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MEASUREMENT OF THE TOTAL PHOTOABSORPTION
CROSS SECTION ON H, D, C, Cu, AND Pb FOR
PHOTON ENERGIES FROM 26 to 125 GEV

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Submitted by

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PROPOSAL SUMMARY

1. Title of Experiment: Measurement of the Total Photoabsorption Cross Section on H, D, C, Cu, and Pb for Photon Energies from 26 to 125 GeV.
2. Experimenters:
 - D. Caldwell
 - V. Elings
 - A. Greenberg
 - B. Kendall
 - R. Morrison
 - F. Murphy
 - Graduate Students

3. Summary of Experiment

We propose to measure the total photoabsorption cross section for hadron final states on H and D for photon energies from 26 to 125 GeV. In addition, we wish to measure the A dependence of the cross section by making measurements on C, Cu, and Pb at photon energies of 32 and 65 GeV. The measurements will be made to a statistical accuracy of 1% in photon energy bins of 5 GeV. The experimental method using counters is similar to that we used at SLAC to measure total photoabsorption cross sections for photon energies from 4 to 18 GeV.

4. Equipment Required

- a. Modification of the 3.5 mrad beam so that it can be used as an electron beam.
- b. A 120" x 18" x 4" H magnet capable of 18 kg (tagging magnet).
- c. A 240" x 18" x 4" H magnet capable of 18 kg (ditching magnet).
- d. A liquid H (D) target with a cell 10 cm in diameter and 1 m in length.

5. Running Time

298 hours of prime time (10^{13} protons/pulse) for data taking and equipment checkout and 100 hours of low-priority time for beam checkout.

INTRODUCTION

From the results of Serpukhov it is clear that unexpected results are certain to occur at NAL energies. Clues to the understanding of the elementary particles are, as in the past, likely to turn up in the study of electromagnetic interactions and we feel strongly that photon physics should be included in the first round of NAL experiments. The total photoabsorption measurement which we propose here is one of the two photon experiments which we feel is straightforward and simple and which will quickly show the gross features of high energy photon physics.

Measurements of total photoabsorption cross sections have recently provided fundamental information on the nature of the photon and of the electromagnetic interaction, but further measurements at much higher energies are needed.

To illustrate the importance of this type of measurement, we shall list briefly some of the theoretical information which has been obtained from recent experiments, particularly the one done by the Santa Barbara group at SLAC. By utilizing different nuclear targets, the A dependence of the photoabsorption cross section was obtained.¹ If the photon produced interactions of only electromagnetic strength, every nucleon in each nucleus would have an

equal probability of absorbing a photon, and the cross section should be proportional to A . However, it was found that the nucleons shadowed each other, just as would be the case for a strongly-interacting particle incident. The results can be explained in terms of the coherence of a photo-produced ρ meson wave and the incident photon wave. The results are in qualitative but not quantitative agreement with the vector-meson-dominance model (VDM). Both the A dependence and a comparison of the proton-photoabsorption cross section with ρ photoproduction from hydrogen yield ρ -nucleon coupling constants on the photon mass shell which differ by $(29 \pm 7)\%$ from the e^+e^- colliding beam value on the ρ mass shell.

Our proton and neutron cross sections up to 18 GeV differ from each other but appear to be approaching the same value at infinite energy.² The data can be fit by a simple Regge-pole model involving the P , P' , and A_2 , with the ratio $A_2/P' = 0.19 \pm 0.04$ giving the ratio of isovector to isoscalar exchange in the energy-dependent part of the cross section. Using an energy dependence implied by A_2 and P' exchange (approximately the inverse square root of the energy), one can also utilize the data in Compton-scattering dispersion relations. In this way it has been found³ that the dispersion relations can be satisfied provided that the real part of the forward amplitude has an additive constant, consistent with the Thomson limit, which could correspond to a fixed pole of $J=0$.

Finally, it is interesting to note that the proton total cross section even has cosmological implications. Because photons from the 2.7°K black-body radiation remaining from the initial stages

of the expansion of the universe can collide with very high energy protons to produce other hadrons, the lifetime of such protons in the universe is shortened. The intensity and shape of the high energy cosmic ray spectrum then reflects the magnitude and energy dependence of the proton photoabsorption cross section.

Since the above results come from existing experiments up to 18 GeV, what additional information can be obtained by extending the measurements at NAL? First, with regard to the total cross sections for complex nuclei the degree of validity of VDM is still not clear. If our measurements are compared with the ρ -photo-production results of the DESY group, there is fair agreement with VDM, but if they are compared with the Cornell or SLAC measurements the photon would have to be about half vector dominant. In the latter case one explanation of the results could be the existence of one or more very heavy ($\gtrsim 3$ GeV) vector mesons which could produce nucleon shadowing only for higher energy photons than have so far been used. The presence of such vector mesons would then show up clearly in the energy dependence of the A dependence. Even if the SLAC and Cornell measurements are not correct, it is still true that, relative to what is expected from the e^+e^- colliding beam ρ -nucleon coupling constant, we have observed too little shadowing in the nuclei, and this discrepancy could be explained by the existence of very heavy vector mesons. It is then very important to clear up this point, both in establishing the validity of VDM and for the sake of finding such heavy vector mesons.

Next, with regard to the energy dependence of the nucleon

cross sections, while our (γ, p) and (γ, n) cross sections extrapolate to a common value at infinite energy, similar extrapolations for hadron-hadron cross sections unexpectedly have been shown to be incorrect by the Serpukhov data.⁴ Not only will it be extremely interesting to find out if photoabsorption cross sections display the sort of energy dependence shown by π^- , K^- , and \bar{p} cross sections at Serpukhov, but also such results could negate many of the conclusions given above. For instance, the existence of a fixed pole from the Compton scattering dispersion relations is very dependent on the correctness of the $a+bS^{-1/2}$ form of energy dependence. The conclusion regarding the A_2/P' ratio could also be changed, and the simple Regge-pole picture which is successful for the current data might have to be discarded.

Thus qualitative changes may occur at high energies which give a completely different energy dependence from that which now appears to exist. Even if there is no qualitative change in slope with energy we can do a much better job at NAL of determining the asymptotic values of the cross sections than we were able to do at SLAC. Not only will the energy be higher, but, as will be shown below, measurements can be made with nearly an order-of-magnitude smaller errors than were obtained in the SLAC experiment. Such measurements can then serve as a much more severe constraint on theory. In short, to understand the very high energy domain the photoabsorption total cross sections will be a necessary ingredient, and because of our past experience we believe the UCSB group is best qualified to provide this essential information. The experiment is relatively simple and $\pm 1\%$ cross sections will be available

on line.

EXPERIMENTAL METHOD

The experimental method which we propose is similar to the one which our group used at SLAC to measure the γ -nucleon total cross sections from 4 to 18 GeV on H, D, C, Cu, Pb. The layout of the experimental equipment is shown in Fig. 1. The general idea of the experiment is quite simple; photons of known energy are produced by electron tagging, these photons impinge on a target, and photon absorptions in the target are detected by 1) the absence of a photon or e^+e^- pair emerging from the target and 2) the appearance of hadrons or their decay products coming from the target.

The main problem with measuring a photoabsorption cross section is to avoid including in that cross section electromagnetic events such as pair production and Compton scattering. This electromagnetic background is about 100 times the absorption cross section in deuterium and 800 times in Pb and so one must be very careful to discriminate against it. In the experimental method which we propose, the separation of hadronic events and electromagnetic events is done geometrically by taking advantage of the fact that products from electromagnetic events leave the target at much smaller angles (typically m_e/E_γ) than hadronic products from absorption events. Photons which do not interact in the target and e^+e^- pairs produced in the target pass through a hole in the hadron detector, S2, and register in the total absorption

shower counter, S1. Photons which are absorbed in the target produce no signal in S1 and create hadrons which are detected in S2. We had good success with this experimental method at SLAC and, from our experience, feel that there will not be any major problems in doing the experiment at NAL. Actually, because of the 1,000 times better duty cycle at NAL, the experiment should be significantly easier than the one we did at SLAC. In the following sections we describe, in some detail, the various parts of the experimental apparatus.

A. Beam

In order to do this and other photon experiments at NAL, we propose, as others have, that the 3.5 mrad beam be designed so that it can be operated as an electron beam. The method for doing this has been investigated by Toner,⁵ Heusch,⁶ and Diebold and Hand.⁷ They proposed that a sweeping magnet be placed in the beam line before the first beam transport element to sweep out all charged particles. Gamma rays from the decay of π^0 's strike a 0.3 r.l. converter farther downstream to produce e^+e^- pairs. The electrons are produced with a typical transverse momentum of 1 MeV/c which multiple scattering broadens to 7 MeV/c. Pions produced by neutrons in the radiator have transverse momentum of ~ 300 MeV/c and therefore appear to come from a diffuse source and can be removed by collimation farther down the beam. The beam is tuned for negatives to avoid the large flux of protons produced by the neutrons in the radiator.

The expected π^0 , γ ray, and electron yields are shown in

figure 2. The π^0 yield is assumed to be the average of the π^+ and π^- yields calculated by Awschalom and White.⁸ The γ ray and electron yields are calculated neglecting the change in angle in the decay of the π^0 and in the production of the e^+e^- pair. These yields are taken from the 1969 Summer Study Report of Diebold and Hand.⁷ We have recalculated these yields and agree with their numbers. Also shown in figure 2 is an estimate of the π^- contamination in the beam as designed by Barish.⁹ Up to 140 GeV it is estimated that the π^- contamination will be less than 10^{-3} of the electrons.

It is difficult at the present time to be more specific about the beam because the 3.5 mrad beam is still in the design stage. We are aware that the addition of a sweeping magnet in the front of this beam may be a serious perturbation and one of us (R. Morrison) while attending the 1970 Summer Study will investigate the details involved in making the sweeping magnet compatible with the rest of the beam.

B. Tagging System

The electron tagging system is shown in figure 3. The electron beam strikes a 0.002 r.l. radiator producing bremsstrahlung in the forward direction. In order to eliminate the effects of any beam halo, we propose to put a veto counter A'_0 , shown in Fig. 1, around the radiator. The electrons are bent by an ordinary H magnet with a 4" x 18" x 120" magnetic volume. The bending angle, and therefore the momentum of the electrons which have radiated, is determined by a set of 6 tagging channels, each of which corre-

sponds to bins of 5% in photon energy, i.e. for an incident electron energy E_0 , the tagging channels correspond to photon energies from $0.94 E_0$ to $0.64 E_0$ in 5% bins. Each tagging channel will be composed of a two-counter telescope with the second counter being a crude shower counter to insure that the particle being tagged is indeed an electron and not a negative particle which is produced in the radiator by the π^- 's in the beam.

It was found when we did the total photoabsorption measurements at SLAC that a concern in the experiment was the occurrence of a signal from the tagging system without the production of a photon. Such an event could happen, for example, if the incident electron produces a trident ($e^+e^-e^-$) in the radiator with one of the electrons going into the tagging system. The reason that such events, or false tags, are of concern is that with a tagging signal and no photon, it appears to the shower counter, S1, that a photon was absorbed in the target. One must then rely on S2, the hadron counter, to indicate whether the event was a false tag or a real absorption of a photon. If the number of false tags is high, accidental coincidences between false tags and interactions in S2 can become a source of serious error. This is not as important at NAL due to the much better duty cycle. Also, one would like to check the experiment by measuring the photoabsorption cross section using only the shower counter, i.e. counting an absorption as a tagging signal with no shower in S1. In this absorption check measurement the false tags have to be separated out by doing target-empty and target-full runs. If the occurrence of false tags is

much greater than the occurrence of real absorptions, this subtraction does not give, statistically, a very good number. Without taking special precautions, we found at SLAC that the ratio of false to real tags was 0.05 and the ratio of false tags to real photoabsorptions in deuterium was 50.

The number of false tags was decreased by placing anticounters in strategic positions downstream of the radiator to veto tags accompanied by another charged particle. These anticounters A_1 , A_2 , A_3 shown in Fig. 1 decreased the false tag rate by more than a factor of 10 at SLAC. At NAL, these anticounters will also help to veto events in which a π^- interacts in the radiator.

One of the disadvantages of using a negative beam is that knock-on electrons can make false tags. We have calculated these effects and find that at NAL energies electron-electron scattering will contribute less than 0.1% false tags except at the lowest beam energy in the highest photon channel, where the worst case is about 1%. Another contribution to false tags, not present at SLAC, is caused by the Dalitz pairs and correlated photons from the interaction of the π^- 's in the beam ($\pi^- \rightarrow \pi^0 \rightarrow \gamma e^+e^-$). A .002 r.l. copper radiator is only 2.4×10^{-4} of a collision length so that the $< 10^{-3}$ pion contamination cannot give more than 0.01% false tags. We believe that the ratio of false tags will be better than the 0.3% of the SLAC experiment. Since the instantaneous count rates will be lower by about a factor of 50, we then expect accidentals to be $< 0.1\%$ and $< 0.5\%$ for D_2 and Pb targets, respectively.

We have chosen the geometry of the tagging system such that

none of the tagging counters is less than 3" in size. The reason for this is that we anticipate that the size of the electron beam at the tagging system will be about 2",¹⁰ and it makes little sense to have the tagging counters smaller than the size of the beam. We have chosen not to tag more than 30% of the bremsstrahlung beam in order to be able to optimize the hadron counter geometry with energy. The distance between the target and the hadron detector must be chosen so that products from electromagnetic events go through the hole in the detector, whereas at least one π from forward-produced ρ^0 's does not go through the hole. The opening angle of these products vary with the photon energy and so the distance between the target and the hadron detector must vary directly with the photon energy. If we tagged more than 30% of the bremsstrahlung beam, we feel that the range of photon energies would be too large to pick an optimum position for the hadron detector. Immediately downstream of the tagging system is a 240" long magnet (or two 120" long magnets) to bend the main electron beam away from the rest of the experiment into a beam dump.

C. Target

It is proposed that the target material be varied from H to Pb, more specifically H, D, C, Cu and Pb. The targets should be about 0.1 r.l. thick in order to minimize multiple scattering of electron positron pairs produced in the target and to keep the photon attenuation low. The H target will be about 1 m. long and ~ 10 cm in diameter with thin windows on the ends. The same target would be filled with deuterium.

As has already been mentioned, the distance between the target and the hadron detector must be varied as the photon energy varies. Because the electron beam will be fairly large and have a large divergence, $\sim \pm 1.5$ mrad, we propose that S2 be stationary with the beam focused on the hole in the counter array. The reason for this is explained in the next section. In order to vary the distance between the target and the hadron counter, we propose that the target be movable in the direction of the beam line. The target, as explained in the next section, will need to move through a total distance of about 15 meters in order to measure photoabsorption cross sections over the energy range of 30 to 125 GeV. This moving of the target is no problem for the solid targets of C, Cu, and Pb but may present a difficulty for the liquid target. We have, however, used such a moving liquid hydrogen assembly at the Lawrence Radiation Laboratory.

If wide-angle bremsstrahlung is produced in the .002 r.l. radiator, there is a chance that the photon can strike S2 directly, creating what appears to be an absorption in the target. To veto these few events an anti-counter, A_0 , with a hole in its center is placed in front of the target. This counter is a shower counter consisting of alternate layers of lead and scintillator and will be more than 99% efficient for vetoing photons which do not go through the hole.

D. Hadron Detector and Total Absorption Shower Counter

As has been described briefly above, downstream of the target there is a counter array whose function it is to decide if 1) the

photon is absorbed in the target or 2) if the photon traverses the target unaffected or simply interacts electromagnetically in the target. The counter array consists of two main parts, a high-resolution total-absorption shower counter, S1, to detect electromagnetic products emerging from the target, and a hadron counter, S2, to detect hadrons and their decay products emerging from the target. The separation of the electromagnetic events and hadronic absorption events is done mainly by geometry. The electromagnetic products, most of which are e^+e^- pairs produced in the target, have typical opening angles of m_e/E_γ where m_e is the mass of an electron. The hadron detector has a hole in it through which these electromagnetic products pass and strike the total absorption shower counter, which measures their total energy. The angle subtended at the target by the hole in S2 is made small enough so that hadrons resulting from photon absorptions in the target have a small probability of going through the hole. The hadronic reaction which determines the size of the hole is diffraction production of ρ^0 's. This reaction accounts for about 12% of the total absorption cross section and one must make sure that the 2π 's from the decay of the ρ^0 cannot both go through the hole in S2. The typical angle at which these π 's emerge from the target is $m_\rho/E_\gamma = 23$ mrad for $\bar{E}_\gamma = 32$ GeV and 7 mrad for 105 GeV. To be safe, one would actually want the hole to subtend a smaller angle than this so that pion pairs with an invariant mass above 400 MeV do not get through the hole. Events in which the hadrons do pass through the hole in S2 are single pion photoproduction events in

the forward direction. These events, though, are a negligible part of the total photoabsorption cross section and can be ignored. At SLAC we found for a photon energy of 16 GeV, that if the hole in S2 subtended a half angle of $m_\rho/2E_\gamma$, the wide-angle e^+e^- pairs which did not go through the hole were 0.1% of the absorption rate for deuterium and $\sim 8\%$ for lead.

As shown in figure 4, the hadron counter S2 is divided into two parts, S2a and S2b, so that one can vary independently the inner and outer acceptances of the counter. The upstream counter, S2a, determines the outer acceptance whereas the downstream counter, S2b, determines the inner acceptance. S2b is fixed in position with the beam focused at the hole in its center. The reason for this is that the divergence of the beam, $\sim \pm 1.5$ mrad, is half of the angle subtended at the target by the hole in S2b at the higher photon energies. If the beam were not focused on the hole, it might become difficult to intercept small angle hadronic events in S2b, such as ρ^0 production, without intercepting part of the beam. The angle subtended at the target by the hole in S2b is varied by moving the target up and down the beamline. For a 12-cm-diameter hole in S2b, the distance to the target must vary from 5 meters at $\bar{E}_\gamma = 32$ GeV to 17 meters at 105 GeV. The target therefore must be able to move over a total distance of about 15 meters. The outer acceptance of the hadron detector is varied by having the counter S2a on a movable platform so that it can be moved between the target and S2b.

The hadron counter must be sensitive to both charged particles

and γ rays from π^0 decays. One would also want the detector to not be sensitive to low energy (below 1 BeV) electrons and γ rays, since the wide-angle electromagnetic products which hit S2 will in general be of low energy. We propose to construct the counters S2a and S2b of alternate layers of lead and scintillator, as shown in figure 4. We used a similar arrangement at SLAC with 4 layers of 2.5-cm-thick Pb and 1.2-cm-thick scintillator with each layer of scintillator being viewed by two photomultipliers, one at each end. By requiring either a fourfold coincidence between the planes, or a total pulse height (sum of the 4 planes) corresponding to a 3 GeV shower, we found that the counter was $99.6 \pm 0.4\%$ efficient for detecting hadrons emitted from the target for an incident photon energy of 16 GeV.

We feel that a similar detector would work well at NAL with two major changes: 1) the thickness of the lead layers would be increased from 2.5 cm to 3.7 cm to accommodate the higher energies at NAL and 2) we would separate the second layer of scintillator in S2a into 3 pieces as shown in figure 4. The reason for this separation is to obtain a measure of the angular distribution of hadrons striking the counter without having to move the counter closer to the target and taking the difference between successive measurements. We feel that this will greatly reduce the amount of time spent checking to see that the number of hadron events in which all particles miss the hadron detectors is negligible. As mentioned in the electronics section, the pulse heights from the separate scintillator planes in both S2a and S2b will be recorded

for each event or likely event so that the experiment can be "replayed" on a computer.

The total-absorption shower counter will consist of alternate layers of lead and scintillator. Each lead layer will be 1.5 r.l. ($\sim 3/8$ ") thick and there will be a total of 20 layers. The 20 layers of scintillator will be optically coupled together and viewed by two photomultipliers whose outputs will be summed together. The energy resolution of the counter at NAL energies will be more than adequate to reject electromagnetic events. A similar shower counter in our experiment at SLAC had a resolution of 10% fwhm at 12 GeV. Since the resolution goes as $E_\gamma^{-1/2}$, the resolution at NAL energies will be around 5% fwhm, which is equal to the uncertainty in photon energy due to the size of the tagging channels.

E. Effect of Pion Contamination in the Beam

A potential source of error is the 10^{-3} pion contamination of the beam. For each photon in the energy range of the tagging system we can expect $\sim 10^{-4}$ pion interactions in the radiator. If each of these gave a tagging signal and also a neutral hadron through the hole in A_0 we would have a 2% background due to the pions. This will be reduced by a factor of between 100 and 1,000 by the veto counter A_1, A_2, A_3 and by the requirement of a shower for the tagging signal.

F. Estimates of Other Errors

The estimated rates of data collection at energies up to

60 BeV are at least 2×10^4 events/hour for a one-meter D target. At the low energies we can perform the necessary checks with high precision. We estimate that systematic errors due to counter efficiency, geometrical effects, accidentals, electromagnetic contamination, target thickness, monitoring, etc. will be below 0.5%. We feel that the rates are such that we can acquire $\sim 1\%$ statistics in each 5% bin, or better than 0.5% for the 30% energy range at each beam energy setting. The errors for the measurements with complex nuclei should be $\lesssim 2\%$.

G. Electronics

A simplified schematic diagram of the electronics for the experiment is shown in figure 5. The electronics is essentially the same as that which we used at SLAC except for the PDP-15 computer which will enable us at NAL to calculate final cross sections on line.

A master trigger for the experiment consists of 1) a coincidence from one of the tagging-counter telescopes, 2) no signal from any of the anticounters, and 3) no large pulse in S1 or a "hadronic" signal from S2. This hadronic signal consists of either a four-fold coincidence between the planes of S2a or S2b or a pulse from the sum of all planes in S2a and S2b which corresponds to an energy deposition in the counter of $\sim 25\%$ of the incident photon energy. Such a requirement is very loose and includes false tags. The idea, though, is to trigger on loose criteria and let the computer make the decision as to whether the event was a photon absorption or not. When a master trigger occurs,

the pulses from the planes in S2a and S2b and from S1 are gated into analog-to-digital converters. For each event 11 pulses (6 from S2a, 4 from S2b, and 1 from S1) are digitized and temporarily stored until read into the computer. Other information read by the computer for each event is:

1. The tagging channel which fired.
2. The status of the discriminators connected to the S2a and S2b planes. These discriminators will be set at a level corresponding to one-half minimum ionizing.
3. The status of the discriminator connected to S1. This discriminator will probably be set around 2/3 of the incident photon energy.
4. Whether the total pulse height in S2 (a & b) was greater than 25% of E_γ .

Because the computer knows the pulse heights from S2a, S2b, and S1, the information in 2, 3, and 4 is redundant but serves as a check on the fast electronics. The computer will display a warning if the information is not compatible with the pulse height information. Every thousand events or so the computer will write the raw data (throwing out events which are definitely false tags) on magnetic tape so that the experiment can be replayed, if need be, at a later date. The computer, via a 10" CRT display, will show the pulse height spectra of the various counters, various correlations of the pulse height spectra* and the photoabsorption

*For instance, one way to identify wide-angle electron pairs which may strike S2b is to look at the correlation between the pulse heights in S2b and S1; if the event is a wide-angle pair the sum of the pulse heights will correspond to the incident photon energy.

cross section as a function of incident photon energy. After performing the analysis of the data from the SLAC experiment, we feel that we could program the computer such that it would give us on-line the total photoabsorption cross sections to an accuracy of 1%.

Several quantities are counted on 100 mc scalers and at the end of a run these numbers are read into the computer so that it can normalize the cross sections.

UCSB owns all of the electronics (including the computer) shown in the logic diagram and, therefore, will not need to borrow any from NAL.

RUNNING TIME REQUIRED

Table I lists the amount of running time required to measure the γ -nucleon total cross sections on H and D for photon energies from 26 to 125 GeV and on C, Cu, and Pb at selected energies. The times are based on: 1) the electron yields shown in figure 2, 2) a 0.002 radiation-length radiator to produce photons, 3) a tagging system which tags 30% of the bremsstrahlung beam such as the one in figure 3, 4) targets which are 0.1 r.l. thick, and 5) a statistical accuracy of 1% in photon-energy bins of 5 GeV. If no problems are encountered in using a thicker radiator, we may be able to extend the measurements to ~ 150 GeV on H and D.

The electron energies were chosen so that there would be an overlap from run to run corresponding to two tagging channels. It was assumed for the C, Cu, and Pb runs that the cross section goes like $A^{0.9}$, which it does at 16 GeV.

As shown in Table I, the measurements at the lower energies (electron energies from 40 to 80 GeV) go relatively quickly because of the large flux of electrons at these energies. This will enable us to check out our equipment and perform geometrical and rate dependence checks in a reasonably short period of time. This checkout time is listed in Table I.

The total time for data taking and checking the equipment is estimated to be 298 hours under the conditions mentioned above. We would need an additional 100 hours of low-priority time to check out the electron and photon beams.

TABLE I

Proposed Running Time

	40 (26-38)	50.8 (33-48)	64.5 (42-61)	82 (53-77)	104 (69-98)	132 (86-125)	Electron Energies (Photon) Energies
	1	1	2	4	13	54	Data taking
H	-	-	-	-	-	-	Checks (including MT target data)
	1	1	1	2	7	30	
D	10	-	10	-	20	-	"
	2	-	-	6	-	-	"
C	-	-	-	-	-	-	
	6	-	-	25	-	-	
Cu	-	-	-	20	-	-	"
	12	-	-	50	-	-	
Pb	20	-	-	-	-	-	"

Total = 298 hours

FOOTNOTES

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8. M. Awschalom and T. O. White, Secondary Particle Production at 200 GeV, National Accelerator Laboratory Report FN-191, June 9, 1969.

9. B. C. Barish, A 3.5 Mrad High-Intensity Beam, National Accelerator Laboratory 1969 Summer Study Report SS-30, Volume I, p 55.
10. Klaus Pretzel, private communication.

FIGURE CAPTIONS

- Figure 1. Layout of the experimental equipment. The drawing is not to scale but a few dimensions are shown on the diagram.
- Figure 2. Expected π^0 , γ , and electron yields for the 3.5 mrad beam modified for electrons. The yields are for 10^{13} interacting protons per pulse, a solid angle of $4 \mu\text{sr}$, and a momentum bite, $\Delta p/p$, of 5%.
- Figure 3. Scale drawing of the tagging system showing the positions of the 6 counter telescopes.
- Figure 4. Detail drawing of the hadron detectors S_{2a} and S_{2b} . Both counters consists of 4 alternate layers of lead and scintillator.
- Figure 5. Simplified electronics diagram. The 100 mc scalers and associated electronics are not shown, along with many detailed parts of the logic. Also not shown is a 2048 channel pulse height analyzer which will be used for counter checkout.
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SIDE VIEW - NOT TO SCALE

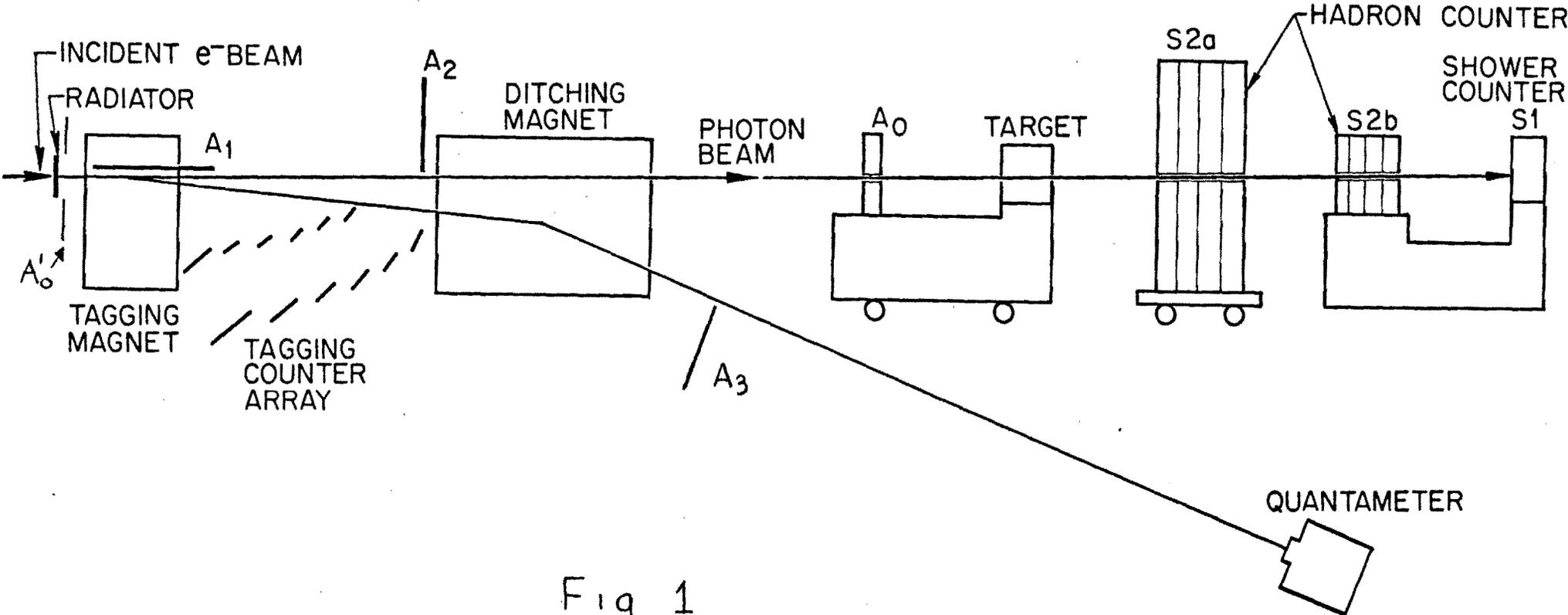
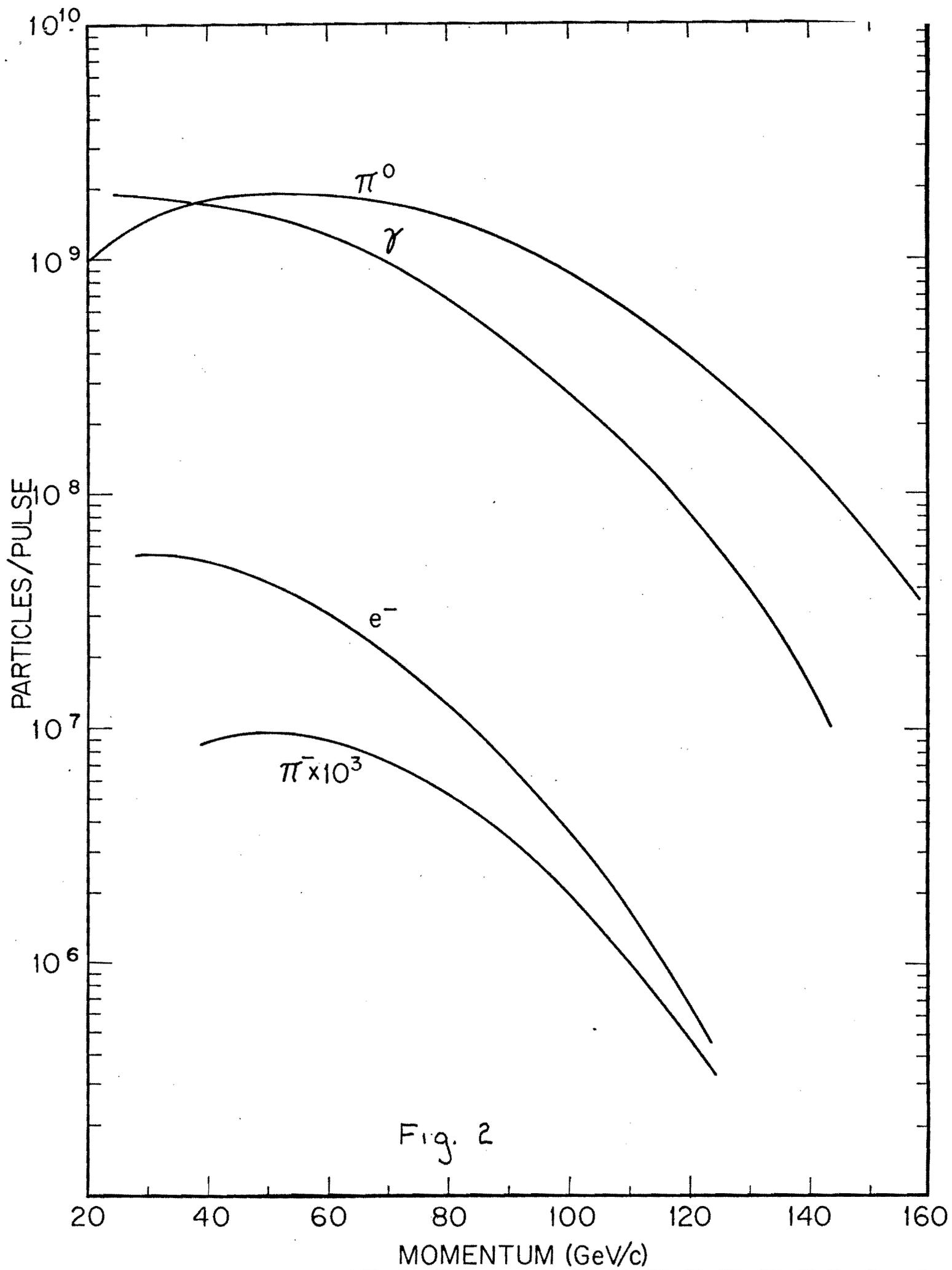


Fig 1



ELECTRON TAGGING SYSTEM

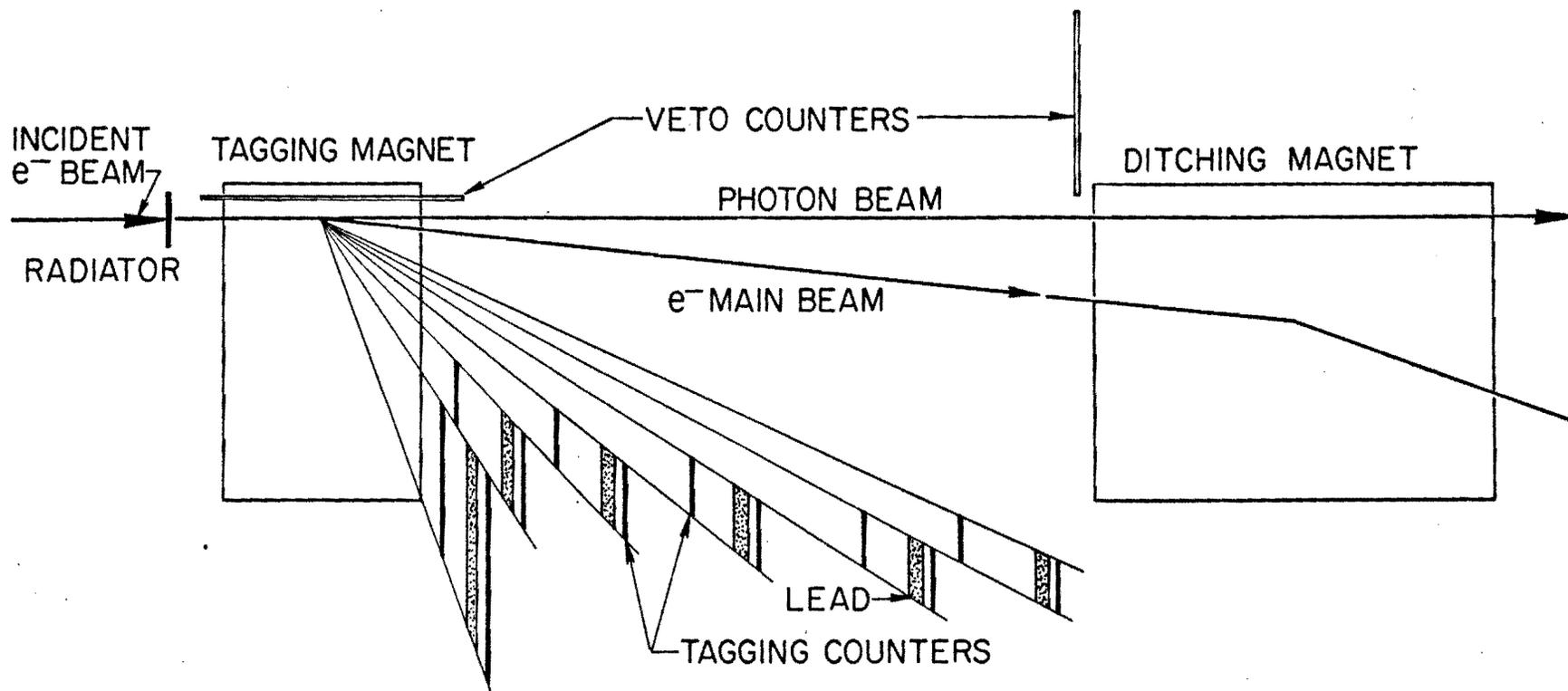
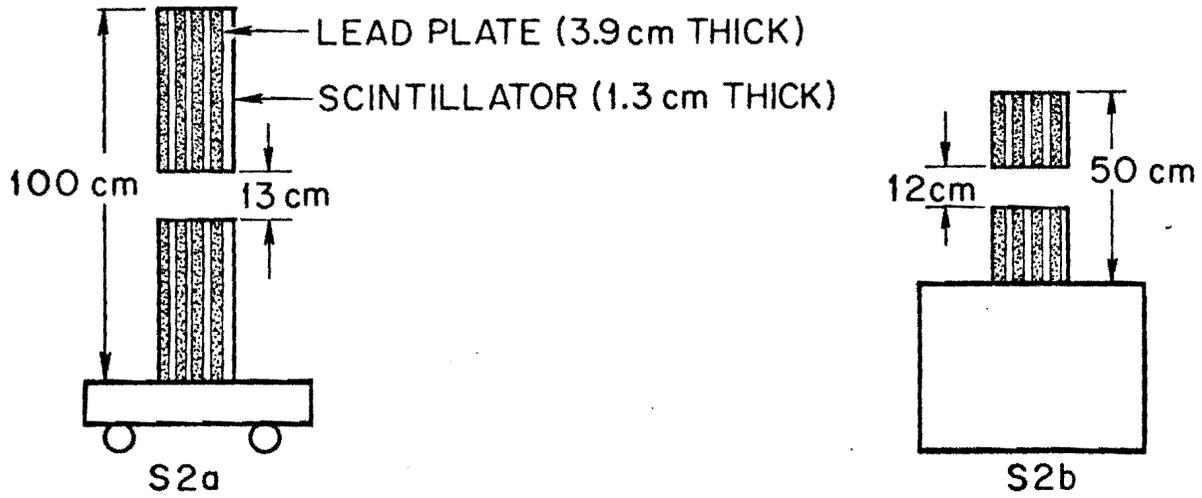
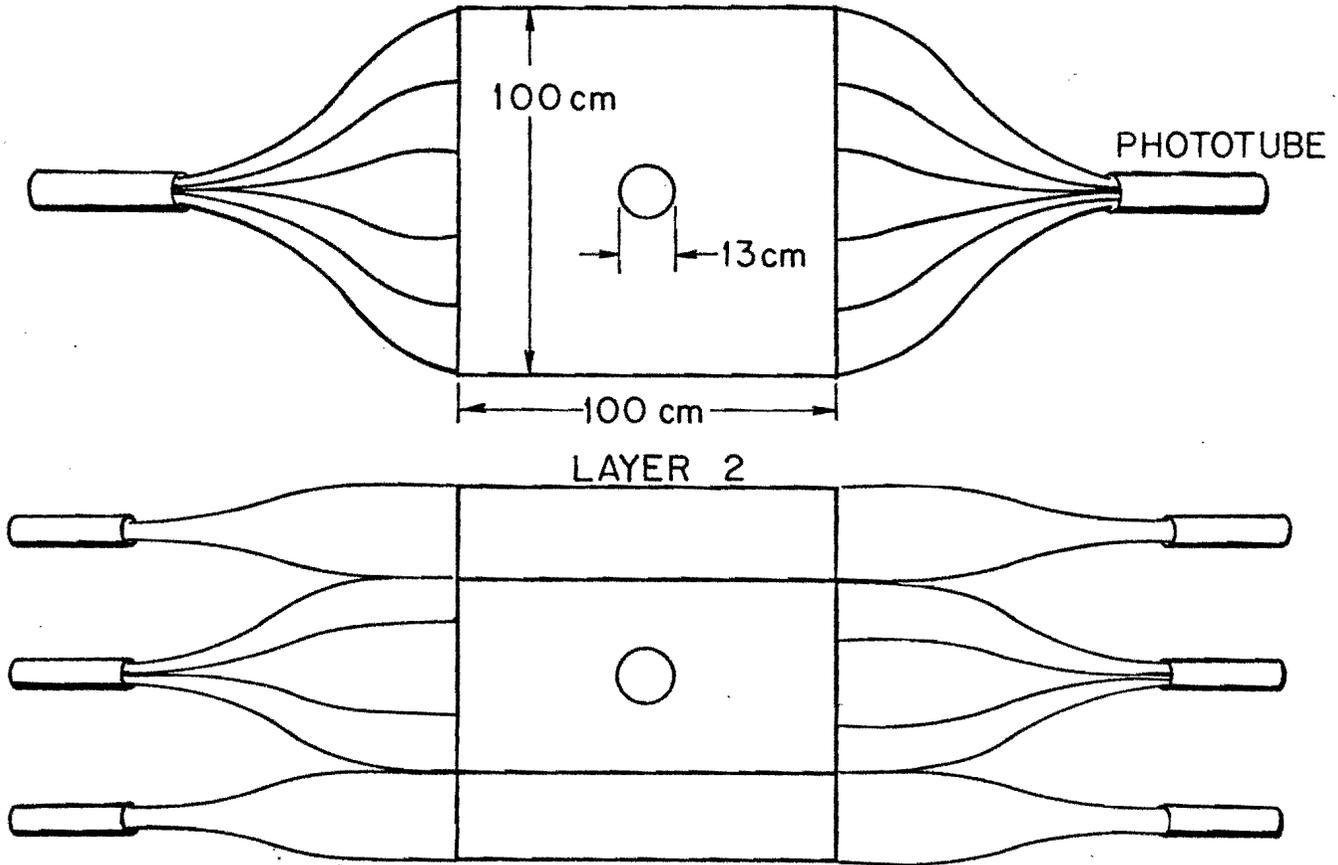


Fig. 3

HADRON DETECTOR

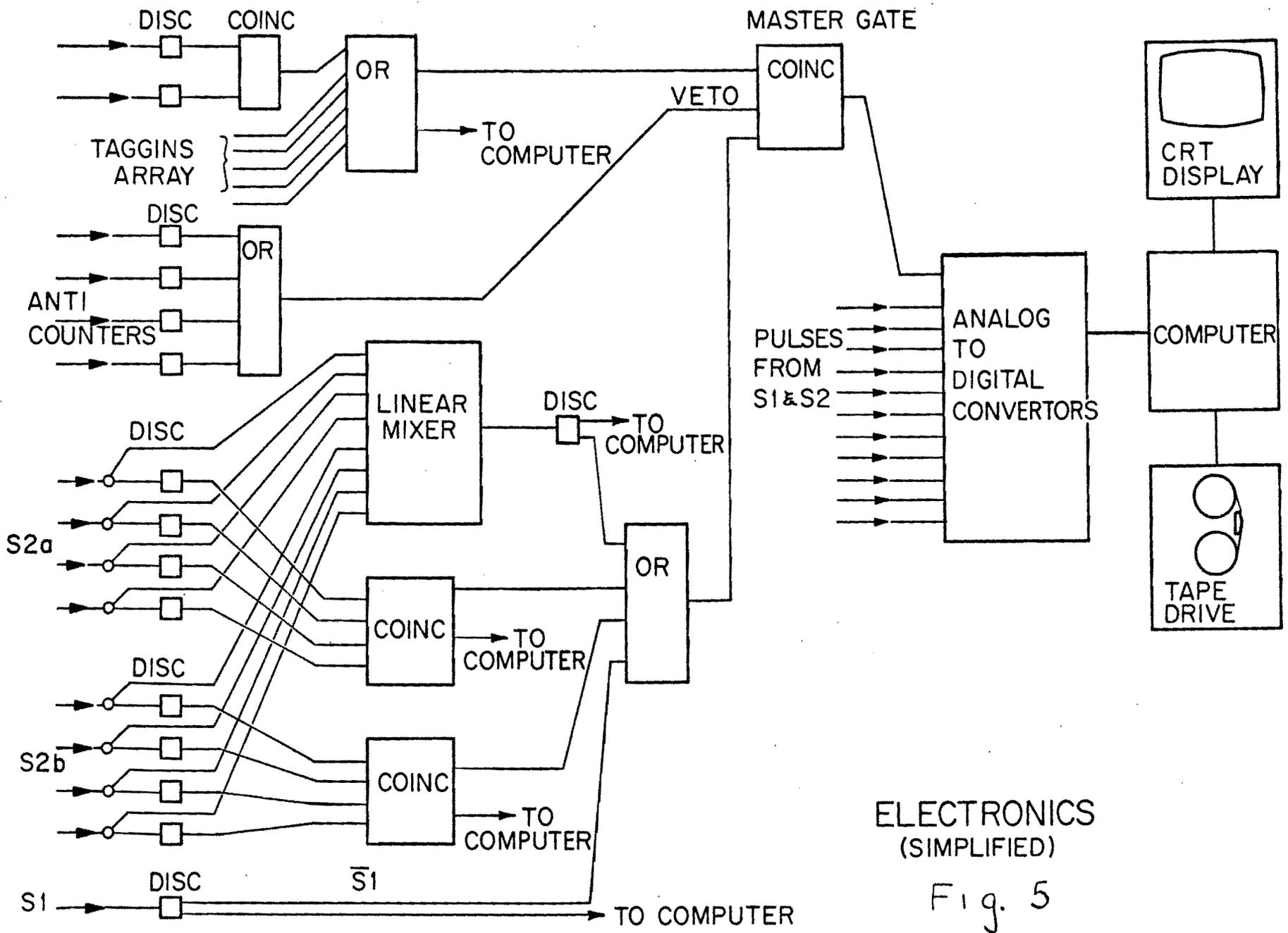


S2a (FRONT VIEW); LAYERS 1,3,4



NOTE: S2b IS BUILT THE SAME AS S2a EXCEPT THAT ALL LAYERS ARE THE SAME AND ARE SIMILAR TO THE CENTER DIAGRAM ABOVE.

Fig. 4



ELECTRONICS
(SIMPLIFIED)

Fig. 5

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MEASUREMENT OF THE TOTAL PHOTOABSORPTION
CROSS SECTION ON H, D, C, Cu, AND Pb FOR
PHOTON ENERGIES FROM 14 TO 300 GeV,
AND A SEARCH FOR THE PHOTOPRODUCED MONOPOLE

Submitted by

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PROPOSAL SUMMARY

1) Title: Measurement of the Total Photoabsorption Cross Section on H, D, C, Cu, and Pb for Photon Energies from 14 to 300 GeV, and a Search for the Photoproduced Monopole.

2) Experimenters: D. Caldwell B. Kendall
A. Eisner R. Morrison
V. Elings F. Murphy
UCSB Graduate Students
VPI-BNL Group in the monopole search

3) Summary:

We propose to measure the total photon cross section for hadronic final states on H and on D at photon energies from 14 to about 300 GeV in 5% energy bins and (for the A-dependence) to measure this cross section on C, on Cu, and on Pb at 60 and at 170 GeV. The statistical precision will be better than $\pm 1\%$; the systematic uncertainty should also be less than $\pm 1\%$. The counter method proposed differs only in detail from that used by the Santa Barbara group to measure the same cross sections from 4 to 18 GeV at SLAC. In addition, there would be a simultaneous search for the Dirac monopole as a step increase in the total cross section, or by its manifestation as a multi-gamma shower, via the Ruderman-Zwanziger mechanism.

4) Equipment:

- a) A three-stage beam of about 2.5 microsteradians aperture, $\geq 1.5\%$ energy acceptance up to 300 GeV, with at least two bends, a dispersed focus, a recombined focus for contamination removal by collimation, and an achromatic final focus. The thick target should be viewed at zero degrees with 500 GeV protons incident, and the experiment itself must be at least 25 feet from the forward proton direction.
- b) A liquid hydrogen-deuterium target 10 cm in diameter, one meter long.
- c) The optimum tagging system should have magnets totaling 100 KG-m, with 4-inch gaps.
- d) Scintillation and shower counters, fast logic and scalers, and a PDP-15 computer will be furnished by UCSB.

5) Running Time:

400 hours at 10^{13} protons/pulse for equipment check-out and data taking; 200 hours at low intensity for beam tune-up.

INTRODUCTION

The hadronic total cross sections measured at Serpukhov have provided several surprises, despite the measurements being only about a factor of two higher in energy than the precision results from CERN and BNL. At NAL the total photoabsorption cross section can be measured to at least an order of magnitude higher energy than has been possible at SLAC, and hence further surprises seem likely. One such surprise could be the production of monopole pairs, but even if qualitatively new phenomena do not appear, the data will still provide important information. The measurements at SLAC and DESY of the total cross sections for the photoproduction of hadrons have already provided fundamental information on the nature of the photon and of the electromagnetic interaction, but these results indicate a need for much higher energy data.

To how high an energy can the total photoabsorption cross sections be measured? Assuming the circulating proton beam reaches 500 GeV at an intensity of 10^{13} protons per pulse and that the statistical model gives correct π^0 yields, we calculate that (γ, p) and (γ, n) cross sections can be measured to about 300 GeV. An analysis¹ of yields at Serpukhov indicates that the statistical model may overestimate π^0 production by a factor of five. Should the yield be down by an even order of magnitude from that we have assumed for NAL, the main effect this would have on the experiment would be to reduce the top energy for cross section measurements to about 200 GeV, which would not qualitatively change the value of the experiment. This points up one of the important reasons for doing this experiment as a first attempt at photon physics at NAL: its success is rather unaffected by flux, whereas the feasibility of many other experiments is very sensitive to the flux. In addition, this general type of experiment may point

the way to the most interesting detailed experiments to follow.

We feel assured of the success of the experiment not only because of its weak dependence on e^- flux, but also because we have successfully done a quite similar experiment at SLAC under more difficult conditions than will be encountered at NAL.

THEORETICAL INFORMATION OBTAINABLE FROM THE EXPERIMENT

To illustrate the importance of this type of measurement, we shall list briefly some of the theoretical information which has been obtained from recent experiments, particularly the one done by the Santa Barbara group at SLAC. By utilizing different nuclear targets, the A dependence of the photoabsorption cross section was obtained.² If the photon produced interactions of only electromagnetic strength, every nucleon in each nucleus would have an equal probability of absorbing a photon, and the cross section should be proportional to A. However, it was found that the nucleons shadowed each other, just as would be the case for a strongly-interacting particle incident. The results can be explained in terms of the coherence of a photo-produced ρ -meson wave and the incident photon wave. The results are in qualitative but not quantitative agreement with the vector-meson-dominance model (VDM). Both the A dependence and a comparison of the proton-photoabsorption and ρ photoproduction cross sections from hydrogen yield ρ -nucleon coupling constants on the photon mass shell which differ by $(33 \pm 11)\%$ from the ρ -mass-shell value obtained from e^+e^- colliding beams.

Our proton and neutron cross sections up to 18 GeV differ from each other, with the difference being consistent with finite-energy sum rules, but they appear to be approaching the same value at infinite energy.³ The data can be fit by a simple Regge-pole model involving the P, P', and A_2 , with the ratio $A_2/P' = 0.26 \pm 0.07$ giving the ratio of isovector to isoscalar exchange in the

energy-dependent part of the cross section. Using an energy dependence implied by A_2 and P' exchange (approximately the inverse square root of the energy), one can also utilize the data in Compton-scattering dispersion relations. In this way it has been found⁴ that the dispersion relations can be satisfied, provided that the real part of the forward amplitude has an additive constant, consistent with the Thomson limit, which could correspond to a fixed pole of $J=0$.

It is interesting to note also that the proton total cross section even has cosmological implications. Because photons from the 2.7°K black-body radiation remaining from the initial stages of the expansion of the universe can collide with very high energy protons to produce other hadrons, the lifetime of such protons in the universe is shortened. The intensity and shape of the high-energy cosmic-ray spectrum then reflects the magnitude and energy dependence of the proton photoabsorption cross section.

Since the above results come from existing experiments up to 18 GeV, what additional information can be obtained by extending the measurements at NAL? First with regard to the total cross sections for complex nuclei, the degree of validity of VDM is still not clear. If our measurements are compared with p -photoproduction results, there is fair agreement with VDM, but some discrepancy remains, which can be caused by as an additional interaction at very short range. One explanation for such a short-range interaction would be the existence of one or more very heavy ($\approx 3 \text{ GeV}/c^2$) vector mesons which could produce nucleon shadowing only for higher energy photons than have so far been used. The presence of such vector mesons would then show up clearly in the energy dependence of the A dependence. Relative to what is expected from the e^+e^- colliding beam p -nucleon coupling constant, we have observed too little

shadowing in the nuclei, and this discrepancy also could be explained by the existence of very heavy vector mesons. It is then very important to clear up this point, both in establishing the validity of VDM and for the sake of finding such heavy vector mesons which partly mediate the photon-hadron interaction.

Next, with regard to the energy dependence of the nucleon cross sections, while our (γ, p) and (γ, n) data extrapolate to a common value at infinite energy, the BNL-CERN hadron-hadron cross section extrapolations unexpectedly have not been verified by the Serpukhov data.⁵ Many of the conclusions given above from the photon data up to 18 GeV would be negated by the unusual energy dependences shown by some of the Serpukhov data. For instance, the deduction of a fixed pole from the Compton scattering dispersion relations is very dependent on the correctness of the $a+bs^{-\frac{1}{2}}$ form of energy dependence. The conclusion regarding the A_2/P' ratio could also be changed, and the simple Regge-pole picture which is successful for the current data might have to be discarded.

It is possible that at high energies one may see the onset of completely new processes. For example, should the Dirac monopole exist it must be very strongly photoproduced in pairs, probably appearing as a distinct step in the total cross section, provided the interaction detectors were sensitive to it or its decay products. By the Ruderman-Zwanziger⁶ argument, the monopole pairs might not appear at all, but instead the energy would be manifested in the form of an anomalous multi-gamma shower, such as has been seen in some cosmic-ray events.⁷ To detect and identify this kind of shower we would use as auxiliary equipment our lead-glass shower detectors and the proportional chambers of the VPI-BNL group, who have indicated a desire to collaborate with us as a sequel to their approved monopole search in a proton beam. Unless there is some unknown hadronic coupling of the monopole to the proton, the photon beam should provide about two orders of magnitude greater sensitivity in the monopole search

than will the proton beam, and the signal-to-noise ratio may be vastly improved.

Monopole production is an extreme example of a process which may occur at high energy which would give a completely different energy dependence to the total cross section than that which now appears to exist. Even if there is no qualitative change in slope with energy we can do a much better job at NAL of determining the asymptotic values of the cross sections than we were able to do at SLAC. Not only will the energy be higher, but, as will be shown below, measurements can be made with much smaller errors than were obtained in the SLAC experiment. Such measurements can then serve as a far more severe constraint on theory. In short, to understand the very high energy domain, the photoabsorption total cross sections will be a necessary ingredient, and because of our past experience we believe the UCSB group is best qualified to provide this essential information. The experiment is relatively simple and $\pm 1\%$ cross sections will be available on line.

EXPERIMENTAL METHOD

The experimental method which we propose is similar to the one which our group used at SLAC to measure the total photoabsorption cross sections from 4 to 18 GeV on H, D, C, Cu, and, Pb. The layout of the experimental equipment is shown in Fig. 1. The general idea of the experiment is quite simple: photons of known energy are produced by electron tagging, these photons impinge on a target, and photon absorptions in the target are detected by 1) the absence of a photon or e^+e^- pair emerging from the target and 2) the appearance of hadrons or their decay products coming from the target.

The main problem with measuring a photoabsorption cross section is to avoid including in that cross section electromagnetic events such as pair production

and Compton scattering. This electromagnetic background is about 100 times the absorption cross section in deuterium and 2600 times that in Pb, so one must be very careful to discriminate against it. In the experimental method which we propose, the separation of hadronic events and electromagnetic events is done geometrically by taking advantage of the fact that products from electromagnetic events leave the target at much smaller angles (typically m_e/E_γ) than hadronic products from absorption events. Photons which do not interact in the target and e^+e^- pairs produced in the target pass through a hole in the hadron detector, S2, and register in the total absorption shower counter, S1. Photons which are absorbed in the target produce no signal in S1 and create hadrons which are detected in S2.

We had good success with this experimental method at SLAC and, from our experience, feel that there will not be any major problems in doing the experiment at NAL. Actually, the experiment should be somewhat easier than the one we did at SLAC, both because of the higher energy and because of the 1000 times better duty cycle at NAL. In the SLAC experiment the lower energy measurements were the harder, particularly in separating electromagnetic and hadronic events. Another advantage of higher energy is that the shower counters used in the tagging system and the S1 veto have resolutions proportional to $E^{-\frac{1}{2}}$, so that their relative accuracies improve, giving a better check on the validity of events. Special efforts were necessary to reduce errors due to accidental coincidences at SLAC, but at NAL accidentals should be unimportant. Even with the most optimistic beam estimates, the instantaneous rates at NAL will be an order of magnitude lower than we had at SLAC.

In the following sections we describe, in some detail, the various parts of the experimental apparatus.

A. Beam

It has now been decided to have a tagged photon beam in the Proton Area at NAL, although the final form of that beam has not yet been settled. We shall, therefore, give a general description of this type of beam, followed by details of a beam we have designed for this experiment. We could, however, use other beams such as that designed by Reeder⁸ at NAL, or a modification of that of the DESY-MIT Group. While our own beam has a better solid angle, we can do the experiment with the other beams, since a reduced counting rate means mainly a little lower cut off on the highest energy at which we can get data.

The general idea is that the proton beam strikes a target, producing π^0 's, which decay into γ -rays, which are separated from charged particles by magnetic sweeping before they strike a 0.5 radiation length converter to produce e^+e^- pairs. The electrons are produced with a typical transverse momentum of 1 MeV/c which multiple scattering broadens to 7 MeV/c. Pions produced by neutrons in the radiator have transverse momentum of ~ 300 MeV/c and therefore appear to come from a diffuse source and can be removed by collimation at a subsequent focus. The beam is tuned for negatives to avoid the large flux of protons produced by the neutrons in the radiator.

A beam for this purpose should have about 2 microsteradians aperture and a momentum acceptance of at least $\pm 1.5\%$ up to 300 GeV/c. It would probably have to be of three stages, with at least two bends, and a dispersed focus and a recombined focus for contamination removal by collimation, but an achromatic final focus. The thick target should be viewed at zero degrees with up to 500 GeV protons incident, and there must be sufficient bending so that the experiment itself can be at least 25 feet from the forward direction.

A beam design satisfying these criteria is described in Table I. This

beam has a second-order acceptance of $2.5 \mu\text{ster}$. ($\Delta x = \pm 0.8 \text{ mrad}$. and $\Delta y = \pm 0.9 \text{ mrad}$.) and is achromatic after the second bend, giving a momentum acceptance of $\pm 1.5\%$, although this could be increased to $\pm 3\%$ with the use of sextupoles. The experimental area is $\sim 10 \text{ m}$ from the incident proton direction, which is adequate for getting the apparatus away from the forward muon flux. The beam shape at the tagging radiator is such that five standard ring magnets (6.8-1.5-60) can be used to tag and dump the e^- beam.

Standard NAL magnets are used: 4, 6-2-240; 2, 5-1.5-240; 11, 3Q84; and 2, 3Q120. To simplify power requirements, only 9 independent currents are used, permitting many magnets to be connected in series: (S1, S2), (M1, M2, M3, M4), (Q1a, Q1b), (Q2), (Q3, Q6, Q7), (Q4, Q5, Q8), (Q9), (Q10), and (QF1, QF2).

Discussions of the e^- intensity obtainable and the π^- contamination in the beam will appear in later sections of this proposal.

B. Tagging System

A typical electron tagging system is shown in Fig. 1, in which the photon energy is determined by the difference between the incident e^- energy and that of the recoil e^- produced with the bremsstrahlung in a thin radiator. The recoil e^- is momentum analyzed by means of a magnet and counters. The counter hodoscope should permit tagging about 30% of the bremsstrahlung spectrum, since the hadron-detector geometry can be optimized for about that range of energies. This 30% energy range can be divided conveniently into six channels, corresponding to photon energies from 0.95 to 0.65 of the incident energy in 5% bins. Actually in the tagging system envisaged, in which each channel consists of a scintillator and a lead-glass Cerenkov counter, the latter will provide better energy resolution as a total absorption device than will the geometry. Thus the energy channels for the data can be rebinned to some extent later.

This good energy resolution of the tagging Cerenkov counters has additional advantages when coupled with the similar good energy resolution of the lead-glass Cerenkov used as S1, the straight-through beam veto. From our experience with these counters, we would expect S1 to have a resolution of about 1.5% (full width at half maximum) at 200 GeV. Thus quite precise consistency checks can be required among the beam energy, tagging channel momentum determination, tagging channel energy determination, and the beam energy from S1. This also makes the system self-calibrating in energy, with the stopped-down electron beam itself being run into the tagging counters for a check. In addition, this over-determination of energy is useful in eliminating any spurious events. This is an advantage we did not have in the SIAC experiment.

The specific tagging system shown in Fig. 1 is one that could be used if suitably large magnets were available. The magnets shown both are 120 inches with 4-inch gaps, one having an 8-inch width and the other a 12-inch width. The advantage of using magnets with wide gaps is that the tagging direction can then be the narrow direction of the beam, permitting better geometric definition and hence better energy resolution in the tagging channels. The disadvantage of this system is that NAL does not have such magnets at hand. As an alternative, Fig. 2 shows a tagging system which uses standard NAL beam transport magnets (five of the type 6.8-1.5-60). Because of the narrow gaps (1.5 inches) the beam deflection must now be in the direction of the larger beam dimension, making the momentum resolution poorer. However, as noted above, the recoil e^- energy is determined more precisely by the Cerenkov counters anyway, so this merely results in a somewhat inconvenient rebinning of events, as well as a poorer energy consistency check.

The beam size affects the choice of tagging counter cross-sectional area,

and this with the available beam-to-counter distance and magnetic field strength determines the tagging channel resolution, which is roughly 5% in the tagging systems described above. Keeping the geometry constant and reducing the field would increase resolution, at the expense of utilizing a smaller fraction of the bremsstrahlung spectrum, but for the slowly varying total cross section, 5% is adequate. As mentioned above, not more than 30% of the bremsstrahlung beam is tagged in order to be able to optimize the hadron counter geometry with energy. The distance between the target and the hadron detector must be chosen so that products from electromagnetic events go through the hole in the detector, whereas at least one π from a forward-produced ρ^0 does not go through the hole. The opening angle of these products vary with the photon energy, and so the distance between the target and the hadron detector must also be made to vary with photon energy. If more than 30% of the bremsstrahlung beam were tagged, the range of photon energies would be too large to pick an optimum position for the hadron detector. One other use of the tagging magnets should be mentioned: to bend the main electron beam away from the rest of the experiment into a beam dump.

C. Anticoincidence Counters

In Figs. 1 and 2 various counters labeled A are shown which have functions related to the beam and tagging systems. We shall describe these in numerical order (i.e., reading from the left or downstream end in Fig. 1).

Counters A_1 , A_2 , and A_3 have central holes through which the e^- beam passes and all have as one of their functions the detection of hadronic interactions in the radiator. While the degree of beam contamination will be discussed later, it is clear that some negative pions will accompany the e^- in the beam, and these could cause difficulties if they interact in the radiator, sending a

negative particle into one tagging channel and either a neutral particle down the γ beam line or some strongly-interacting particle directly into the hadron interaction detector, S2. Since such an interaction in the radiator will usually produce several particles, if any of these go into A_1 , A_2 , or A_3 the event will be ignored. In addition, A_1 serves to define the incident beam, eliminating any effects of beam halo.

A_3 has an additional function, which it shares with A_4 , A_4' , and A_5 , of reducing the false tagging rate; this is the occurrence of a signal from the tagging system without the production of a photon. With a well-designed system, such an event will happen mainly because the incident electron produces a trident ($e^+e^-e^-$) in the radiator, with one of the electrons going into the tagging system. The reason that such events, or false tags, are of concern is that with a tagging signal and no photon, it appears to the beam shower counter, S1, that a photon was absorbed in the target. One must then rely on S2, the hadron counter, to indicate whether the event was a false tag or a real absorption of a photon. If the number of false tags is high, accidental coincidences between false tags and interactions in S2 could become a source of error. This is not so important at NAL as it was at SLAC because of the much better duty cycle. False tags can also impair the good experimental check provided by measuring the photoabsorption cross section using only the shower counter; i.e., counting as an absorption a tagging signal with no shower in S1. In this absorption check measurement the false tags have to be separated out by doing target-empty and target-full runs. If the occurrence of false tags is much greater than the occurrence of real absorptions, this subtraction does not give, statistically, a very good number. Without taking special precautions (other than a well designed beam), we found at SLAC that

the ratio of false to real tags was 0.05 and the ratio of false tags to real photoabsorptions in deuterium was 50. The number of false tags was reduced by a factor of 10 by using counters similar to A_4 , A_4' , and A_5 . Analysis of the SLAC results shows that a significant improvement could be provided by using in addition a counter like A_3 .

One of the disadvantages of using a negative beam is that knock-on electrons can make false tags. We have calculated these effects and find that at NAL energies electron-electron scattering will contribute less than one false tag per 10^3 real tags, except at the lowest beam energy in the highest photon energy channel, where in this worst case the ratio is about one per 10^2 tags. Another contribution to false tags, not present at SLAC, is caused by the Dalitz pairs and correlated photons from the interaction of the π^- 's in the beam ($\pi^- \rightarrow \pi^0 \rightarrow \gamma e^+e^-$). The 0.01 r.l. copper radiator is only 10^{-3} of a collision length, so that with the expected small pion contamination this will produce a false tag rate of $\ll 0.1\%$. We believe that the ratio of false tags will be less than the 0.3% of the SLAC experiment. Since the instantaneous count rates will be lower by about a factor of 50, we then expect accidentals to be $< 0.1\%$ and $< 0.5\%$ for D_2 and Pb targets, respectively.

The counters designated as A_6 serve to veto events arising from the unused lower energy portion of the bremsstrahlung spectrum. Since shower counters are used, the energy of these photons will be determined well, so that some use may be made of these events, particularly in providing geometric checks (since the positions of S1 and S2 will not be optimum for these events).

The counters A_7 and A_7' have central holes and serve to define the photon beam and to protect the hadron detector, S_2 , from particles produced upstream of the target. The large scintillator, A_7'' , protects particularly against

muons and charged particles produced in the beam dump, while A_7 , a lead-scintillator shower counter, picks up neutral particles and eliminates wide-angle bremsstrahlung coming from the radiator.

D. Target

It is proposed that the target material be varied from H to Pb, more specifically H, D, C, Cu, and Pb. The targets should be about 0.1 r.l. thick as a compromise between counting rate and keeping small both photon attenuation and multiple scattering of electron-positron pairs produced in the target. The H target will be about 1 m. long and ~ 10 cm in diameter with thin windows on the ends. The same target would be filled with deuterium.

E. Hadron Detector and Total Absorption Shower Counter

As has been described briefly above, downstream of the target there is a counter array whose function it is to decide if 1) the photon is absorbed in the target or 2) if the photon traverses the target unaffected or simply interacts electromagnetically in the target. The counter array consists of two main parts, a high-resolution lead-glass total-absorption shower counter, S1, to detect electromagnetic products emerging from the target, and a hadron counter, S2, to detect hadrons and their decay products emerging from the target. The separation of the electromagnetic events and hadronic absorption events is done mainly by geometry. The electromagnetic products, most of which are e^+e^- pairs produced in the target, have typical opening angles of m_e/E_γ where m_e is the mass of an electron. The hadron detector has a hole in it through which these electromagnetic products pass and strike the total absorption shower counter, which measures their total energy. The angle subtended at the target by the hole in S2 is made small enough so that hadrons resulting from photon

absorptions in the target have a small probability of going through the hole. The hadronic reaction which determines the size of the hole is diffraction production of ρ^0 's. This reaction accounts for about 12% of the total absorption cross section and one must make sure that the 2π 's from the decay of the ρ^0 cannot both go through the hole in S2. The typical angle at which π 's emerge from the target is $m_\rho/E_\gamma = 43$ mrad for $\bar{E}_\gamma = 17.5$ GeV and 3 mrad for 253 GeV. To be safe, one would actually want the hole to subtend a smaller angle than this so that pion pairs with an invariant mass above 400 MeV do not get through the hole. Events in which the hadrons do pass through the hole in S2 are single-pion photoproduction events in the forward direction. These events, though, are a negligible part of the total photoabsorption cross section and can be ignored. At SLAC we found for a photon energy of 16 GeV, that if the hole in S2 subtended a half angle of $m_\rho/2E_\gamma$, the wide-angle e^+e^- pairs which did not go through the hole were $< 0.1\%$ of the absorption rate for deuterium and $\sim 2\%$ for lead.

As shown in Figure 3, the hadron counter S2 is divided into two parts, S2a and S2b, so that one can vary independently the inner and outer acceptances of the counter. The upstream counter, S2a, determines the outer acceptance whereas the downstream counter, S2b, determines the inner acceptance. The angle subtended at the target by the hole in S2b is varied by moving the counter up and down the beamline. For a 12-cm-diameter hole in S2b, the distance to the target must vary from 2.8 meters at $\bar{E}_\gamma = 17.5$ GeV to 40 meters at 253 GeV. The outer acceptance of the hadron detector is varied by having the counter S2a also on a movable platform so that it can be moved between the target and S2b.

The hadron counter must be sensitive to both charged particles and γ rays from π^0 decays. One would also want the detector not to be sensitive to low

energy (below 1 GeV) electrons and γ rays, since the wide-angle electromagnetic products which hit S2 will in general be of low energy. We propose to construct the counters S2a and S2b of alternate layers of lead and scintillator, as shown in Fig. 3. We used a similar arrangement at SLAC with 4 layers of 2.5-cm-thick Pb and 1.2-cm-thick scintillator with each layer of scintillator being viewed by two photomultipliers, one at each end. By requiring either a four-fold coincidence between the planes, or a total pulse height (sum of the 4 planes) corresponding to a 3-GeV shower, we found that the counter was $99.6 \pm 0.4\%$ efficient for detecting hadrons emitted from the target for an incident photon energy of 16 GeV.

We feel that a similar detector would work well at NAL with two major changes: 1) the thickness of the lead layers would be increased from 2.5 cm to 3.7 cm to accommodate the higher energies at NAL and 2) we would separate the second layer of scintillator in S2a into 3 pieces as shown in Fig. 3. The reason for this separation is to obtain a measure of the angular distribution of hadrons striking the counter without having to move the counter closer to the target and taking the difference between successive measurements. We feel that this will greatly reduce the amount of time spent checking to see that the number of hadron events in which all particles miss the hadron detectors is negligible. As mentioned in the electronics section, the pulse heights and timing of pulses from the separate scintillator planes in both S2a and S2b will be recorded for each event, or likely event, so that the experiment can be "replayed" on a computer.

F. Electronics

A simplified schematic diagram of the electronics for the experiment is shown in Fig. 4. The electronics is essentially the same as that which we used at SLAC, except for the PDP-15 computer which will enable us at NAL to

calculate final cross sections on line.

A master trigger for the experiment consists of 1) a coincidence from one of the tagging-counter telescopes, 2) no signal from any of the anticounters, and 3) no large pulse in S1 or a "hadronic" signal from S2. This hadronic signal consists of either a four-fold coincidence between the planes of S2a or S2b or a pulse from the sum of all planes in S2a and S2b which corresponds to an energy deposition in the counter of $\sim 25\%$ of the incident photon energy. Such a requirement is very loose and includes false tags. The idea, though, is to trigger on loose criteria and let the computer make the decision as to whether the event was a photon absorption or not. When a master trigger occurs, the pulses from the planes in S1, S2a, S2b, and from the tagging shower counters are gated into analog-to-digital converters. For each event 17 pulses (one from S1, six from S2a, four from S2b, and one from each of the six shower counters in the tagging system) are digitized and temporarily stored until read into the computer. Other information read by the computer for each event is:

1. The tagging channel which fired.
2. The status of the discriminators connected to the S2a and S2b planes. These discriminators will be set at a level corresponding to one-half minimum ionizing.
3. The status of the discriminator connected to S1. This discriminator will probably be set around $2/3$ of the incident photon energy.
4. Whether the total pulse height in S2 (a & b) was greater than 25% of E_γ .
5. The time between the tagging signal and the hadronic signal from S2, permitting recording and separating by the computer of real and accidental events.

Because the computer knows the pulse heights from S1, S2a, S2b, and the tagging shower counters, the information in 2, 3, and 4 is redundant but serves as a check on the fast electronics. The computer will display a warning if the information is not compatible with the pulse height information. Every thousand events or so the computer will write the raw data (throwing out events which are definitely false tags) on magnetic tape so that the experiment can be replayed, if need be, at a later date. The computer, via a 10 inch CRT display, will show the pulse-height spectra of the various counters, various correlations of the pulse-height spectra,* and the photoabsorption cross section as a function of incident photon energy. After performing the analysis of the data from the SLAC experiment, we feel that we could program the computer such that it would give us on-line the total photoabsorption cross sections to an accuracy of 1%.

Several quantities are counted on 100-mc scalers and at the end of a run these numbers are read into the computer so that it can normalize the cross sections.

UCSB owns all of the electronics (including the computer) shown in the logic diagram, and therefore, will not need to borrow any from NAL.

EXPECTED EXPERIMENTAL PERFORMANCE

A. Electron Beam Intensity

It is fortunate that the success of this experiment does not depend very

*For instance, one way to identify wide-angle electron pairs which may strike S2b is to look at the correlation between the pulse heights in S1 and S2b; if the event is a wide-angle pair the sum of the pulse heights will correspond to the incident photon energy.

much on the electron intensity attainable, for there are large uncertainties in this quantity. At this time, the proton beam intensity is of course unknown. We have assumed 10^{13} protons per pulse at 500 GeV, instead of the usual 10^{13} protons per second, so we are hopefully pessimistic by a factor of 5.

Another large uncertainty is the forward π^0 yield at 500 GeV. For want of anything better, the statistical model of Hagedorn and Ranft⁹ is usually used to obtain the π^0 production, but the work of Wang¹ suggests that the theoretical yields from such a model may be as much as five times too large at Serpukhov energies.

With these caveats we present the electron yield curve in Fig. 5, which is a somewhat modified and scaled up version of the 400 GeV calculation by Morrison¹⁰ in the NAL 1970 Summer Study. This curve is based on 10^{13} 500 GeV protons/pulse and a beam acceptance of 2 μ ster. with a momentum acceptance of $\pm 3\%$. For comparison, it is more pessimistic by factors of about three than the yield by Reeder⁸ and about four than the results we have seen of the MIT Group.

Thus our electron yield can be considered conservative by standards prevailing at present, but we wish to emphasize that the uncertainties are very large.

B. Pion Contamination in the Beam

The fraction of pion contamination in the beam is also a very uncertain quantity at present, but again quite fortunately the success of the experiment does not depend in any foreseeable way on the degree of that contamination. Calculations show the π^- contamination increasing with energy, but even at 300 GeV the π^-/e^- ratio generally does not exceed about 1%. We would like to show here that the contamination would have to be much more than a thousand times larger than this before it would be a problem in this experiment.

The type of event which could cause trouble would be the interaction in the tagging radiator of a π^- (or K^-) to produce a neutral particle forward, accompanied by another particle which counts in one of the tagging channels. Let us ignore for the moment the difficulties involved in producing a tagging signal and in not firing one of the veto counters. The forward neutral particle is more likely to be a K_L^0 by a factor of at least 20 than it is to be a neutron,¹¹ and the probability per interaction length for K_L^0 production is about 3×10^{-6} , according to the study by Zdanis.¹¹ The corresponding figure for e^- production of tagged γ 's is ~ 6 , because there can be ~ 20 radiation lengths per interaction length and 30% of the bremsstrahlung spectrum is tagged. On the other hand the K_L^0 is more likely by a factor of ~ 200 than the γ to produce a hadronic interaction in the target, so the overall ratio of contamination events per pion to real events per electron is $(3 \times 10^{-6})(200)/6 \sim 10^{-3}$. Thus even a π^-/e^- ratio of 10 (instead of 10^{-2}) would produce at most a 1% effect. Even this is a gross overestimate, because the interaction in the radiator is likely to produce several particles, any one of which can veto the event in A_1 , A_2 , or A_3 , and because it is very difficult to produce a particle which will fire the tagging system. The use of shower counters provides a discrimination against pions counting in the tagging channel of between 10^2 and 10^3 .

For this last reason one should consider also a charge exchange in which the π^0 produces a Dalitz pair (or one γ converts, the two processes being of comparable frequency for this radiator thickness) and the other γ goes down the beam line. Again the extra e^+ and other particles from the interaction can kill the event, but even ignoring this, the ratio of such false events per π to real events per electron varies from $\sim 10^{-6}$ at 20 GeV to 10^{-7} at 200 GeV.

Thus there seems to be no possibility that beam contamination can hurt this experiment.

C. Experimental Errors

With the electron intensities of Fig. 5, it is practical to get sufficient data on H and D to achieve statistical errors of 1% in each tagging channel (i.e., in a 5% energy band), or better than 0.5% for the 30% energy range at each beam energy setting. At the energies at which the C, Cu, and Pb cross sections would be measured, the statistics would give 1% errors over the 30% energy band. The A dependence presumably changes slowly enough with energy that such a band provides sufficient accuracy.

From our past experiences, we estimate that systematic errors due to counter efficiency, geometrical effects, accidentals, electromagnetic contamination, target thickness, monitoring, etc. can be kept below 0.5%, and therefore it is meaningful to try to achieve 1% statistical errors. To be sure of the systematic errors, extensive checks are necessary, and a substantial part of the running time must be devoted to them.

D. Estimated Running Time

Table II lists the amount of running time required, on the bases described in parts A and C above, to measure the (ν, p) and (ν, n) total cross sections from 14 to 300 GeV and the A dependence of the ν -nucleon cross sections, using C, Cu, and Pb at $\bar{E}_\nu = 173$ and 56 GeV. To recapitulate, the times are based on: 1) the electron yields shown in Fig. 5 (hence 10^{13} 500 GeV protons/pulse, statistical model π^0 production, 0.5 r.l. converter, 2 μ ster. and $\Delta p/p = \pm 3\%$ acceptance), 2) a 0.01 r.l. radiator to produce photons, 3) a tagging system utilizing 30% of the bremsstrahlung beam, 4) targets 0.1 r.l. thick, 5) statistical accuracy of 1% in each 5% photon-energy bin for H and D and 1% for the combined six bins for C, Cu, and Pb, and 6) C, Cu, and Pb cross sections which go as $A^{0.9}$, as we found at 16 GeV. The program of Table II

provides also for extensive checks and for overlap in energy of the (γ, p) and (γ, n) cross sections with our SLAC measurements. Coupled with our SLAC results, the two energies of the A dependence measurements should show whether additional very heavy vector mesons exist.

In total 400 hours of running is requested, of which 110 hours is devoted to checks. An additional 100 hours of low-priority time is desired to check out the electron and photon beams.

Hopefully we have made a pessimistic estimate of the electron yield, but should the proton beam or π^0 production estimates be optimistic by a factor of 10, we would have to eliminate the top energy band of Table II (i.e., go only to 205 GeV) and lower the energy of the higher A-dependence measurement. If the estimates were optimistic by a factor of 100, a similar program could be carried out with 3% statistics. It is rare that an experiment has this much flexibility.

The search for photoproduced monopole pairs is entirely simultaneous, since we shall be looking for a step increase in the total cross section. Exceeding threshold for monopole-pair production could be a dramatically large effect, provided the monopoles do not appear in the form of a sufficiently small-angle shower of annihilation gamma rays that they are vetoed by S1. To avoid this possibility and to better identify this kind of event, proportional chambers will be set up ahead of S1 and triggered on large multiplicity. We wish to emphasize that not only can this search be about two orders of magnitude more sensitive than the similar one by p-p collisions (unless there is a monopole hadronic interaction or unless our electron flux estimates are incorrect), but perhaps more importantly the signal-to-background ratio could be as much as 10^6 times better. This large improvement is possible because the signal goes up with the direct use of photons to produce the pairs (instead of a two-step

process) and because the background π^0 's are produced far less efficiently by photons than by protons. In a recent preprint J. L. Newmeyer and J. S. Trefil¹² emphasize that the super-strong interaction between a monopole and antimonopole causes them to annihilate, making their direct detection very difficult, while their indirect detection by the annihilation shower is rendered also very difficult by background problems when p-p collisions are used as the production mechanism. It seems not unlikely that the production and detection method proposed here may be the best way to test for the existence of the magnetic monopole.

We have been spending some time on beam design and we are willing to continue to give help at any time for beam development. At present, we have a commitment at SLAC which will probably last through January 1972, but since we have most of the apparatus for the measurement proposed here, we could be ready to move equipment to NAL on about three months notice. Particularly convenient for us would be running in the summer of 1972.

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TABLE I. e^- BEAM ELEMENTS

Position meters	Name	Pole Face Field, KG	Type	Comments
0	Target			Be, about one inter- action length
3.5	S1	17	5-1.5-240	Sweep the proton beam ~ 20 cm at the radiator
10.5	S2	17	5-1.5-240	
23	Radiator			$0.5X_0$ tungsten
26.5	Q1a	- 4.06	3Q 120	
29.7	Q1b	- 4.06	3Q 120	
42.4	Q2	+ 5.04	3Q 84	
46.5	M1	13.4	6-2-240	Bend 16.4 mrad for momentum analysis
49.6	M2	13.4	6-2-240	
58.8	Q3	+ 4.32	3Q 84	
71.0	Q4	- 5.34	3Q 84	
122.8	QF1	+ 2.95	3Q 84	Field Lens
123.4				← h. and v. image dispersed 1.53 cm/%
124.1	QF2	+ 2.95	3Q 84	Field Lens
175.9	Q5	- 5.34	3Q 84	
188.1	Q6	+ 4.32	3Q 84	
192.5	M3	13.4	6-2-240	Bend to recombine momenta: beam is now achromatic
198.6	M4	13.4	6-2-240	
204.5	Q7	+ 4.32	3Q 84	
216.7	Q8	- 5.34	3Q 84	
267.8	Collimator			← h. and v. image of target; collimator removes π^-
318.9	Q9	+ 6.35	3Q 84	
331.1	Q10	- 5.63	3Q 84	
352.1	Tagging Radiator			
412.1	LH ₂ Target			
452.1				← Final image on hole in counter S2b

TABLE II. RUNNING TIME ESTIMATE

e ⁻ Energy	γ Energy	e ⁻ /10 ¹³ protons	Time in Hours								
			H	D	MT	C	Cu	Pb	MT	Checks	
316 GeV	300-205 GeV	0.009 × 10 ⁸	110	50	22						50
216	205-140	.012 × 10 ⁸	8.2	3.8	2	2.8	11.2	23	23		20
148	140- 96	.45 × 10 ⁸	2.2	1.0	1						
102	97- 66	.82 × 10 ⁸	1.2	.6	1						
70	66- 45	1.13 × 10 ⁸	.9	.4	1	.3	1.3	2.4	3		20
48	46- 31	.90 × 10 ⁸	1.1	.5	1						
33	31- 22	.75 × 10 ⁸	1.3	.6	1						
22	21- 14	.52 × 10 ⁸	1.9	.9	1						20

Total running time for checks: 110 hours

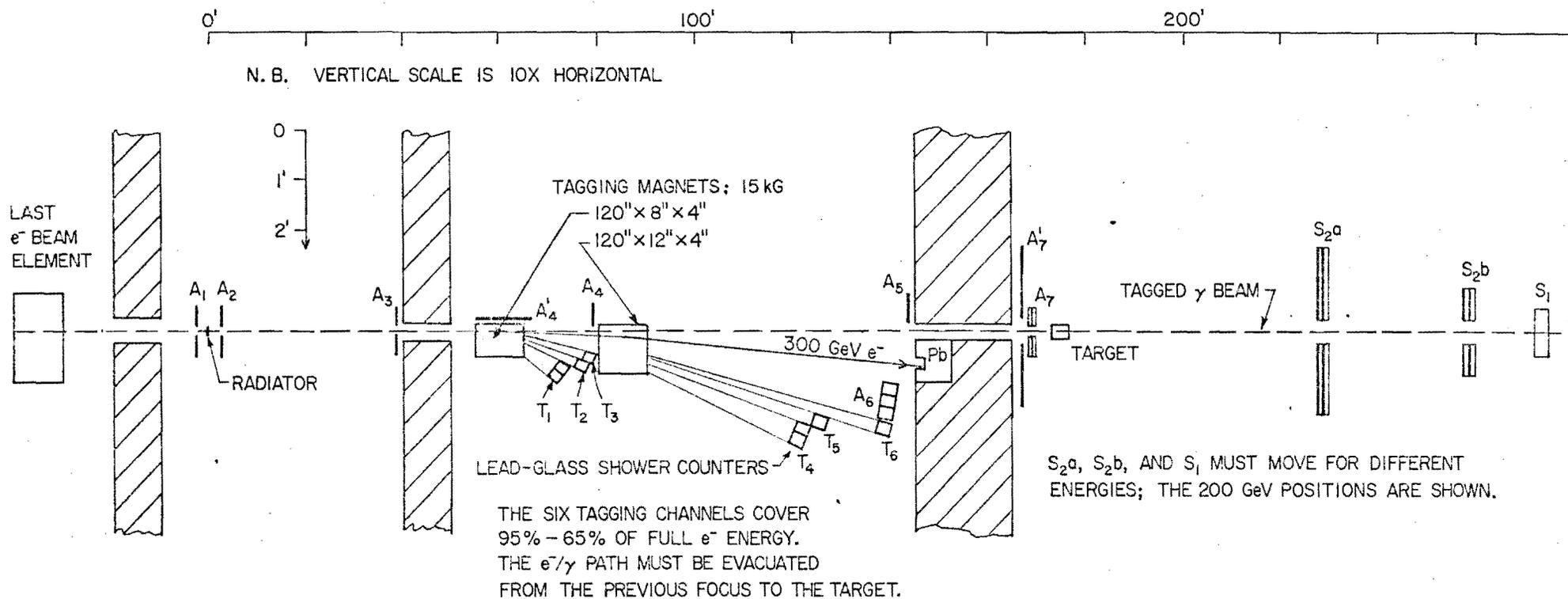
" " " " data : 290

Total Running Time for Checks 400 hours

The above is based on the e⁻ yields of Fig. 5; an 0.001 r.l. radiator; tagging 30% of the bremsstrahlung; 0.1 r.l. targets; 1% statistical accuracy in each of the 5% tagging channels for H and D (i.e., 60,000 counts) and 1% for all six channels for C, Cu, and Pb (i.e., 10,000 counts); < 1% errors in the cross section for each empty target run (designated as "MT"); and C, Cu, and Pb cross sections proportional to A^{0.9}.

FIGURE CAPTIONS

- Fig. 1 Layout of the experimental equipment, with different horizontal and vertical scales, as noted. The tagging system is a possible one if magnets with 4-inch gaps are available.
- Fig. 2 An alternative tagging system using only standard NAL beam transport magnets with 1.5-inch gaps. Note that the shape of the shower counters is distorted because of the difference in the horizontal and vertical scales.
- Fig. 3 Drawing of the hadron detectors S2a and S2b. Both counters consist of 4 alternate layers of lead and scintillator.
- Fig. 4 Simplified electronics block diagram. The 100-mc scalers and associated electronics are not shown, nor are many detailed parts of the logic.
- Fig. 5 Expected number of electrons per pulse for 10^{13} 500 GeV protons per pulse and a beam of 2 μ ster. and $\Delta p/p = \pm 3\%$ acceptance. A statistical model was used for the π^0 production rate and a 0.5 r.l. converter is assumed.



PROPOSAL 25 - TOTAL HADRONIC PHOTOABSORPTION

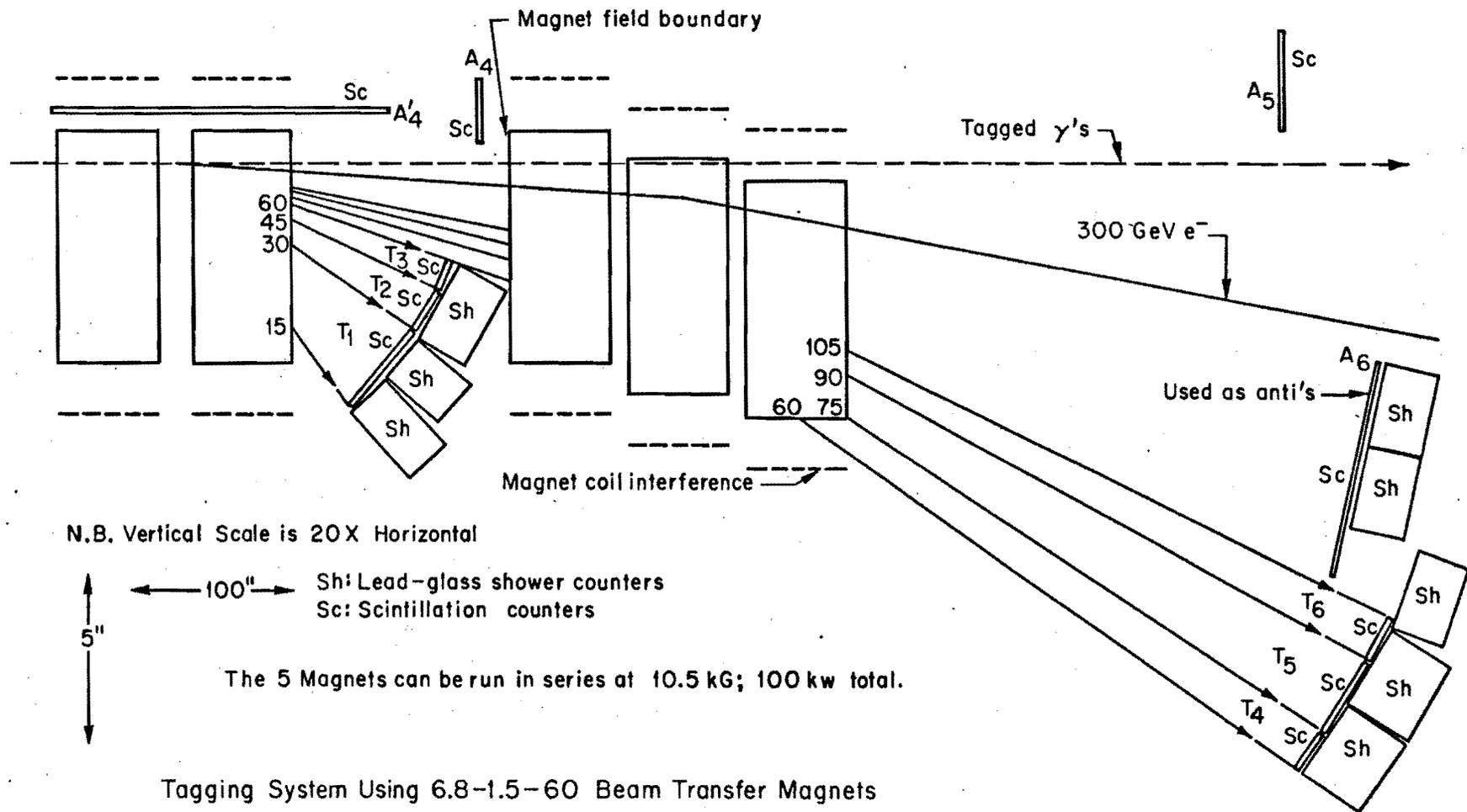
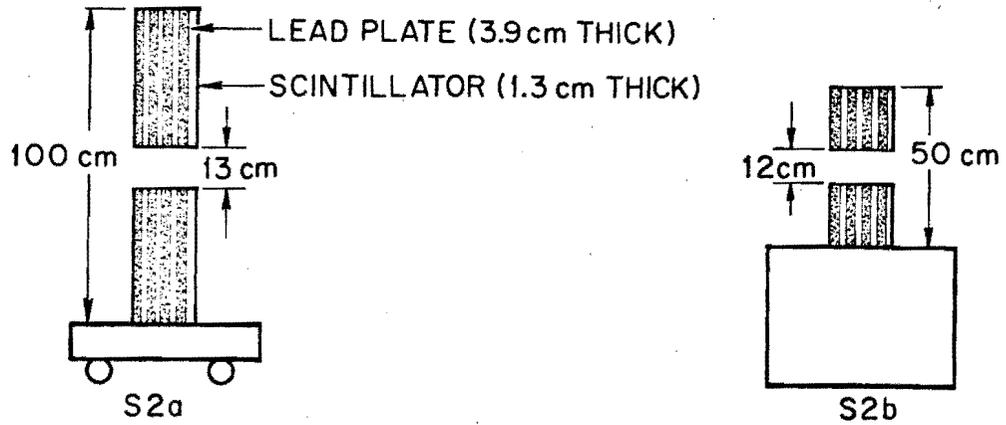
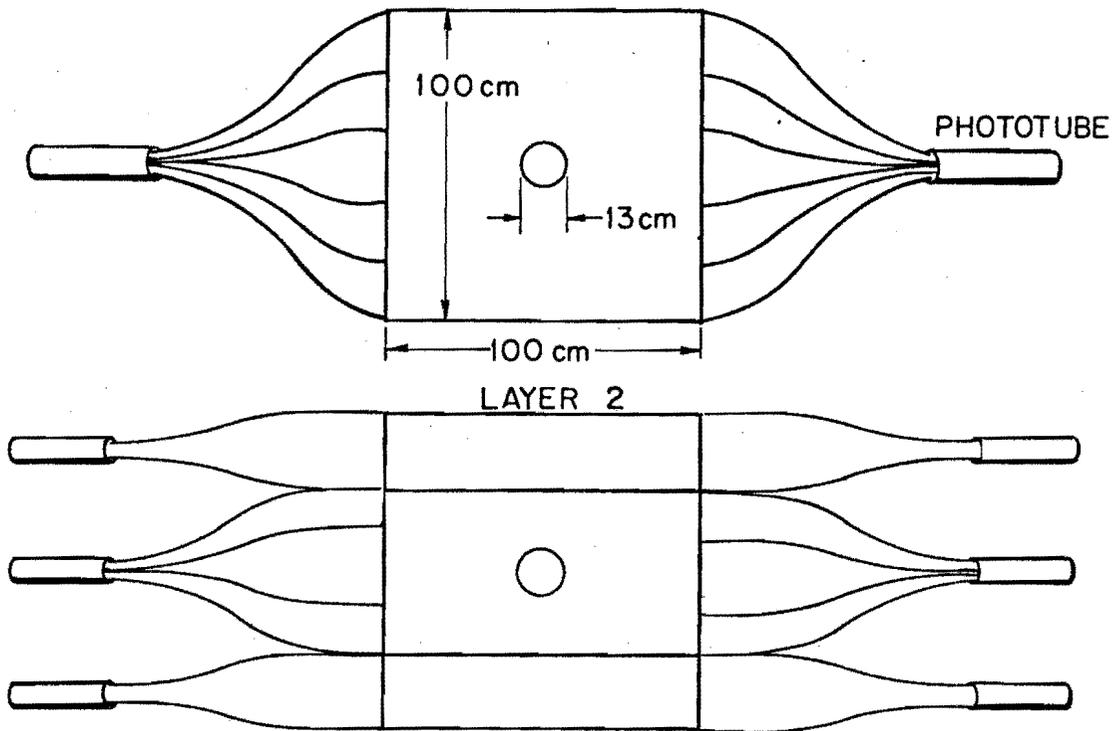


Fig. 2

HADRON DETECTOR



S2a (FRONT VIEW); LAYERS 1,3,4



NOTE: S2b IS BUILT THE SAME AS S2a EXCEPT THAT ALL LAYERS ARE THE SAME AND ARE SIMILAR TO THE CENTER DIAGRAM ABOVE.

Fig. 3

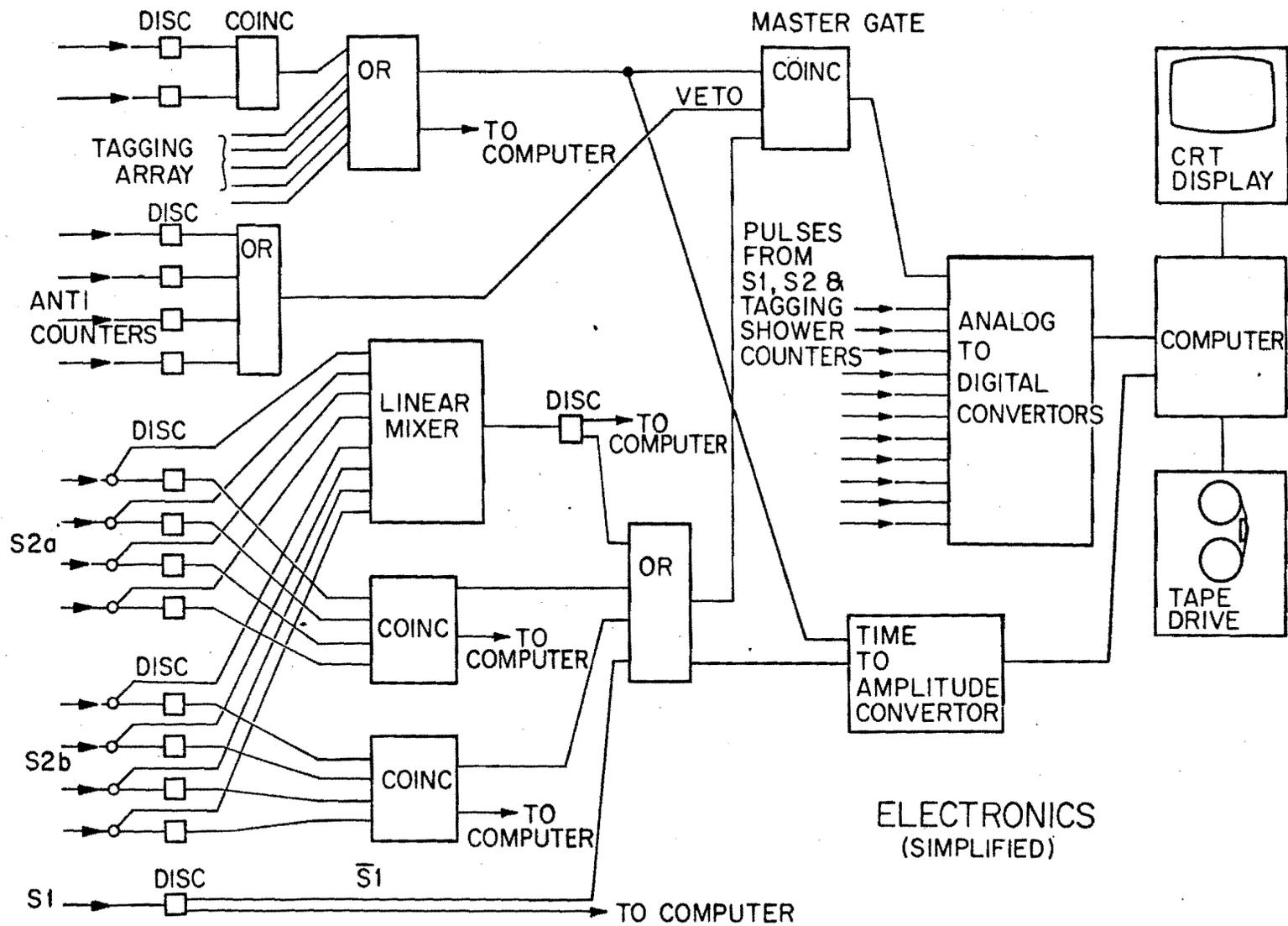


Fig. 4

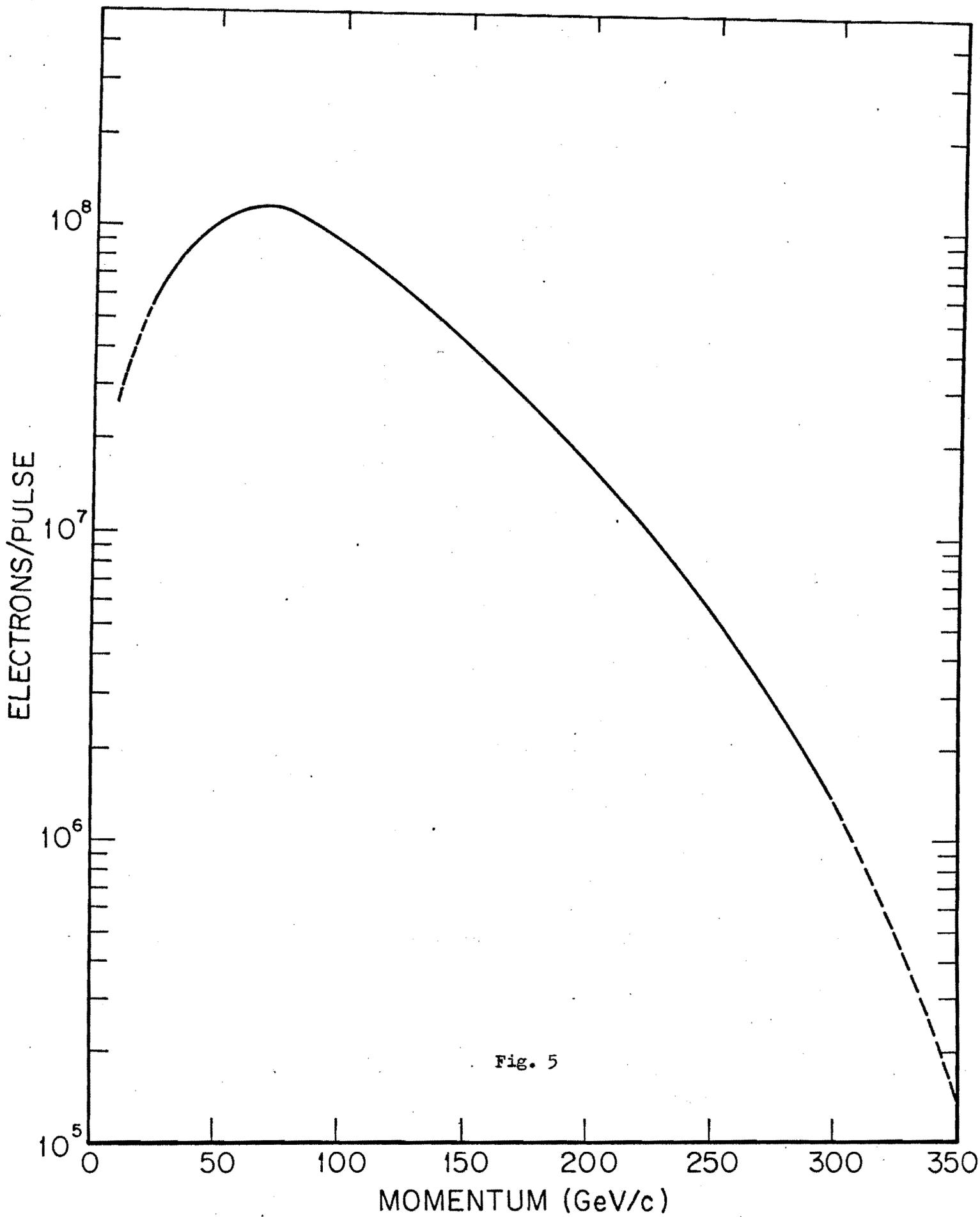


Fig. 5

Addendum

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CHARMED PHYSICS AT THE TAGGED PHOTON LAB

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CHARMED PHYSICS AT THE TAGGED PHOTON LAB

I. INTRODUCTION

The recent discoveries of heavy narrow resonances at masses of 3.1^{1,2,3} and 3.7 GeV⁴ came at the same time as the successful testing by our group of the electron beam in the Fermilab Tagged Photon Facility.¹⁰ The timing is perfect, as this facility with its clean environment and relatively high photon fluxes and energies will be the ideal location for several important experiments suggested by the new results. We outline below the new significance of our experiment to measure the photon total cross section (Experiment 25A), as well as six other experiments to study the new phenomena we can perform with little increase in running time and with the apparatus already being prepared for Experiment 25. This apparatus is particularly well suited for these experiments which include a definitive check on whether the new resonances are photo produced, a search for a pseudoscalar particle made of charmed quarks and a study of neutral decay modes (which may well be dominant) of new particles. Several of these experiments can most likely be performed nowhere else but the Tagged Photon Lab. We propose to spend some time during testing of the tagging system and the Experiment 25 apparatus to determine the feasibility of these new experiments.

The tests of the electron beam demonstrated that tagged photons with fluxes and backgrounds with $\pm 30\%$ of predictions will be a reality by May, 1975. An informal report on these tests is included as an appendix. These tests and our consideration of

these new experiments lead us to conclude that both the study of $\sigma_{\text{tot}}(\gamma p)$ and $\sigma_{\text{tot}}(\gamma A)$ and the new measurements we here propose will make substantial contributions to the understanding of these new phenomena. We, therefore, request that the Laboratory continue to give as high a priority as possible to the completion of the tagged photon beam.

II. NEW SIGNIFICANCE OF σ_{tot} MEASUREMENTS

The discovery of the ψ (3105) and ψ' (3695) suggests that there may be higher mass strongly interacting vector particles coupled to the photon. Higher mass resonances of this type will be extremely difficult to detect because of the high multiplicity of their decay rates. If these particles interact strongly with the nucleon, it is to be expected that such states would contribute to the nuclear shadowing already observed at SLAC energies in the $\sigma_{\text{tot}}(\gamma, A)$ measurements and attributed to the contribution of the well known vector mesons ρ , ω and ϕ .^{5,6} The energy and A dependence of the photo production total cross section may provide the only handle on the existence of such high mass states.

The onset of shadowing between $E_\gamma = 2$ GeV and $E_\gamma = 4$ GeV results from the quantity $\frac{2 E_\gamma}{m_V^2}$ becoming large compared to the nuclear size for $m_\rho^2 \sim .5 \text{ GeV}^2$.

For strongly interacting vector particles above the ψ mass, we can expect a corresponding increase in nuclear shadowing as E_γ is increased above 100 GeV.

III. Photoproduction of the ϕ_c and η_c

One possible explanation of the ψ (3105) is that it is ϕ_c , $c\bar{c}$ analogue of the ϕ (1015).

With the Experiment 25 apparatus and the tagged photon beam we can:

1. Determine whether the ψ is photoproduced, a critical question in determining whether the new particle is an intermediate boson or not. The tagged photon beam with fluxes similar to those of the other Fermilab photon beam, a well defined energy and a far cleaner environment is the ideal tool for a definitive resolution of this question.
2. Study the photoproduction of the ψ (3105) and ψ' (3695) from H and heavier nuclei.
3. Measure the energy t dependence of these cross sections.
4. If the ψ and ψ' are copiously produced, we can measure the $\sigma(\psi(\psi'), N)$ by observing the A dependence of $\sigma(\gamma A \rightarrow \psi(\psi') A)$.
5. Search for neutral decay modes of the ψ and ψ' into 3γ , $\gamma\pi^0$, $\gamma\eta$, or $\gamma\eta_c$ where η_c is the 0^- , $c\bar{c}$ boson predicted by Gaillard, Lee and Rosner.⁷
6. Search for the direct production of the η_c by Primakoff effect.

We propose to demonstrate the feasibility of these experiments during the installation and test phase of Experiment 25. This will require no new equipment other than that already in preparation for E-25. To be specific, we ask for 100 hours of additional test time.

If the ψ (3105) is a 1^- state of $c\bar{c}$ quarks then the 0^- state, the η_c , should also exist with a similar mass and with even charge conjugation. Since the strong interaction of charmed with non-charmed quarks is unknown and could be small, we believe that it is advantageous to search for η_c by an electromagnetic process. The Primakoff production of such a particle of mass m depends on only one unknown quantity, namely the $\gamma\gamma$ width $\Gamma_{\gamma\gamma}$. This width has been estimated to be 100 - 200 KeV.⁸ We would look for the $\gamma\gamma$ final state with our proportional chamber - lead glass array shown in Figure 1. The branching to this state $\Gamma_{\gamma\gamma}/\Gamma_{\text{tot}}$ depends upon the rates for competing decay modes and could be as high as 50%, if we can take the width of the ψ as a guide. We note that the Primakoff cross section is proportional to the square of the nucleon or nucleus form factor. Since the minimum momentum transfer to the target is $\frac{m^2 \eta_c}{2E}$ the process is strongly inhibited, even on the nucleon, at energies lower than those available at Fermilab. The Fermilab tagged photon beam and the lead glass arrays of Experiment 25 are ideally suited to this process.

A crucial experiment at the present time is the photoproduction of the ψ . If it is a normal vector meson, like the ϕ , it will be photoproduced with a large and nearly energy independent cross section. SPEAR results indicate that the coupling to the photon $\frac{4\pi}{\gamma\psi^2}$ is similar to that of the ϕ . The total

Elastic diffractive cross section is:

$$\sigma_{el}^{\tau}(\gamma p \rightarrow \psi p) = \frac{\alpha}{4} \frac{4\pi}{g_{\psi}^2} \frac{e^{at_{min}}}{a} \frac{(\sigma_{\psi p}^{\tau})^2}{16\pi}$$

where a is the slope of the diffraction peak, $\sigma_{\psi p}^{\tau}$ is the total ψ nucleon cross section and $t_{min} \approx -\frac{m_{\psi}^2}{4E^2}$

is the minimum momentum transfer squared. The latest upper limit on

is about $30 \mu\text{b}^9$. A smaller value of

would imply that the ψ nucleon cross section is anomalously small

(the ϕ nucleon cross section is $\sim 12 \mu\text{barns}$). Any measurable value

would indicate that the ψ is not the weak intermediate boson.

We can detect the ψ most clearly by observing its e^+e^- final state, which apparently has about 5% branching ratio. We can also search for $\psi \rightarrow \gamma\pi^0$, $\gamma\eta$ and $\gamma\eta_c$ and $\psi^1(3.695)$ decays to the same channels by observing 3γ final states.

Experimental Apparatus

The detection apparatus, predicted counting rates and estimated backgrounds are as follows (See Figure 1).

We will use our 7 x 7 stack of 23" long x $(2.5")^2$ lead glass blocks as a multi element shower hodoscope. Electron track positions and gamma ray positions will be measured by a 3 radiation length lead converter followed by 6 planes of multiwire proportional chambers immediately in front of the lead glass stack.

The mass resolution depends upon the Pb glass resolution, the position resolution as determined by the wires and the thickness of the target. For this calculation, we assume a pessimistic $\pm 2\%$ energy resolution for the Pb glass. Then the mass resolution is not markedly improved by

being further from the target than 8 feet. At this position, we have a geometrical acceptance for $\psi \rightarrow e^+e^-$ assuming a t slope of 5.5 GeV^{-2} of 42%. The weighted acceptance for $\eta_c \rightarrow \gamma\gamma$ and $\psi \rightarrow \pi^0\gamma$ including conversion efficiencies are about 48% and 42% respectively. The mass resolution is about $\pm 2.3\%$.

Acceptance vs E

ACCEPTANCE (E)			
<u>E</u>	<u>$\psi \rightarrow e^+e^-$</u>	<u>$\eta_c \rightarrow \gamma\gamma$</u>	<u>$\psi \rightarrow \gamma\pi^0$</u>
50	.07	.064	.056
75	.34	.35	.27
100	.57	.52	.46
125	.67	.59	.54
60 - 115 (aver)	.42	.48	.42

Rates

The details of the Primakoff rate calculations are given in Appendix I. Since the rates may be quite low, we have assumed the use of a .2 r.l. radiator, a .3 r.l. Be target and 3×10^{12} 300 protons/pulse. Primakoff rates are then: 7^{12} (MeV) $BR_{\gamma\gamma}$ events/hour. This is based on measurements of beam yields made during the recent tests.¹⁰

For the ψ photoproduction, we have assumed 1/3 the upper limit on the ψ cross section of 30 nbarns, energy independence, and a 5% branching to e^+e^- . With the same target and beam we then expect 5 events/hour at 50 GeV. For 3_γ final states, the rate would be $100 \times BR_{3\gamma}$ events/hour.

These rate predictions are conservative in that 400 GeV protons would give a factor of 3 increase and running at 6×10^{12} protons/pulse another factor of 2. It is expected that the target and dump can handle 10^{13} p/pulse at 400 GeV. If the machine intensities are high enough to provide this many protons, a factor of 10 higher experimental fluxes than predicted above can be anticipated.

Backgrounds

The Tagged Photon Lab will be an extremely clean environment in which to measure these low cross sections. The electron beam has been measured to have less than a few tenths of a percent pion contamination, and the tagging system reduces the rate of hadrons in the photon beam by many more orders of magnitude. The total photon interaction rate (neglecting small angle electron pairs) is only 600/pulse. The probability that a low energy electron from a pair scatters into the

chambers is about .15 per incident beam electron, or about 10^6 /pulse. This should cause a negligible problem in identifying the charge of the shower.

Since the photon energy is known, we require that the detected energy in the lead glass array be consistent with the tagging energy within the resolution of the system, which is $\sim \pm 5\%$ with a thick radiator. Since the mass of the objects is so high, we require two electromagnetic particles each with a large P_T . An event with two π^0 's carrying all of the incident energy and each having a large P_T would cause a background. We have not seen any data that is relevant to estimating this background. Consequently, the lower limits in the measurable cross sections can probably not be determined without making experimental tests. Of course, this two particle correlated high P_T "background" is of physics interest itself.

Acknowledgement

We would like to thank Profs. B. W. Lee and B. Margolis for very useful discussions. In particular we thank Prof. Lee for his suggestions regarding the Primakoff production of η_c .

FOOTNOTES

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APPENDIX I.

Rate Calculations

The Primakoff differential cross section on the nucleus Z is:

$$\frac{d\sigma}{d\Omega} = 8\alpha Z^2 \sqrt{\gamma\gamma} \left(\frac{\beta}{m}\right)^3 \left(\frac{E^2}{-t}\right)^2 \sin^2\theta F_Z(E, \theta)$$

where the 4 momentum transfer squared is:

$$-t = \frac{m^4}{4E^2} + E^2 \theta^2$$

and β = the velocity of the particle.

The total cross section involves an integration over angles with a convergence at large angles due to the form factor fall off.

$$\sigma_{tot}(E) = \frac{8\alpha Z^2 \sqrt{\gamma\gamma}}{m^3} 2\pi \int_0^{\theta_{max}} \frac{\theta^3 d\theta F^2(E, \theta)}{(\theta_0^2 + \theta^2)^2}, \quad \theta_0^2 = \frac{m^4}{4E^2}$$

The value of $\sigma^{tot}(E)$ increases with energy due to the effect of the

form factor. Using the Be form factor $f(-t) = \left(1 + \frac{(-t)}{.078 \text{ GeV}^2}\right)^{-3}$,

we have evaluated this integral for a mass of 3.1 GeV. The result is shown in Figure 2 and is labelled $\sigma_{(Z=4)}^{coh}$

For high masses ~ 3 GeV even at Fermilab energies σ_Z^{coh} is not dominant.

We also have an incoherent contribution from the individual nucleons.

$$\sigma_Z^{incoh}(E) = \frac{8\alpha Z \sqrt{\gamma\gamma}}{m^3} 2\pi \int_0^{\theta_{max}} \frac{\theta^3 d\theta}{(\theta_0^2 + \theta^2)^2} \left(1 + \frac{-t}{.71}\right)^{-2}$$

This integrand has a significant value out to $-t \sim .11 \text{ (GeV/c)}^2$.

The data rate is then given by

$$\text{Yield} = N_e t_r N_Z A(N_Z) \int_{E_{min}}^{E_{max}} \frac{dE}{E} \left(\sigma_Z^{incoh}(E) + \sigma_Z^{coh}(E) \right) \text{Acc}(E)$$

where N_e is the number of incident electrons, t_r is the radiator thickness (thin target approximation), N_Z is the number of target nuclei/cm², $A(N_Z)$ is the average correction due to beam attenuation in the target, and $\text{Acc}(E)$

Appendix I. (cont'd.)

is the acceptance of the detector for η_c .

We have evaluated this yeild for the following conditions:

$$E_0 = E^{\max} = 115 \text{ GeV}$$

$$N_e = 6 \cdot 10^6 / \text{pulse} \text{ corresponding to } 3 \cdot 10^{12} \text{ protons/pulse at } 300 \text{ GeV.}$$

$$tr = .2 \text{ r.l.}$$

$$N_{(Z=4)} = 1.3 \cdot 10^{24} \text{ nuclei/cm}^2 = .3 \text{ r.l. Be.}$$

$$\text{We then obtain a yeild/hour} = 12 \Gamma_{\gamma\gamma} (\text{MeV}) BR_{\gamma\gamma}.$$

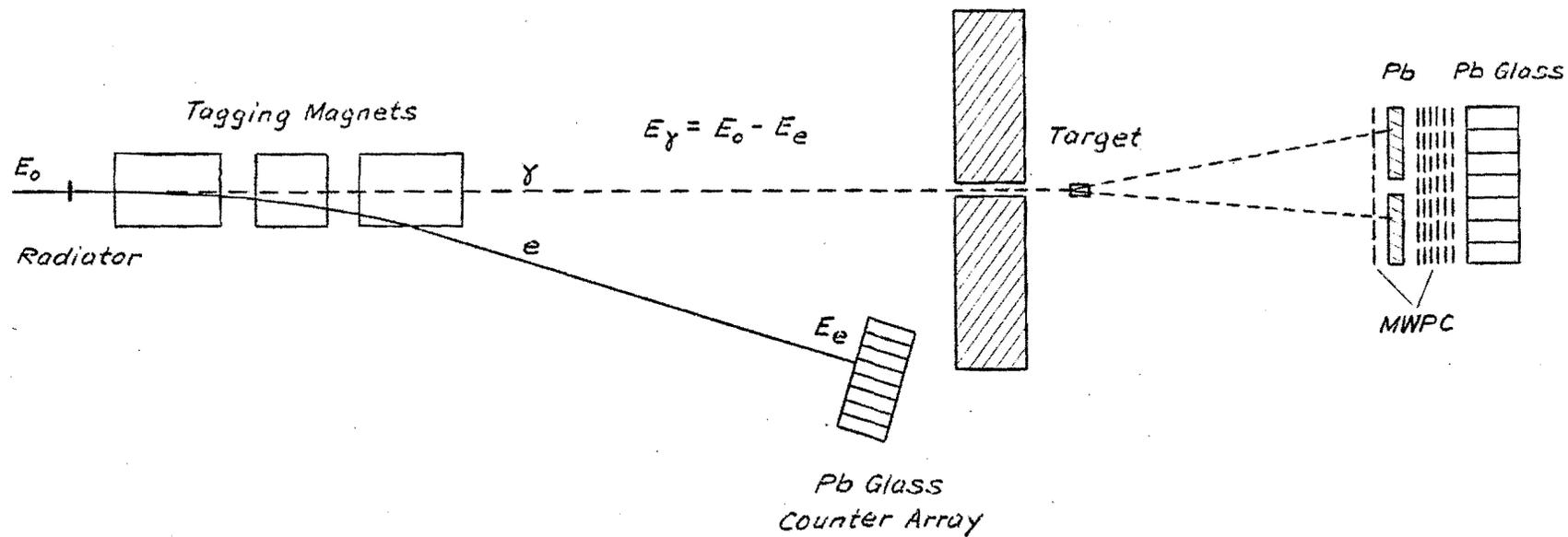


Figure 1
 Schematic of Experimental Setup

Fig. 2

PRIMAHOFF CROSS SECTION ON BE

M = 3.1 GeV

46 1320

10 X 10 TO 1 1/2 INCH 7 X 10 INCHES
KLEFFEL & ESSER CO. MADE IN U.S.A.

170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10

0 20 40 60 80 100 120 140 160 180 200
E GeV

σ_{tot}^{p-p}
 $\sigma_{inel}^{p-p} + 4 \sigma_p$

$\sigma_{inel}^{p-p} = 4 \sigma_p$