NAL PROPOSAL No. 148

Scientific Spokesman:

K. Ruddick
School of Physics
University of Minnesota
Minneapolis, Minnesota 55455

FTS/Off-net: 612 - 725-4242
373-5805

COULOMB PRODUCTION OF VECTOR MESONS

K. Ruddick, E. Peterson, M. Marshak, E. Marquit, H. Courant,
E. Coleman and two graduate students - University of Minnesota

July 15, 1971

COULOMB PRODUCTION OF VECTOR MESONS

Abstract

We propose to measure the Coulomb production of rho and K* mesons in the coherent nuclear electromagnetic field. This analog of the Primakof effect can provide precise determinations of $\Gamma_{\rho\pi\gamma}$ and $\Gamma_{K^*K\gamma}$. The principal detectors are wire proportional planes and a high-precision shower counter, on line to a PDP-9 computer.

Experimenters

K. Ruddick, E. Peterson, M. Marshak, E. Marquit, H. Courant, E. Coleman and two graduate students - University of Minnesota

July 15, 1971

Scientific Spokesman:

K. Ruddick

School of Physics

University of Minnesota

Minneapolis, Minnesota 55455

(612)373-5805

I. INTRODUCTION

We propose to measure the Coulomb production of rho and K* vector mesons in the coherent nuclear electromagnetic field. Although these reactions have not been observed to date, they have received considerable attention in the theoretical literature.[1] A high momentum secondary beam at NAL will provide a first opportunity to accurately measure $\Gamma_{\rho\pi\gamma}$ and $\Gamma_{K^*K\gamma}$ due both to the probable decrease of the strong interaction background and to the increase in magnitude of the Coulomb processes at high energies.

In particular, we wish to measure the process

$$M^- + A \rightarrow M^{*-} + A$$

where A is a nucleus, M^- is an incident pion or kaon, and M* is a vector meson - rho, K* or a heavier analog (if they exist). This process can be separated from the strong interaction background through three independent characteristics - a very sharp forward peak in the differential cross section, a logarithmically increasing energy dependence at very high energies, and a Z^2 dependence. We intend to use all three factors to definitely establish the existence of the Coulomb process. Measurements are planned at four incident momenta from 25 GeV/c to 200 GeV/c with five target elements ranging from carbon to lead. The acceptance in four-momentum transfer covers the range from 0 to $-1(\text{GeV}/c)^2$ so that the incoherent production can also be investigated.

The experimental requirements of the proposal are minimal, since calculations discussed in the next section indicate that the cross-sections are relatively large. A moderate resolution secondary beam $(\delta p/p \sim 1\%)$

with an intensity of 5×10^5 particles/pulse will be sufficient. The incident beam and secondary charged particle will be detected with wire proportional chambers, and the final state gammas will be measured with a combination of proportional planes and a lead-glass Cerenkov counter. The proportional chambers and the electronics system will be proven in an earlier experiment (E-305) at the Argonne ZGS.

II. PHYSICS JUSTIFICATION

The previous experimental measurements of $\Gamma_{\rho\pi\gamma}$ are based on bubble chamber experiments of the type $\gamma + p \rightarrow p + n(\pi^+ \pi^-)$ isolating $\rho^- \Delta^{++}$ from a background of $p\pi^+\pi^- + n(\pi^0)$ events. This separation is difficult, and in a bremsstrahlung beam only upper limits on the cross section are possible.[2] Further problems have recently arisen in the more precise tagged photon experiments.[3] Here the energy variation of the cross section is not consistant with the OPE process unless $\Gamma_{\rho\pi\gamma} \gtrsim .5$ MeV, an unreasonable value in SU3.

A direct measurement of the branching ratio of $\rho \rightarrow \pi^0 \gamma$ is currently being analyzed by members of this group.[4] The main difficulty of this technique is achieving adequate resolution to separate the small broad rho contribution from the dominant 3γ state $\omega \rightarrow \pi^0\gamma$. A more selective technique will be necessary in order to achieve a precise value for this decay. The only attempt to date[5] to observe the Coulomb production directly was severely limited by statistics: it resulted in an upper limit $\Gamma_{\rho\pi\gamma} < .5$ MeV.

The advantage of Coulomb production is that the exchange mechanism is clearly understood and that the shape and energy dependence of the differential cross section is known. The only difficulty is in achieving sufficient angular resolution to isolate the forward coherent peak. The expression for the cross sections is:[1]

$$\frac{d\sigma}{d\Omega} = Z^2\alpha\, F(t)\ \frac{24\Gamma_{\rho\pi\gamma}}{m_\rho}\ \frac{1}{m_\rho^2}\ \frac{\theta^2}{(\theta^2+\theta_{max}^2)^2}$$

The characteristics of the process are: 1) a sharp forward peak at θ_{max} of width $3\theta_{max}$ and magnitude $1/\theta_{max}^2$ where $\theta_{max} = m_\rho^2/2E^2$; 2) the Z^2 dependence; 3) the production of transversely polarized vector mesons; and, 4) a complicated energy dependence of the total cross section: proportional to $(p/R)^4$ for p (in GeV) $\lesssim$ 3 R (in fm), and to $\log(p/m_\rho)$ for higher energies. These cross sections can be large at high energy, e.g. at 100 GeV on lead (assuming $\Gamma_{\rho\pi\gamma} \sim .1$ MeV) the total cross section is 1.5 mb , a number more typical of strong interactions. The cross sections at various energies for various targets are listed in Table I (page 9).

There are, of course, other production mechanisms for vector mesons. The acceptance of our system includes a large part of the incoherent production from single nucleons. This is expected to be small at high energies, but is still observable and interesting both for the energy dependence in the high energy region, and for the A dependence - which leads to a value for the rho-nucleon total cross section.[6] An independent measurement of this quantity would be useful for the interpretation of recent photoproduction data, and for the extraction of $g_{\rho\pi\pi}$.[7]

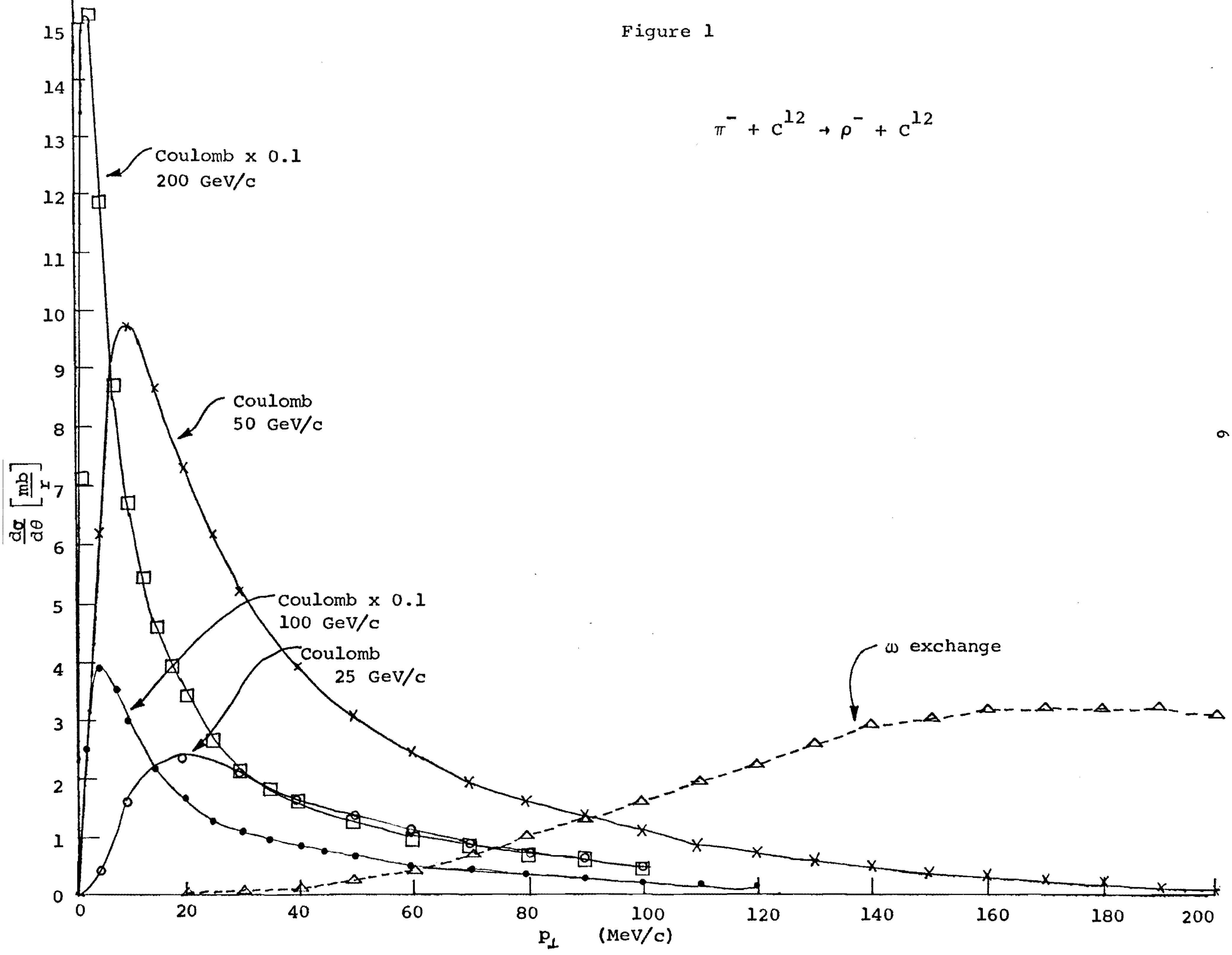
We will also be able to observe the strong coherent production of vector mesons. These coherent processes should be dominated by the exchange of vector mesons, particularly by the ω trajectory. The angular distribution for such processes is much broader, however, and can be separated from the Coulomb peak. It is possible to relate the coherent rho production by ω exchange to coherent K_2 regeneration.[8] The characteristics of the latter process are an A dependence of $A^{3/4}$ and an energy dependence of $p^{-1/2}$. Based on this data (from 6 to 14 GeV/c and on materials from deuterium to copper)[9], one can predict the coherent contribution to rho production:

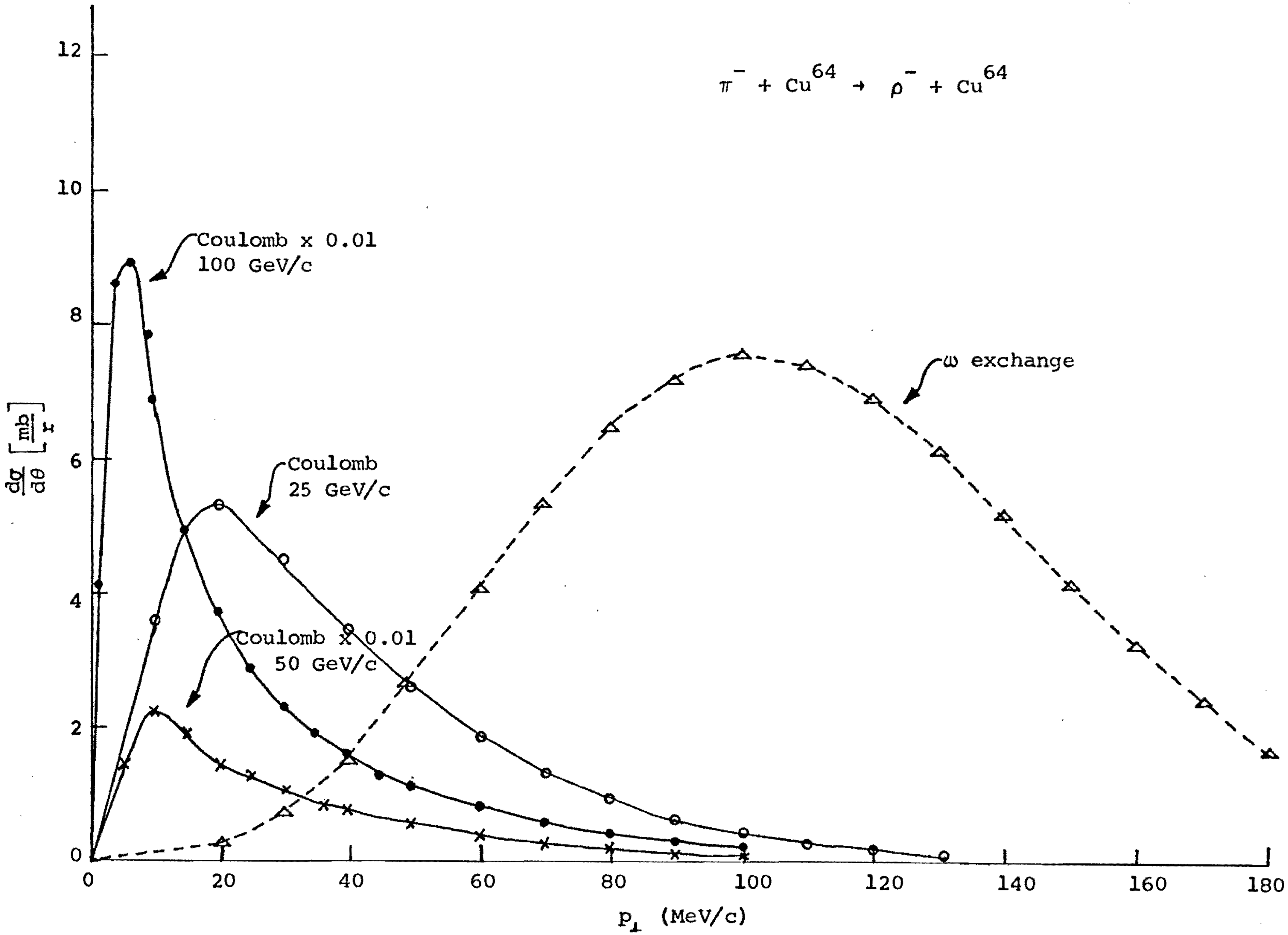
$$\frac{\delta\sigma}{\delta\Omega} \approx 10\, F(t)\, A^{3/2}\, p^3(\mathrm{GeV})\, \sin^2\Theta \left(\frac{\mathrm{mb}}{\mathrm{sr}}\right).$$

F(t) is the nuclear form factor $\sim e^{R^2/4}$. The characteristics of this cross section are: 1) an $A^{3/2}$ dependence; 2) a total cross section proportional to 1/p; and, 3) a broad maximum at $(p\Theta) \sim \sqrt{6}/R$. The magnitude is inherently uncertain to at least a factor of 2, and could, of course, be wildly different if the energy dependence does not extrapolate to very high energies. Nevertheless, the fact that the peak value occurs at a relatively large angle allows the separation of the Coulomb production portion of the cross section. This separation is shown in Figure I for C^{12}, Figure II for Cu^{64} and in Figure III for Pb^{208}.

Two other processes are also of interest, and observable with the same equipment. The first is the obvious SU3 analog of rho production - Coulomb production of K* by incident K's. The angular distributions and background processes should be very similar, and an equivalently

Figure 1


$\pi^- + C^{12} \rightarrow \rho^- + C^{12}$
Coulomb x 0.1
200 GeV/c
Coulomb
50 GeV/c
Coulomb x 0.1
100 GeV/c
Coulomb
25 GeV/c
ω exchange
$\frac{d\sigma}{d\theta}\left[\frac{mb}{r}\right]$
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
0
20
40
60
80
100
120
140
160
180
200
$p_\perp$ (MeV/c)



$\pi^- + Cu^{64} \rightarrow \rho^- + Cu^{64}$
Coulomb x 0.01
100 GeV/c
Coulomb
25 GeV/c
Coulomb x 0.01
50 GeV/c
ω exchange
$\frac{d\sigma}{d\theta}\left[\frac{mb}{r}\right]$
0
2
4
6
8
10
12
0
20
40
60
80
100
120
140
160
180
$p_\perp$ (MeV/c)

Figure 2

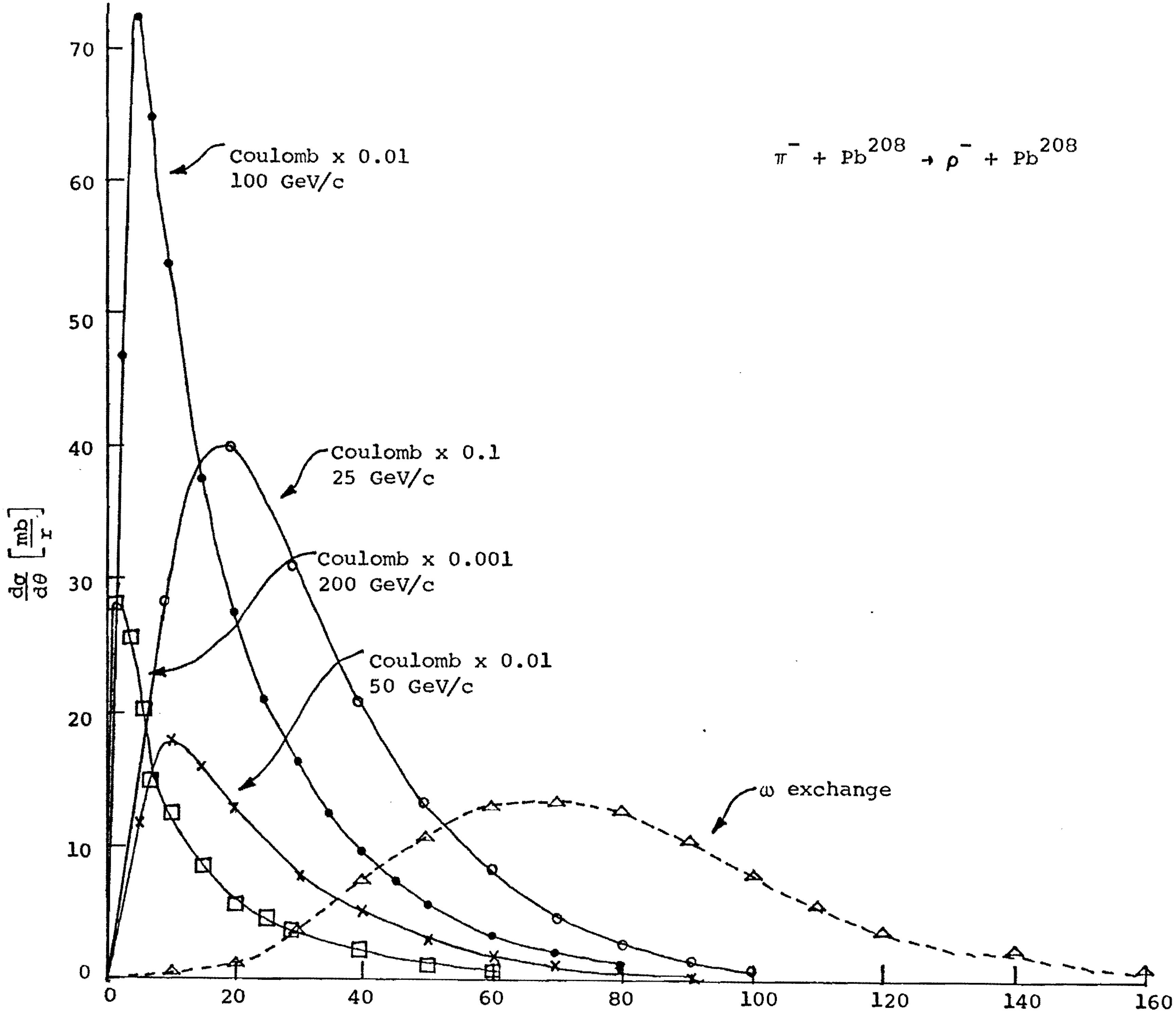

$\pi^- + Pb^{208} \to \rho^- + Pb^{208}$
Coulomb x 0.01
100 GeV/c
Coulomb x 0.1
25 GeV/c
Coulomb x 0.001
200 GeV/c
Coulomb x 0.01
50 GeV/c
ω exchange
$\frac{d\sigma}{d\theta}\left[\frac{mb}{r}\right]$
$p_\perp$ (MeV/c)
0
10
20
30
40
50
60
70
0
20
40
60
80
100
120
140
160

Figure 3

precise determination of $\Gamma_{K^*K\gamma}$ should be possible. This would represent another fundamental test of theories of SU3 breaking.

There is also the possibility of Coulomb production of heavier (and currently unobserved) vector mesons. With the current design the mass region from threshold to about 1500 MeV can be covered with adequate resolution ($\lesssim$ 25 MeV). If the backgrounds are small, the region between 1500 and 2000 can also be explored, at the expense of somewhat broader resolution ($\lesssim$ 80 MeV). The background in this mass region may be the Coulomb production of the g meson. This process would be extremely interesting in itself, demonstrating the existence of a $\pi\gamma$ decay mode. It should be possible to estimate the ratio of g and ρ' production from the angular distributions of the decay pions (the acceptance in $\cos\Theta_{decay}$ is improved at the broad-resolution settings).

TABLE I: CROSS SECTIONS FOR COULOMB PRODUCTION OF RHOS

Energy	C^{12}	Cu^{64}	Pb^{208}
25 GeV	.0062 mb	.10 mb	.61 mb
50	.0085	.16	1.00
100	.011	.21	1.44
200	.013	.27	1.89

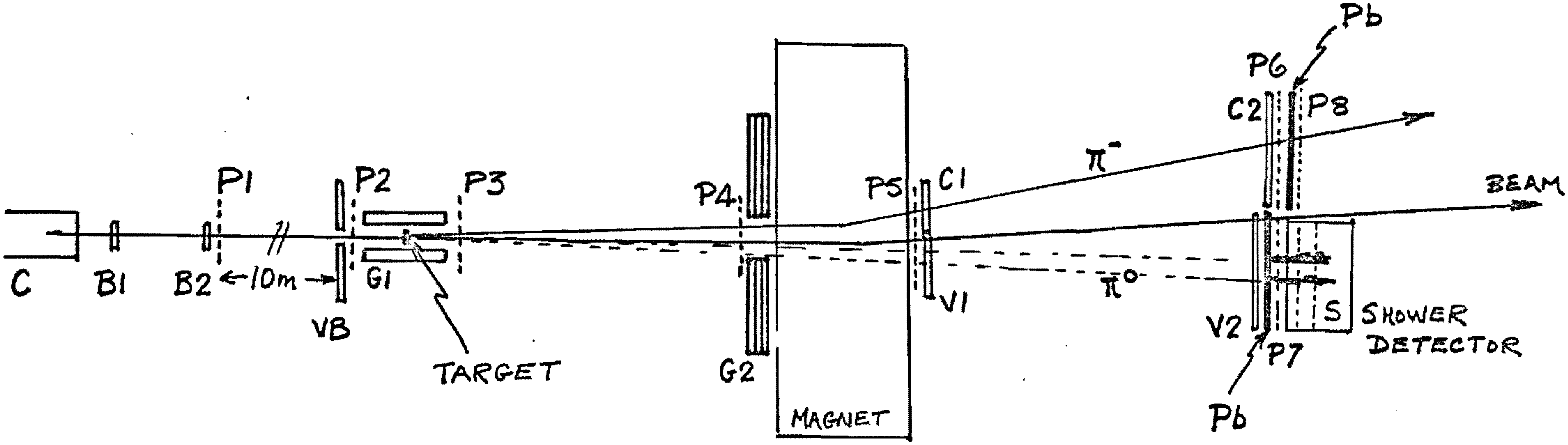
III. EXPERIMENTAL ARRANGEMENTS

The proposed layout of the experiment is shown in Figure IV. The linear dimensions shown are for p = 50 GeV/c; for the other incident momenta, we will scale the experiment in the beam direction proportionally to the momentum in order to keep the same acceptance and (approximate) resolution.

The incident beam is defined by two scintillation counters B_1 and B_2, and anticoincidence counter V_B, and the direction of the incident particle is measured by two proportional planes P_1 and P_2 with a resolution of ± 0.1 mr. The incident particle is tagged by a threshold Cerenkov counter approximately 40m in length and filled with helium gas at a partial vacuum.[10] An additional Cerenkov counter will be required for kaon identification.

The target, which will be 0.1 radiation lengths thick, will be surrounded with leaded glass anti-counters G_1, to veto any event with photons or fast charged particles emerging at more than 30 mr from the beam axis. This allows the observation of incoherent production but vetoes most multiparticle reactions. An additional anticoincidence counter G_2, of lead-scintillator layers, will be located further downstream to define the acceptance of the spectrometer system.

Negative pions scattered to one side of the beam direction pass through a bending magnet with a field of 40 kG-m and an aperature of 12" vertical by at least 18" horizontal. The pions are detected by scintillation counters C_1 and C_2 and their trajectories determined by



TRIGGER = C.B1.B2.$\overline{VB}$.$\overline{G1}$.$\overline{G2}$.C1.C2.$\overline{V1}$.$\overline{V2}$.S

SCALE: 0 1 2 M.

proportional chamber planes $P_{3,4,5,6}$. The initial trajectory of the pion is determined to an accuracy of 0.3 mr and its momentum determined to within one per cent. P_6 is followed by a 5 radiation length lead plate and a further proportional chamber P_8 to identify any photons emitted in that direction.

Photons from the π^o decay are detected in the other side of the spectrometer. They pass through anticoincidence counters V_1 and V_2 and produce electromagnetic showers in a 3 conversion length lead plate. Their conversion points are measured in proportional chamber plane P_7 . The total energy of the two showers will be measured in a total shower absorption detector consisting of 50 radiation lengths of lead and glass in layers 1/4". thick. This will provide an energy resolution of better than 4 per cent for π^o momenta above 15 GeV/c. This detector has two additional planes of proportional chambers with 0.5" wire spacing situated at additional depths of 2 and 7 radiation lengths to determine the approximate energies of the individual showers. The shower detector is discussed in more detail in Appendix I.

Monte Carlo calculations have been made in order to determine the fraction of events detected by the system as a function of dipion mass and of momentum transfer from the incident beam to the dipion. At the rho peak we find that 37 per cent of the pion pairs from coherent processes will be detected, falling to 21 per cent at $-t = 0.5\ (\mathrm{GeV}/c)^2$. The acceptance for a dipion mass of 1.0 GeV is 32 per cent. As already described, one run will be taken with a wider acceptance and proportionally poorer resolution in order to search for higher mass objects. The acceptance and resolution scale proportionally to the length of the system. These values for the acceptance include the factor of two arising from the fact that we detect π^- and π^0 only on opposite sides of the beam.

The chief background to the process to be investigated arises from diffraction dissociation of the beam to $\pi^- \pi^0 \pi^0$ where two of the photons from the $\pi^0 \pi^0$ decays are not detected. The cross-section for this process is approximately $A^{2/3}$ mb [11] at the highest energies to be investigated. This cross section is approximately 25 times greater than the expected rho production cross section on lead at 100 GeV/c and approximately 400 times greater than that on carbon. Monte Carlo calculations for the acceptance of $\pi^- \pi^0 \pi^0$ events have been made, using the known mass distribution of these events and it is found that less than one per cent of such events are produced with all five final state particles in the acceptance of the system. The efficiency of the anticoincidence counters which define the acceptance will be more than adequate to prevent the balance of such events producing a trigger. Those events which do have all five particles within the system acceptance are strongly discriminated against in the data analysis. The proportional planes in the shower detector and the plane P_8 will signify the existance of more than two photons with an efficiency greater than 1 in 10^6. Thus we expect this background to be entirely negligible. However, in the runs made with wide acceptance, the trigger rate will be dominated by this reaction and it will be necessary to limit these runs to high Z targets only. The background arising from material downstream of the target can be made negligible by the use of helium bags. Table II indicates the expected rates for the processes to be studied for carbon, copper and lead at all four incident momenta. The table also shows the expected trigger rate and the number of hours required to obtain 2000 rho events from coherent Coulomb production. The target thickness has been assumed to be 0.1 radiation length.

The resolution in p-perpendicular ($\sqrt{-t'}$) is a slowly varying function of the incident momentum, ranging from ± 37 MeV at 25 GeV/c to ± 18 MeV at 200 GeV/c. If we accept only the 50 per cent of the events with the largest $\pi^0 \rightarrow \gamma\gamma$ opening angles, these figures can be improved by 30 to 40 per cent. This cut is not necessary to isolate the Coulomb peak from the possible strong coherent background, but will allow us to explore (partially) the dip in the forward direction for the low-energy/low-Z runs. The resolutions are more fully discussed in Appendix II.

The time requested totals 7 weeks, approximately 150 shifts. Thirty shifts are requested for normal tuning, and 18 shifts for equipment relocation and retuning after a change in incident momentum. The complete survey of rho production for four energies and five elements should be accomplished in 20 shifts with approximately 2000 events per run (based on a 100 KeV partial width).

The balance of the shifts are requested for the particle search and for the K^* production experiments. Due to the strong mass

TABLE II: TRIGGER AND COUNTING RATES FOR RHO PRODUCTION

Element	Trigger rate per pulse	Coulomb events per pulse	Hours for 2000 events
25 GeV/c			
C^{12}	15.9	.24	12
Cu^{64}	3.7	.21	13
Pb^{208}	1.9	.21	13
50 GeV/c			
C^{12}	8.5	.33	8
Cu^{64}	1.9	.32	8
Pb^{208}	1.0	.35	8
100 GeV/c			
C^{12}	6.3	.42	7
Cu^{64}	1.5	.43	7
Pb^{208}	1.0	.50	6
200 GeV/c			
C^{12}	6.3	.51	5
Cu^{64}	1.5	.56	5
Pb^{208}	1.0	.66	4

Other elements planned are Sn and W.

dependence of the Coulomb production process ($\sim 1/m^4$), the search for high mass objects (above 1500 MeV) is feasible only for one element and energy - the most favorable is lead at 200 GeV/c. At the highest mass accepted (2 GeV), a run of 12 shifts will accumulate 1000 events for 100 KeV of $\pi\gamma$ width, assuming that the $\pi\pi$ decay mode is dominant. The K* production is limited by the incident flux, assumed to be 5 per cent of the beam. Due to the combination of a slightly smaller acceptance for K* events, the branching ratio of 1/3 to $K^- \pi^o$, the mass dependence (see above) and the somewhat reduced partial width that is expected for $K^* \rightarrow K\gamma$,[12] the exploration of this process is feasible only for two elements at the single highest energy. Sixty-five shifts should produce approximately 1000 K* events for each element. The Z^2 dependence and the angular distribution will be sufficient evidence for the Coulomb process. If this group is to install and test the beam Cerenkov counter system, additional time will be needed.

IV. Apparatus

The apparatus to be furnished by NAL includes:

a) An unseparated π and K beam of negative sign capable of:
   1) momenta from 25 GeV/c to 200 GeV/c,
   2) a $\Delta p/p$ less than or equal to 1 per cent, and
   3) identification of π's and (preferably) K's.

b) A moderate-bore bending magnet capable of 40 kG-m over an aperature of 18" x 12" minimum.

We will undertake the construction of the beam Cerenkov system if that seems desirable.

The balance of the equipment will be provided by the University of Minnesota and includes:

a) an on-line PDP-9 computer with DEC-tape, CRT and plotter capability

b) proportional wire chambers and associated read-out systems (several, from 4" to 24" square)

c) targets and target anticoincidence system and

d) the shower detector.

The PDP-9 has been acquired and is being interfaced to the proportional chamber system. The computer and the majority of the chambers (including the largest planes) will be tested in experiment E-305 at the Argonne National Laboratory scheduled for late summer of 1972. The major piece of new apparatus to be built for this experiment is the shower detector. We estimate that we will be able to complete E-305 and construct this detector by April of 1973. Since the major portion of the equipment will exist prior to this experiment, we have sufficient manpower at Minnesota and do not envisage either additions from the NAL staff or collaborations with any other group.

APPENDIX I: Shower Counter

The shower counter will be used to determine the total energy of the π^0 with an uncertainty of less than 4 per cent above 15 GeV/c. The energies of the two individual photons will be determined with modest resolution by determining the number of electrons in the showers at two points in the shower counter with proportional planes 5 and 10 radiation lengths into the detector complex.

Monte Carlo calculations show that the total number of electrons and positrons detected in a photon induced shower in lead is approximately 60/GeV incident photon energy,[13] when the shower is sampled at one radiation length intervals. The resolution of a detector based on a measurement of this number should be determined by the fluctuations in the number observed. Thus an energy resolution of approximately 4 per cent should be realizable for a 15 GeV neutral pion. Such a detector using plastic scintillator as the detecting medium has been found to have a resolution of 4.9 per cent at 10 GeV, with an energy dependence of $E^{-1/2}$ as expected.[14]

The detector proposed here uses glass as the detecting medium. Cerenkov light from relativistic electrons is totally internally reflected and thus transmits efficiently to the edges of the detector where it is detected by at least two photomultiplier tubes. The total thickness of the detector will be 50 radiation lengths, to give the capability for a linear response to 200 GeV.

In order to resolve the two-fold ambiguity in the direction of the π^o meson, which arises if only the total energy of the π^o and the direction of the two photons are known, the energies of the individual photons will be determined by wire proportional planes at depths of 5 and 10 radiation lengths into the detector. Since the mean radius of the showers is less than 1 cm , and the minimum separation between showers is 10 cm , the wires of the chambers can be separated by 1/2" . These chambers will be operated in the proportional mode to give signals proportional to the number of electrons in the showers. The trigger rates for the experiment are small enough so that the analog-to-digital conversion time is not a problem.

The energy resolution obtainable by this means will be better than 20 per cent. This is adequate to resolve the ambiguity in the π^o direction except in the region where the ambiguity is small, and where the bisector assumption is utilized (see Appendix II).

The two additional planes also serve a function in the elimination of background events. Since they are at depths of 4 and 8 conversion lengths, the probability that two photons from a $\pi^- \pi^o \pi^o$ event will not convert is totally negligible. Thus, while these events will trigger our apparatus, they cannot be confused with single π^o events.

APPENDIX II: Resolutions

Since the identification of the Coulomb production process over background processes depends strongly on the existence of a very sharp forward peak in the differential cross section, the success of the experiment will depend on the angular resolution of the reconstructed rho meson angle. The input parameters are:

a) the angular resolution for the π^-: $\delta\theta_- = 0.3$ mr

b) the momentum resolution for the π^-: $\delta p_- = 3.5\text{x}10^{-4}\ p_-^2$ (GeV)

c) the momentum resolution for the π^o: $\delta p_o = 0.16 \sqrt{p_o(\text{GeV})}$ and

d) the angular resolution for the π^o: see below.

The numbers in a) and b) are for 50 GeV/c incident momentum - they scale inversely with the incident momentum. The units are always GeV.

The best resolution for the π^o direction is obtained by an either/or decision: if the opening angle of the decay is minimum within resolution limitations, the bisector is the best choice; away from minimum, a calculation (based on the total π^o energy and the knowledge of which is the most energetic γ) gives a better value. With the parameters of our system (1/8" wire spacing at 11 meters - at 50 GeV) the resolution in the 2 γ opening angle is 0.3 mr . The resolution in the (calculated) minimum opening angle is set by the total energy measurement: $\delta\theta_{min} = 2\ \delta\gamma/\gamma^2 = 0.32/p_o^{3/2}$.

The value for θ_o , the π^o angle, in terms of θ_1 , θ_2

the γ angles and α , the CM decay angle (measured from symmetric decay) is:

$$\theta_o = (\theta_1 + \theta_2)/2 + (\tan\alpha)/\gamma$$

so that the error in the bisector assumption is

$$\delta\theta_o = \delta\theta_i/2 + (\tan\alpha)/\gamma \quad .$$

The decay angle α is determined from the opening angle from

$$\cos\alpha = \theta_{min}/(\theta_1 - \theta_2).$$

If the opening angle is beyond minimum, within resolution, the corresponding expression for the resolution is

$$\delta\theta_o = \delta\theta_i + \left\{ \left[\sqrt{2}\ \delta\theta_i (1 + \csc\alpha) \right]^2 + \left[\delta\gamma(\cot\alpha)/\gamma^2 \right]^2 \right\}^{1/2} .$$

For large opening angles, the resolution improves by almost a factor of two. Thus there exists the capability of clearly resolving the Coulomb peak and, in C^{12} , seeing the dip in the exact forward direction. The resolutions are approximately independent of the incident momentum - the slight improvement with increasing momentum is due to the slow increase in the resolution of the shower counter. The resolutions are presented below in terms of $p_\perp = \sqrt{-t'} = p_\rho \theta_\rho$, which is the relevant parameter for the strong coherent background (see Figures I - III).

Energy	Resolution	with opening angle cut
25 GeV	37.2 MeV	22.5 MeV
50	28.8	17.7
100	22.7	14.8
200	18.4	13.0

REFERENCES

1. S. M. Berman and S. D. Drell, PR 133B, 791 ('64); M. Gourdin, CERN TH 1307 (3/18/71); and many others.
2. L. J. Lanzerotti + , PRL 15, 210 ('65); H. R. Crouch + , PRL 13, 640 ('64); A. D. Franklin + ,PRL 13, 491 ('64) and D. McLeod + , PRL 7, 383 (61).
3. J. Ballam + , PRL 26, 995 ('71)
4. Experiment E-219, Argonne National Laboratory
5. F. R. Huson + , PL 20, 91 ('66)
6. S. D. Drell and J. S. Trefil, PRL 16, 552 ('66) and many others. The transition to incident π (K) is trivial - J. S. Trefil, private communication.
7. e. g. S. C. C. Ting, 14th Int. Conf. on HEP (Vienna - 1968)
8. J. Rosner, private communication.
9. A. Bohm + , PL 27B, 594 ('68); M. Bett-Bodenhausen + , CERN 1969 Weak Int. Conf., p. 329 ; D. Darriulat + , PL 33B, 433, ('70); S. Bennet + , PL 29B, 317 ('69)
10. NAL Summer Study, 1970
11. P. Franzini, 3rd Intl. Conf. on HE Coll. (Stony Brook - 1969)
12. M. Gourdin, CERN TH 1320 (4/27/71)
13. D. F. Crawford and H. Messel, NP 61, 145 ('65) and U. Volkel, DESY 67/16 ('67)
14. G. Backenstoss + , NIM 21, 155 ('63)