PHI PRODUCTION WITH PI MESONS

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I. INTRODUCTION

One of the most interesting groups of strongly interacting particles is the nonet of vector mesons. Members of this nonet play an important role in the nucleon form factor while the neutral vector mesons exhibit a close similarity to the photon.

Over the last several years a large amount of bubble-chamber data has been accumulated on the production of rho mesons. From many standpoints it would be useful to accumulate complementary information on the phi and omega mesons to elucidate the differences among the nonet members. Unfortunately, the omega decay modes are rather difficult to handle experimentally. The production cross section of the phi meson is down by a factor of roughly 100. However, it has a particularly clean decay mode. It decays to a K^+ and a K^- meson 50% of the time. The kaons tend to come off close together because of the very low center-of-mass kinetic energy. This is illustrated in Fig. 1 where the angular distribution of the phi and rho are compared at a momentum of 1.5 BeV/c. The mass width of the phi is also small so that it is easy to separate it from its background. This is in contrast to the case for the rho where subtraction of the background constitutes a difficult theoretical and experimental problem.

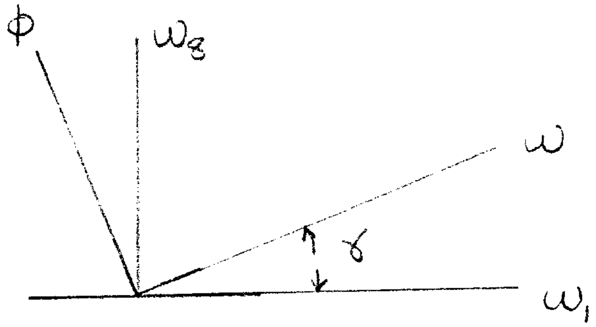
The following note discusses a particular phi production process $\pi^- + p \rightarrow n + \phi$. The apparatus is such that it would be quite simple to extend the method to other reactions such as $K^- + p \rightarrow \Lambda^0 + \phi$, the process in which the ϕ was originally discovered.

II. THE NATURE OF THE PHI-PRODUCTION PROCESS

Extensive theoretical work has not been done on phi production as such, probably because of the lack of experimental data. Instead most theoretical studies have concentrated on explaining the large omega to phi-production ratios.

In the following a quark model will be used to explain the reduced phi cross section relative to omega production. Then a Regge-pole omega production model will be used to illustrate the form phi production might take.

In the ω - ϕ mixing model[1,2] the physical phi and omega are constructed from an isospin singlet member of the octet, ω_8 and a unitary singlet, ω_1. The relative amplitudes are related by the mixing angle γ. This can be represented as



where $\omega_8 = (p\bar{p} + n\bar{n} - 2\lambda\bar{\lambda})/\sqrt{6}$

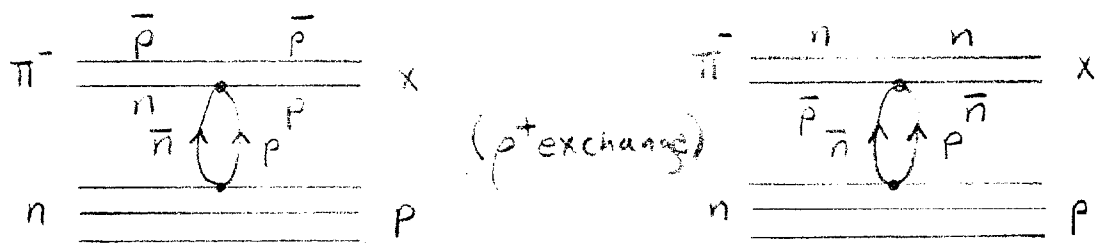
$\omega_1 = (p\bar{p} + n\bar{n} + \lambda\bar{\lambda})/\sqrt{3}$

and p, n, λ are the three quark states. The phi can be expanded as

$$\phi = \omega_8 \cos\gamma - \omega_1 \sin\gamma$$
$$= (p\bar{p} + n\bar{n})(\cos\gamma/\sqrt{6} - \sin\gamma/\sqrt{3}) - \lambda\bar{\lambda}(2\cos\gamma/\sqrt{6} + \sin\gamma/\sqrt{3})$$
$$\omega = (p\bar{p} + n\bar{n})(\sin\gamma/\sqrt{6} + \cos\gamma/\sqrt{3}) + \lambda\bar{\lambda}(\cos\gamma/\sqrt{3} - 2\sin\gamma/\sqrt{6})$$

Notice that if $\cos\gamma_o = \sqrt{2/3}$ (i.e. $\gamma_o = 35°$) the phi essentially consist of two strange quarks, i.e., $\phi = -\lambda\bar{\lambda}$ while the omega consist of non-strange quarks.

Now consider a production process for the phi. In an exchange model a phi (or an omega) can be produced by the exchange of a $\rho^+(1^-)$ or a $B^+(1^+)$ meson. The ρ^+ is a $p\bar{n}$ quark combination. With this exchange two diagrams are possible:



The outgoing state consist of $p\bar{p}$ and $n\bar{n}$, with no strange particle quarks. The relative phi and omega contribution can be found by adding the omega and phi amplitudes so as to eliminate the $\lambda\bar{\lambda}$ contribution:

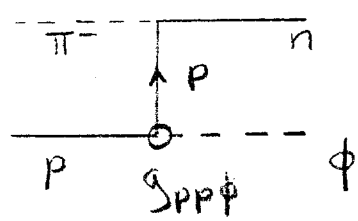
$$(p\bar{p} + n\bar{n})/\sqrt{2} = \{\cos\gamma/\sqrt{3} - 2\sin\gamma/\sqrt{3}\}\,\phi + \{2\cos\gamma/\sqrt{6} + \sin\gamma/\sqrt{3}\}\,\omega$$
$$= A_\phi\,\phi + A_\omega\,\omega$$

(Notice that at $\gamma = \gamma_o$ $A_\phi = 0.$) The relative cross-section ratio is given by the square of the amplitudes times some phase-space factors:

$$\frac{\sigma_\phi}{\sigma_\omega} = \frac{A_\phi^2}{A_\omega^2}\,\frac{F_\omega}{F_\phi}$$

The cross-section values are typically compared for cases with the same Q in the final state. Clearly the phi cross section can be suppressed by making the mixing angle very close to $\gamma = \gamma_o$. The actual cross section is down by a factor of 100 indicating $|\gamma - \gamma_o| \simeq 7°$. This implies that the phi must have some non-strange quark constituents. In fact, there is evidence for a 13% decay mode of the phi to a rho and pion, both of which consist of non-strange quarks.

The quark model also gives some indication of the nature of phi production at 180°. Here the process could go by proton exchange:



However, the coupling constant $g_{pp\phi}$ is essentially zero. Simply stated, this comes about because the proton consists of three non-strange quarks while the phi consists only of strange quarks. Since the coupling constant is zero, the backward production should be suppressed.

With some handle established on the relative ϕ/ω ratio, it is possible to infer the phi-production cross section as a function of energy and momentum transfer by studying the corresponding behavior for the omega. The most straightforward Regge models for rho production assume the only contribution to the cross section is from a ρ^+ trajectory. Then Regge theory requires that the differential cross section goes to zero at the momentum transfer value where Re α (the angular momentum) is zero. For the ρ trajectory this should occur at about $-t = 0.6$. In fact, the experimental data shows no sign of going to zero there. Actually it has the appearance of a diffraction peak. In addition, simple Regge theory predicts that ρ_{oo}, one of the elements of the density matrix relating the decay to the production distribution, should be zero; in fact, the value is 0.4.

There appear to be several ways out of these problems. One possibility is to introduce a second trajectory such as the B (with unnatural parity). The required trajectory has coupling parameters of the same order of magnitude as the ρ trajectory. This is unsatisfactory since other reactions show little such effect. It is also true that the B doesn't appear to couple to the phi at all, although it does couple to the omega (the B decays to $\omega\pi$ approximately 100% of the time). One then has the interesting possibility that the B trajectory would not contribute to phi production and a dip would appear; while in omega production, the B might contribute and wash out the dip.

Another method by which the dip can be partially removed is to introduce Regge cuts. Effectively this is equivalent to introducing absorption in the initial and final states. Henyey, et al.[3] have studied this possibility and find that it can also go some distance toward increasing ρ_{00}. Again the phi and omega predictions might be appreciably different because the phi-scattering cross section (which appears in the absorption models) is somewhat less than the omega-scattering cross section.

The experimental total cross section is shown in Fig. 2. Most of the data is from a Berkeley bubble-chamber run[4] while there is another bubble-chamber point at 2.10 BeV/c[1] and a point near threshold from a counter experiment employing neutron detection.[5] Preliminary results for an experiment at 11.2 BeV/c have been reported at Vienna by Hyams et al.[6] According to the results of the counter experiment, the cross section near threshold goes as the final state center-of-mass momentum. The experimental data are in remarkably good agreement, although the statistics are very poor. (The most prominent bubble-chamber point has about 35 events in it.) Clearly it is impossible to properly study angular distributions with this sort of statistics. However, the energy dependence of the total cross section is very tantalizing. Several questions immediately come to mind. Is the enhancement near threshold an S-wave ϕN resonance, perhaps the first hint of an isobar, or the effect of some sort of scattering length? Does the cross section drop deeply at 2.7 BeV/c and rise again, or is it relatively flat? A relatively flat cross section would indicate a diffractive process which doesn't seem plausible with a ρ^+ exchange process.

Threshold enhancements, such as the one which may be indicated by these data, have occurred in eta and f production. The eta threshold behavior has been discussed successfully by F. Uchiyama-Campbell and R. K. Logan[7] with a 2-channel S-wave Breit-Wigner resonance. The same techniques could be applied to phi production if angular distributions were available.

Some recent extremely high-energy cosmic-ray data[8] has given a tenuous indication that an $N\phi$ isobar (the so-called aleph) might play an important role at these energies. The suggested mass of the resonance lies close to the maximum of the phi-production cross section. Lohrmann[9] has suggested that the presence of the aleph could go some distance in explaining the Keuffel effect found in cosmic rays. Certainly one of the easiest ways to examine the possibility of $N\phi$ isobars is to investigate the $N\phi$ cross section.

Currently the need for phi-production cross-section information plays a significant role in many other interesting theoretical problems which will only be indicated here. It is required for discussions of vector dominance in photoproduction.[10] An interesting tool might be ω - ϕ regeneration in complex nuclei to determine ϕN cross sections.[11] It has also recently been suggested that the low value of the phi-production cross section can be inferred using duality diagrams.

III. A POSSIBLE PHI-PRODUCTION EXPERIMENT

Any experimental system for detecting phi production has to take into account the low cross section and the unique signature of two K mesons with a small opening angle. In addition, the design will be colored by the desire to detect a large part of the production and decay distributions. The paragraphs that follow discuss a number of aspects of a possible design.

Background

A number of two-prong processes occur as background here; however, the dominant processes are

$$\pi^- + p \rightarrow \pi^+ + \pi^- + n$$
$$\rightarrow p + \pi^- + \pi^0$$
$$\rightarrow \pi^+ + \pi^- + \text{neutrals}$$
$$\rightarrow p + \pi^- + \text{neutrals}$$

Typically the two pions come out as a ρ^0 meson. The cross section for these processes is 14 millibarns. If there is no K identification and the invariant mass of the $\pi^+\pi^-$ system is small, this process can fake K^+K^- production and hence phi production. An extensive analysis of existing bubble-chamber data (from a University of Toronto 3.0 BeV/c π^- exposure) **has** been performed to evaluate how much background of this sort occurs. The results are given in some detail in Appendix I. They are summarized here.

All two-prong events were rerun with the hypothesis that the charged particles were K^+ and K^-. Then a cut was made on small-opening angles. The cross section for events passing this is 1.5 mb, compared to the total K^+K^- cross section of about 17 μb that is expected at this beam momentum.

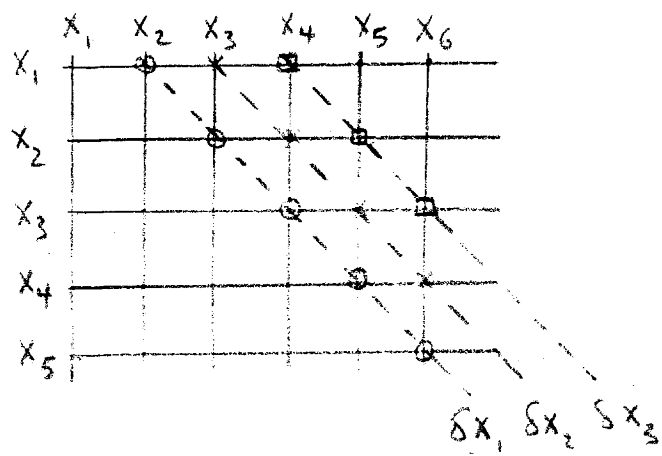
Thus with no K identification the trigger rate would be approximately 100 times the useful event rate. The kinematics of the process is then used to resolve the ϕ mass peak from the nonresonant K^+K^-. In addition the recoil mass can be checked to see if it corresponds to a neutron. With these checks only the $\pi^+\pi^-$(MM) channel contributes significantly to the background at a level of $5 \pm 4\,\mu b$. It is possible that part of this contribution may actually be real ϕ events.

Angular Acceptance

Some idea of the required angular acceptance for phi production can be obtained by plotting the point where the K meson intercepts a plane for a number of different production and decay angles. This has been done for center-of-mass production angles of 0, 30, 60 and 90 degrees and decay angles of 30, 90 and 150 degrees. The plots have been made for a phi, rho and a pseudo-rho with a mass of 400 MeV at incident pion momenta of 2.0 and 5.0 BeV/c. The results are shown in Fig. 3. Notice that for phi production all decay angles lie inside the 90° decay cone, while for the other cases some lie outside. This is because of the very small angular decay cone of the phi. The rectangle shows the size of the exit aperture for a large Argonne magnet, SCM105, placed at a convenient distance for an experiment. Distributions have been taken relative to a plane set at an angle of 25° relative to the incident beam, in order to better catch the lower momenta, large-angle decays. This magnet has no trouble at all in catching the entire decay distribution at production angles of 5 BeV/c. That is to say, both K mesons can easily pass through the magnet. At 2.0 BeV/c it may be necessary to make azimuthal cuts on the decay distribution. Hardly any normal rho mesons can pass through the magnet; however, the low-mass rhos can pass through the magnet, and it is useful to make some dynamic cut on the angular distribution.

Matrix Coincidence Techniques and Large Opening Angle Discrimination

It is possible to trigger on small-opening angles by placing a hodoscope just before the entrance of the magnet and requiring pairs of counters separated by no more than a certain distance to register counts. For example, consider an array of x counters--x_1, x_2, . . . , x_n and a similar array of y counters y_1, y_2, . . . , y_m. Let the array of x counters be run into a matrix such that any crossing point can be turned into AND circuit and its output fed to a master OR:



Any signal on the AND-OR line δx_1 means a coincidence where the separation was $\delta x = 1$, etc.

The same arrangement can form a δy_j set and the δx_1 and δy_j can then be fed into a third matrix such that δr is less than a certain value. This achieves the desired effect of limiting the opening angle to small values. Notice that $\delta x = 0$ or $\delta y = 0$ but not both are possible. This possibility requires that some additional ORs be added to the master trigger. It is not necessary that the hodoscopes consist of counters. Instead they might be constructed of proportional planes which would result in less multiple scattering. Matrix coincidence circuits utilizing new integrated circuit techniques have recently become available from several manufacturers. This experiment would require about 8 such circuits.

System Resolution

The requirements on system resolution are set by the recoil mass resolution (for the phi) and the neutral missing-mass resolution (the neutron). The missing-mass resolution equation is quite complicated. The resolution should be good enough to identify missing π^o mesons and help in finding incorrectly identified two-charged pion events.

Reasonable goals for the apparatus seem to be 1.0 mrad angular resolution (corresponding to 1.0 mm spatial resolution at a plane separation of 1.0 m) and 1% momentum resolution (for a 12 kG-m field length with a 100 mrad bend). Using these values, the resolution in the recoil mass (δm_n) and in the invariant mass of the charged K's (δm_ϕ) has been calculated using the Monte Carlo program FAKE. Details and results are presented in Appendix I. At a beam momentum of 3 BeV/c the values are $\delta m_\phi \sim 2$ MeV and $\delta m_n \sim 30$ MeV. Thus the apparatus does not contribute appreciable broadening to the apparent phi width of 3.7 MeV. In Dahl et al.[4] the phi data is binned into 10-MeV intervals and there is no difficulty in distinguishing the peak. Multiple scattering does not appear to seriously limit the possibility of obtaining these resolution requirements.

K Identification

Cerenkov counters, ionization, neutron recoils and time of flight have all been examined as possibilities for distinguishing the low mass two pion events from two K events. The pions from low mass "rho" decays for incident pion momenta greater than 4.0 BeV/c come off with one pion always having greater than 1.8 BeV/c momentum. (This is for $-t < 1.0$.) This is sufficient to count in a 3 atmosphere freon threshold Cerenkov counter. Any Cerenkov count would serve to veto the event. For energies below 4.0 BeV/c the required Cerenkov counter pressure rises rapidly and this technique will not work. Instead the experiment will rely on distinguishing the phi mass and utilizing gamma-ray counters for anti-coincident triggers.

These two approaches tend to separate the experiment into a low and high beam momentum region. Coverage of both regions is desirable from a theoretical standpoint.

An Example of an Experimental Apparatus

Figure 4 shows a single magnet system which can achieve a reasonable momentum resolution and acceptance (out to production angles such that $-t = 1.0$). The upstream magnetostrictive wire planes are similar to ones being fabricated by a Michigan-Argonne collaboration for another experiment. Large magnetostrictive planes similar to the back ones are being made by a group at Notre Dame. Some planes are placed close to the magnet to achieve long field free regions without decreasing the aperture. Many groups have had difficulty with y coordinate readouts this close to magnets. The group at Notre Dame is in the process of designing and testing magnetic mirrors (magnetic shields near the pole tips) which they feel will solve this problem. The required Cerenkov counter is a fairly ambitious project. Michigan has constructed a similar one with roughly one-half the linear dimensions. The design of a specific readout system for the magnetostrictive planes is presented in Appendix II.

The low momentum apparatus would be constructed with the same planes. The length of the apparatus would be decreased to about two-thirds of the length shown since the momentum resolution requirements are less stringent.

An alternative approach is to make a system which accepts a narrower range of production angles. This results in a smaller Cerenkov counter and smaller planes. However about twice as much beam time is required for the experiment. This technique can only be carried to the point where the vertical and horizontal apertures are nearly equal.

Event Rate

In the experimental data reduction it may be necessary to make some cuts on the decay distribution of the phi. Decay angles less than $10°$ relative to the production direction may pass through only one counter and not trigger. A cut at $10°$ eliminates only 1.5% of the events. For low beam momenta it may be necessary to cut at $60°$ in the center-of-mass to achieve an unbiased sample. This would eliminate half the possible events.

Pion beams of 10^6/pulse are possible in the beam in which the large magnet is presently located at Argonne. However if the beam is run directly into the planes, it may be necessary to reduce it by a factor of ten. To some extent this can be ameliorated by desensitizing the planes in the region of the beam.

For 10^5 pions incident at 5.0 GeV/c, a total cross section of twenty microbarns with an exponential slope of $\lambda = 5$ BeV/c^{-2}, and a 15 cm hydrogen target, roughly 600 counts can be obtained per day in the interval $0.0 < -t < 0.2$ while 0.3 counts are obtained in the interval $1.0 < -t < 1.2$.

IV. CONCLUSIONS

Experiments on phi production with wire planes can add an entire new dimension to the understanding of vector meson processes. Although the rates are low, the experiments appear quite feasible. Some attention will have to be paid to the magnetic shielding of the magnetostrictive lines for the planes and the construction of the Cerenkov counter. Application of the matrix coincidence technique will give valuable experience in constructing more elaborate triggers for future hybrid systems. It appears that all of this can be accomplished by utilizing a system that is similar to one that has already been built and is available at Argonne. All in all, it seems an eminently suitable project for an early research effort at NAL.

V. ACKNOWLEDGMENTS

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APPENDIX I.

ESTIMATION OF BACKGROUND

An attempt has been made to estimate the rates of ϕ production and the amount of background expected. Since it is intended to impose a majority trigger which will allow the apparatus to accept final states which have two, and only two, charged outgoing particles, the discussion is limited to such states. For beam momenta below about 4 BeV/c it is not feasible to identify kaons from pions in the final state, so the separation of signal from noise will have to be achieved mainly by kinematic analysis. This appendix is concerned with this problem. A separation of events produced by beam momenta greater than 4 BeV/c will be easier as a Cerenkov counter can be used to anti-coincidence pion events.

There are three levels at which background separation must be made:

1. An attempt must be made to impose sufficiently stringent triggers on the spectrometer to ensure that the data accepted for further analysis is not swampedby unwanted events.
2. A considerably more refined separation of the final state nK^+K^- must be achieved by kinematic analysis.
3. The final state of interest, $n\phi$, must be separated from the events remaining after step 2.

The main source of background will come from the following final states:

$$\pi^- p \rightarrow \pi^+ \pi^- n \qquad (1)$$

$$\rightarrow p \pi^- \pi^o \qquad (2)$$

$$\rightarrow \pi^+ \pi^- (MM) \qquad (3)$$

$$\rightarrow p \pi^- (MM) \qquad (4)$$

Here, MM stands for two or more neutral particles.

To estimate the contribution of these states an investigation has been made of a 60, 000 picture exposure of $\pi^- p$ interactions at 3 BeV/c in the MURA-ANL chamber from a University of Toronto- University of Wisconsin-ANL experiment. It may be desirable to repeat this analysis at other beam momenta if suitable data can be made available. However this analysis gives a good indication of the difficulties to be faced. Presumably at a beam momentum of 3 BeV/c the problem is particularly severe, since the cross section for ϕ production is close to a minimum at this point (see Fig. 2).

The final states $\pi^+ \pi^- n$ and $p \pi^- \pi^o$ provide 1-constraint fits to the data used. The state $p\pi^-$(MM) contains events which did not fit these, but in which the proton was identifiable by ionization. The $\pi^+ \pi^-$ (MM) events comprise all remaining two-prong interactions in which no decay, as evidenced by a kink in one of the tracks, was observed. This channel will presumably also contain final states with a K^+ and a K^-.

In order to compare these reactions with ϕ production, events of the type:

$$\pi^- p \to n K^+ K^- \text{ (nonresonant)}, \tag{5}$$

$$\pi^- p \to n \phi \to n K^+ K^- , \tag{6}$$

have been generated by the bubble-chamber Monte Carlo program FAKE, suitably modified. It has been assumed that the production distribution is isotropic, in agreement with the available data.[4]

Figure 5 shows the opening angle between the pions in the final states $\pi^+\pi^- n$ and $\pi^+\pi^-$(MM), and Fig. 6 shows the same angle for the FAKE-generated states $n\phi \to nK^+K^-$ and nK^+K^- (nonresonant). As previously indicated in Fig. 1 the distribution in opening angle of the kaons from ϕ decay is considerably narrower than that from the other states. A cut in this angle, θ, imposed by the counter hodoscope, of $0 < \theta < 25°$, removes 94% of the $\pi^+\pi^- n$ final state, 85% of the $\pi^+\pi^-$(MM) state and 89% of the nonresonant nK^+K^- state (events with a K^+K^- invariant mass above about 1.3 BeV are rejected), while retaining 92% of true ϕ production.

This information is summarized in Table I, which gives the total cross section for these states (σ_T) and that remaining when this angular cut is applied [$\sigma(25°)$].

Table I. Final States from $\pi^- p$ Interactions at 3 BeV/c.[a]

Channel Number	Final States	σ_T (mb)	$\sigma(25°)$[d] (mb)	$\sigma(''n\phi'')$[e] (μb)
1	$\pi^+\pi^- n$	3.9	0.25	1 ± 1
2	$p\pi^-\pi^o$	2.8	0.20	1 ± 1
3	$\pi^+\pi^-(MM)$[b]	6.1	0.90	5 ± 4
4	$p\pi^-(MM)$[b]	2.0	0.20	2 ± 2
5	$K^+K^- n$	0.15 ± 0.10	0.017	
6	$''\phi'' n$[c]	0.009	0.008	8 ± 6
	ϕn	0.006	0.006	6 ± 8

[a] Channels 1 through 4 are from data from a University of Toronto-University of Wisconsin-ANL collaboration, channels 5 and 6 from Dahl et al., Phys. Rev. 163, 1377 (1967).

[b] These events did not fit the 1c fits for channels 1 and 2. (MM) stands for two or more missing neutrals.

[c] "ϕ" indicates events with $1.00 < m(K^+K^-) < 1.04$ BeV.

[d] $\sigma(25°)$ is the cross section for events in which the opening angle between the outgoing charged particles is less than 25° It is estimated from FAKE results for channels 5 and 6.

[e] $\sigma(''n\phi'')$ is the cross section for events with the opening angle cut, the "ϕ" cut, and $0.90 < (MM) < 0.98$ BeV.

Another experimental constraint which was considered was the use of a neutron counter. If an ideal neutron detector was available, the final states $p\pi^-\pi^o$ and $p\pi^-(MM)$ would be rejected, and the severe loss in rate (a counter efficiency of 35% with a geometrical efficiency of 50% at these momenta might possibly be achieved) might be acceptable. The $\pi^+\pi^- n$ and $\pi^+\pi^-(MM)$ events accepted by the system would be separated by the kinematic analysis. However, it appears that discrimination between γ rays from the conversion of the π^o's and the neutrons is difficult and the rejection would thus be far short of ideal.

In any case Table I shows that the major contribution to background after the angular cut has been imposed comes from the $\pi^+\pi^-$(MM) events, followed by the $\pi^+\pi^-n$ events. It would then be reasonable to use a neutron counter to discriminate against this background only if the neutron from these reactions had an angular emission whose distribution was remarkably different from that of the neutrons from the ϕn final state.

Figure 7(c) shows that for the ϕn events, all neutrons are contained in a core of approximately 45° in half-angle. If only $\pi^+\pi^-n$ events with neutrons inside this cone are chosen, approximately 65% of this final state would still be accepted as Fig. 7(a) shows. (Note however, that this number may be somewhat in error as the 25° angular cut has still not been made on the data.) For the $\pi^+\pi^-$(MM) events the neutron direction is not known. However the direction of the neutral shown in Fig. 7(b) is less than 40° in 98% of the cases, indicating that either the neutron or one of the γ rays from a π^o would probably lie within the 45° cone. Although it is clear that some further study is necessary, it appears that a neutron counter may provide only poor discrimination against the background considered here.

An alternative method of reducing the background is to place a radiator in such a way as to convert the γ's from any π^o's and to then use the signal from a counter behind it in anti-coincidence. The radiator would form a curtain around the beam outside the 45° cone of neutrons from the ϕn events. It is difficult to estimate the reduction in background this would achieve, since, for example, the direction of the π^o's in $\pi^+\pi^-$(MM) is unknown. Studies on the four-prong sample ($\pi^- p \rightarrow \pi^-\pi^+\pi^- p \pi^-$) from the 3 BeV/c data, on the state $\pi^+\pi n \pi^o$ generated by FAKE, and on the best design of such a counter system are continuing.

The background states from strange-particle production in $\pi^- p$ interactions which allow two and only two charged particles to traverse the spectrometer and give a signal, have not yet been studied in detail. However it should be noted that the production cross sections of these final states are at least an order of magnitude lower than the final states considered above.

The present estimates, excluding consideration of the strange-particle background and the use of a gamma-ray anti-coincidence counter, indicate that the ratio of true ϕ events to background received on the data tape may be approximately 1 : 200 at 3 BeV/c. This ratio is not unacceptable.

An estimate has been made of the number of background events which fake the final state $n\phi$ even after imposition of the opening-angle cut. In order to do this an estimate of the experimental resolution has been obtained by studying the ϕn events generated by FAKE. The invariant mass of the K^+K^- pair (m_ϕ) and the effective mass of the recoil mass (m_n) have been calculated using the momenta (p) and angles (θ) of the beam and of charged kaons. These momenta and angles are then allowed to vary as if they had Gaussian errors with standard deviations given by $\sigma(p) = 1\%$ and $\sigma(\theta) = 1$ mrad. (These errors seem quite reasonable: the calculation will be repeated as soon as more accurate estimates have been made.) A recalculation of m_n and m_ϕ is made and the values so obtained subtracted from the unmodified values. The full widths at half-height of the distributions of these differences provide an estimate of the mass resolution of the system. The results of these calculations are presented in Fig. 8. It is of course equally important to estimate the resolving power of the system for the background events. Since the momenta and angles of all events accepted on the data tape will be similar, it is assumed here that the resolutions for signal and background are equal.

Figure 9 indicates that, at 3 BeV/c, a K^+K^- mass spectrum from 1.0 to 1.04 BeV (called "ϕ" events) should be sufficient to allow the separation of the ϕ signal from the nonresonant background. A cut on the missing mass ("n") of $0.90 < m(\text{"n"}) < 0.98$ BeV should be sufficient to accept all genuine nK^+K^- final states.

An estimate of how many of the events of channels (1) to (4) above will be misidentified as n "ϕ" events have been obtained from the 3 BeV/c data assuming that the charged final-state particles in these channels are kaons. The invariant mass and the missing neutral mass is then calculated from the momenta of the charged particles and the beam. The results of this procedure are shown in Fig. 9 for the $\pi^+\pi^-$(MM) and $p\pi^-$(MM) events.

The intersection of the "ϕ" and "n" cuts on this scatter plot gives an estimate of the events from these channels which will kinematically fake true "n" "ϕ" events. As mentioned earlier some of these events may actually be genuine nK^+K^- events misidentified as $\pi^+\pi^-$(MM). The contribution from the final states $\pi^+\pi^-n$ and $p\pi^-\pi^o$ is actually zero: for the purposes of this estimate it has been assumed that this number is one event per channel.

The results are summarized in Table I where σ("n ϕ") indicates the expected cross sections of the pion production channels which will contribute to the final sample of genuine n "ϕ" events. For comparison the measured cross section for true "ϕ" events [$1.0 < m(K^+K^-) < 1.04$ GeV] as given by Dahl et al.[4] is also shown. According to these results, the true ϕ production comprises about 60% of these events.

The FAKE calculations used above have assumed that the ϕ production is isotropic in the center-of-mass. The available data, though very sparse, indicates that this is a reasonable assumption for beam momenta near threshold. Above about 2.3 BeV/c effectively nothing is known and it may be that ϕ production becomes more peripheral, in analogy to the production of other vector mesons in pion-nucleon interactions. In order to examine whether such an effect might affect the conclusions drawn above, the calculations have been repeated assuming that the square of the four momentum transfer from the incoming pion to the ϕ meson (t) is distributed as e^{6t}. Figure 8, for example, shows that the resolution in the mass of the neutral is increased (that is, poorer) while that of the invariant K^+K^- mass is little affected. The opening angle between the K pair is sharply decreased, and at 3 BeV/c, for example, a cut at 12° contains about 90% of the true ϕ events, while achieving a large reduction in the background events over the 25° cut. It would thus appear that peripheral ϕ production would present only slightly different problems, and that the rejection of background events would be at least as good as the case discussed above.

It is clear from Table I that, at 3 BeV/c, the signal-to-noise ratio is fairly low, particularly when it is noted that, with the present equipment, only about 25% of the total ϕ cross section will be accepted (the branching ratio of $\phi \rightarrow K^+K^- / \phi \rightarrow$ all modes $\simeq 0.5$, and for roughly 1/2 of the events at least one K will decay before reaching the final wire plane).

However the following points should be noted:

1. The γ-ray converter and counter suggested above will certainly improve the discrimination against background.
2. Of the (5 ± 3) μb remaining from the $\pi^+\pi^-$(MM) final state an appreciable portion may consist of genuine ϕ events. Present

statistics are not sufficient to distinguish the ϕ signal from background however.

3. The cross section for ϕ production at a π^- momentum of 3 BeV/c is very close to a minimum. The signal-to-noise ratio will certainly be much higher at lower momenta.

4. It is worth emphasizing that the existing data on the reaction $\pi^- p \rightarrow n K^+ K^-$ (including the $n\phi$ final state) is very sparse. Dahl et al.,[4] for example, who give the most complete study of this reaction for beam momenta in the range 1.5 to 4.2 BeV/c, see a total of only 224 measurable events. It is estimated that the contamination in these events from misidentified channels rises from 10% to 50% as the beam momentum increases from threshold to 4.2 BeV/c. At the same time the efficiency for detection of the $n\phi$ final state drops from about 8% to 1%. All estimates of cross sections obtained from existing data should thus be treated with due caution.

APPENDIX II.

MAGNETOSTRICTIVE READOUT SYSTEM

This appendix discusses a magnetostrictive readout system and associated logic to detect K^+K^- pairs. The system has been studied in some detail to provide an example which might be used. Figure 10 gives a block diagram of the system.

Two fiducial signals are put on a magnetostrictive wire by two coils in series at the ends of the wire planes. Then the pulses detected by the pickup coil are in a train with the first and last pulses being the fiducial pulses. A quad scaler is turned on by the first fiducial pulse. The scaler system contains a clock with a crystal oscillator (the frequency is typically 20 MHz/sec). The scalers count the clock pulses until the first spark pulse turns off the first scaler and the second spark pulse turns off the second scaler, etc. Then the numbers in the scalers represent the spark coordinates. The last fiducial pulse turns off the third scaler provided that the spark chambers count two charged particles simultaneously. Some cases are:

1. One spark. The second fiducial goes to the second scaler. This indicates that one of the particles is scattered away.
2. Three sparks. Second fiducial goes to the fourth (last) scaler. This could occur with an accidental track or an edge spark, etc.

3. The four spark case may be detected by the number in the fourth scaler, which is checked against the expected fiducial number.
4. A "more than four spark" case is indicated by a spark overflow signal (SPOF).
5. A scaler overflow signal (SCOF) is given when a specific scaler has reached full scale without measuring a spark coordinate.

After the scalers are set an "output ready" signal goes to the computer interface from the master control. This may be an interrupt signal to the computer if the computer is used to process the previous data. The computer sends a "ready" signal back to the master control.

Then the scanner proceeds to nondestructively read each address and the data in sequence by application of a strobe signal to the data bus. The data contents of the selected scaler are then applied to the data bus which go to the computer interface as voltage levels (0, +4 volts) which remain until the strobe signal is removed. The data is scanned through 24 bit cables: 14 bits for the spark coordinates and fixed data (run number, etc., which can be put on a data box), 8 bits for the addresses and 2 bits for the SPOF and SCOF. The addresses, the spark coordinates, the SPOF and the SCOF can be displayed on an indicator. This might be a fast light display and it is not generally useful except for set-up testing. Then the master control can be set so that the contents of a selected address, the address, the SPOF and SCOF are displayed. The 14-bit information stored in each scaler is scanned simultaneously through the 14-bit lines. After the data is taken by the computer a signal from the computer goes to the scanner. This advances the scanner by one address (this is a weak link if the shift register scaler skips). Thus the scanning proceeds at a stepping rate determined by the computer. The end of the scan is also selected by a row of toggle switches labeled EOS. When this last address is reached, a "complete" condition is transmitted to the interface. This allows the computer to go on to other tasks. The "end of scan" signal may be another interrupt for the computer.

Such a system might utilize a test generator by which the operation of the whole system could be tested.

Gated tagging modules can also be used to store coincidence events from the hodoscope. The information is loaded into bistables only at the trailing end of the "load" pulse (- 0.7 V, 5 nsec). This information may be read into the computer in the same way as the information from the scalers.

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FIGURE CAPTIONS

Fig. 1. Decay distribution for a rho and phi meson with a momentum of 1.5 BeV/c.

Fig. 2. Total cross section for phi production as a function of beam momentum.

Fig. 3. Intersection points on a plane 25° to the beam line for phi, rho, and rho (400) decays at pion-beam momenta of two and five BeV/c. The solid lines are decays at 90° in the center-of-mass while the dotted lines are decays at 30° and 150°. The rectangles represent typical magnet exit apertures.

Fig. 4. A preliminary design for a high-momentum spectrometer.

Fig. 5. Distribution in the opening angle between outgoing charged particles in the reactions

(a) $\pi^- p \to \pi^+ \pi^- n$

(b) $\pi^- p \to \pi^+ \pi^- (MM)$

Fig. 6. Distribution in the opening angle between outgoing charged particles in the reations

(a) $\pi^- p \to n K^+ K^-$ (nonresonant)

(b) $\pi^- p \to n \phi \to n K^+ K^-$

Fig. 7. Distribution in the angle between the beam direction and the neutral particle(s) in the final states

(a) $\pi^+ \pi^- n$

(b) $\pi^+ \pi^- (MM)$

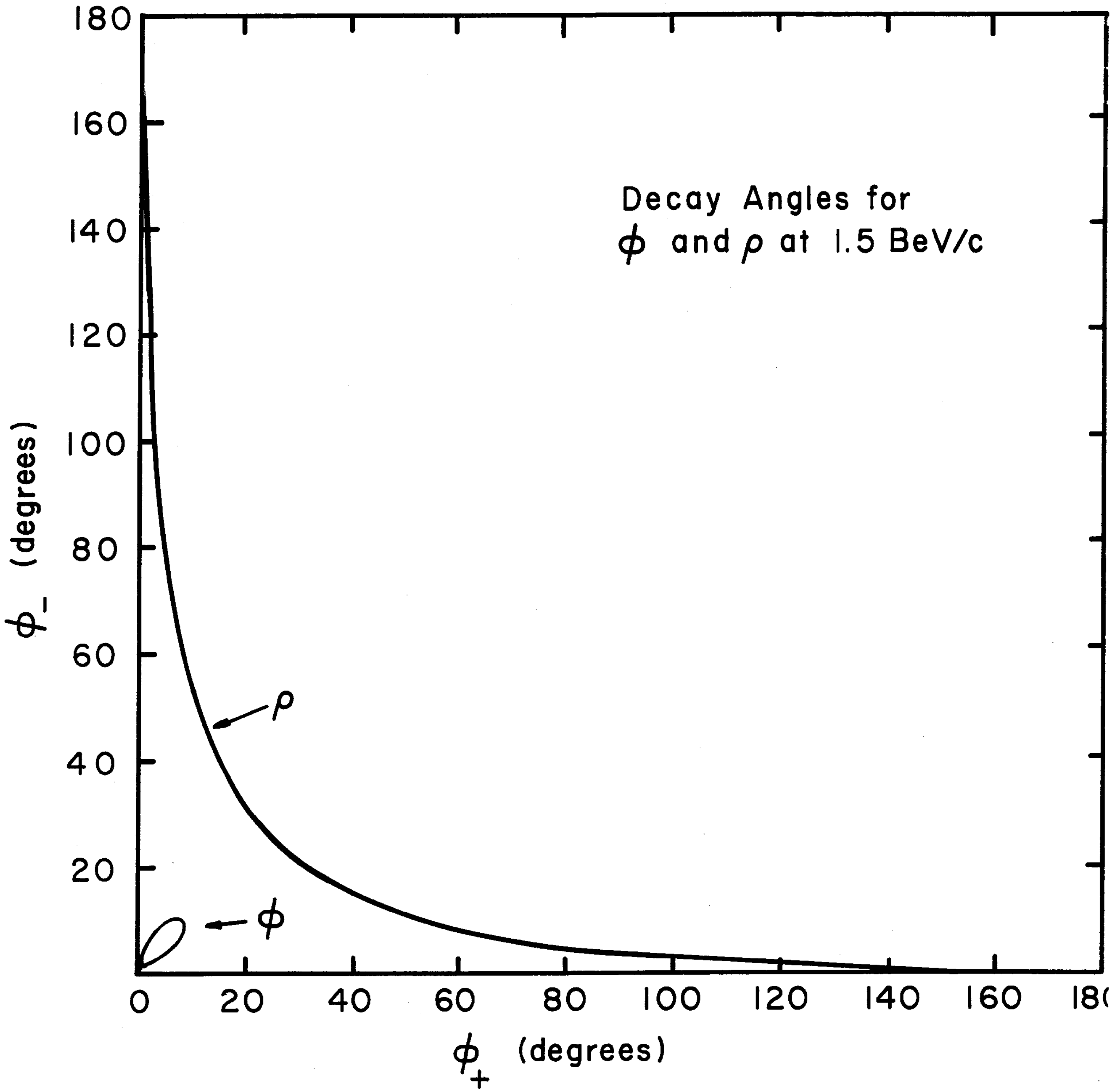
(c) $n \phi \to n K^+ K^-$

Fig. 8. Mass resolution for (a) neutron, (b) ϕ meson, assuming errors in momenta of 1% and errors in angle of 1 mrad.

Fig. 9. Scatter plot of invariant mass of outgoing charged particles against missing neutral mass in the final states $\pi^+ \pi^-$ (MM) and $p \pi^-$ (MM) where the charged particles are treated as kaons for the purposes of calculation.

Fig. 10. A block diagram of the spark-chamber readout system for the $\pi^- p \rightarrow n\phi$ experiment.

Figure 1


Decay Angles for
φ and ρ at 1.5 BeV/c
ρ
φ
180
160
140
120
100
80
60
40
20
0
20
40
60
80
100
120
140
160
φ_ (degrees)
φ+ (degrees)

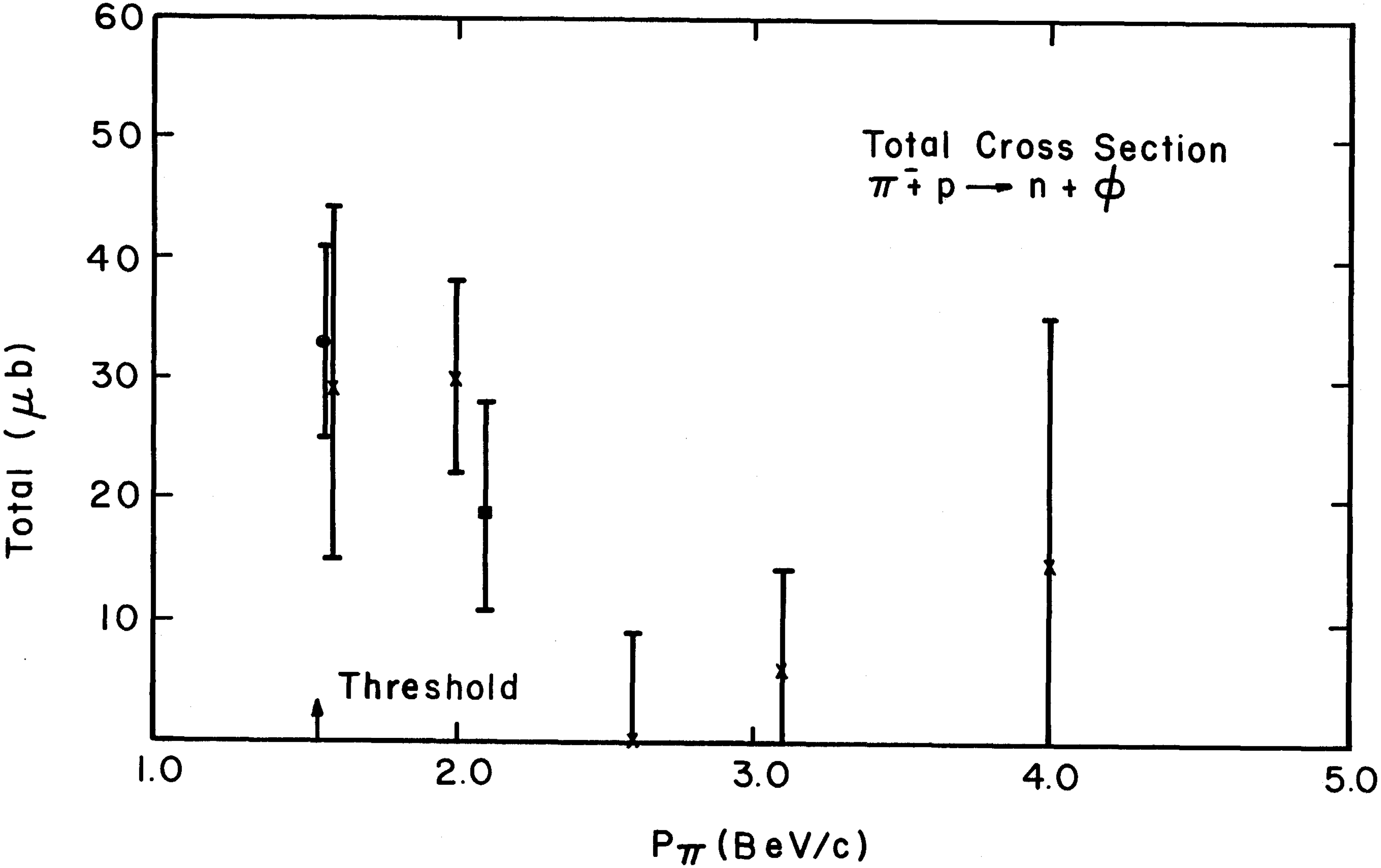


Figure 2

TM-174
2021

Figure 3

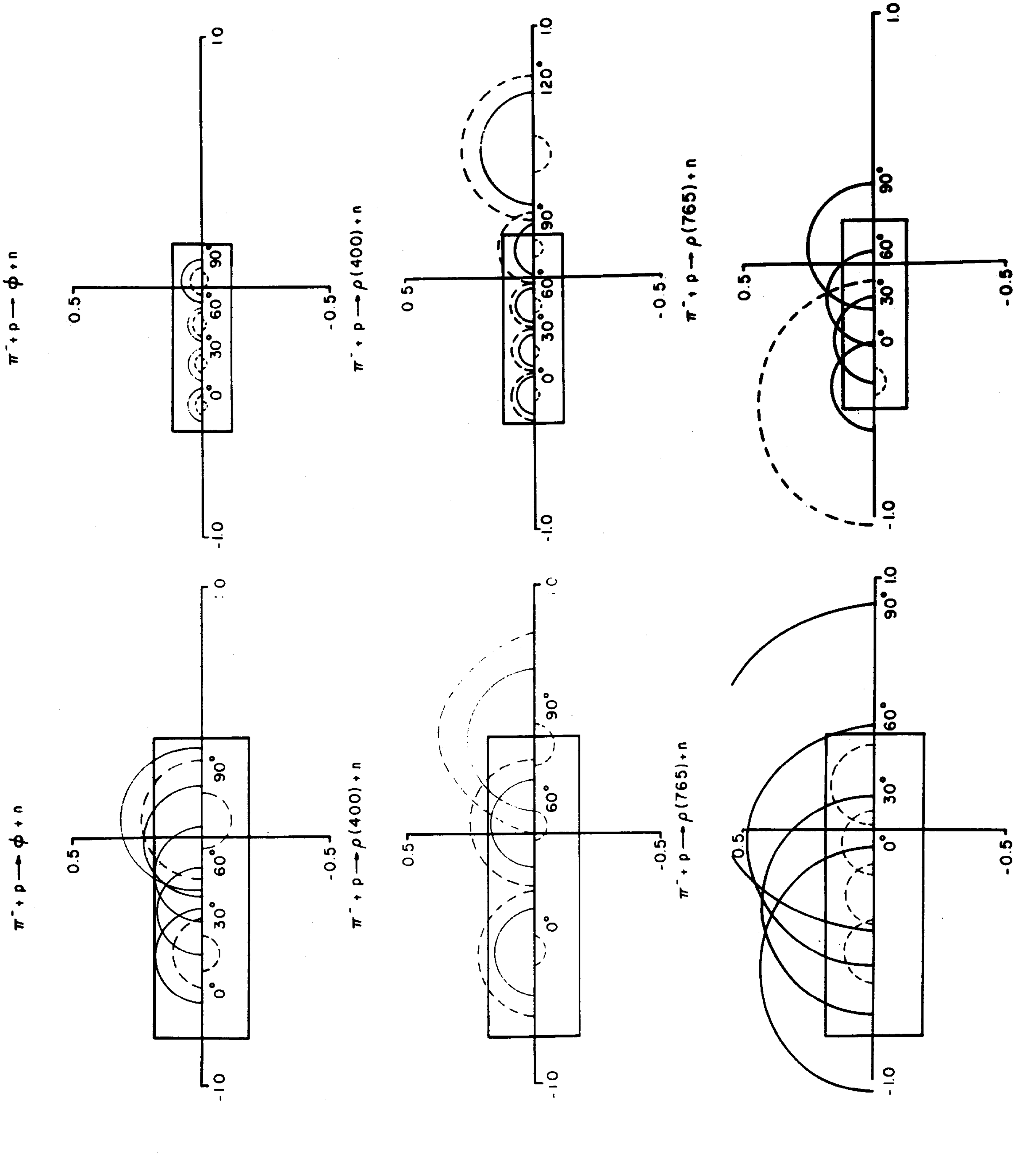
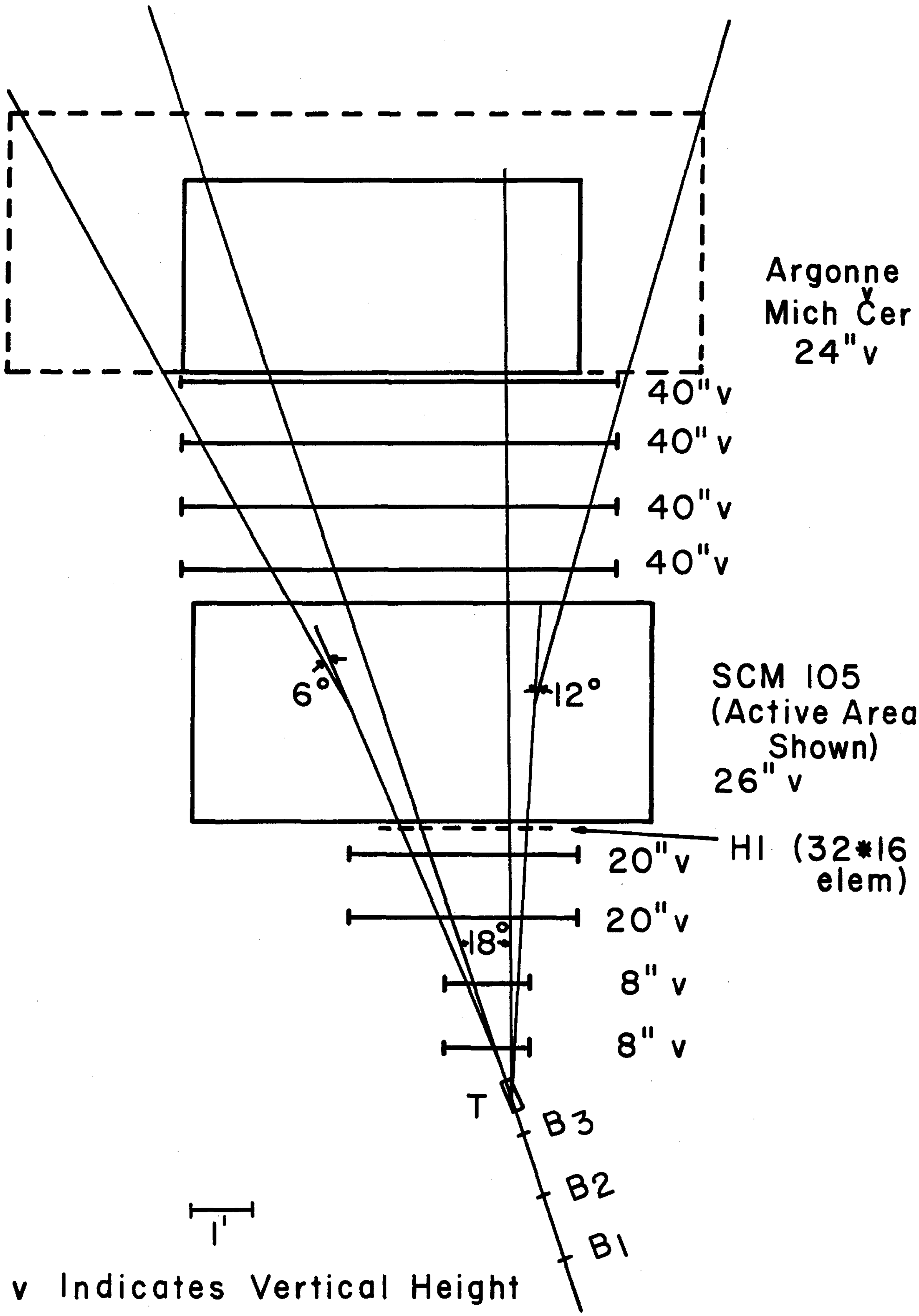

π⁻ + p ⟶ φ + n
π⁻ + p ⟶ ρ(400) + n
π⁻ + p ⟶ ρ(765) + n
π⁻ + p ⟶ φ + n
π⁻ + p ⟶ ρ(400) + n
π⁻ + p ⟶ ρ(765) + n
0°
30°
60°
90°
120°
0.5
-0.5
1.0
-1.0

Figure 4


Argonne
Mich Cer
24"v
40"v
40"v
40"v
40"v
6°
12°
SCM 105
(Active Area
Shown)
26" v
H1 (32*16
elem)
20"v
20"v
18°
8" v
8" v
T
B3
B2
B1
1'
v Indicates Vertical Height

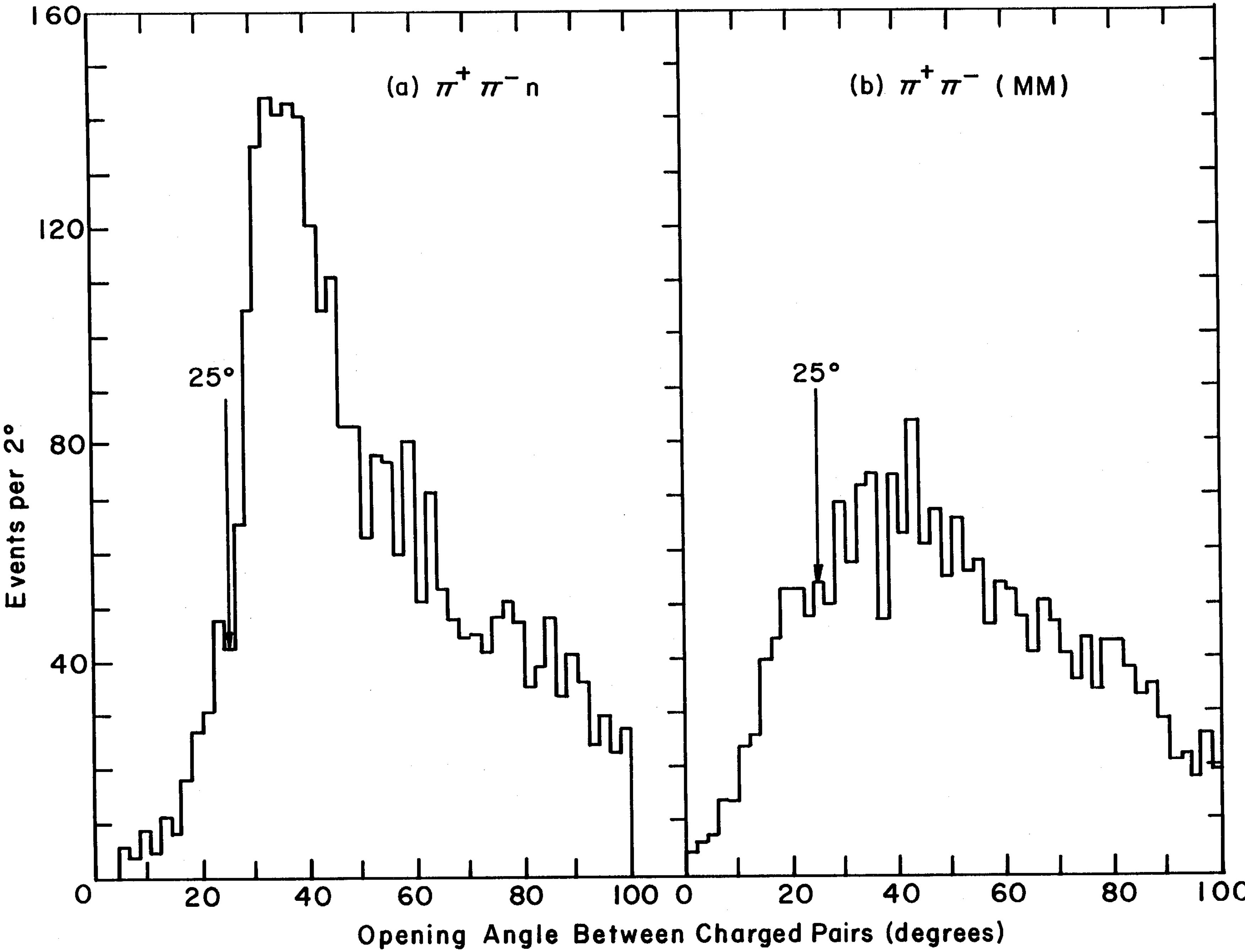


Figure 5

TM-174
2021

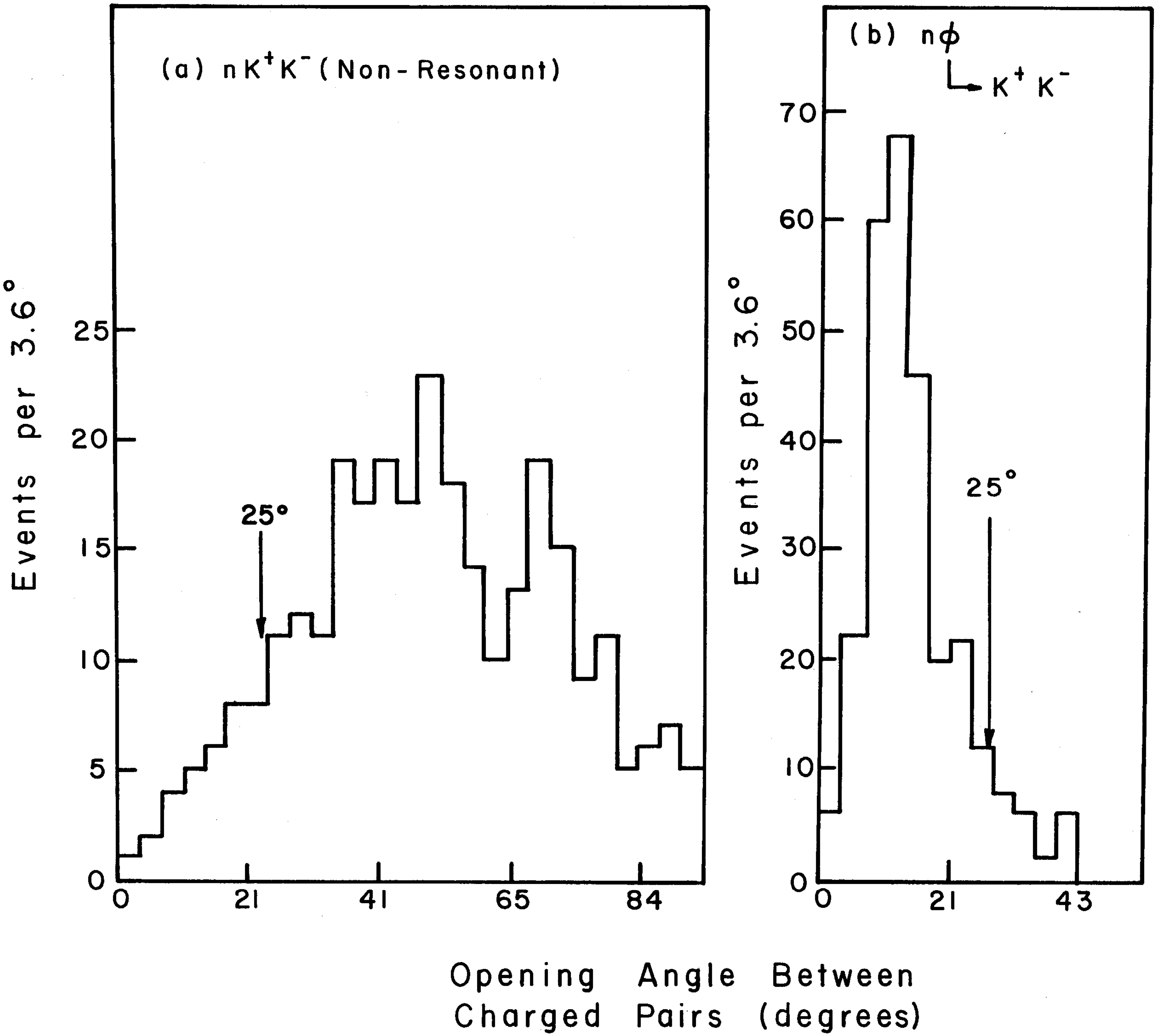
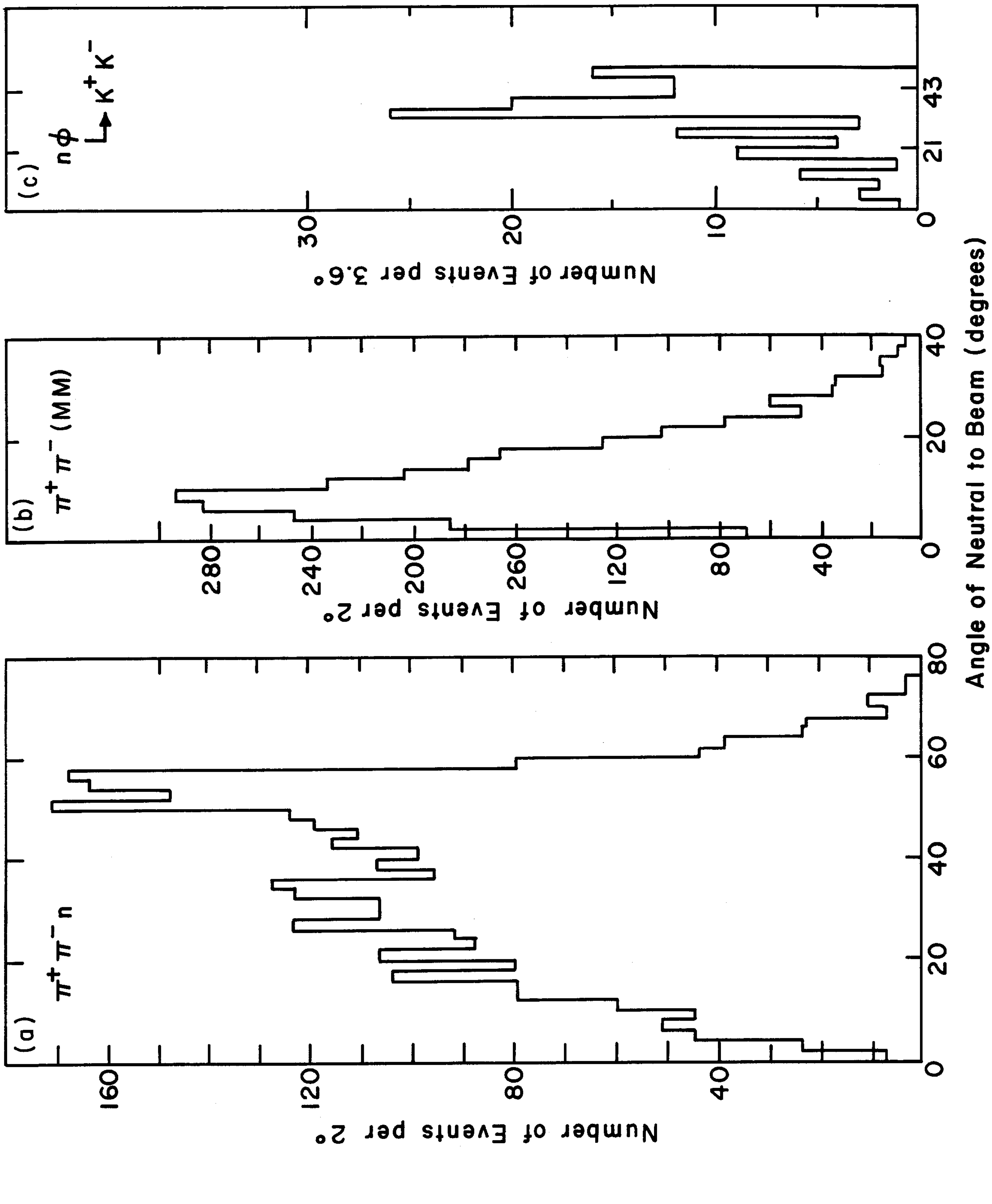


Figure 6

TM-174
2021

Figure 7


(a)
π⁺π⁻n
(b)
π⁺π⁻(MM)
(c)
nφ
↳K⁺K⁻
Number of Events per 2°
160
120
80
40
0
Number of Events per 2°
280
240
200
260
120
80
40
0
Number of Events per 3.6°
30
20
10
0
0
20
40
60
80
0
20
40
21
43
Angle of Neutral to Beam (degrees)

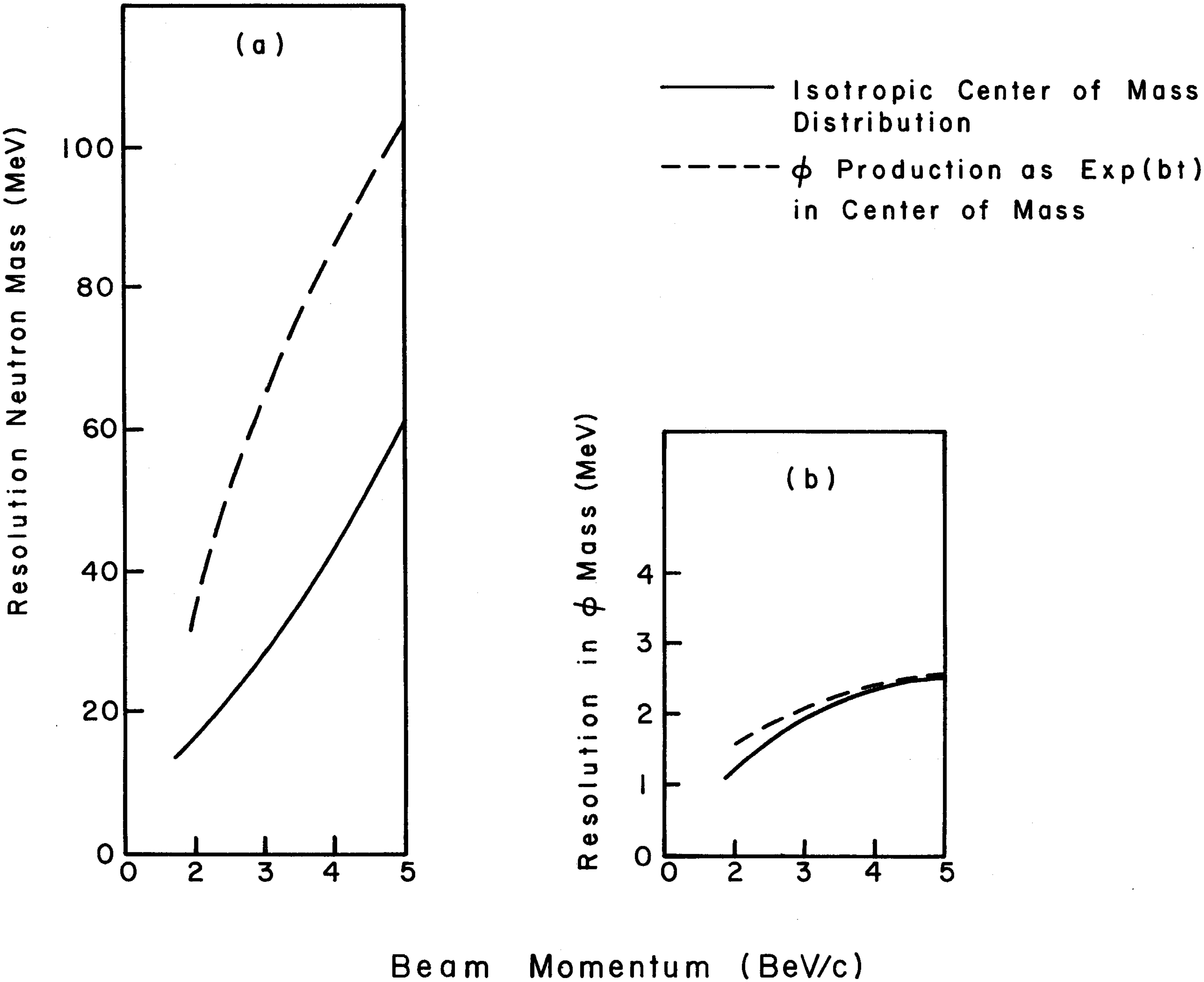
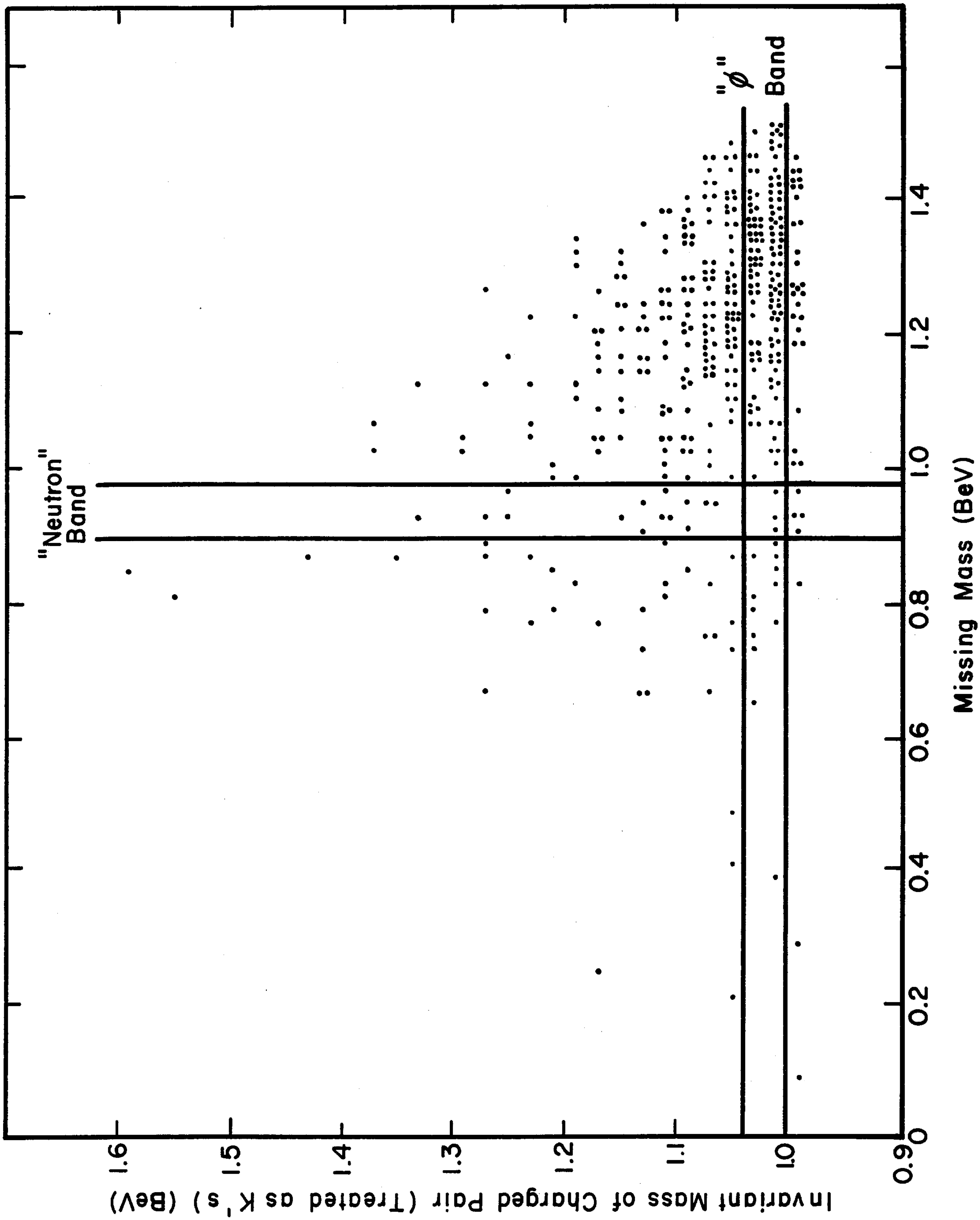

(a)
Resolution Neutron Mass (MeV)
0
20
40
60
80
100
0
2
3
4
5
Isotropic Center of Mass Distribution
φ Production as Exp(bt) in Center of Mass
(b)
Resolution in φ Mass (MeV)
0
1
2
3
4
0
2
3
4
5
Beam Momentum (BeV/c)

Figure 8

Figure 9


"Neutron"
Band
"ϕ"
Band
Missing Mass (BeV)
Invariant Mass of Charged Pair (Treated as K's) (BeV)
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
0.90
1.0
1.1
1.2
1.3
1.4
1.5
1.6

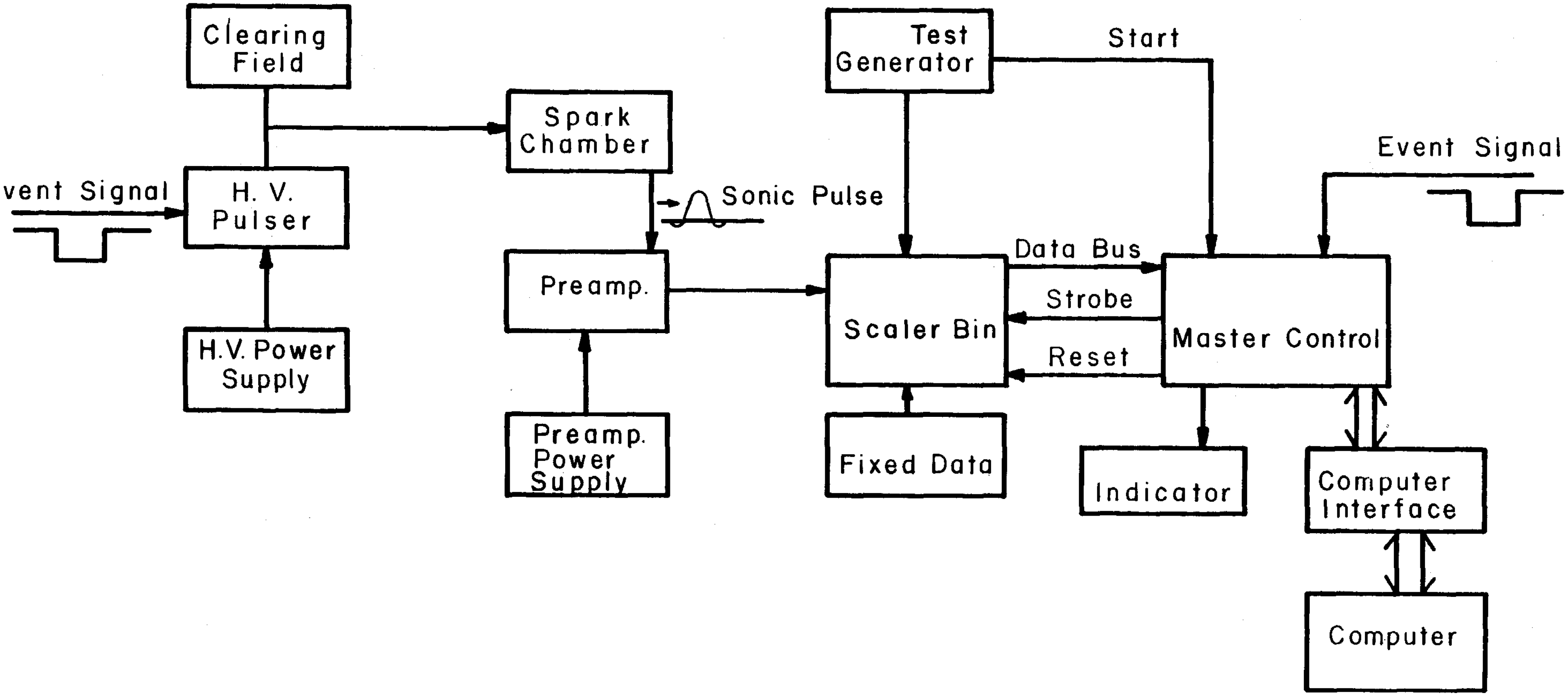

Clearing Field
Spark Chamber
Test Generator
Start
Event Signal
vent Signal
H. V. Pulser
Sonic Pulse
Data Bus
Preamp.
Strobe
Scaler Bin
Master Control
Reset
H.V. Power Supply
Preamp. Power Supply
Fixed Data
Indicator
Computer Interface
Computer

Figure 10