PROPOSAL TO STUDY

MULTIHADRON SYSTEMS WHICH INCLUDE

CHARGED AND NEUTRAL MESONS

***

E. Bleser and D. Johnson

Fermi National Accelerator Laboratory
Batavia, Illinois 60510

B. Gobbi, J. Keren, R. Lipton, D. Miller, J. Rosen
R. Ruchti and D. Spelbring

Northwestern University
Evanston, Illinois 60201

September 26, 1975

Correspondent:
J. Rosen
Evanston: (312) 492-5457, 5463, 3644
Fermilab: (312) 840-4139, 3057

I. INTRODUCTION

We propose to construct a sectorized shower detector to enhance the detection capabilities of the spectrometer equipment presently deployed in the M3 beam line. The principal equipment that now exists consists of an array of PWC detectors and wire spark chambers used in conjunction with a BM 109 magnet. The position detectors in front of the magnet are exclusively PWC, while those in the rear are primarily wire spark chambers. The equipment is now configured for Experiment 397 -- Search for the Associated Production of Charm Particles. During the next year, we plan to replace all the rear chambers with drift chambers.

The addition of the proposed $\pi^o(\eta^o)$ shower detector will increase our spectroscopic options. We outline two specific experimental applications.

A. Enhanced Capability for New Particle Searches

The primary goal of Experiment 397 is the study of the physics accompanying prompt muon production ($p_\perp \sim 1 - 2$ GeV/c). Given our new prompt muon trigger, we will be searching for two basic effects. The foremost of these is a search for $\mu^\pm e^\mp$ correlations. A significant yield of such events would provide good circumstantial evidence for the associated production of new particles followed by leptonic or semileptonic decays.

The second more problematic aspect of the experiment is the search for structure in the mass spectrum of hadrons accompanying prompt muon production. We envision the muonic decay of one of the two new particles and hopefully, a fully detected hadronic decay of the other.

We will be studying mass plots in 2, 3 and 4 charged particle modes. The kinematical identification of particle rest mass (π, K or p) will be difficult in decay modes with multiplicity >2. This is because the permuted possibilities for mass assignments rapidly increase with multiplicity. Hence, the escalation of the search to higher multiplicities will be greatly facilitated if the additional hadrons are added in the form of π^o and/or η^o. We propose to look for structure in the mass spectra of charged hadrons and neutral mesons. Clearly, the variety of final states that will become available for study will be materially enhanced by the proposed addition of the shower detector.

There exist good circumstantial arguments which suggest that new heavy particles may not be readily observed in low multiplicity channels. The e^+e^- storage data on hadron production in the mass range 2-4 GeV indicate that two-body final states are rare indeed; branching ratios are typically $\sim$ few x 10^{-3}.

B. Measurement of the Coherent Reaction $K_L^o + A \rightarrow A + (K_S^o + \pi^o)$

There is adequate K_L^o flux in the M3 beam to permit the measurement of the above reaction. This reaction is closely related to the reaction $\pi^- + A \rightarrow A + \rho^-$ that we have previously studied (see appended reprint). The measurement calls upon some of the special equipment and expertise that has been accumulated during our coherence reaction work over the last few years. We will describe the physics motivation and the specific experimental scheme in Section III.

We have a strategic purpose behind the proposal of this reaction which constitutes a second level of motivation. It is highly desirable to confront a large new detection system (the shower detector) with a very specific low multiplicity reaction. We can then develop the offline analysis software and study the detailed characteristics of the detector before challenging more speculative particle searches.

II. SHOWER DETECTOR

A. Mechanical Features

A schematic diagram of the shower detector hodoscope is shown in Figure 1. Since it is inspired by the ingenious and remarkable design of the C.I.T. group (Tollstrop, Walker et al), the detector should require little explanation. The nature and performance of their detector is well known at Fermilab.

The interleaved vertical and horizontal hodoscopes are pulse height analyzed and thus provide measurement of both shower energy with reasonable resolution, and shower vertices to an accuracy of 1-2 mm.

In order to effectively shadow most of the output aperture of the BM 109 magnet (projected to the rear of the charged particle position detectors), we envisage

in effect, 2 C.I.T. detectors alongside each other. The light pipes emerge from the sides and top.

We have made one critical variation from the C.I.T. design, principally in order to save money and labor. We use liquid scintillation cells of slightly larger cross-section. A considerable savings in scintillator cost is effected, and tedious polishing is eliminated. Total internal reflection in the cell is accomplished by the use of a (1 mil) teflon surface, bonded to the cell defining Al sheet prior to formation by bending. The teflon provides total internal reflection up to an angle of 24°. Liquid scintillator also has substantially better light transmission properties (the attenuation length is about twice that of plastic).

A cell fabrication device has been constructed. Prototype cells have been formed and their properties studied with a β source. A test counter suitable for insertion in a high energy beam is under construction. The design will then be fine-tuned. The C.I.T. design employs a number of tricks to compensate the light collection so as to make the response uniform over the length of the cell to an accuracy of a few %. We have adapted these tricks to our own cell design. By fine-tuning, we mean that the cells are partially blackened under the teflon skin and the precise pattern of blackening needs to be finalized in a test beam study.

There are a few complications in our design. The entire shower detector lattice must be enclosed in a leak tight vessel.

A significant cost and labor savings in light pipe fabrication is achieved by using 3/8" D. Lucite rods. Only the cut ends need to be machined and polished. It is also easy to join them to the detector vessel. The top and sides of the detector vessel will be viewed through 1/16" Lucite sheets. However, the hydrostatic pressure of the liquid scintillator in the container (in the case of the side panels) will be transmitted to Aluminum bars which will have 3/8" holes bored in them. These holes will be aligned with the scintillation cells and the light pipe rods will plug into them.

B. Electronics

The detector requires 4 x 70 = 280 2" D., 10 stage P.M.'s. Each subset of 70 will be arranged in a 14 x 5 array. Each sub-grouping of 5 P.M.'s (consisting of 5 adjacent hodoscope elements) will be formed of matched P.M.'s. The five tubes, then can share a common high voltage divider. We may apportion 1 divider/ 10 P.M.'s for the outer regions of the detector. Two types of signal outputs will be available:

1. All anode signals will be piped through 400 ns. cables to (event gated) A.D.C.'s.

2. Dynode signals from the sub-grouping of 5 adjacent elements will be daisy chained together and provide a summed output. This provides (two) coarser 14 x 14 hodoscopes to be used for trigger purposes. We can simply use the signals for energy threshold triggering or by linearly mixing outputs through programmed resistors, we can develop a high $p_\perp$ trigger.

C. Detector Cost Considerations

We break down the costs into four categories:

1. Mechanical Detector Proper

Aluminum vessel	$ 2,000
4500 lbs Pb	2,500
Al cells, teflon	2,500
Acrylic light pipes	3,000
Liquid scintillator	1,000
Detector carriage (motor driven horizontal and vertical motions for calibration studies)	3,000
Miscellany - light pulsers for monitoring stability, thermal stabilization, etc.	
Construction jigs, exigencies	4,000
	$18,000

2. Supplementary Labor $20,000

Most of the labor will be provided by existing budgeted manpower. We would like to purchase some drafting and supplementary machinist time.

3. P.M.'s, magnetic shielding, voltage dividers, cables, connectors, etc.
   280 channels @ $150/channel + 40 spare tubes — $45,000

4. A.D.C.'s (288 channels)
   If commercial A.D.C.'s are purchased, the cost per channel should run ~ $200. (E.g. L.R.S. 2249A 12 channel unit) — $55,000

<u>We propose that this be provided by P.R.E.P.</u>

The possibility of constructing lower cost A.D.C.'s on our own does not appear particularly attractive. Design, documentation, and labor costs will seriously erode any apparent savings based only on component costs. Further, there are special components and tools which are only readily available to a manufacturer. Other P.R.E.P. equipment costs are minor, by comparison. The existence of the new shower detector will retire our present 38 channel one dimensional shower hodoscope. The H.V. supplies, distribution boxes and fast electronics freed up by this will provide most of the needs of the new system.

Table I - Shower Detector Properties

Number of cells	70 x 70 in each of 2 halves
Cell size	3/8" x ½" x 36" (mirror at blind end).
Number of sampling layers	9 horizontal, 9 vertical
Detector thickness	20 radiation lengths
Primary light pipes	3/8" D x 30" long (total > 1 mile)
Number of 2" 10 stage P.M.'s	4 x 70 = 280 (+ spares)
Detector weight	3 tons
Energy resolution (σ)	$\approx 0.10/\sqrt{E}$(GeV)
Fraction of shower energy depicted in scintillator	$\sim$ 15%
Transverse momentum resolution	$\lesssim$ 10MeV/c

III. COHERENT REACTION STUDIES

A. Physics

Several interesting coherent reactions can be studied in the M3 beam with the aid of the shower detector. We single out for special attention the reaction

$$K_L^o + A \rightarrow A + (K_s^o + \pi^o) \qquad (1)$$
$$\searrow \pi^+\pi^-$$

This reaction will proceed by a coherent mixture of photon (coulomb) and ω^o exchange amplitudes. At Fermilab energies, we expect the former to strongly dominate for high Z targets.

We call attention to a unique aspect of reaction (1). Because of C invariance, the reaction

$$K_L^o + A \rightarrow A + [K_s + m(\pi^o)]$$

via Pomeron exchange is <u>forbidden.</u>

In previous experimental work, $\pi^- + A \rightarrow A + \rho^-$ (1) and $K^o + A \rightarrow A + K^{o*}(\rightarrow K^-\pi^+)$ (2), it was necessary to subtract background from diffractive dissociation leading to the final state $\rho^- + \pi^o$ (undetected) and $K^-\pi^+ + \pi^o$ (undetected). The coherent background channels are intrinsically an order of magnitude larger in yield. After appropriate kinematical cuts, a residual background subtraction of approximately 10% was still necessary. In the case of the ρ^- experiment, the kinematical cuts were made at the expense of a loss in event acceptance efficiency.

Therefore, the <u>absence</u> of such diffractive background for reaction (1) is a consideration of real practical value.

Upon the completion of the measurement of reaction (1), three physical quantities can be extracted from the data.

1. The coulomb dissociation amplitude which directly provides the radiative width $\Gamma\ (K^{*o} \rightarrow K^o + \gamma)$.
2. The strength of the ω^o exchange amplitude.
3. The relative intrinsic phase of amplitudes (1) and (2).

The generic reaction, vector meson → pseudoscalar meson + γ is thought to be fundamentally a magnetic transition involving the quark substructures. The present experimental situation is puzzling.

REACTION	Γ EXPERIMENT (KeV)	Γ THEORY (KeV)
$\omega^o \to \pi^o \gamma$	890 ± 70	-
$\rho^- \to \pi^- \gamma$	35 ± 10	100
$\overline{K^{*o}} \to \overline{K^o} \gamma$	75 ± 35	280

It is desirable to study $V \to M + \gamma$ transitions at Fermilab energies. The ratio of the coulomb amplitude to the ω^o amplitude will then be substantially larger (the former increases with energy while the latter decreases as $E^{-\frac{1}{2}}$). The high Z measurements will then give a radiative width which is largely decoupled from the other 2 parameters. <u>We believe that an accuracy of (5-10)% in $\Gamma(V \to M + \gamma)$ is achievable.</u>

Note for example, Figure 3b of reference 1 (attached). The coulomb and ω^o relative contributions are comparable for Pb, U at a beam energy of 23 GeV. At a projected energy of 70 GeV the relative ratio of cross-sections will be $\sim$10. (The coulomb-ω^o amplitude ratio is approximately the same in the ρ^- and $\overline{K^{*o}}$ measurements if the lower energy ($\sim$11 GeV) of the latter is taken into account.)

In the experimental geometry we have in mind, we will simultaneously obtain information on the reaction

$$K_L^o + A \to A + (K_S^o + \omega^o) \qquad (2)$$
$$\omega^o \to \pi^o \gamma$$

This diffractive dissociation reaction is at present unmeasured. Basically, it should have physics content similar to the reaction $\pi + A \to A + (\rho\pi)$ [3]. We do not expect to be inundated with such events , but as an educated guess the yield averaged over the range of targets we shall employ will be comparable to that of reaction (1).

Obviously, we could also study (and with less difficulty) neutron induced coherent reactions

$$n + A \to A + (p\pi^- + \pi^o) \qquad (3)$$
$$2\,\pi^o$$
$$\eta^o$$
$$\omega^o \quad \text{etc.}$$

B. Description of the Experiment

1. Beam

The M3 beam collimators can be opened to $\sim 10\,cm^2$ with little difficulty. The K_L^o beam component should be a few %. We do not have a measurement of this at 400 GeV, but it is expected that the K_L^o/n ratio should be somewhat higher than that measured at 300 GeV. In any case, the beam will be filtered with low Z material to enrich the K_L^o component. Recall that $\sigma_T\ (n + N)/\sigma_T\ (K_L^o + N) \approx 2$. If we attenuate the neutrons by 16, the K_L^o will be attenuated by 4, etc. We expect

$$10^5\ K_L^o\ /\ \text{pulse}\ (\sim 6\text{x}\ 10^4\ K_L^o\ /\ \text{pulse with}\ E > 50\ \text{GeV})$$
$$6 \times 10^5\ n\ /\ \text{pulse}$$

2. Normalization and Calibration

The absolute measurement and monitoring of a neutral beam required for a precision absolute cross-section measurement is generally a difficult problem. In this particular experiment, there is a very elegant resource. A decay process which has the same topology as the reaction to be studied is

$$K_L^o \rightarrow \pi^+ + \pi^- + \pi^o \qquad (3)$$

Given the allotted decay path, we expect to record about 10 decays/pulse. Thus, a beautiful normalization is a built-in feature. Further, since the decay reaction is overconstrained, all the system resolution properties can be checked, e.g. the decay constitutes a pseudo $t' = 0$ reaction.

3. Experiment Configuration

Figure 3 illustrates the relative positioning of the key elements.

1. Target
2. Evacuated 3m decay region (the m.f.p. for decay of 40 GeV K_s^o is 2m).
3. BM 109 magnet. The limiting aperture subtends ± 15 mr (V) and ± 45 mr (H) relative to the target.
4. Shower detector. Subtends ± 15 mr (V) and ± 30 mr (H) with respect to the target.

P.W.C. chambers positioned on either side of the magnet are not shown.

A variety of baffle veto counters (existing) will be positioned so as to reject events having reaction products passing outside of the limiting aperture.

Targets of U, Ag, Cu, C of thickness ≤ 0.25 radiation lengths will be used. Substantially thicker targets would result in appreciable π^o decay γ conversion in the target. Targets will be placed in the veto counter anulus that we have previously employed. This system surpresses incoherent reactions.

The essence of the event trigger is

1. $K_s^o \rightarrow \pi^+\pi^-$. Two and only two charged particles leave the decay box and exit through the magnet. On average, the K_s^o will have ~ 0.6 of the energy of the incident K_L^o.
2. π^o. Neutral shower reactions with an energy threshold ≥ 10 GeV.

4. Event Rate

Using the Primakoff formula for energy extrapolation, we estimate that the small t coulomb yield from a Pb nucleus (Z = 82) will be

$$\sigma \approx 2 \text{ mb/nucleus/mean energy 70 GeV.}$$

Given a 1.6 g/cm^2 Pb target, we expect

$$10^{-5} \quad K^{*o} + \overline{K^{*o}} \;/\; \text{incident } K_L^o$$

1. $K^{*o} + \overline{K^{*o}} \xrightarrow{1/3} K_s^o \pi^o \xrightarrow{2/3} (\pi^+\pi^-) + \pi^o$.
2. Factor for π^o escaping target conversion = 0.7.
3. K_s^o decaying in 3m = 0.7.
4. Useful K_L^o flux = 6×10^4.
5. Geometrical acceptance of magnet and shower detector ≥ 0.5.

$\rightarrow$ Yield of events/pulse = $(6 \times 10^4)\ (10^{-5})\ (2/9)\ (0.7)\ (0.7)\ (0.5) = \underline{\underline{1/30}}$

This event rate will be sufficient for obtaining several thousand events in a 500 hour experiment. We have carefully considered the similarities and differences between this proposed experiment and our earlier successful ρ^- measurement. The event rate in the latter was lower. We believe that the above estimates constitute a very conservative design. There are some measures that could be instituted to increase the event rate, but we will not guarantee that they are foolproof at this time. We list a few of these.

1. Raise the beam intensity. Note that our high Z targets are only a few % of an interaction length. We would like some information on the

neutron background capability both in triggering and in data analysis before we optimistically propose to do this.

2. Open the magnet vertical aperture.

3. Accept events where one of the π^o decay γ rays produces an e^+e^- pair in the target. The pair would then be momentum analyzed. We could then increase the target thickness.

We make a final observation concerning target thickness. In coherent dissociation work, one usually limits the target thickness in order to limit the coulomb multiple scattering of charged particles leaving the target. Good t' resolution in required for physics reasons. In the present instance, the target thickness is limited in order to allow the escape of γ rays. The diffractive dissociation process $K_L^o + A \rightarrow A + (K_S^o\ \omega^o)$ will be optimally measurable in a low Z target (e.g. Carbon). The r.l. equivalent of a fairly thick target will be low, e.g. 5 g of Carbon $\approx$ 0.1 r.l.

IV. SCHEDULE CONSIDERATIONS

We presume that prompt approval by Fermilab will aid us in our request for certain supplementary funds, most of which are required for P.M.'s.

We anticipate the completion of the shower detector in Summer 1976.

Approval for 500 hours of beam time is requested. This should be sufficient for the K^* experiment. Particle searches will require additional time.

No costly or unusual rigging requests are anticipated. The bulk of the PREP request will be in the form of 24 12-fold A.D.C.'s (noted earlier).

A BISON Computer System is required, to become available in early Summer 1976. Fortunately, Northwestern owns a PDP 11 Computer which constitutes $\sim$ 70% of a BISON system. With the addition of several peripherals provided by the laboratory, we will have a BISON System.

***

REFERENCES

1. B. Gobbi et al. Phys. Rev. Letters 33, 1450 (1974). *Reprint appended.

2. W.C. Carithers et al. Phys. Rev. Letters 35, 349 (1975).

3. V. Kruse et al. Phys. Rev. Letters 32, 1328 (1974).

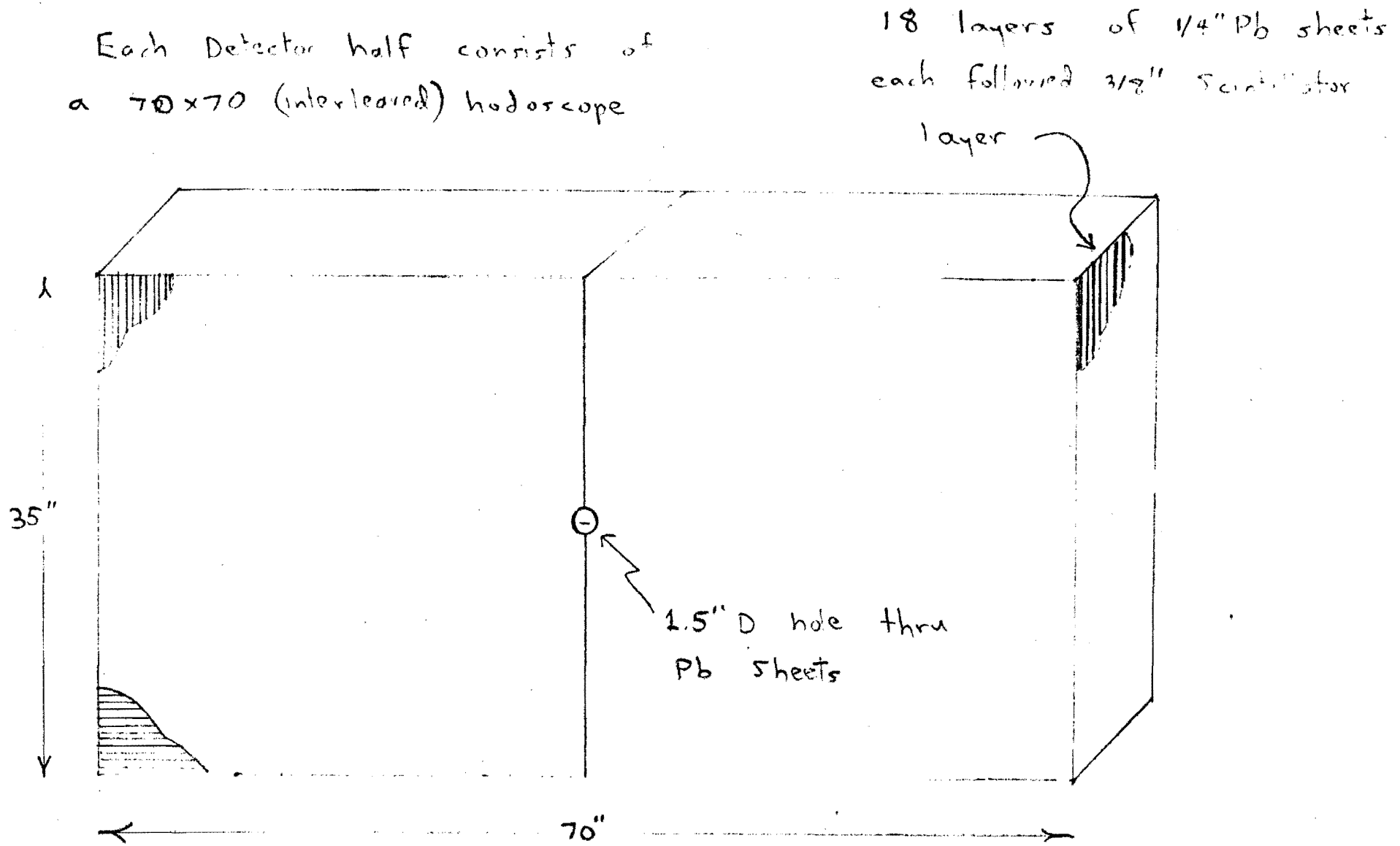
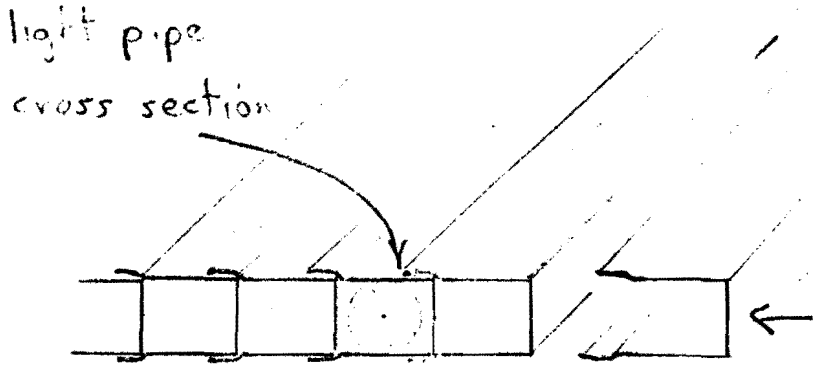
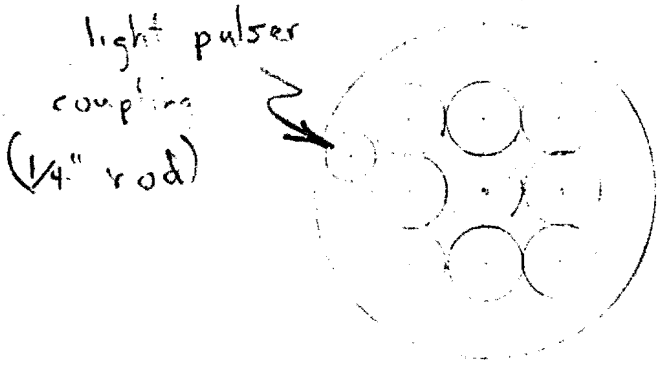


FIGURE 1. SCINTILLATION HODOSCOPE SHOWER DETECTOR



Scintillation Cells

Formed from 16 mil Al., Teflon lined
3/8" x 1/2" x 36"



Lightpiping

There are 9 horizontal scintillation layers and 9 vertical layers.

9 (33" long x 3/8" D) lucite rods couple to 1 (1 3/4" D.) cylinder and then to P.M.

FIGURE 2

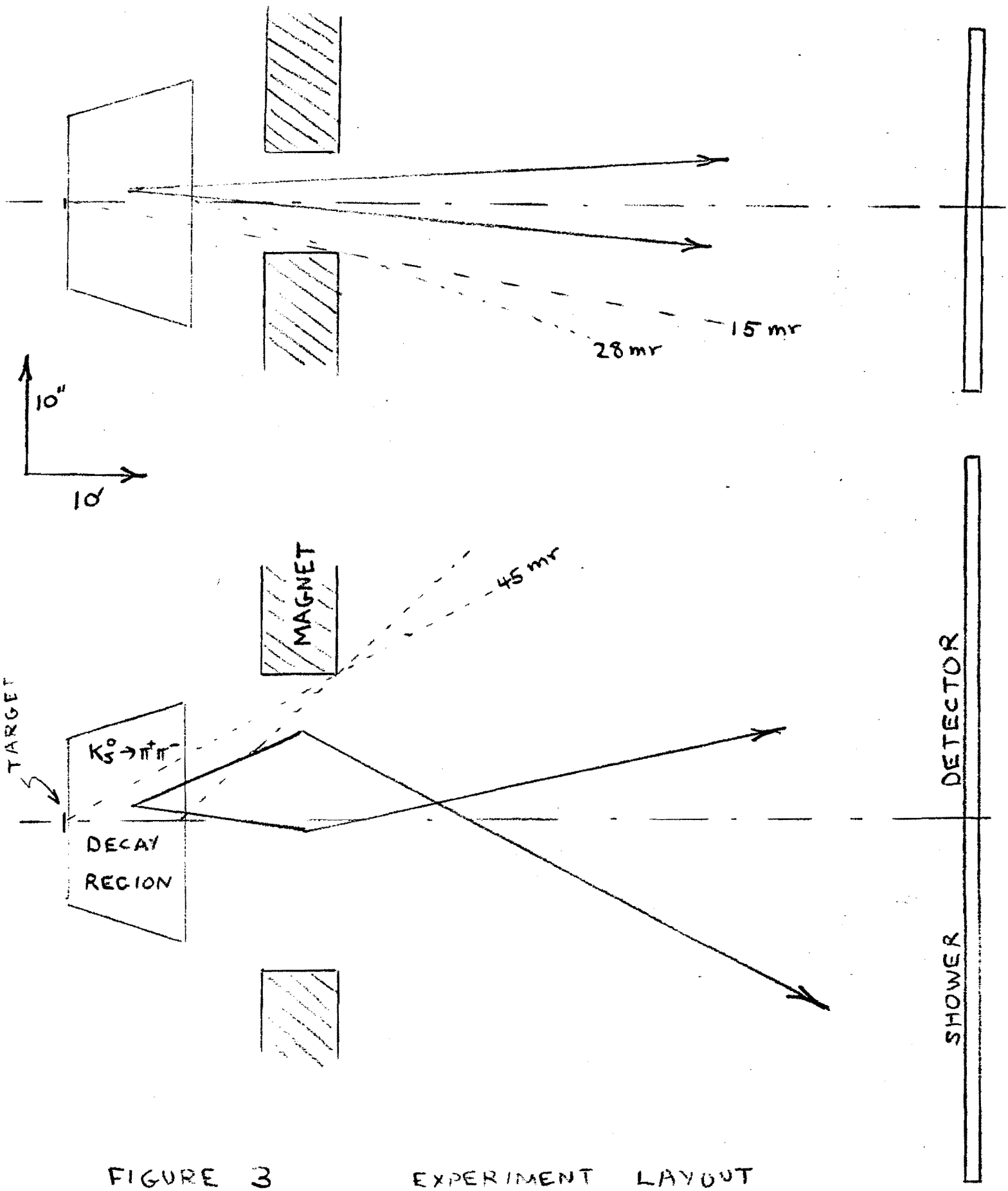


FIGURE 3 EXPERIMENT LAYOUT

Production of ρ^- in the Nuclear Coulomb Field*

B. Gobbi, J. L. Rosen, and H. A. Scott
Northwestern University, Evanston, Illinois 60201

and

S. L. Shapiro† and L. Strawczynski
University of Rochester, Rochester, New York 14627

and

C. M. Meltzer‡
Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213
(Received 12 August 1974)

The coherent process $\pi^- + A \to A + \pi^- + \pi^0$ has been measured using nuclear targets. Sharp peaks are observed in the t' distributions. The $\pi\pi$ mass spectrum is dominated by the ρ^- meson produced in the nuclear Coulomb field and by ω^0 exchange in the nuclear surface. The Coulombic process yields a measurement of the radiative width, $\Gamma(\rho^- \to \pi^- + \gamma) = 35 \pm 10$ keV, which is in poor agreement with the simple unbroken-SU(3) prediction of 100 keV.

In an experiment performed at the Brookhaven National Laboratory using the spectrometer facility developed by the Lindenbaum-Ozaki group, we have measured the reaction[1] $\pi^- + A \to A + \pi^- - \pi^0$ at a beam momentum of 22.7 GeV/c. The target nuclei C, Al, Cu, Ag, Pb, and U have been used.

Primakoff and Good and Walker[2] have pointed out that coherent Coulomb field reactions provide a measurement of the process $x + \gamma \to x^*$. In particular, the radiative widths of various hadronic resonances can be determined. Our primary motivation was the measurement of $\Gamma(\rho^- \to \pi^- + \gamma)$. Vector-meson radiative transitions are fundamental processes closely related to the magnetic properties of the quarks which are believed to underlie hadron structure.

Figure 1(a) shows in schematic form the detection geometry. Incident and final-state π^- were measured with counters and wire spark chambers.[3] Detection of the final π^- was restricted to the upper half-plane while the lower half-plane was reserved for π^0 detection in an optical spark chamber. The target (0.1 to 0.25 radiation lengths in thickness) was surrounded by an almost 4π system of veto counters constructed of interleaved sheets of scintillator and Pb. This arrangement suppressed triggers with superfluous hadron production or incoherent nuclear excitation.

Events are reconstructed *assuming* that the nuclear recoil energy was negligible as expected for coherent reactions. Consequently $E_{\pi^0} = E_1$

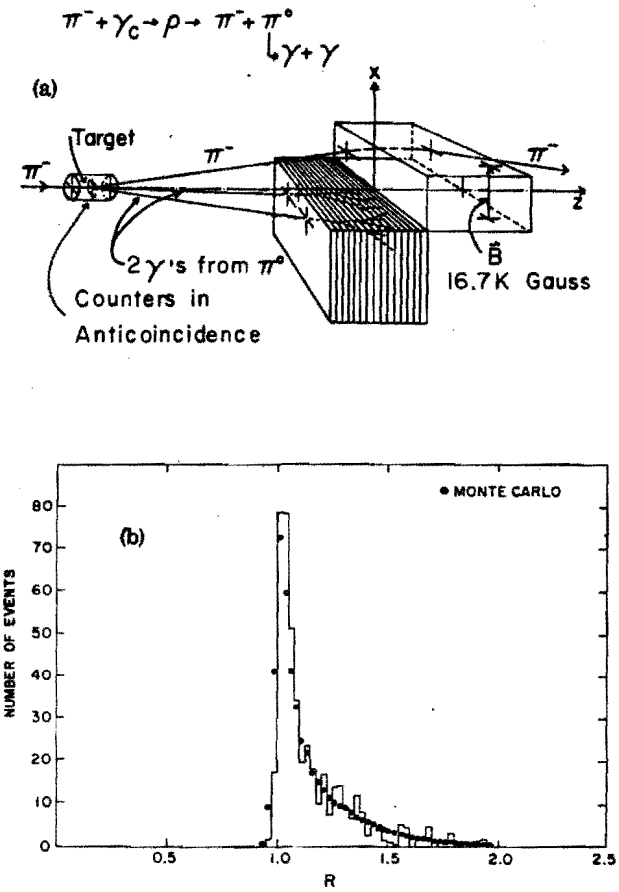


FIG. 1. (a) Schematic diagram illustrating the basic experimental geometry. (b) R distribution for π^- U data. The data have been subjected to the cuts $E_\gamma > 1.0$ GeV and $t' < 0.0116$ (GeV/c)^2. Background has been subtracted and the Monte Carlo prediction is superimposed.

$-E_2$, where E_1 and E_2 are the energies of the initial and final π^- each measured to an accuracy of $\pm 0.25\%$. The first signature of coherent reactions was the characteristic sharp Jacobian peak in the π^0 opening-angle distribution. The sharp peak in effect confirms longitudinal momentum balance. The $\gamma\gamma$ opening angle θ was determined by the measured target vertex and the γ-ray shower vertices. A typical plot of the quantity $R \equiv \sin(\theta/2)/\sin(\theta_m/2)$ is shown in Fig. 1(b). The minimum angle θ_m is given by $\sin(\theta_m/2) = m_{\pi^0}/E_{\pi^0}$. The factor R determines the ratio of the γ-ray energies. An attempt to independently measure this ratio by estimating the relative strengths of the γ-ray showers proved to be quantitatively unreliable and was abandoned. Consequently a twofold ambiguity regarding the identity of the higher energy γ ray remained. We chose to use the solution producing the smaller value of t' (the square of the transverse momentum transfer). A slight artificial sharpening of the t' structure and a small smearing of the $\pi^0\pi^-$ mass spectra and other experimental distributions resulted. The parametrized theoretical distributions were used as input to a Monte Carlo simulation of the experiment. The γ-ray energy mispairing effect was automatically corrected for by subjecting the Monte Carlo events to the same γ energy assignment criteria. Final data were subjected to the cuts $E_\gamma > 1.0$ GeV and $0.95 < R < 1.125$.

The data of Fig. 1(b) have been corrected for a background of approximately 7% in the cut region. The largest subtraction was $\approx 15\%$ for carbon data. The background was determined from the events in the regions $R < 0.9$ and $R > 2.0$ using a model based on the assumption that background originates from the reaction $\pi^- + A \to A + \pi^- + \pi^0 + \pi^0$. This reaction is closely related to the well-studied reaction $\pi^- + A \to A + \pi^- + \pi^+ + \pi^-$.[4] The $2\pi^0$ reaction produces background when two of the four γ rays escape detection. The yield of events versus A with $R < 0.9$ is in excellent agreement with the background model. Further confirmation of this model is afforded by the observation of events with three and four γ showers and the yield of large t' events. An empty-target subtraction ranging from < 2% in C to 6.0% in U was also made.

Two measurements were performed with the apparatus which served as controls, checking efficiency, acceptance, and resolution. The first of these, the decay in flight of $K^-(14\ \mathrm{GeV}/c) \to \pi^- + \pi^0$, is topologically similar to ρ^- decay and the decay rate is accurately known. The second control was provided by the measurement of $p(23\ \mathrm{GeV}/c) + \gamma \to \Delta^+$, using the same Coulomb field technique.[5] The cross section $\sigma(\gamma + p \to \Delta^+)$, or equivalently $\Gamma(\Delta^+ \to p + \gamma)$, is well known. The Coulomb production of Δ^+ was found to agree with photoproduction data to an accuracy of $\pm 10\%$.

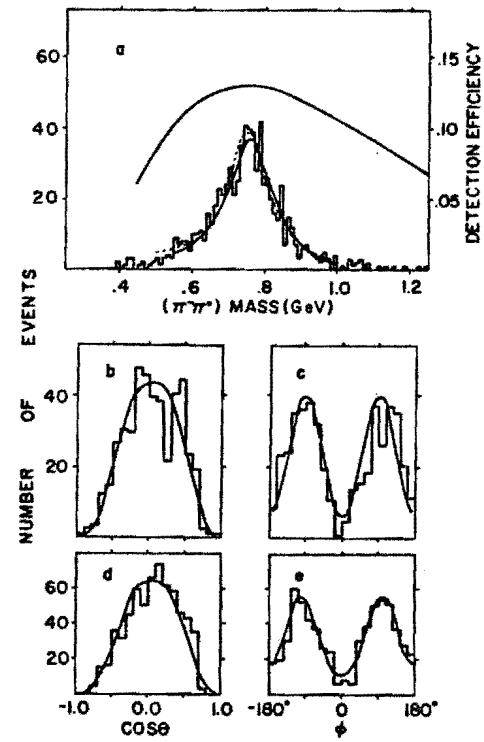


FIG. 2. (a) Mass acceptance of the apparatus and the $\pi^-\pi^0$ mass distribution of the low t' events for Pb and U data combined. The best-fit values for the Coulomb model (solid curve) are $m_0 = 768 \pm 3$ MeV, $\Gamma_0 = 161 \pm 11$ MeV. The best-fit values for the hadronic model (dashed curve) are $m_0 = 754 \pm 4$ MeV and $\Gamma_0 = 130 \pm 9$ MeV. (b)–(e) The polar and azimuthal angle distributions in the Gottfried-Jackson frame with $E_\gamma > 1.0$ GeV, $0.95 \leq R \leq 1.125$, and $t' < t_{max}' = 0.44A^{-2/3}$ (GeV/c)^2. The solid lines are a Monte Carlo prediction based on a $\sin^2\theta \times \sin^2\varphi$ distribution; (b), (c) carbon data; (d), (e) Pb and U data.

Figure 2(a) shows the mass spectrum of the small-t' data for U and Pb data combined. The yield is well fitted by a p-wave Breit-Wigner formula with parameters in agreement with compiled measurements.[6] The Coulomb and ω^0 exchange processes have slightly different mass dependences. Mass dependence enters through the square of the longitudinal momentum transfer, $t_0 = (m^{*2} - m^2)^2/4p^2$. The two superimposed curves in Fig. 2(a) correspond to the two exchange mechanisms. The true situation is a mixture of the two. The fit analysis indicates that the final state

is pure ρ^- with no more than 10% intensity of other coherently produced states. Note that Coulomb production of states with mass higher than the ρ^- is strongly suppressed by t_0 dependence.

Figures 2(b)–2(e) show the measured distributions of decay angles in the center of mass of the $\pi^-\pi^0$ system. The Gottfried-Jackson angles θ and φ are displayed. The data are in good agreement with the $\sin^2\theta\sin^2\varphi$ distribution expected for both Coulomb and ω^0 exchange. The φ distribution is determined by the recoil momentum of the nucleus ($\vec{q}'$). This is typically ~50 MeV/c for Pb and U. Thus the azimuth angle distribution is a convincing demonstration of the experimental $\vec{q}'$ resolution ($\approx$15 MeV/c).

The background-subtracted $d\sigma/dt'(A)$ distributions were fitted by a coherent superposition of Coulomb and nuclear amplitudes.[7] An optical model parametrization using a Woods-Saxon distribution for the nuclear density distribution $\rho(r)$ and including Coulomb phase shifts has been employed. We have used $\sigma_{\rho N}=\sigma_{\pi N}=26$ mb in the calculation of nuclear attenuation. The three fitting parameters are $\Gamma(\rho^-\to\pi^-+\gamma)$, the amplitude coefficient of the nuclear amplitude C_0, and the relative phase of the two amplitudes φ.

It was not possible to get a unique solution by fitting a single element. Sets of values for Γ and C_0 are determined for each *ad hoc* choice of φ. Only the destructive-interference solution $\varphi=180°\pm45°$ is clearly ruled out. On the basis of shape fits only, upper and lower limits for Γ of 30 ± 10 and 80 ± 10 keV can be inferred. Figure 3(a) illustrates for a particular set of parameters the t dependence of the Coulomb and strong components. The former is more sharply peaked. The best-fit solid curve is the sum of the two dashed curves plus an interference term which is not shown. In the heavy elements it is clear that both components are present.

A unique solution is achieved if we require C_0 to be independent of A. Figure 3(b) shows the solution obtained by fitting $\sigma_T(A)$. After weighing the uncertainties in normalization, t' resolution, optical model parameters, and statistical accuracy we conclude that $\Gamma(\rho^-\to\pi^-+\gamma)=35\pm10$ keV, $C_0=4.0\pm1.0$ mb/(GeV/c)^4, $\varphi=270°\pm45°$. The measured value for C_0 is in agreement with a value of $C_0=4.9\pm1.1$ mb/(GeV/c)^4 extrapolated from lower energy hydrogen data.[8]

There has been considerable theoretical speculation concerning vector-meson radiative decays.[9] The SU(3) symmetry scheme can be used to relate the various decays, while specific dynamical

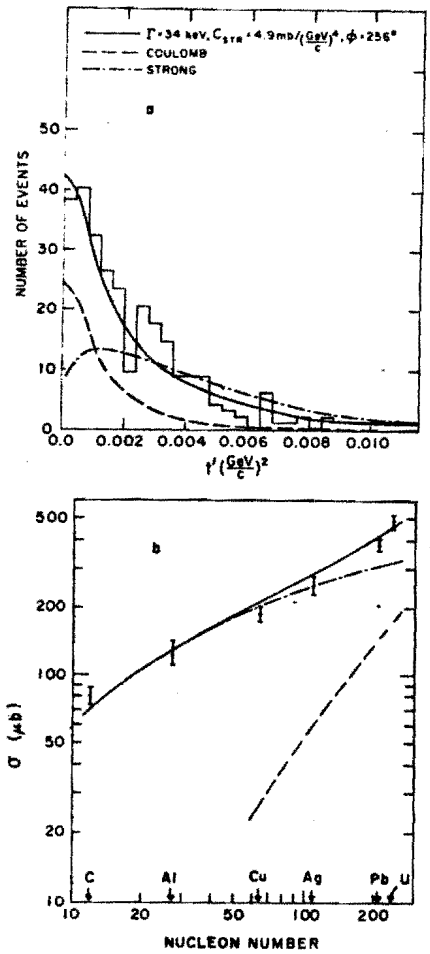


FIG. 3. (a) Background-subtracted angular distribution of the U data together with a particular acceptable fit. The Coulomb and strong production contributions are shown separately. (b) Integrated total cross sections [$t'<t_{max}'=0.44A^{-2/3}$ (GeV/c)^2] together with the result of the best fit obtained from the angular distributions.

schemes such as the pole model with vector dominance coupling constants or the quark model can be used to determine the absolute amplitudes. The only previously reported measurements,[6] $\omega^0\to\pi^0+\gamma$ and $\varphi^0\to\eta^0+\gamma$, are in accord with the quark model although the predictions depend explicity on vector and pseudoscalar meson mixing angles. Bemporad *et al.*[7] report an upper limit for $\Gamma(K^{*+}\to K^++\gamma)$ of 80 keV (95% confidence level). Our measured value for $\Gamma(\rho^-\to\pi^-+\gamma)$ is significantly smaller than various theoretical predictions which are typically 100 keV.[9]

The cooperation of Dr. R. Rau, Dr. D. Berley, the members of the Lindenbaum-Ozaki group, and the staff of the alternating-gradient synchro-

tron is gratefully acknowledged.

---

*Work supported in part by the U. S. Atomic Energy Commission.

†Present address: Stanford Linear Accelerator Center, Stanford, Calif. 94305.

‡Present address: Elscint, Inc., Palisades Park, N. J. 07650.

[1]L. Strawczynski, Ph.D. thesis, University of Rochester, 1974 (unpublished).

[2]The Coulomb field process was first discussed by H. Primakoff in connection with $\gamma+\gamma\to\pi^0$ [Phys. Rev. 81, 899 (1951)]. M. Good and M. Walker first discussed the general possibility of Coulomb field hadron dissociation [Phys. Rev. 120, 1855 (1960)].

[3]K. Foley *et al.*, Nucl. Instrum. Methods 108, 33 (1973).

[4]C. Bemporad *et al.*, Nucl. Phys. B33, 397 (1971); U. Kruse *et al.*, Phys. Rev. Lett. 32, 1328 (1974).

[5]Northwestern–Rochester–Carnegie Mellon Collaboration, to be published.

[6]T. A. Lasinski *et al.*, Rev. Mod. Phys., Suppl. 45, S1 (1973).

[7]cf. Ref. 1; C. Bemporad *et al.*, Nucl. Phys. B51, 1 (1973); G. Fäldt *et al.*, Nucl. Phys. B41, 125 (1972); S. Berman and S. Drell, Phys. Rev. 133, B791 (1964); A. Halprin, C. Anderson, and H. Primakoff, Phys. Rev. 152, 1295 (1966); L. Stodolsky, Phys. Rev. Lett. 26, 404 (1971).

[8]$C_0=13.7\pm2.2$ mb/(GeV/c)^4 at 5 GeV, D. J. Crennell *et al.*, Phys. Rev. Lett. 27, 1674 (1971). $C_0=6.9\pm1.5$ mb/(GeV/c)^4 at 16 GeV, J. Bartsch *et al.*, Nucl. Phys. B46, 46 (1972); an E^{-1} energy dependence has been assumed for extrapolation.

[9]W. Thirring, Phys. Lett. 16, 335 (1965); C. Becchi and G. Morpurgo, Phys. Rev. 140, B687 (1965); L. Soloviev, Phys. Lett. 16, 345 (1965); Y. Anisovitch *et al.*, Phys. Lett. 16, 194 (1965); A. Dar and V. F. Weisskopf, Phys. Lett. 26B, 670 (1968); L. M. Brown, H. Munczek, and P. Singer, Phys. Rev. Lett. 21, 707 (1968).