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A Proposal to Study Resonance Production in $\pi^- p \rightarrow X^- p$ at 40 to 80 GeV/c

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Abstract

We propose a study of $d\sigma/dt$ vs. s and t for various known resonances in order to elucidate exchange mechanisms and the validity of strong interaction theories. We plan to study resonances with masses less than 2 GeV/c^2 having decay modes into $\pi^+\pi^-\pi^-$, $\pi^-\pi^\circ$ and $\pi^-\eta^\circ$ over the range $0.04 < |t| < 0.55$, for incident pion momenta from 40 to 80 GeV/c. This counter/wire-spark chamber experiment utilizes the excellent mass resolution at modest apparatus cost obtained by measuring the direction and energy of the recoil proton, and the directions of the fast secondary particles. The estimated resolution, between ±10 and ±50 MeV/c^2, depends upon the precision with which γ-conversion vertices can be determined. Moderate accuracy momentum measurements are included for the fast secondaries in order to add constraints. The experiment has two phases: 1) a study of $\pi^+\pi^-\pi^-$ decays, using conventional wire plane techniques, and 2) a study of the modes involving γ's, requiring a large γ detection and localizing array.

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Physics Justification

We propose an experiment to study several quasi-two body reactions involving a low energy recoil proton and a moderate mass (< 2 GeV/c^2) resonance of high laboratory momentum decaying into no more than three final state particles. With good angular resolution on the downstream particles the resonance mass may be reconstructed very well if both the recoil proton angle and energy are measured. We plan to measure the particle angles with wire spark chambers, the recoil proton energy with E and dE/dx counters and fast particle momenta (to moderate accuracy) with a magnet about one meter long and by gamma ray opening angles.

We wish to study some peripheral interactions at extreme energies, making use of the quantum number restrictions corresponding to the production of known resonances to help disentangle the behavior of various exchanged trajectories. The results will be complementary to other reactions, such as peripheral scattering and charge exchange, which are likely to be studied early at NAL. In addition to the intrinsic interest, the information about single particle production and single trajectory exchanges is needed in order to study Regge exchanges in multiparticle production and in the different multiperipheral models.

There are two separate cases to be investigated, which it appears practical to run simultaneously: 1) three fast charged particles: $\pi^-\pi^+\pi^-$, $K^-K_1^\circ \rightarrow K^-\pi^+\pi^-$ (if possible); 2) one fast charged particle, two gamma rays: $\pi^-\pi^\circ$, $\pi^-\eta^\circ$. In addition, we would expect to analyze K induced reactions by tagging incident K's. Some running with positively charged beam will be considered.

Resonances leading to the $\pi^-\pi^+\pi^-$ final state include the A_1, the A_2's, and the π (1640). The A_1 can be made by diffraction dissociation, and thus is expected to have a continued large cross section at very high energies. The A_2 resonances, presumably produced by ρ exchange, would be expected to decrease as $\sim S^{-1}$ in cross section, both from extrapolation and from the simplest Regge theory models. Both these effects would, of course, be looked for experimentally.

The $\pi^-\pi^\circ$ states, while experimentally more difficult than the 3 charged particle states, are well worth study. The ρ, g, etc. can be produced by π, ω, etc. exchange. A comparison of ρ^-p, ρ^+p and $\rho^\circ n$ (another experiment) should, in principle, suffice to disentangle π and ω exchange by isotopic spin arguments. Extrapolations and simple theories predict a "catastrophic" (S^{-2}) decline in cross section with increasing energy; it will be interesting to see if this is really so.

$\pi^-\eta^\circ$ decays, easily identified when η° decays into $\gamma\gamma$, include a relatively clean A_2 signal and probably also the

δ (962). Additional information about this decay mode may be forthcoming from a current ZGS experiment[1] (Conforto et. al.). These experimenters suggest the δ is produced by η exchange, an interesting and not commonly observed exchange.

We hope to be able to identify $K^- K_1^\circ$ decays into $K^- \pi^+ \pi^-$ by analysis of the bad-vertex-fit events. This mode gives an especially good signal-to-noise on A_2 events. Incident K's will produce some K* states similar to the above, with more limited statistics. The $Q \rightarrow K\pi\pi$ is especially worth noting as a probable diffraction dissociation product.

The kinematics are one of the essential points of this proposal. We wish to point out that very good mass resolution may be obtained by measuring the direction and energy of the recoil proton to attainable accuracies, and also measuring only the directions of no more than three fast secondaries to high accuracies ($\lesssim$ 0.1mr). This feature seems to have been overlooked by other experimenters who, aware of the poor resolution[2] resulting from standard missing-mass techniques (measuring only the recoil proton) for low resonance masses, are proposing to obtain adequate resolution by measuring the directions and the momenta of the

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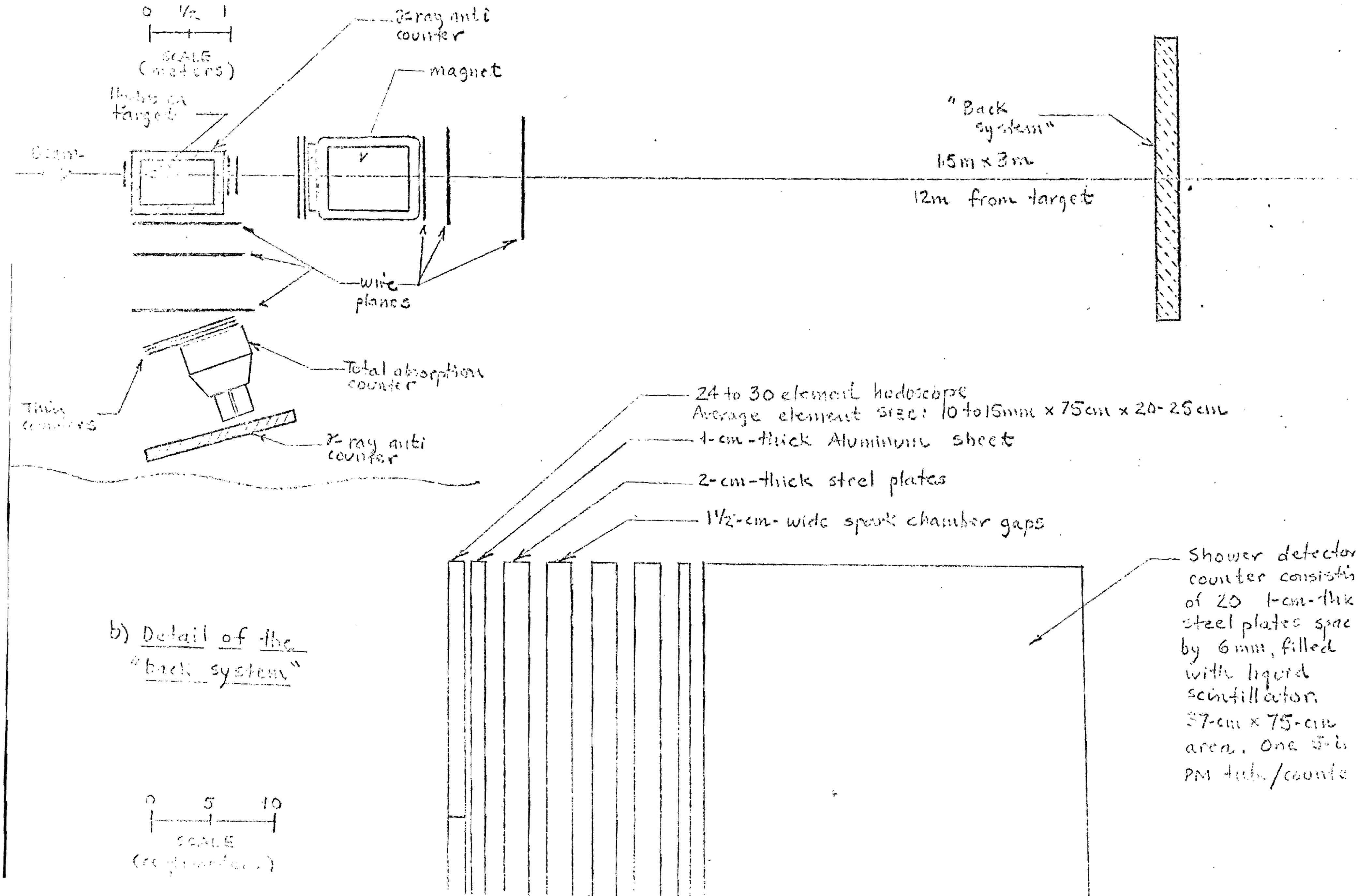
1. G. Conforto, ZGS experiment E-259.

2. G. Ascoli, in "NAL 1969 Summer Study", Vol. 4, 55-108, p. 281.

Figure 1

a) Plan view of the experiment



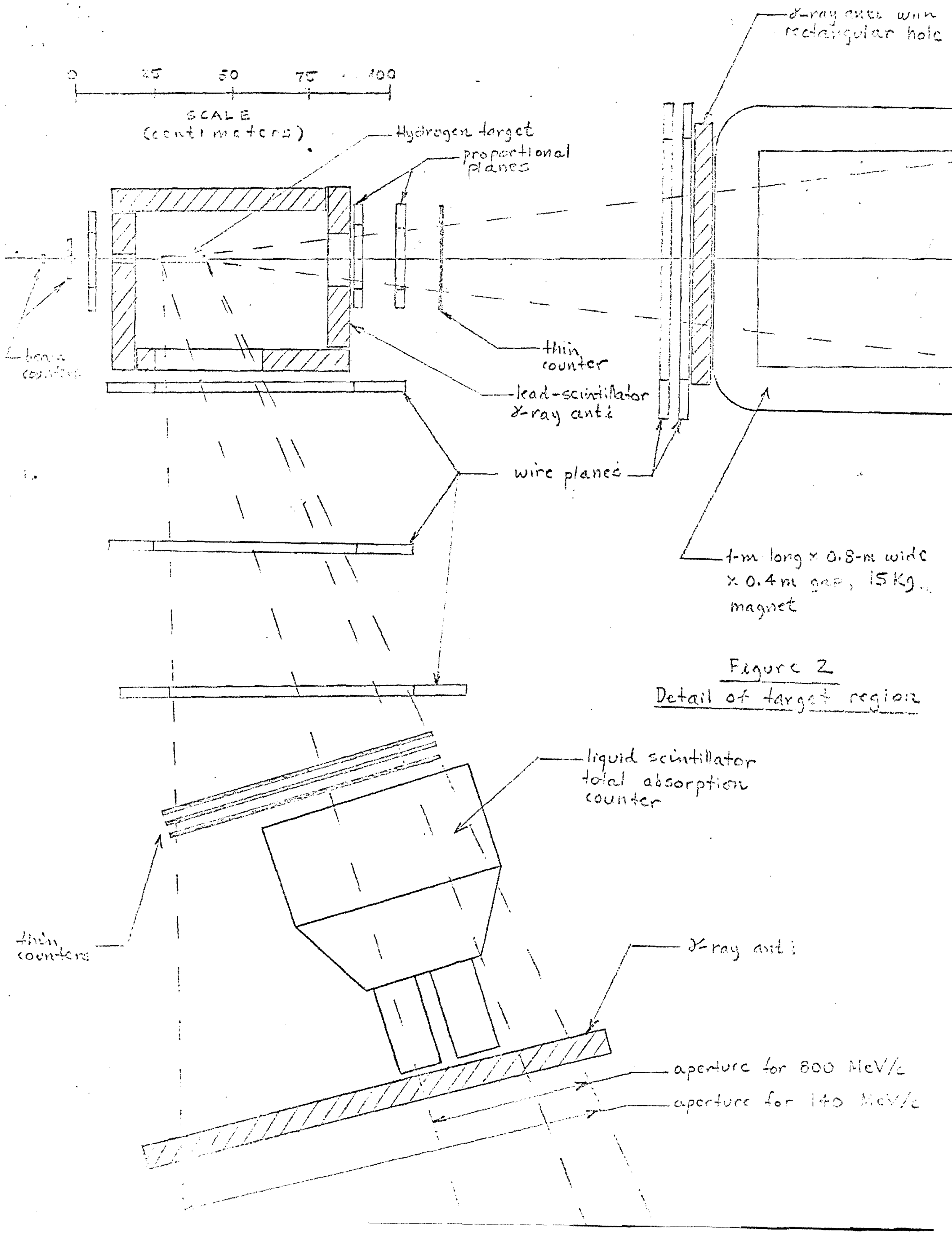


Figure 2
Detail of target region

secondaries to very high accuracy. Clearly this procedure is very expensive (although necessary for final states of high multiplicity).

The Experiment

A general plan view of the experiment is shown in Fig. 1. The pion beam, after passing through a beam counter system, is incident on a liquid hydrogen target almost completely surrounded by γ-ray detectors. Slow recoil protons emerge through a side slot in these counters, pass through direction-determining wire planes, through dE/dx counters, and into a total-absorption energy detector. Fast decay secondaries (and the incident beam) pass through a downstream slot, and through a series of spark chamber planes and an analyzing magnet. A large γ detector is located about 12 meters downstream of the target. An on-line computer is used to record data and to perform preliminary calculations.

The NAL Medium Energy High Resolution (MEHR) beam encompasses the desired incident pion momentum range of 40 to 80 GeV/c. Hopefully, this range is below the predicted disappearance of the $\rho^- p$, etc. cross sections into the undergrowth. Somewhat lower energies might be studied by compressing the experimental arrangement longitudinally. The momentum transfer range to be studied, $0.04 < |t| < 0.55$ (GeV/c) is determined by technical considerations: the recoil proton must escape the target yet must be stopped within a reasonable thickness of material.[3]

Because of the decision to study resonances of mass less than 2 GeV/c^2, the detection aperture for decays in the resonance center-of-mass system (CMS) is quite large. Furthermore, since these are "known" resonances of relatively low spin, the loss (depending upon the resonance mass and beam energy) of some secondaries at extreme backward CMS angles will not be as serious as it would be for high-mass, high-spin resonances. Nevertheless, some loss of accuracy in determining density matrix elements is expected under certain conditions: at 40 GeV/c, for the A_2, for example.

One of the main features of this experiment, as mentioned previously and elaborated in Appendix I, is that very good mass resolution can be obtained by measuring the energy and direction of the recoil proton to attainable accuracies, and also measuring the direction of the secondaries (3 or less) to high accuracy; precise momentum determinations for the secondaries are not required. Measurements on the recoil proton give excellent information on the energy, momentum and direction of the resonance(X). This is true despite the poor X mass resolution due to the independent errors in Ex and Px, the energy and momentum of the resonance, in the very small (for $Mx < 2$ GeV/c^2) difference term appearing in the expression ......

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3. The rather interesting larger $|t|$ range should be studied in a subsequent experiment employing a magnet spectrometer in the proton arm.

$Mx^2 = (Ex - Px)(Ex + Px) \cong 2 \, Pinc \, (Ex - Px)$. Precise measurements of the directions of no more than three resonance decay particles (of known mass) then yield an accurate value of Mx. If we number the secondaries 1, 2, 3, then particle 1 and X determine a decay plane for particle 1 and the 2 - 3 system. Unless 1, 2, 3 and X are coplanar, or nearly so, the 2 - 3 plane intersection with the first plane determines the 2 - 3 system direction. Since $\vec{P}x$ is determined, $\vec{P}_1$, $\vec{P}_2$ and $\vec{P}_3$ may then be found and Mx can be calculated if the secondary masses are known. Misidentified events, such as $K^+K^-\pi^-$, would add to background as small displaced peaks.

With only directions measured, there is one constraint. When background events consisting of one extra $\pi°$ are considered, it can be shown that this constraint (e.g. the lab energy of X by two different methods of calculation) has the effect of confining the $\pi°$ to nearly the direction of one or the other fast particle in, for example, $\pi^-\pi°$ decay. In a typical example, including resolution effects, the $\pi°$ can go almost anywhere in the π^--other $\pi°$ decay plane within about ±25mr of forward, with no momentum measured.

Since charged particle momenta are measured, 1 constraint (for $\pi^-\pi°$) or 3 constraints ($\pi^+\pi^-\pi^-$) are thus added. The $\pi°$ or $\eta°$ mass adds another constraint. Hence, the proposed experiment has 3 constraints for $\pi^-\pi^\circ$, or 4 constraints for $\pi^+\pi^-\pi^-$. One effect of these "weak" (because of low resolution) constraints is to restrict an extra π° to $\lesssim$ 1 - 2 GeV/c in the laboratory, as well as to ±25 milliradians of forward, as described above. Such a situation can easily arise from e.g., N* $\pi^-\pi^\circ$ production decaying to $(p\pi^\circ)\ \pi^-\pi^\circ$. However, fewer than 1/10% of these events give a π° in the kinematically allowed solid angle, and, furthermore, a π° this slow is nearly certain to be vetoed by the gamma detectors surrounding the target since the minimum opening angle is larger than the aperture left open for the desired fast particles.

The result of all this is that we expect a mass resolution of about ±10 MeV/c^2 on 3π decays, and about ±10 to ±50 MeV/c^2 on $\pi^-\pi^\circ$, etc., decays, depending on the resolution in γ-ray angle (conversion point location) that can be obtained. It is easy to show that the insertion of a magnet does not spoil the resolution based on a full lever arm of 12 meters. Thus, it should be possible to separate the produced resonances.

Experimental Arrangement

A plan view of the apparatus is shown in Fig. 1, and a detail of the target region in Fig. 2. We propose to use the MEHR beam (80 GeV/c maximum) brought to a focus about

3mm in diameter with about 0.3mr angular divergence. A 4 X 4 element beam hodoscope far upstream gives ≤ 0.1mr angular determination. Cerenkov counters for beam particle identification are assumed to be available. The 15 - cm - long X 5-mm - diameter hydrogen target follows an array of beam counters and a multiwire proportional plane. The target is almost completely surrounded by a box of lead-scintillator γ-ray and charged-particle veto counters.

The proton detector is an array of E and dE/dx counters. Three thin counters are followed by a liquid scintillator tank 50 cm X 79 cm X 40 cm deep for stopping more energetic protons (up to 800 MeV/c). All pulse heights are digitized, as is the proton time-of-flight over the 2 meter flight path. The proton energy is determined by the total light and the other data aid in its identification. The resolution of this technique is claimed to be excellent,[4] being < 2% in kinetic energy at 150 MeV. Even at 800 MeV/c, it promises to work better than might be expected because of the detection of absorbed products which would otherwise smear the resolution. (We have started developing this technique. The liquid scintillator detector has already been built, and is currently being tested in light collection studies.) The proton angle is measured

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4. D. Garelick (Brookhaven & Northeastern), private communication; see also NAL Summer Study SS-38

with conventional magnetostrictive chambers and is, of course, limited in resolution by multiple coulomb scattering. The angular intervals in figure 1 correspond to 80 GeV/c.

The downstream detector array consists of a "back system" to be described below, at least 5 gaps (10 planes) conventional wire planes and at least two wire proportional chambers. Deadening of conventional wire planes near the target in the moderately high flux beam would obscure too many tracks we wish to detect. Gap-transfer proportional planes[5] with magnetostrictive readout may be the solution most compatible with our present electronics. A thin counter is placed downstream of the target as shown. We assume that chambers,etc. are thin enough that multiple scattering is negligible for the downstream particles. The magnet suggested is 1 meter long X 0.8 meter wide with a 0.4 m gap, and has a 15 kg field. This gives $\Delta p/p \cong 4\%$ at 40 Gev/c.

The high energy gamma analyzer at the end of the system requires further study; first thoughts are described below. The main concern is accurate location of the shower to determine the γ-ray direction. Strip chambers, as used in a recent Rochester-Cornell collaboration[6], appear to work but lack the desired resolution. We wish to study means for determining the centroid of the multiple tracks of a high-energy shower, e.g., by electronically processing the magnetostriction signals. High multiple

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5. As developed by J. Fischer at Brookhaven.
6. Behrend et al., Physical Review Letters 24,1246 (1970).

track efficiency is manifestly important; we hope to circumvent the corresponding track digitizing overload.

The γ-ray analyzer shown in Fig. 1 has a 24 to 30 element scintillator hodoscope in front to determine the number of charged particles, an initial spark chamber gap(s), then alternate x-y and u-v (rotated 15^{0}) gaps between one-radiation-length steel plates. The gaps are to be at least 15mm wide for multiple spark efficiency and easier impedance matching (note the large dimensions), but cannot be too large for fear of excessive lateral shower spread. A slot about 2 cm high x 10 cm wide is cut in all plates to allow passage of the beam and of elastically scattered pions corresponding to detected protons, which, otherwise, are likely to interact and cause triggering background. An anticoincidence counter is positioned covering the beam only; the wire mesh will cover the slots in order to register charged particles from the proper trigger. Losses due to gamma rays passing through the slot will not be severe. The spark chamber array is followed by sixteen 37 cm x 79 cm steel-liquid scintillator shower detectors, each with a 5-in. photomultiplier. The system trigger will include a requirement of <u>either</u> exactly three charged hodoscope hits plus no large shower pulses, <u>or</u> exactly one charged hit and one <u>or</u> two large pulses from the 16 shower counters.

The data will be collected using our magnetostrictive chamber readout system, analog-to-digital multiplex and OMNILOGIC counter-hodoscope electronics, and will be processed using a relatively powerful on-line computer system (Data General Super-Nova; see the next section). We hope to analyze a good fraction of the events on-line, and the rest later off-line using the same computer.

The event rate can be determined easily, but the trigger rate is harder to estimate. Since the proton detector coverage is sufficient for the $|t|$ range which can be measured, the fraction of events detected is proportional to

$$\Delta\sigma = (\Delta\phi/2\pi) \int_{t_{min}}^{t_{max}} (d\sigma/dt)dt,$$

where $\Delta\phi$ is the azimuthal aperture. If $d\sigma/dt$ is assumed proportional to $\exp(-a|t|)$, then we get

$$\Delta\sigma = (\Delta\phi/2\pi)\sigma_{total}[\exp(-a|t_{min}|) - \exp(-a|t_{max}|)].$$

If we use $a=10\ (GeV/c)^{-2}$ and $\Delta\phi=0.19$ for our apparatus, then $\Delta\sigma=0.02\sigma_{total}$. As shown in Appendix I, the fraction of the resonance decay solid angle detected averages 0.9. Assuming that 80% of the protons are detected properly without losses, this results in 0.95 interaction per μb, per 10^8 incident pions, yielding a detected recoil proton. Thus, for a $10\mu b$ process we expect 95 events/hr for 10^6 pions/pulse, 10^3 pulses/hr.

The trigger rate requires a careful estimate of background processes yielding triggers, probably including Monte-Carlo calculations. A principle source of background would be $p\pi^-\pi^0\pi^0$ final states arising from pion diffraction dissociation. If the π^o decays are near minimum opening angle, the probability of two, and not three or four, γ counters being triggered is high. If the cross section is 0.5 mb[7] for $p\pi^-\pi^o\pi^o$, if one-third of these events give 2γ or 1γ triggers and no large-angle γ anti, and if 2% give a detected recoil proton, there result 2.1 background triggers/pulse at 10^6 incident π's/pulse. The reaction of interest, including all $p\pi^+\pi^-\pi^+$ events, total perhaps 0.5 mb, or 6.4 triggers/pulse, including background between and under resonance peaks, etc. Including other processes, we estimate 10 to 15 triggers/pulse at 10^6 pions/pulse.

The actual events of interest may total 200 to 300μb, including 150μb from p"A"[8], and perhaps 10μb each, average, for other individual channels not produced by diffraction dissociation. Considering the losses mentioned above, we anticipate 2 to 3 events of interest per pulse at 10^6 pions/pulse, and about 1 event/10 pulses (on the average) per non-diffractive channel. These figures do not include the effects of spark-chamber losses and other event cuts.

Based on the above figures, actual running time of 100 hrs, is sufficient for about $1\text{-to-}1.5\times10^6$ triggers,

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7. Assumed the same as that for $p\pi^+\pi^-\pi^+$, evaluated by A. R. Clark, et al. in "NAL 1969 Summer Study," Vol. 4, SS-38, p. 237.
8. Ibid.

which would yield 10^4 events for each of the relatively rare modes. To achieve this we request 50 shifts of running time, plus about 50 shifts in intermittent, perhaps parasitic, operation, spread out over as long a time as possible prior to serious data taking. Possible modes of tune up and testing would be discussed with NAL staff when appropriate. Operation in tandem with other experiments using a defocussed beam (up to 2 cm dia.) and a very thin target would be a very useful parasitic operation (our apparatus contains very little material in the beam).

Apparatus

We believe we already possess a large fraction of the necessary apparatus, but obviously major components remain to be built. As mentioned previously we have constructed a prototype proton detector which is now being tested. We have on order eight wire-spark chambers from Science Accessories Corporation (D. Drickey's design) with dimensions up to 1m x 1m active area, but will need to construct (or purchase) additional chambers about 0.6m x 1.2m in area. The exact number depends on our experience with chamber efficiency, determining the number of chambers necessary to reconstruct three tracks. All counters will have to be constructed. We plan to use liquid scintillator for several of the detectors, including the downstream shower detectors, to reduce costs. (We are experimenting with techniques to allow total internal reflection light collection despite the use of a liquid.) Of the approximately 80 photomultipliers required, 74 are on hand, including twenty 5-in. tubes.

We have sufficient fast electronics for the experiment, except for 8 to 16 channels of LeCroy OMNILOGIC triggers and coincidence registers. (2 – 4 modules). We own a 64-scaler wire spark chamber digitizing system, which appears to be sufficient for most of the conventional wire planes. About 24 additional scalers would be required for the "back system" gaps, assuming analog shower centroid determination without individual spark digitizing. Digitizing all sparks appears formidable. Rather than this expensive addition, we wish to investigate "postponed readout"[9] using the remnant magnetization of the magnetostrictive wires, and reading the "back system" data into the original 64 scalers.

The biggest construction project is the downstream end spark-chamber system. Costs will be reduced by using the steel plates as part of the spark chambers, with wire cloth glued to the plates. Prototype tests of construction methods and wire alignment problems (using Moire patterns) should be performed. With the aid of parasite tests)at Argonne or elsewhere), lateral shower spread and methods for determining the shower centroid

9. K. Young, University of Washington (Seattle), to be published.

can be investigated.

The computer being purchased (see Appendix II for details) is expected to be a Data General "Super Nova". This is a 16-bit machine with 16K memory, 800 ns cycle time, with 4 registers and 256 K word fixed-head disc (very fast access). It is somewhat faster than a PDP-15 because of the multiple registers.[10] A single 37 ips, 9 track tape unit, a teletype, a card reader, a line printer, and a display scope are included. The general software available is extensive, including Fortran IV. In addition, we expect to benefit by cooperation with a University of Chicago group, which is purchasing similar computers, on spark chamber software development. Event filtering and some analysis will be done on-line. The computer will also be employed for considerable off-line analysis. We also have access to an IBM 360/50 at UICC, due to be replaced by an IBM 60/65 or a XDS Sigma 7 this fall.

The biggest item required from NAL is, of course, the magnet. At 15 Kg, the 1 meter length assumed gives a conservative momentum resolution of 4% at 40 GeV/c. Thus, greater length (and a wider aperture) would be preferred. Possibilities might be other accelerator transport magnets with enlarged gaps. The uniformity of field need not be high.

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10. D. Jensen, University of Chicago, private communication.

The proportional planes used near the target are not on hand. Borrowing such chambers and interfacing would spare us much effort. We would wish NAL to provide the hydrogen target, and we expect the beam system to include Cerenkov counters for incident particle identification.

We would like to borrow the additional four OMNILOGIC modules or their equivalent (16 discriminators and coincidence latches). Some (about 20) additional high voltage divider channels and power supplies would be appreciated. We will have almost no spare fast logic units, and expect the availability of an NAL electronics pool.

Assistance with rigging and some of the alignment will be required, but we intend to include our own alignment devices (Axicon optical system).

To carry out a project of this magnitude in a limited time, we will attempt to enlist collaborators as soon as possible. Additional financial support for graduate assistantships and summer research would make possible more rapid completion of this work.

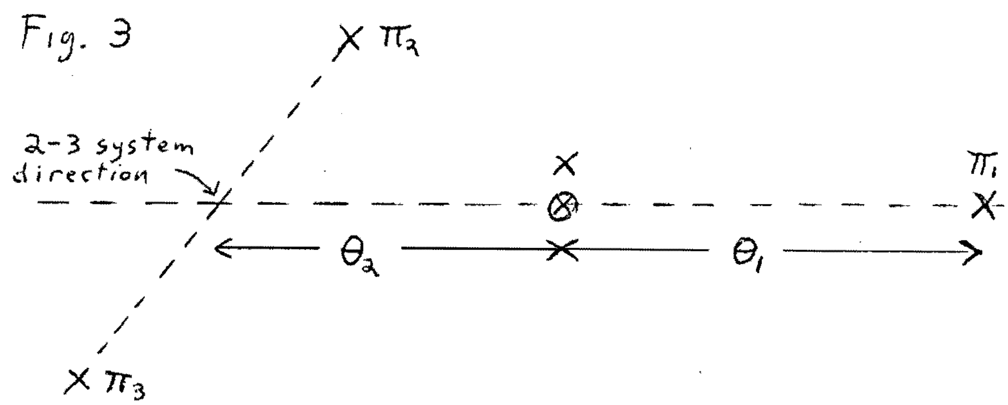
Appendix I

Kinematics

Since the resolution improves with decreasing incident pion momentum, our estimates are made at the upper limit of 80 GeV/c. We first compute the resolution on the downstream resonance system angle, momentum, and energy using the beam and recoil-proton information. Generally, the resolution varies with kinematic conditions, and only typical values are considered.

For a recoil proton momentum of 550 MeV/c (a kinetic energy of 150 MeV), a 2% energy error is equivalent to 6 MeV/c. A ±10mr proton angular error (from multiple scattering) also yields an error of about 6 MeV/c. These correspond to errors of ±0.05mr in the resonance direction at 80 GeV/c. To this is added a ±0.04mr incident particle angular error, obtained using a beam hodoscope as mentioned in the text.

The mass resolution may be best understood from a geometric argument followed by a calculation for a simplified case. Consider a polar plot (See Fig. 3) of an $X \to 3\pi$ resonance decay, where $\vec{p}_X$ is known. Except for the all-coplanar case, the secondary pion momenta, $\vec{p}_{\pi 1}$, $\vec{p}_{\pi 2}$, $\vec{p}_{\pi 3}$, can be deduced (poorly, if the decay is nearly coplanar), and the resonance mass M_X can then be calculated. The error discussion is simplified if a 2-body decay is considered instead. The π_2-π_3 system direction is known with



easily computed errors of the same order as the individual directional errors, if θ_2 is not too large compared to θ_1, and the decay is not nearly coplanar. We further assume that both the π_1 and the π_2-π_3 system masses are small compared with M_X. (This is valid, for example, for $\pi^\circ \rightarrow 2\gamma$, but not for $\pi\rho$.) If μ_1 and μ_2 are the π_1 and π_2-π_3 system masses, and θ_1 and θ_2 are the angles indicated in the sketch, then it is easy to show that

$$M_X{}^2 \approx \mu_1^2 \left[1 + \frac{\sin\theta_1}{\sin\theta_2}\right] + \mu_2^2 \left[1 + \frac{\sin\theta_2}{\sin\theta_1}\right]$$

$$+ \frac{2p_X{}^2 \sin\theta_1 \sin\theta_2}{1 + \cos(\theta_1 + \theta_2)} + 0\ (\mu^4/M_X{}^4)$$

The angles involved here are sufficiently small that for the error discussion we can use

$$M_x^2 \cong \mu_1^2\left(1+\frac{\theta_1}{\theta_2}\right)+\mu_2^2\left(1+\frac{\theta_2}{\theta_1}\right)+P_x^2\theta_1\theta_2$$

If θ_1 and θ_2 are not too different and if $\mu \ll M_X$, only the last term need be used. In this case, $4\ M_X dM_X \cong (\theta_{12}^2 - \bar{\theta}^2)\ PxdPx + Px^2\theta_{12}d\theta_{12} + Px^2\bar{\theta}d\bar{\theta}$, where $\bar{\theta} = \theta_1 - \theta_2$ and $\theta_{12} = \theta_1 + \theta_2$ is the opening angle.

We first obtain the result for three charged tracks, assuming ±2/3 mm position measurement errors. We can show that, because of the highly correlated momentum and angle errors, the analyzing magnet has practically no effect on the results obtained assuming a 12 meter lever arm; i.e. no magnet. The angular errors are then about ±0.06mr. Assume that the 2 - 3 direction error is twice as big, or ±0.12mr, and, conservatively, that $\Delta\theta_{12} = \pm 0.15$mr. The error $\Delta\bar{\theta}$, containing also the beam angle error, is $\Delta\bar{\theta} \lesssim \pm .15$mr. We assume $\Delta Px/Px = 10^{-3}$ obtained from the incident beam resolution. At $M_X = 1$ GeV/c^2, equal angles $\theta_1 = \theta_2$ give $\theta_{12} \cong 2\ M_X/P_X = 25$mr., $4\ M_X dM_X \cong 2\theta_{12}\ M_X dP_X + 2\ M_X P_X d\ \theta_{12} = 5$ MeV/c ⊕ 24 MeV/c where ⊕ denotes addition in quadrature. Thus, $\Delta M_X \cong \pm 7$MeV/c^2. The error is somewhat larger if $\theta_1 \neq \theta_2$. If $\theta_2 = 5\theta_1$, we obtain $\Delta M_X = \pm 10$MeV/c. Note that since $\theta_{12} \propto M_X$, ΔM_X is approximately independent of M_X until the μ^2 terms become important.

With decays involving γ rays the resolution is probably much larger because of the problems in locating the shower. If the showers can be located to only ±1cm., the error in

θ_{12} is about ±0.7 X 0.01 me/12 Me = ±0.7 mr. Repeating the above calculation yields $\Delta Mx \approx \pm 33$ MeV/c^2 for $\theta_1 = \theta_2$. Thus, it is important to do better than this in locating the shower.

We now examine the decay aperture at 4.0 GeV/c, on the assumption that the apparatus layout is kept the same over a 2:1 range in incident momenta. (Less conservatively, we could plan rearrangement of the apparatus at different incident momenta and obtain better resolution and/or aperture.) The laboratory angle of a particle from a 2-body decay is given by

$$\tan \theta_{lab} \cong \frac{M_x}{P_x} \frac{\sin \theta_c}{E_c/P_c + \cos \theta_c}$$

in the approximation $Ex \cong Px$. Here, θ_c = CMS angle of the particle in question, with E_c and P_c evaluated in the CMS. If this particle has mass $\mu \ll Mx$, $Ec/Pc \cong 1 + 2\mu^2/Mx^2$, and we get

$$\tan \theta_{lab} \cong \frac{M_x}{P_x} \frac{\sin \theta_c}{1 + \cos \theta_c + 2\mu^2/M_x^2}$$

We have plotted θ lab vs. cos θc for Mx = 1 and 2 GeV/c^2, $\mu = M\pi$, and Px = 40 and 80 GeV/c. To find the center of mass solid angle acceptance we have combined these results with the results of integrating the above with $\mu^2 = 0$ over a rectangular aperture. The conclusions are that, at 80 GeV/c, all the 1 GeV/c^2 particles go inside a cone equal to the vertical aperture of ±63 mr, while at 2 GeV/c^2 75% of the π^- and π° go into this aperture (i.e. all particles forward of cos θc = -0.79 are detected. Thus, in 75% of the cases both particles are detected.). At 40 GeV/c, the corresponding figures are 80% and about 25%. However, we find that in the simplified case where $\mu = 0$, an integration over the actual ±63 mr X ±125 mv aperture yields about half the solid angle loss of a 63 mr cone. This is conservative, since $\mu \neq 0$ leads to less loss. Thus in the first three cases we get detection apertures of ~100%, $\gtrsim$ 85% and $\gtrsim$ 90%, while the last case (2 GeV/c^2, 40 GeV/c) the $\mu = 0$ integral gives a somewhat approximate 30%. However, the maximum horizontal aperture of ±125 mr corresponds to cos θc = -0.74 at 2 GeV/c^2, 40 GeV/c, so there will be many events available even at this backward angle.

The above discussion is based on the simplifying assumption of a two-body, rather than the actual three-body, decay. Considering a 3-pion decay, the laboratory angles tend to be forward of the $\pi^-\pi^\circ$ decay situation discussed because of the lower CMS momentum available to an individual pion. This generally more than compensates for the combinatorial factor (3/2 as many opportunities for missing the aperture). For $\pi^-\pi^\circ$ and $\pi^-\eta^\circ$ decays, we have not yet discussed losses due to the escape of γ rays from π° or η° decay. To some extent, at these energies the same arguments can be applied to $\pi\ \gamma\ \gamma$ as were applied to the 3π case above. To aid in estimating the loss effects, we state some γ-ray spatial separations at minimum opening angle: At 40 GeV/c, a π° yields γ rays separated by 8 cm. at the back planes when the opening angle is minimum (90° cm). The corresponding number for an η° is 33 cm. These numbers also allow an estimate of momentum resolution obtained using the π° or η° mass constraint and the opening angle. If the γ-ray position resolution is ±0.3 cm. (note estimates above ranging from 0.1 - 1.0 cm.), the momentum resolution for a 40 GeV/c π° is ±5%, and is much better for an η°. This is to be compared with the ±4% momentum resolution of the postulated magnet. Examination of the background suppressing effect of added constraints suggests that increasing the momentum resolution for the charged π's much beyond that of the neutral π's does not result in an appreciable gain. This consideration is one factor in determining the magnet dimensions.

Appendix II

Equipment and Facilities

This section contains additional details regarding major equipment available as of Fall, 1970, as well as information on shop and computing facilities at UICC.

1. On-line computer. This is now in the process of negotiation, with a budget of $75K. We expect to buy a Data General "Supernova" system, which has a 16k core, 4 hardware registers, 800 ns cycle time, and 300 ns register-to-register time, hardware multiplication and division, multiple interrupt and block data transfer ability, a 256K word fixed-head (rapid access) disc, a 9 track 37 ips tape unit (we hope to add a second later on), a card reader, a 300 lpm line printer, oscilloscope display and interface hardware. The software includes Fortran IV, as well as the more usual assem ler, string type text editor, "conversational" compiler, etc. We hope to use it for much off-line batch processing using the disc-based monitor system. Read-only memory is available for very high speed routines.

2. Read-out equipment. We possess a LeCroy wire-spark chamber readout system, including 64 wire plane scalers, 24 channels of gated latches (which will accept photo-multiplier pulses), an ADC with 8 sample-and-hold channels,

32 fast (50 MHz) blind scalers, an oscilloscope character display, an interface to LeCroy OMNILOGIC, etc.

3. Fast logic. We have 20 channels of conventional discriminators, about 17 assorted conventional coincidence circuits, 32 channels of LeCroy OMNILOGIC discriminators and coincidence-latches, and 5 OMNILOGIC switch logic and 3 logic matrix units. Also, we have various miscellaneous modules such a TAC, gate generators, etc.

4. Photomultipliers and associated equipment. We have 20 5-in. tubes (XP1040, 4522), 16 8575 2-in. bialkali photocathode tubes, 30 4517 1½-in. bialkali tubes, 8 6655 2-in. tubes, plus bases for most of these. Also, 60 channels of high-voltage dividers, high-voltage power supplies, and a digital voltmeter for monitoring.

5. Spark Chambers. We have ordered 8 wire chambers from Science Accessories Corporation, following the D. Drickey design. These have wire cloth and a conducting backing on one plane. Three have useful areas of 17-in. x 26-in. three are 23-in. x 33-in., and 2 are 36-in. x 36-in. Some planes are rotated 15°.

6. Electronics Trailer. A 10-ft. x 29-ft. trailer, similar to recent purchases by NAL and Notre Dame has been ordered.

The trailer is sufficient for our compact on-line computer, readout and fast-logic electronics.

7. Shop Facilities.

   a. Machine shop. The Physics Department at UICC has a 6-man, well equipped machine shop. No outside contracting is anticipated for any of the equipment proposed for this experiment.

   b. Electronics shop. The Department also has a 3-man electronics shop, complete with facilities for the latest integrated circuit modules.

   c. High-Bay area. A 3200 $ft.^2$ high-bay area, containing a 25 ton crane, to be used for assembling and testing, belongs to the UICC high-energy physics group. This area, together with several laboratory rooms, is contained in a new building on campus (downtown Chicago).

8. Computer. In addition to the on-line computer described above, an IBM 360/50 is available on campus. This computer will be replaced by either a 360/65 or a Sigma 7 this Fall.

An Addendum To

A Proposal To Study Resonance Production In

$\pi^- p \to X^- p$ At 40 to 80 GeV/c

(NAL Proposal No. 35)

Experimenters: University of Illinois at Chicago Circle
R. Abrams, S. Bernstein, H. Goldberg,
S. Margulies, D. McLeod, and J. Solomon

D. McLeod, Correspondent

1 December 1970

Abstract

An addendum to Proposal No. 35, motivated by the recent NAL Workshop on a Multiparticle Spectrometer, is presented. The addendum is in two parts. The first part describes modifications which are independent of the proposed Multiparticle Detection System (MDS) collaboration. Principally, these modifications permit investigation of high-mass, high-spin resonances produced polarized along the beam direction. The second part, which includes the physics of the first part, is predicated on the realization of the MDS collaboration. The additional feature of this second part is the investigation of decay modes involving charged kaons.

$\pi^-\pi^\circ$, and $\pi^-\eta^\circ$. These can be detected without a 4π vertex spectrometer if the incident energy is sufficiently high. As an example, at 80 GeV/c beam pion momentum, if a 3 GeV/c^2 resonance decays into $\pi^-\pi^\circ$ with the π^- having a center-of-mass angle whose cosine is -0.995, the corresponding laboratory angle is 24°.[4]

In addition, the extension takes us into a region where multiperipheral models may be very useful. In this region, for $\pi^-\pi^\circ$ for example, the momentum transfer from the target proton to the recoil proton is small, as is the momentum transfer from the beam pion to the outgoing π°, while both the $\pi^-\pi^\circ$ and $\pi^\circ p$ invariant masses are large.

B. Apparatus

A plan view of the modified apparatus is shown in Fig. 1. Note that the minimal 1 m-long x 0.8 m-wide x 0.4 m-high magnet described in the original proposal is quite sufficient for this experiment, although the considerably larger "consensus magnet" is shown in the diagram.

The NAL Medium Energy High Resolution beam, after passing through beam identifying and defining counters and proportional planes, is focused on a 30 cm-long hydrogen target. Except for slots for outgoing particles, the target is completely surrounded by lead-scintillator γ-ray counters, the γ counters on the downstream side being segmented to form a hodoscope.

Recoil protons pass through a set of wire planes, and then out through a slot in the right-hand wall of the anti counter. The protons are identified and detected by an array of E and dE/dx counters, followed by a liquid scintillator total-energy counter.

The three (or one) fast forward pions from $\pi^+\pi^-\pi^-$ (or $\pi^-\pi^\circ$ or $\pi^-\eta^\circ$) decay are detected in a forward spectrometer system. The system consists of a scintillator hodoscope covering the open hole in the downstream anti wall, a series of exterior wire and proportional planes, and the magnet. As mentioned above, a magnet considerably smaller than the "consensus magnet" would be adequate.

A downstream γ detector, to detect the π° or η°, is located some 12m from the target. It remains essentially unchanged except for a small reduction in size to 1.2 m x 2.4 m.

4/ However, high-mass particles of lower spin, such as "daughters", are more difficult to detect because of aperture limitations.

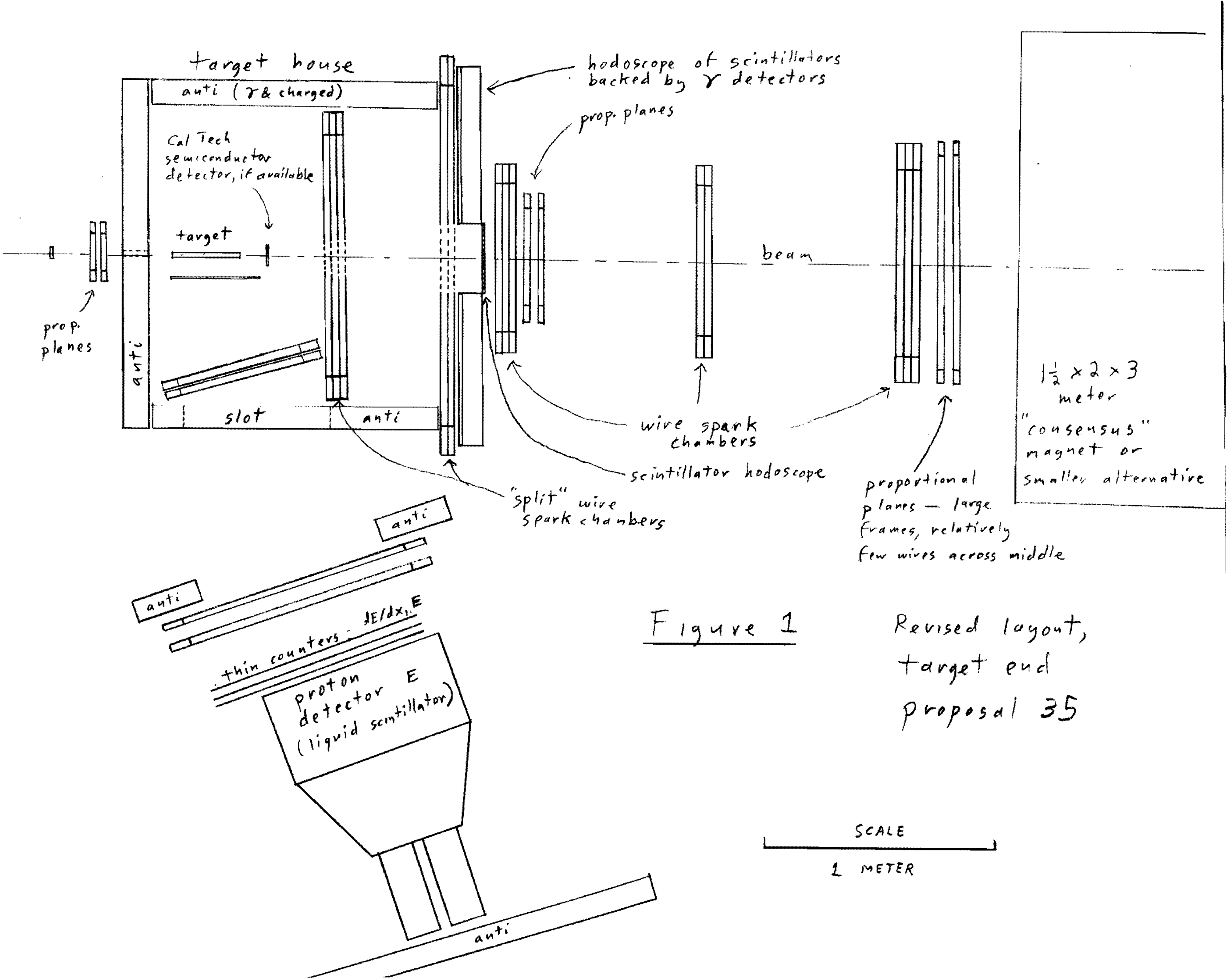


Figure 1

Revised layout, target end proposal 35

High-mass, high-spin resonances resulting in a wide-angle π^- will be studied using the apparatus described above plus two additional wire chambers, located within the target anti house, subtending a cone of about 30° at the target. The second chamber is located directly before the downstream anti wall, and is divided into two halves on each side of the hole. This chamber is used in conjunction with the hodoscope comprising the downstream wall of the anti house, which will veto all γ rays except those passing through an element also traversed by a charged particle.

C. Resolution

Extending the experiment to include large laboratory pion angles requires a re-examination of the resonance mass resolution obtained from measurements of decay product angles. This resolution becomes worse because of the increased dependence of the mass on the angle of the forward particle. A table of mass resolution, measured in MeV/c^2 at full width at half maximum (or 2.36 σ), is shown below. The first three rows are resolutions based on measurements of the angle and energy of the recoil proton.[5/] The last five rows are resolutions obtained from the recoil proton and the decay particle angles, $\pi^-\pi^\circ$ decay being assumed.

The assumptions used in computing the resolution are:

1) 4% FWHM proton kinetic energy resolution at 150 MeV, with $\Delta T \propto \sqrt{T}$ at other energies (photoelectron statistics). This contributes a nearly constant 12 MeV/c momentum width.
2) 2 mm. FWHM on γ vertex location at 15 meters (since this error and the recoil proton energy and beam angle error are comparable, an increase to 4 mm. would increase the mass error by less than 38%).
3) 0.15 milliradian FWHM on beam direction, from upstream planes.
4) 10 milliradian FWHM error on recoil proton angles at 150 MeV, scaling as $1/P\beta$ (multiple scattering).
5) 3 milliradian error on large angle (>7°) charged pions.

5/ In proposal 51 the masses are higher and/or the beam energy lower; the proton lab angle is smaller, Hence, the mass resolution is better.

Resonance Mass Resolution (FWHM)
in MeV/c^2 for $\pi^-\pi^\circ$ Decay Modes

Measurement		Resonance Mass (MeV/c^2)		
	$-t_p$ (GeV/c)	0.75	1.7	3.0
Recoil proton only (Momentum transfer in first column)	0.1	835	359	194
	0.3	576	246	128
	0.5	529	225	116
	$\cos\theta^*_{\pi^-}$			
Decay particle angles (Center of mass π^- angle in first column)	-0.99	805	21	59
	-0.98	57	20	65
	-0.95	11	36	56
	-0.80	15	27	29
	0	13	14	14

D. Rates

The modifications described above make no significant changes in the event rates estimated in the original proposal. We still request 50 shifts of running time, plus about 50 shifts, spread out over a long interval, for setting up and tuning. The beam intensity can be lower because of the longer target.

E. Costs

The original cost estimates submitted to NAL7/ have been re-examined in view of the modifications described above. The only substantial change is an increase of about $20K to purchase, rather than to construct, interfacing in order to obtain full three-charged-track-detection capability.8/

7/ D.McLeod, Cost Estimates for P-35, 25 July 1970 (unpublished).
8/ This interfacing could easily be obtained from the equipment pool should the MDS collaboration be realized.

F. Operation

The modifications described in this section represent a relatively minor change in the experiment described in the original proposal. Furthermore, these modifications are independent of either the "consensus magnet" or of the proposed MDS collaboration. As mentioned in the original proposal, collaborators would be required to successfully complete a project of this magnitude in a reasonable time.

III. Extension Based on the MDS Collaboration

A. Physics

Should the MDS collaboration be realized, we would wish to extend our experiment beyond the modifications described in the previous section. Principally, we would employ the Cal Tech (Proposal No. 54) atmospheric pressure downstream Cerenkov counter to investigate meson resonances decaying into rarer modes involving a charged kaon, such as $K^{\pm}K^{\circ}$ and $K^{\pm}K^{\mp}\pi^{\pm}$. In addition, since a beam Cerenkov counter will most likely be available as well, we would also investigate decays such as $K^{\pm}\pi^{\circ}$ and $K^{\pm}\pi^{+}\pi^{-}$ from meson resonances produced in kaon-proton interactions. Data for these extended investigations would be accumulated simultaneously with those for the pion induced, pion decay processes described previously.

B. Apparatus

With the exception of the addition of the Cal Tech Cerenkov counter and some minor dimensional changes to accomodate the "consensus magnet", the apparatus in this case is not essentially different from that described in Section II. A plan view of the modified experiment is shown in Fig. 2. Employing the Cerenkov counter to extend the scope of our investigation to include K decay modes has the effect of somewhat reducing the effective solid angle. The availability of the "consensus magnet"-- which, as mentioned earlier, is considerably larger than we require-- will improve background rejection on the basis of kinematic fitting, although the resonance mass resolution will not be improved significantly.

The greater resources which would become available should the MDS collaboration be realized would be of considerable value. For example, we could re-direct our current efforts on our prototype recoil-proton detector, since the Northeastern-Stony Brook (Proposal No. 51) detector is compatible with our

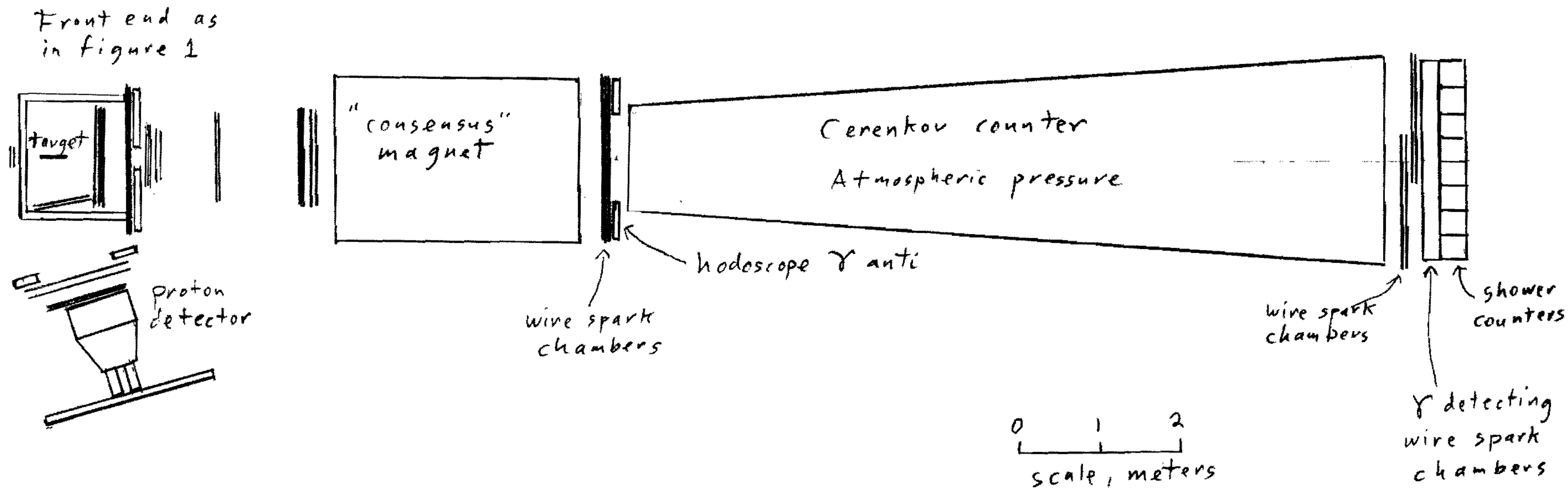


Figure 2 Revised layout including MDS facilities Proposal 35

needs; Cal Tech's high resolution, solid-state, charged-particle detector would be very useful; and additional wire-chamber interfacing, which we would otherwise have to purchase, would become available from the general equipment pool, thus freeing money for other items.

C. Resolution/Rates

As mentioned, the present modifications leave the resolution described in Section II essentially unchanged. Elongating the system to 17 meters (to accommodate the Cal Tech Cerenkov counter) reduces the downstream γ detector solid angle by a factor of 2, but reduces the event rate by a much smaller factor because of kinematic factors. Biases are increased on some event types. Additional set-up time will be required for the Cerenkov counter. Hence, we request an increase to 70 shifts of running time and 70 shifts (well distributed) of set-up time.

D. Costs

Although the MDS collaboration would save us considerable money by not having to duplicate equipment available to other members of the collaboration, committments would be required to furnish apparatus not currently available for use with the system. At the present time, the assignments among the members of the collaboration are too indefinite to permit an estimate of required expenditures.

E. Operation

The modifications described in this section extend those of the previous section, primarily by adding the Cal Tech downstream Cerenkov counter. In addition to designing and constructing apparatus for this specific experiment, we would also be involved in bringing an NAL multiparticle detection system into existence within the framework of the MDS collaboration.[1,2] Thus, although expending additional effort, we would in turn receive assistance and manpower from the other collaborators as required for our own experiment.