot” of where we are to date.

Introduction

In recent years, there have been exciting developments in light-quark spectroscopy. In their talks at this Workshop, C. Meyer and T. Barnes review the status of experimental and theoretical progress, respectively, in this field.

From experimental and theoretical studies of the meson spectrum in the mass regime below 3 GeV, it is now clear that the quark/gluon sub-structure of mesons is far, far richer than what might have been expected from the naïve (albeit initially successful) $q\bar{q}$ model. QCD predicts the existence of more complicated structures, such as glueballs (all glue – no quarks), hybrids ($q\bar{q}$ + valence glue or gluonic excitations) and 4-quark states (meson molecules or diquark-antidiquark), in addition to $q\bar{q}$ states. There has been real progress in QCD-inspired modeling and lattice gauge theory (LGT) calculation giving guidance on where to find glueballs and hybrids. Experiments have uncovered possible candidate glueball states as well as mesons with quantum numbers which are not consistent with $q\bar{q}$ states. Other evidence for non-$q\bar{q}$ mesons comes from the surfeit of mesons in the naïve $q\bar{q}$ picture (several $q\bar{q}$ nonets are overpopulated).

Fig 1 shows a map of light quark mesons. The L = 0 through L = 4 $q\bar{q}$ meson nonets are shown along with some of their radial excitations. The LGT predictions for the masses of glueball states and prediction for masses of hybrid states are also shown. Note that the J^{PC} combinations 0^{+-}, 1^{-+} and 2^{+-} cannot be formed from $q\bar{q}$ and are referred to as *exotic* quantum numbers. The threshold masses for various meson-meson molecular states are included as well. The scalar nonets (L=1 $q\bar{q}$) are examples of complex and overpopulated nonets. The isovector and isoscalar $a_o(980)$ and the $f_o(980)$ have masses and widths which are probably too low and their decay modes suggest that these may be $K\bar{K}$ molecules. Likely replacements for these states, with more appropriate masses and width have been observed. At least five isoscalar scalar states have been reported. Among these, the $f_o(1500)$ and $f_J(1700)$ are likely glueball candidates.

Experimental information to date has come from peripheral and central hadroproduction, $\bar{p}p$ annihilations and J/ψ radiative decays and e^+e^- and $\gamma\gamma$ collisions. This complementarity is essential since the details of production, as well as the decay of mesons, are essential in understanding their substructure. For historical and technical reasons, there is a dearth of information on the photoproduction of mesons with masses below 3 GeV.

There is a wealth of data from hadroproduction experiments and the vast bulk comes from experiments with π beams. Peripheral photoproduction is expected to lead to a very different category of meson excitations. The photon, as a probe, is richer than hadronic probes. It is an electromagnetic probe, but it can also be viewed as a vector meson (via vector dominance) or a $q\bar{q}$ fluctuation. Photons are also expected to be efficient in the production of spin-1 hybrids. In the beam energy range ideal for production of mesons below 3 GeV, the photon can be viewed as an $s\bar{s}$ fluctuation and thus expected to produce states rich in hidden strangeness. The photon beams expected at CEBAF are unprecedented in quality (energy, beam size, flux and duty factor), placing Jefferson Lab in a unique position to make an essential contribution to meson spectroscopy.

Photoproduction of Light Mesons - Beam Requirements

Energy

The message from Fig 1 is that the interesting mass regime for the study of light quark spectroscopy is from 0 to somewhat above 2.5 GeV. Charm threshold sets in around 3.0 GeV. Consider the photoproduction of meson X:

$$\gamma p \rightarrow Xp \qquad [1]$$

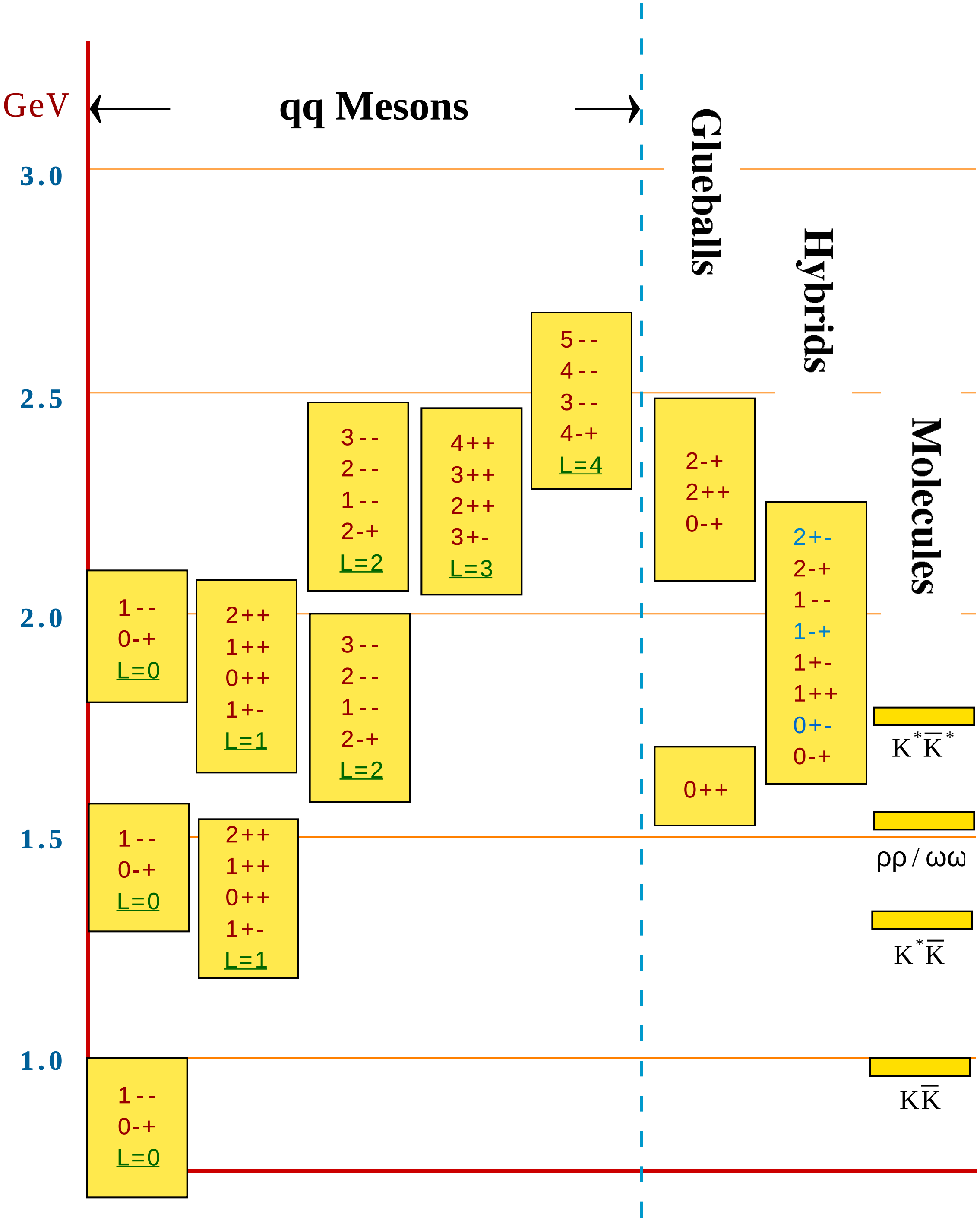

Fig. 1: A map of the mesons showing conventional $q\bar{q}$ states, glueballs, hybrids and meson-meson molecules.

For reaction [1], the maximum mass accessible for X for a given beam momentum (E_γ) is shown in Fig 2. The maximum X mass is given by $\sqrt{m_p(m_p + 2E_\gamma)} - m_p$ where m_p is the proton mass. To access $m_X = 2.5\ \text{GeV}$ requires $E_\gamma \approx 6\ \text{GeV}$ However X must be produced with sufficient boost in order for decay products to be detected with good efficiency. We will show that ideally $E_\gamma \approx 10-12\ \text{GeV}$.

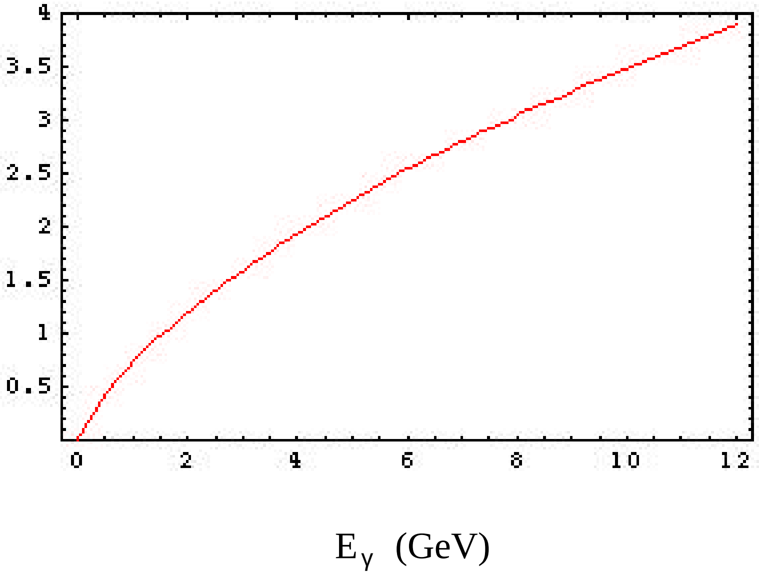

Fig. 2: Maximum mass of X produced in $\gamma p \rightarrow Xp$ as a function of incident photon energy.

Another consideration is the momentum-transfer characteristics of peripheral meson photoproduction. The momentum-transfer-squared from incoming photon to the outgoing meson, X is defined as:

$$t = (p_\gamma - p_X)^2 \qquad [2]$$

where p_γ and p_X are the momentum four-vectors of the photon and meson X. The cross-section dependence on t can be approximated by:

$$\frac{d\sigma}{dt} \quad e^{-a|t|} \qquad [3]$$

where $a \approx 4-8\ \text{GeV}^{-2}$, depending on X. For a given m_X, a minimum momentum-transfer-squared (t_{min}) is required and t_{min} depends on E_γ and m_X. Fig 3 shows the result of integrating Eq. 3 from t_{min} to t_{max} as a function of m_X for E_γ = 6, 8, 10 and 12 GeV assuming $a = 8\ \text{GeV}^{-2}$. Note that for $m_X = 2.5\ \text{GeV}$, the yield is strongly damped at $E_\gamma = 8\ \text{GeV}$ (even though this beam energy is well above threshold) by the t_{min} effect. The line shape given by a Breit-Wigner form for a $m_X = 2.5\ \text{GeV}$ resonance is also distorted at $E_\gamma = 8\ \text{GeV}$ by the t_{min} effect.

In order to probe the meson mass regime up to masses of $m_X \approx 2.5\ \text{GeV}$, photon beams of 10 to 12 GeV are required, implying electron beams of 12 GeV.

$$f = \int_{t(\min)}^{t(\max)} \frac{d\sigma}{dt}\,dt$$

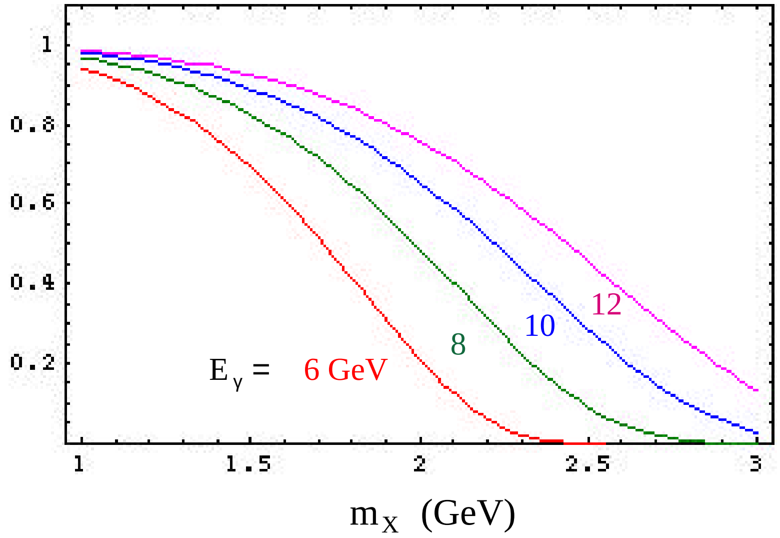

Fig. 3: Damping of meson yields as a function of meson mass due to the t_{min} effect. The dependence of cross-section on |t| is given by eq. [3] with $a = 8\ \text{GeV}^{-2}$.

Flux Considerations

To carry out the photoproduction study proposed here, one needs to collect statistics which are comparable to those in hadroproduction with π beams. These statistics allow a partial wave analysis (PWA) in fine enough bins in meson mass (10 MeV) and |t|. Given that photoproduction cross-sections are typically lower by a factor α compared to hadroproduction, the photon fluxes required are at least two orders of magnitude larger than current pion beams. This sets the required flux at about $3\times10^{8}\ \gamma\text{'s}/\text{sec}$.

Beam Techniques

Various techniques are under consideration to produce photon beams. These include:

- tagged bremsstrahlung beams
- tagged coherent bremsstrahlung beams
- Compton backscattered laser beams

and are discussed in detail by R. Jones in these proceedings and in previous workshops.

The desired fluxes in the energy range $0.75\ E_{electron}$ to $0.95\ E_{electron}$ are obtainable using a 1 µA electron beam. Our preliminary Monte Carlo studies of kinematic identification of exclusive reactions (essential for the PWA) indicated the 0.25% to 0.1 % energy resolution is required. The latter is currently being achieved with the Hall B tagger. The flux of low energy photons passing through the target will produce e^+e^- pairs which will pass through the dipole spectrometer (see below). It is possible to transfer any circular polarization of the electron beam to the photon. However, in the hadronic processes being studied, linear polarization is required for the PWA.

The coherent bremsstrahlung technique is also an attractive possibility. This coherent bremsstrahlung refers to the enhancement which occurs inside a crystal radiator when the momentum transfer from the electron to atom matches the reciprocal lattice vector. Collimation can be used to suppress the incoherent component and narrow the energy spread of the coherent photon spectrum. It is possible to achieve an average linear polarization of 15% in the desired energy range. The polarization decreases to zero at the endpoint, decreasing like $\left(E_\gamma - E_{\text{endpoint}}\right)^{-2}$.

Finally, the beam produced using Compton backscatter of a laser has the attractive feature that the beams are free of low-energy contamination. In addition, 100% linear polarization is available at the endpoint. Unfortunately, the photon beam energies obtainable are too low for our purposes. For example, even with a 100 µA electron beam at 12 GeV and 600 W frequency-doubled (257 nm) Ar laser with a cavity gain of 250, the maximum photon energy is 5.5 GeV with an order of magnitude less flux. Lasers with the specified parameters are not yet available but might be in a few years.

The Detector

General Considerations

Past workshops have studied detector subsystems appropriate for meson spectroscopy. These topics are also being examined in this workshop.

In order to establish the quantum numbers of meson resonances, it is essential to detect and identify their decay products. A proper spin analysis (PWA – partial wave analysis) requires the kinematical identification of exclusive reactions as well – it is essential to identify the baryon system recoiling against the produced meson. All this puts the following requirements on the detector:

- Measurement of the momenta of charged tracks, in all directions, with sufficiently good resolution.
- Determination of the mass of charged particles.
- Measurement of the energies of photons, in all directions, with sufficiently good resolution.
- Simultaneous determination of the production vertex and decay vertex of strange particle decays sufficiently good resolution.

A PWA requires that the acceptance of the detector for decays of resonances have no *holes*. There must be non-zero acceptance (or nearly so) over the entire angular range characterizing the decay for both detection, momentum or energy measurement and particle identification of individual particles and the complete reconstruction of the event. Most important, the acceptance must be well understood using Monte Carlo techniques.

Another consideration includes decays of meson into final state particles, like the η, ω and η' which have multiple decay modes including combinations of neutral and charged π's and/or photons. For example, consider the decay of a candidate resonant state into $\eta\pi$. The η can decay into $\pi^+\pi^-\pi^0$ or

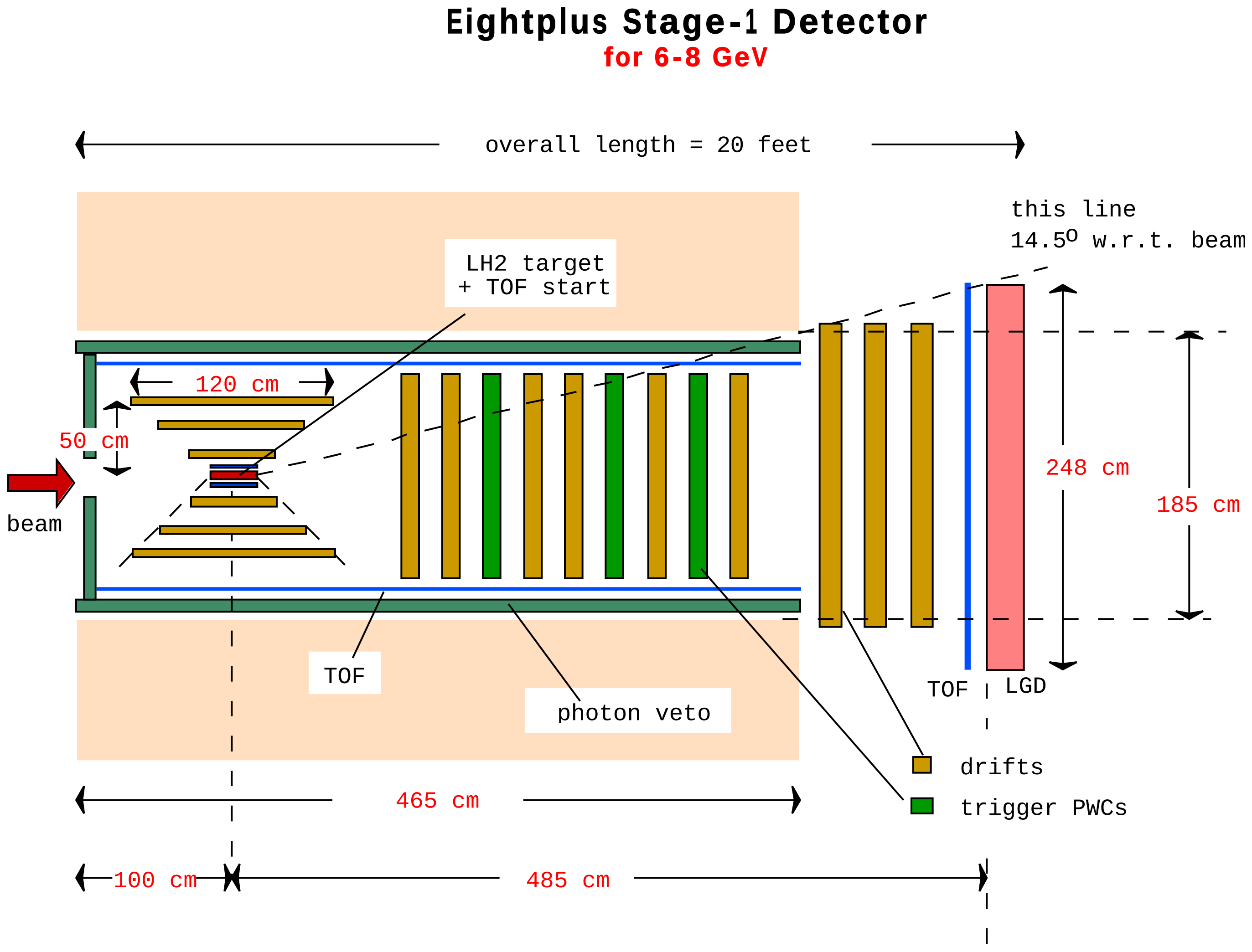

Fig 4: A possible layout for a Stage-1 detector. The target is inside a large solenoidal magnet. For higher beam energies the LGD will be moved downstream to allow for the inserion of a dipole spectrometer.

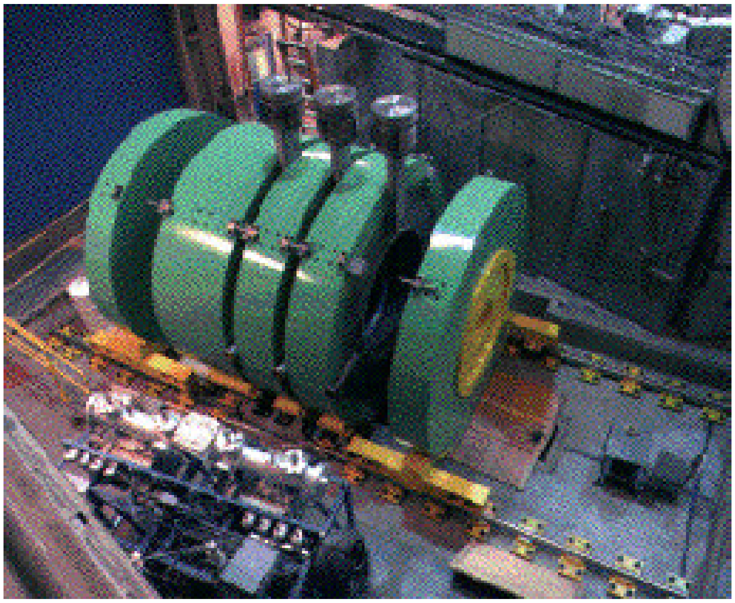

Fig 5: The MEGA/LASS superconducting solenoid being assembled prior to insertion of the MEGA experiment at LANL. Shown here are 3 of the 4 coils used in the LASS spectrometer at SLAC.

into 2γ. The detected decay products of the system are different in the two cases and the acceptance for the two cases will be different – but the PWA had better yield consistent results.

Staging the Detector

The acceptance, measurement/energy resolution and particle identification will depend on the beam energy. From a preliminary study of response of a detector design with respect to the above considerations, we are considering a configuration as shown in Fig 4 to operate with photon beam energies in the range from 6 to 8 GeV.

The detector consists of a large superconducting solenoid with a LH_2 target, tracking, time-of-flight (TOF) counters and a photon veto. All this is followed by more tracking, a forward TOF system and an electromagnetic calorimeter.

As the energy of the CEBAF machine grows beyond 8 GeV, this detector will be modified. A dipole spectrometer will follow the solenoid and the forward TOF will be replaced by a DIRC (detector for internally reflected Cerenkov light – a form of a RICH counter with a novel readout scheme). The lead glass electromagnetic calorimeter of the stage-1 design will likely be replaced and electromagnetic calorimetry will be installed in the target region, inside the solenoid, as well.

Solenoidal Magnet

The superconducting solenoidal magnet being considered for use in this spectrometer is the same magnet which was used for the LASS experiment at SLAC. This magnet was later moved to LANL for use in the MEGA experiment. In the MEGA configuration, one of the original four coils, was not used. A photo of the magnet coils, prior to insertion of the MEGA instrumentation and installation of associated cryogenics, is shown in Fig 5. This magnet was operated at LASS in an 11 GeV K^- beam.

Target

A 30-cm liquid hydrogen target will be positioned with its center approximately 1 meter from the upstream end of the solenoid. Provisions will be made to replace this target with a wheel of several nuclear targets for some part of the running. We will also study the option of a polarized target.

Tracking

The target will be surrounded by several cylindrical layers of drift chambers. The radius of the outermost cylinder is 50 cm. The length of the inner cylinders is determined by a 45° cone from the two ends of the target with axes along the beam. Planar chambers fill the remainder of the solenoid interior. Drift chambers will be used for track reconstruction. Three layers of PWCs will be interspersed to be used for charged particle multiplicity triggers.

The tracking within the solenoid alone will allow for measurement of charged tracks with angles (with respect to the beam direction) of greater than 10° with reasonable resolution. The solenoid system is capable of measuring tracks with angles down to 5°, albeit with a rapid deterioration. For smaller angles, a forward dipole spectrometer is needed. In our resolution studies, we are assuming spatial resolutions achieved in current spectrometers.

Particle Identification with Time of Flight

For incident photon energies between 6 and 8 GeV, a TOF within and outside of the solenoid is adequate for π /K separation. This is based on Monte Carlo studies, assuming a time resolution of 100 ps. The system consists of a segmented scintillator barrel within the solenoid and a segmented wall of scintillator located in front of the electromagnetic calorimeter (see Fig 4). A cylindrical scintillation counter, placed just around the target, will provide the TOF start signal.

Electromagnetic Calorimetry

The calorimeter shown in Fig 4 is the 3000-element lead glass calorimeter used in E852 at Brookhaven. It will be restacked to match the aperture of the current solenoid. A smaller (700-element) detector, with the same segmentation, is currently being used in the Radphi experiment located downstream of the CLAS detector in Hall B. In recent running with 4 GeV electrons, we are successfully reconstructing $\omega \rightarrow \pi^0\gamma$. Other calorimetry options are also being examined.

Dipole Spectrometer

A dipole magnet has been located at Fermilab which would be appropriate for use here. It was used in the tagged photon lab there. It has a central field of 10 kG, an aperture of 32 in, a width of 72 in and is 82 in long. The flux of low-energy photons in the bremsstrahlung beam will lead to e^+e^- pairs which will be contained in the beam pipe passing through the solenoid but will open in the bend plane of dipole leading to a "sheet of flame." We will either deaden detectors in the bend plane or use active or passive flux exclusion techniques to shield the beam region from the magnetic field of the dipole.

Progress to Date

Hall D Location and Beamline

Fig 6 shows the latest option being considered for a beamline and building to be located at the stub in the North Linac. It shows an above ground tagger building and experimental hall. This design, proposed by R. Carlini and others, shows an above-ground tagger building and experimental hall. At this location, the highest energy beam (eventually 5.5 passes) would be delivered to this hall.

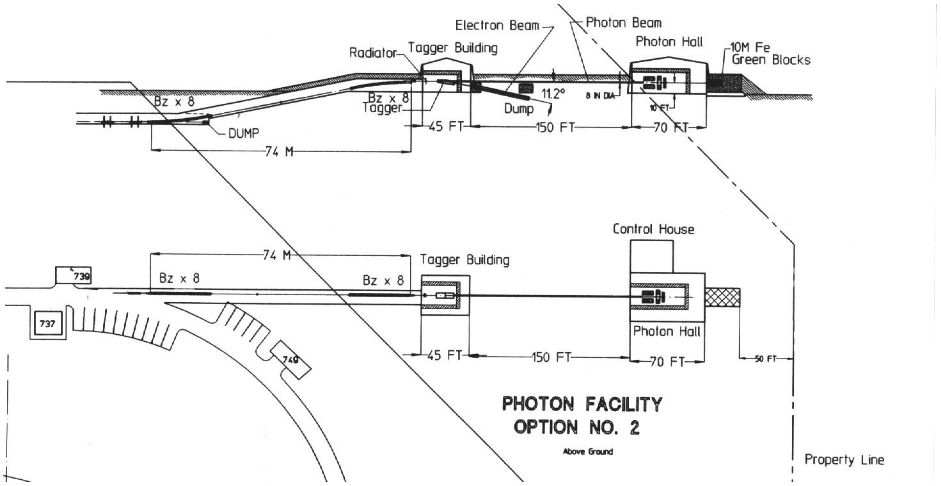

Fig 6: Possible location at of a beamline and experimental hall (Hall D) at the end of theNorth Linac.

Workshops

Workshops on the Physics of Photoproduction have taken place during the last year at:

- Indiana University (July 14-16, 1997)
- North Carolina State University (November 13-15, 1997)
- Carnegie Mellon University (March 13-15, 1998)
- Indiana University (mini-workshop May 13-16, 1998)

At least two workshops are being planned for Fall, 1998.

A Collaboration

A collaboration of physicists has formed from:

- Carnegie Mellon University
- University of Connecticut
- Florida State University
- Indiana University
- Institute for High Energy Physics (Serpukhov)
- University of Pittsburgh
- Rensselaer Polytechnic Institute

Other institutions are considering participation in this effort. There is also a consortium of theorists working in this collaboration. The goal of this group is to submit a proposal for a Stage-1 experiment, using 6 to 8 GeV photons, for consideration by the PAC in early 1999. A full Design Report is under preparation.

For a discussion of technical details and other possible physics, visit the 8+ Working Group Website:
`http://dustbunny.physics.indiana.edu/~dzierba/Eightplus/`