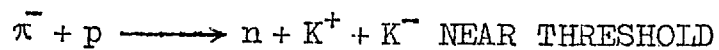


TIME-OF-FLIGHT STUDY OF THE REACTION



by

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ABSTRACT

An account is presented of the application of the neutron time-of-flight technique to a study of the production of the phi meson in the reaction,

$$\pi^- + p \longrightarrow n + K^+ + K^-,$$

near the ϕ threshold.

A description of the design and performance of the apparatus including the electronic logic, is given. An array of neutron counters was used which had a high geometric efficiency for detecting neutrons of low c.m.s. momentum. The arrangement had an intrinsically high mass resolution, and in conjunction with another system of scintillation counters and a Cerenkov counter enabled the separation of the ϕ meson from the backgrounds.

The results of the analysis indicated that the nK^+K^- final state was predominantly produced via the phi meson in the K^+K^- mass region of 1005 - 1035 Mev/c². The results are also in good agreement with the hypotheses that just above threshold the phi production cross section is proportional to the c.m. momentum and that the production and decay angular distributions are isotropic.

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PREFACE

The author joined the Imperial College Spark chamber/Counter Group in October, 1963, and was immediately involved in the $\omega \longrightarrow e^+e^-$ decay experiment, working mainly on the electronics side, and in particular designed and built the electronic logic for operating a Fast Camera that was used for taking Spark chamber pictures in the above and in subsequent experiments.

The experiment described in this thesis was performed by the Imperial College/Rutherford Lab. collaboration in 1966 and, of course, involved the work of several people. The author did much of the work on the design of the apparatus and the electronic logic. This explains the emphasis laid on these subjects in Chapters II and III.

Both spark chambers and counters were used in the experiment. The author is solely responsible for the analysis and interpretation of the data obtained from counters. The analysis of the spark chamber data will be found in reference 24.

CHAPTER I

INTRODUCTION

1:1 General.

This thesis describes an experiment that was designed to investigate, using counter techniques, the production of the Phi meson in the reaction,

$$\pi^- + p \longrightarrow n + \phi \quad (K^+ + K^-) \dots\dots(1:1),$$

near its threshold. This experiment actually formed part of a series of experiments performed by the Imperial College/Rutherford Laboratory collaboration on the Nimrod Proton Synchrotron at the Rutherford Laboratory near Harwell. The first experiment in the series was done to measure the branching ratio for e^-e^+ decay¹ mode of the ω -meson. In this experiment the omega mesons were produced using a beam incident on a liquid hydrogen target, having a momentum slightly above the ω threshold. The electrons from the reaction,

$$\pi^- + p \longrightarrow n + \omega \quad (e^- + e^+) \dots\dots\dots(1:2),$$

were identified using optical spark chambers sandwiched by lead plates. The branching ratio measured in this experiment was 2×10^{-4} . According to the SU(3) symmetry scheme of Strong interaction the $\phi \longrightarrow e^-e^+$ branching ratio, using the

above value for the omega meson and an ω - ϕ mixing angle of 38° , should be 10^{-3} . It was mainly this prediction which the second experiment in the series was supposed to verify. Besides this, the combined results of the two experiments could also throw some light on other concepts in elementary particle Physics, mentioned in section 3 of this chapter.

In order to measure the rate of $\phi \longrightarrow e^-e^+$ decay it was decided to produce Phi mesons in the reaction (1:1) near the threshold, using the copious π^- beam available from Nimrod, and the existing apparatus that had been used reliably in the previous experiment.

A difficulty arose here, however, due to the fact that the cross section for Phi meson production in $\pi^- \rightarrow p$ collision was, in general, believed to be very small and was, of course, unknown near the threshold in reaction (1:1). According to the peripheral model the Phi production by pions requires the exchange of the ρ -meson. From the observed low rate of $\phi \longrightarrow \rho\pi$ and due to the failure of experiments using π^-p reaction to obtain evidence for Phi production, strong doubts were cast on the practicability of the decay experiment using the above reaction, especially without a prior knowledge of the cross section near the threshold. The experimental situation that existed regarding

(3 - 5)
 Phi-production by pions at the time the second experiment was being planned is summarized in table 1-I. This shows that there was a general agreement that the Phi meson cross section was 1/60 times the omega meson cross section or less.

The omega cross section near the threshold of production in reaction (1:2) is known to be about 500 micro-barns. If the above results were believed to hold near the thresholds for the two particles we expected the Phi cross section to be about 8 micro-barns. But in fact it could be even smaller making the decay experiment unfeasible. A preliminary "search" for the Phi meson was thus indispensable, necessitating the present experiment.

1:2 The Experimental Procedure.

The resonance production in the reaction (1:1) was detected by the measurement of the neutron time of flight, over a distance of about 4 metres, to give the missing mass, i.e; the effective mass of the K^+K^- system. An important need of the experiment was high mass resolution so that the resonance could be separated from the K^+K^- backgrounds, like the direct reaction,

$\pi^- + P \longrightarrow n + K^+ + K^- \dots\dots\dots(1:3),$

or the threshold $\bar{K}K$ enhancement ^(6,7) seen by many groups It has been shown in section 2:3 that working near the threshold

Table 1-I

Reference	Momentum GeV/c	Reaction	Remarks
y. y. Lee et al	3.7	$\pi^+ p \rightarrow \pi^+ p + \omega$ $\rightarrow \pi^+ p + \phi$	$\frac{\sigma_\phi}{\sigma_\omega} \leq 0.012$
M. Abolins et al	3.43 } 3.54 }	$\pi^+ p \rightarrow \pi^+ p + \omega$ $\rightarrow \pi^+ p + \phi$	$\sigma_\phi = 0.02 \pm 0.02$ (mb) $\sigma_\phi = 0.02 \pm 0.01$ (mb)
Trilling et al	3.65	$\pi^+ p \rightarrow N^{*++} \phi$	$\sigma_\phi < 10 \mu b$

and detecting neutrons at very small angles in the Lab. affords high mass resolution. The mean angle subtended at the target by the counters that detected neutrons in this experiment was, therefore, made about 4° . The solid angle presented by them was also reasonably high.

The $\pi^- p$ reaction is a prolific source of neutrons of various energies due to which the background to a selection that relies only on the detection of a neutron in the final state is bound to be very high. This was specially true in this case because of the small Φ cross section. However, as the predominant decay mode of the Φ meson is $\Phi \longrightarrow K^+ K^-$ (branching ratio: 48%) a more rigorous selection logic, demanding a neutron plus two charged particles, was possible. This decay mode has a Q value of only 32 Mev with the result that the decay products can emerge only at small angles in the Lab. with respect to the beam direction. Scintillation counters of reasonable dimensions were used to detect them with a fairly high efficiency. Also the K mesons in the decay have low velocities compared to the pi-mesons from the background and were distinguished by the use of a threshold Cerenkov counter. In addition, scintillation counters lined with lead plates were employed to suppress the three-pion and the multi-pion final state backgrounds that were present through the inefficiency of

the Cerenkov counter. Our selection system was able to reduce the background to such an extent that the signal to noise ratio at the optimum momentum was greater than unity.

Time of flight spectra of the background were obtained by working below nK^+K^- threshold and this information was used to determine the number of nK^+K^- events, in a suitable time of flight band, in the spectra taken above threshold. When the number of events for a given number of incident pions is plotted as a function of the beam momentum a narrow resonance (like the ϕ) is detected as an enhancement in this yield curve, the position of whose peak is characteristic of the mass of the resonance. The K^+K^- background was easily separated as its yield behaves in a manner very different from the resonance yield.

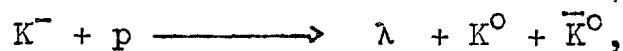
From the analysis of the experimental data we find that the major contribution to the nK^+K^- final state comes from the decay of a resonance of mass $1019 \text{ Mev}/c^2$, the best estimate of whose width is $4 \text{ Mev}/c^2$. We identify this resonance with the well-established $J^{PG} = 1^{--}$ Φ meson.

A brief account of the discovery and determination of the quantum numbers of the ϕ will now be given in the following sections together with a brief account of its role in the symmetry scheme of strong interaction.

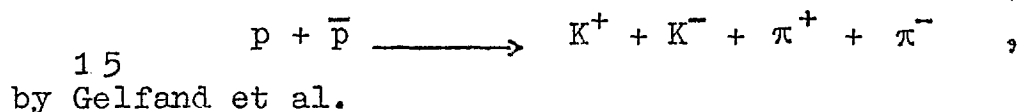
1:3 The Phi Meson.

The existence of two $I = 0$, negative G vector mesons (ω and ϕ) _____ one coupled to the baryon current, the other coupled to the hypercharge current _____ was first discussed within the framework of his Vector Theory of Strong Interactions by Sakurai.⁸ Subsequently Geil-Mann(1962)⁹ and Neeman(1961)¹⁰ in their symmetry model based on $SU(3)$ group also accommodated these two vector mesons, although their inclusion in the model was not necessarily required. The experimental data supports, as regards the quantum numbers and the width of the ϕ , the theory of Sakurai. The observed rate of decay into a ρ and a π is, however, much smaller than estimated by the theory, according to which this decay mode should dominate the $K\bar{K}$ mode by a factor of 3. A more recent theory of $\omega - \phi$ mixing, due to Sakurai, Glashow and others,¹¹ accounts for the violation of the mass formula, accommodates the suppression of the decay mode $\phi \longrightarrow \rho \pi$ and in addition, predicts widths for ϕ decay into $\eta\gamma$ and $\pi^0 \gamma$.

This meson was first detected in 1962 at the Brookhaven National Laboratory by Bertanza et al using a K^- beam at 2.24 GeV/c incident in the B.N.L. 20 inch hydrogen bubble chamber, via its decay into two strange particles ($K, \bar{K}$), in the following processes:-¹²



Soon afterwards the phi was produced in the same reaction^{13,14} by other groups at UCLA and Brookhaven who also determined its quantum numbers. The phi was also observed in proton-antiproton annihilation reaction, viz;



The mass and the width of the phi as measured by Connolly et al were respectively, $1020.5 \pm 0.5 \text{ Mev}/c^2$ and $3.1 \text{ Mev}/c^2$. Gelfand et al found these quantities to be respectively, $1018.6 \pm 0.5 \text{ Mev}/c^2$ and $3.1 \pm 1 \text{ Mev}/c^2$.

1.4 Quantum Numbers.

The C-parity of the charge conjugation number of the phi is odd as it almost always decays into the $K_1^0 K_2^0$ combination and not into $K_1^0 K_1^0$. Since the $K\bar{K}$ system (in fact any boson-anti boson system) has positive CP value the ordinary parity (P) of the phi meson turns out to be odd. The lack of decay into $K_1^0 K_1^0$ in fact distinguished the phi from the broad $K\bar{K}$ S-wave enhancement which some^{6,7} groups had observed.

The isotopic spin of the phi must be zero as the resonance does not show up in the $K^\pm K^0$ system in the

reaction, $K^- + p \longrightarrow \Sigma + K + \bar{K}$.

Another argument in favour of $I = 0$ is as follows:

The branching ratio $(\phi \longrightarrow \pi^+\pi^-)/(\phi \longrightarrow K\bar{K}) \leq 0.08$, and this is too low in order to explain strong phi decay into two pions. Since the G-parity of the pion is negative, the G-parity of the phi must also be odd in order to prevent this decay. Combining this fact with the property that the charge conjugation number(C) is negative, one is led to conclude that all odd assignments of I are ruled out.

The spin J of the phi by virtue of its odd parity and decay into a boson and anti-boson having ~~equal~~ ^{equal} ~~intrinsic~~ intrinsic parities should be odd. For such a case the parity is given by $(-1)^J$. Thus the spin could be either 3 or 1. The latter value, however, is strongly favoured by the experimental results. For example the branching ratio,

$$(\phi \longrightarrow K_1^0 + K_2^0)/(\phi \longrightarrow K_1^0 + K_2^0 + \phi \longrightarrow K^+ + K^-)$$

has been measured to be 0.42 ± 0.07 . According to theory, this ratio for a spin 1 of the phi should be 0.39, whereas only 0.26 for spin 3. The observed value is thus in excellent agreement with spin 1 assignment.

Another indication for spin value 1 has been obtained by Connolly et al and J.Lindsey² who analysed the angular distributions of the decay K_1^0 and K^+ of the reso-

nance in K^-p reactions given above. A coordinate system is defined in the ϕ rest frame, the z-axis being the direction of the incoming K^- , and the x-axis the direction normal to the production plane. In this frame the polar angle θ (Adair angle) and the azimuthal angle ϕ (Treiman-Yang angle) are measured. The expectation for the angular distribution $W(\theta, \phi)$ for the case of a spin 1, has been written down by Gottfried and Jackson¹⁶. The data obtained by Connolly et al can be fitted very well to the form,

$$\int W(\theta, \phi) . d\theta = 1 - (0.64 \pm 0.30) . \cos(2\phi) .$$

The presence of a $\cos^2$ -term only and no higher powers of $\cos(\phi)$ in this equation supports the hypothesis that the ϕ has spin 1.

1:5 A-Parity.

Bronzan and Low¹⁷ in 1963 suggested an empirical selection rule for bosons, whose violation seemed to occur with a few per cent probability. They called the corresponding operator 'A', and assigned the following eigen-values of this quantum number to the pseudoscalar bosons:-

$A_\pi = A_K = A_\eta = -1$ (the minus sign for the K-meson is arbitrary as $AKA\bar{K} = 1$). For Vector bosons the assignments are: $A_\gamma = A_\rho = A_{K^*} = A_\phi = +1$, and $A_\omega = -1$. A-parity thus

forbids the decay of the phi into odd number of pions. This explains the very small branching ratio for the $\phi \longrightarrow \rho\pi$ decay mode. J. Lindsey has found this branching ratio to be 12 ± 8 per cent. According to Sakurai, the proposed $J^{PG} = 1^{--}$ assignment fully allows the decay modes,

$$\phi \longrightarrow \rho^{\pm 0} + \pi^{\pm 0}.$$

Calculations based on the pole-dominance approximation lead¹⁸ to the result,

$$\Gamma(\phi \longrightarrow \rho + \pi) \simeq 9 \text{ Mev.}$$

However, this is only an order of magnitude calculation and the actual $\rho\pi$ mode could well be smaller than the above estimate.

Decay into pions being forbidden, the predominant decay mode is $\phi \longrightarrow \bar{K}K$, in spite of its very low Q value. Conversely it is difficult to produce phi in pion interactions as this requires the exchange of the $\rho(\rho)$ meson according to the peripheral model. Another consequence of A-parity is that the ratio,

$$\Gamma(\phi \longrightarrow e^- + e^+) / \Gamma(\omega \longrightarrow e^- + e^+) \gg 1.$$

From this Bronzan and Low inferred that the isotopic scalar nucleon form factor should be dominated by the phi rather than the omega. It may be interesting to remark here that

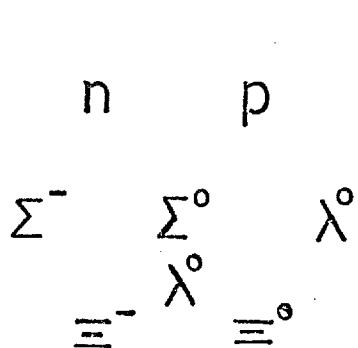
the original quest for vector mesons (ω , ρ , ϕ) had started as a result of the electron nucleon scattering experiments. In 1957 Nambu¹⁹ had also pointed out that the existence of a particle with $I = 0$ and $J^{PG} = 1^{--}$ could account for the approximate equality of the isovector and isoscalar charge form factors at low momentum transfers.

1:6 $\omega - \phi$ Mixing.

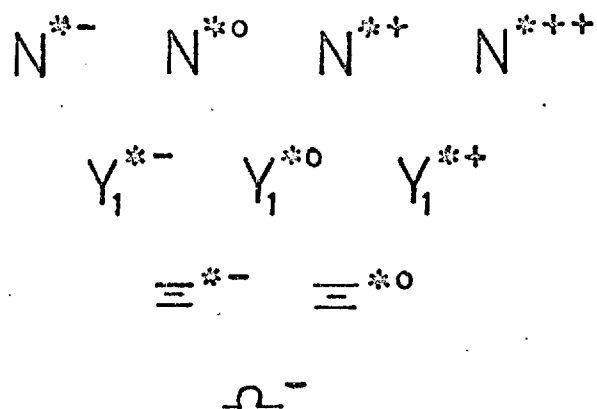
Gell-Mann²⁰ and Neeman¹⁰ proposed in 1962 an attractive scheme of strong interaction symmetry, namely, the octet version of Unitary symmetry, the so-called Eightfold Way. The Gell-Mann and Okubo first order Mass formula,

$$M = a + bY + c \left[\frac{1}{4}Y^2 - I(I + 1) \right] ,$$

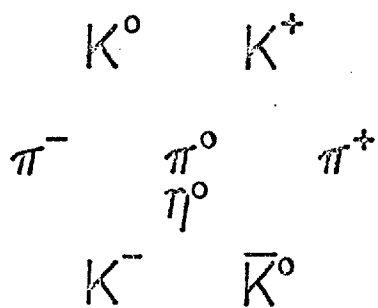
where I is the isotopic spin, Y the hypercharge, and a, b, c are constants, predicts the masses of the baryons in the $\frac{1}{2}^+$ octet and the $\frac{3}{2}^+$ decuplet (figure 1:1) with an accuracy of about 1%. The same formula, incidentally, was used to calculate the mass of the Omega minus before its discovery. The formula is linear in mass for the baryons. The corresponding formula for the mesons involves squares of the masses and is satisfied to an accuracy of only about 5% by the masses of the pseudo-scalar mesons (0^{--} octet in fig. 1:1). This formula is far off when applied to an octet of vector mesons. Using the known masses of the $K^*(888)$ and



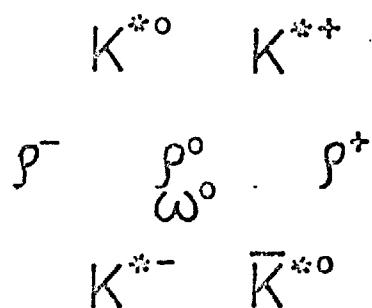
$(\frac{1}{2}^+$ octet)



$(\frac{3}{2}^+$ decuplet)



$(0^-$ octet)



$(1^-$ octet)

Fig 1:1

the $\rho(750)$, the ω mass turns out to be $930 \text{ Mev}/c^2$ which is $148 \text{ Mev}/c^2$ greater than the observed ω mass(782). Also the phi meson with its mass of $1020 \text{ Mev}/c^2$ is too far from $930 \text{ Mev}/c^2$ to be considered a member of this octet.

The explanation of this and the $\phi\rho\pi$ effect is connected with the fact that the phi meson turns out to have exactly the same quantum numbers as the omega meson. It was remarked by Gell-Mann before the phi was discovered that agreement with the octet rule of vector mesons could be obtained if besides the ω there were a second meson with the same quantum numbers. The presence of this second meson(not far above in mass),according to him, was depressing the mass of the ω . It was then assumed that there is a unitary octet state ϕ_0^0 and a unitary singlet state ω_0^0 which are not eigenstates of energy(not real particles), but that they give rise to the observed physical particles, ϕ and ω , by the linear combinations,

$$\begin{aligned}\omega &= \omega_0^0 \cdot \cos \theta + \phi_0^0 \cdot \sin \theta \\ \phi &= -\omega_0^0 \sin \theta + \phi_0^0 \cdot \cos \theta.\end{aligned}$$

The mixing parameter, θ , required to satisfy the first order mass formula is given by,

$$\theta = \tan^{-1}(\pm 0.83) = 39^\circ.$$

The mixing causes the masses of the observed states to be

quite different from those of the original states. The decay properties of the ω and the ϕ also exhibit some interesting effects of the mixing.

Unitary symmetry forbids the coupling $\omega \longrightarrow \gamma$. Therefore, the $\omega\gamma$ coupling that plays a role in the decay processes of the ω and in the electro-magnetic structure of the nucleon is not due to the unitary scalar ω_0^0 , but is a feature of the unitary octet ϕ_0^0 . The $\omega_0^0\gamma$ coupling should also be zero if the quantum number of Bronzan and Low(A-parity) is conserved in electromagnetic processes. The decay processes of the physical particles, namely,

$$\omega \longrightarrow e^- + e^+ \text{ (or } \mu^- + \mu^+ \text{) , and,}$$

$$\phi \longrightarrow e^- + e^+ \text{ (or } \mu^- + \mu^+ \text{) ,}$$

are mediated by a virtual photon (i.e; $\omega \text{ or } \phi \longrightarrow \gamma \longrightarrow e^-e^+$ or $\mu^- + \mu^+$) and, since the coupling $\omega_0^0\gamma$ is forbidden, only the ϕ_0^0 component of the physical states, ω and ϕ leads to the decay processes above. This facts opens the possibility of a check of the theory, in that the ratio of the decay rates of the ω and the ϕ into two electrons (or muons) must be determined by the angle θ . There is some doubt regarding the $\phi_0^0\gamma$ vertex as the momentum transfer is different for the ϕ and ω decay processes. Mass squared terms are involved in the couplings of both the

ω and ϕ to the photon and an uncertainty lies in whether the physical masses of the particles or some average mass such as $930 \text{ Mev}/c^2$, should be used. Therefore, the relation between the mixing parameter and the decay rates might as well involve an $(m_\omega / m_\phi)^2$ term.

1:7 Phi production in $\pi^- p$ Reaction.

While this experiment was being set up ϕ production was reported²¹ by Hess et al, in $\pi^- p$ collision at $2.3 \text{ GeV}/c$. They observed a very significant peak in the $M_{K^+K^-}$ effective mass distribution at $1020 \text{ MeV}/c^2$ whose width was consistent with that pertaining to the ϕ meson. This was the first evidence for the production of phi mesons by pions.

The production mechanisms of the ϕ , in $\pi^- p$ interaction, have not been investigated in any detail so far. Vector meson production in reactions of the type, pseudoscalar meson + baryon $\longrightarrow$ vector meson + baryon, can be explained in terms of an isobar model or the peripheral model.²³ Liu and Singer have discussed in detail the possible production mechanisms of vector mesons (ω , ρ , K^* , ϕ) with particular reference to the ω meson production in the reaction, $\pi^+ + n \longrightarrow \omega + p$. Their results, however, are equally applicable to the charge symmetric

processes such as,

$$\pi^- + p \longrightarrow n + \omega ,$$

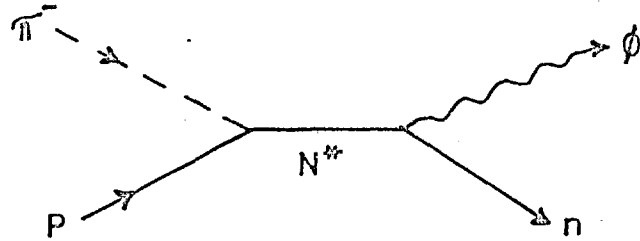
$$\pi^- + p \longrightarrow n + \phi .$$

The various mechanisms that may contribute to ϕ production in the above reaction are shown in figure (1:2). The direct (s-) channel and the crossed(u-) channel can proceed through N , and $N_{\frac{1}{2}}^*$ baryon resonances. The I-spin of the baryon must be half in order to conserve this quantity in the final state. Considering production near threshold, that is, assuming the final state($n\phi$) to be produced predominantly in an s-wave angular momentum state (centre of mass momentum less than 200 Mev/c), the spin of the exchanged baryon can be either $\frac{1}{2}$ or $3/2$. For the same reason its parity must be odd as the ϕ and the neutron have opposite intrinsic parities. This forbids nucleon exchange in the s-channel. The various possible candidates, therefore, are, $N_{\frac{1}{2}}^*(1525)$, $N_{\frac{1}{2}}^*(1570)$, and $N_{\frac{1}{2}}^*(1700)$. But since no such restriction can be applied to the u-channel, nucleon exchange probably will be dominant in this channel.

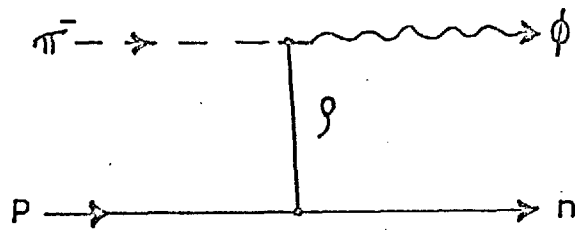
As regards production through the s-channel, the decay angular distribution of the ϕ is expected to be uniform in case of a spin- $\frac{1}{2}$ baryon, and of the form, $a + b.\cos^2\theta$, in case of a spin- $3/2$ baryon resonance. The u-channel is not so clean. The t-channel is characterized by

Possible models for ϕ -production

(s-channel)



(t-channel)



(u-channel)

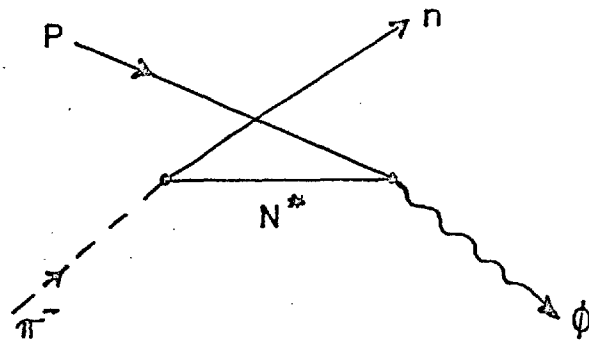


Fig. 1:2

the exchange of the ρ meson. If this be the dominant production mechanism, the distribution of the decay angle (Adair angle) is supposed to be proportional to $\sin^2\theta$. Hess²² et al did not observe this correlation, but they say that the absorptive effects can significantly modify the distribution. Their observed production and decay angular distributions were quite consistent with isotropy, although inclusion of linear and quadratic terms gave a somewhat better fit to the observed decay angular distribution. The linear term can result from interference with background arising from the S-wave threshold enhancement.

CHAPTER II

DESIGN AND PERFORMANCE OF THE APPARATUS.

2:1 The Beam and Hodoscope.

The beam line used for the present experiment was designed by the author's colleague, D.C. Mason²⁴. A diagram of its lay-out appears in figure 2:1. The main requirement of the beam was to provide a very high flux of negative pions with accurately known momentum in the region of 1.58 Gev/c, into the hydrogen target.

Pions (and other particles) produced by the interactions of the circulating proton beam with the internal target (situated in the middle of one of the octants of the Nimrod magnet) were deflected into Experimental Hall No.2 by the help of the fringe field of this magnet.

Although this method enabled us to collect particles emitted at the peak of the angular distribution (zero degree), yet there was the disadvantage that the momentum was set largely by the fringe field and hence by the operating energy of Nimrod.

A double-focus design was adopted for the

Lay out of the Beam

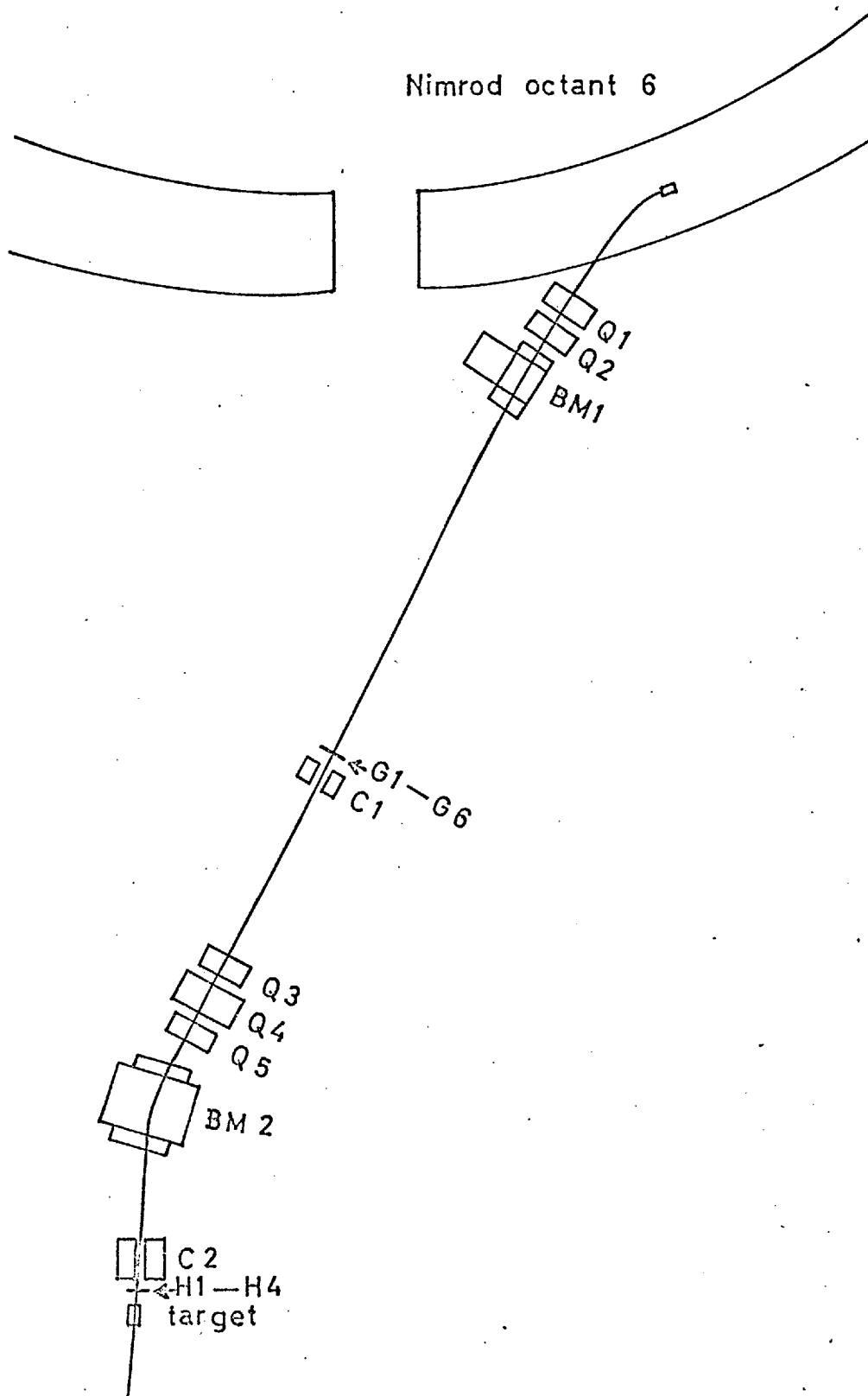


Fig. 2:1

beam itself in order to allow the dispersion produced in the first stage to be cancelled in the second stage, and also to measure the momentum accurately in the 2nd stage.

Two type II quadrupoles Q_1 and Q_2 were placed close to Nimrod, Q_1 focussing in the vertical and Q_2 in the horizontal plane in order to maximize the collection efficiency. They determined the angular acceptance of the beam. They were followed by a type IV bending magnet BM_1 , which bent the particles through 4° . Small changes in the beam momentum could be made by varying the current in this magnet.

Q_1 and Q_2 produced an intermediate focus at the first collimator C1. The momentum bite of the beam was determined by this collimator. At this point the magnifications in the horizontal and vertical directions were 2.3 and 2.33 respectively. The intermediate image was focussed and positioned at the hydrogen target by a quadrupole triplet comprising two type II and one type I quadrupoles, plus a type II bending magnet, BM_2 , which was 2 metres long and bent the particles through 22° . The magnification from the intermediate focus to the hydrogen target was 1.1 in both directions.

Two hodoscopes of thin scintillation counters $G_1 - G_6$ and $H_1 - H_4$ situated in conjugate planes of the quadrupole triplet-bending magnet combination were used to measure the momentum. The H counters were placed just before the hydrogen target and the G-counters just before the first collimator. The purpose of the second collimator C2 which was placed just before the H-counters was to prevent the "halo" of particles around the beam from reaching the scintillation counters placed around and downstream of the target and causing unwanted counts in them. The dimensions of the G counter scintillator were 4 cms(vertical)x 0.8 cm(horizontal)x0.3 cm(thickness), and of the H counter scintillator 6.5 cms(vertical)x 0.88 cm(horizontal)x 0.3 cm(thickness). All the G-counters were placed side by side across the beam as close together as possible so that they were just not overlapping. The H-counters were similarly disposed.

The momentum calibration, i.e; the relation between current in the bending magnet and central momentum of the beam was determined by a series of floating wire measurements by the Author's colleagues, A. Duane and D.C. Mason. Due to uncertainties in the current and

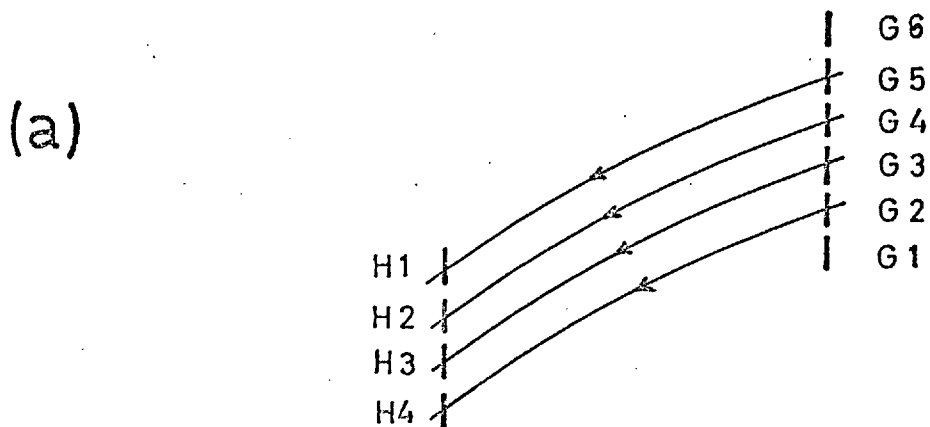
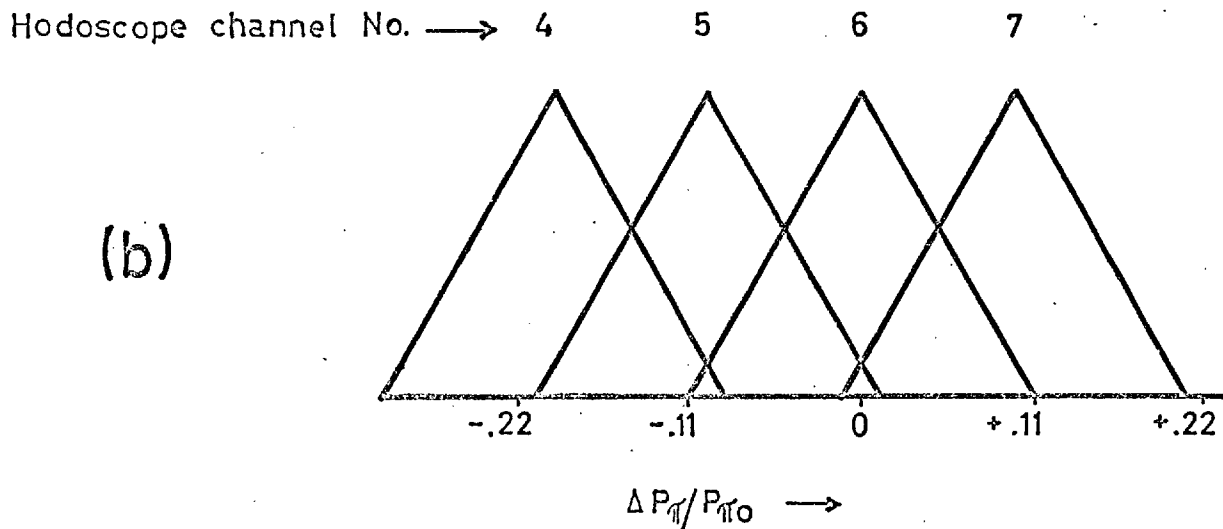
the tension in the floating wire as well as due to hysteresis effects in the bending magnet BM2, an uncertainty of $\pm 0.3\%$ in the momentum measurement was estimated.

Six G and four H counters provided four momentum channels. A $G_i.H_j$ coincidence represented a certain momentum and for a flat incident momentum distribution selected out a triangular momentum distribution of full width at half height of 0.55% .

If G and H counters are numbered in the same direction, the sum of the indices(i,j) is a constant for a given momentum.(In figure 2:2a the G's have been inverted for the sake of convenience). This was done and the coincidences G_4H_2 , G_3H_3 , G_2H_4 , etc, all represented beam particles having the same momentum and were added together electronically to increase the flux in this momentum(P_π) channel. Similarly the sum of the coincidences, G_3H_2 , G_2H_3 , etc, contributed to a neighbouring momentum channel. The separation between adjacent channels was 0.5% of the central momentum(fig. 2:2b).

A block diagram of the electronic logic of the hodoscope showing the formation of only one momentum channel appears in figure 2:3. Other channels were built up in the same way.

Momentum distribution in the hodoscope channels



Typical GH coincidences representing the same momentum

Fig. 2:2

$$P_{\pi 4} = G_1 H_4 + G_2 H_3 + G_3 H_2 + G_4 H_1$$

$$P_{\pi 5} = G_2 H_4 + G_3 H_3 + G_4 H_2 + G_5 H_1$$

$$P_{\pi 6} = G_3 H_4 + G_4 H_3 + G_5 H_2 + G_6 H_1$$

$$P_{\pi 7} = G_4 H_4 + G_5 H_3 + G_6 H_2$$

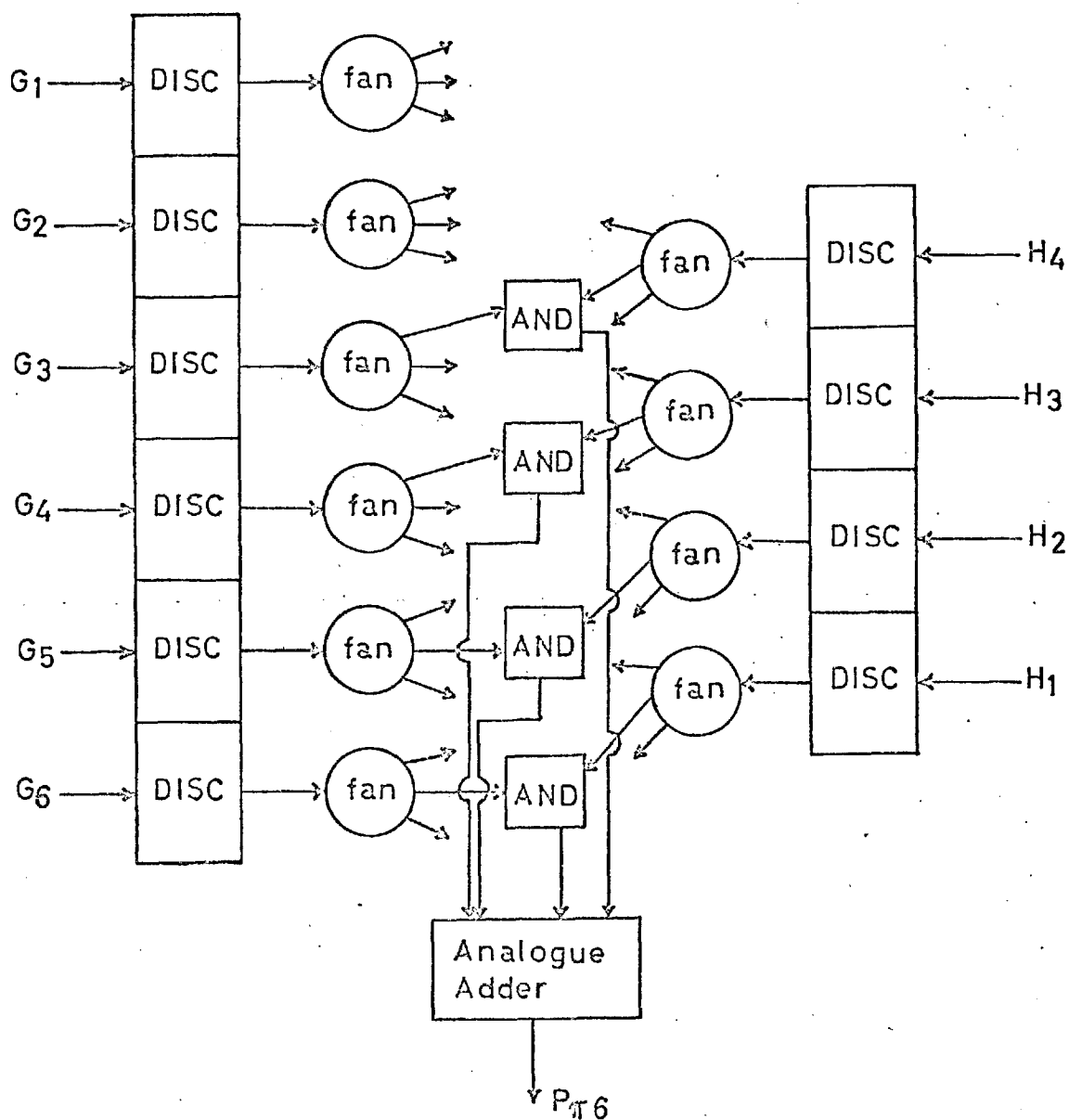


Fig. 2:3 Hodoscope logic

2:2 Beam Constitution.

A knowledge of the percentage of pions in our beam was essential in order to evaluate the cross - section for ϕ meson production.

A high energy particle beam can contain, kaons, pions, muons, electrons, protons or anti-protons as ingredients. The relative amount of these constituents not only depends on the energy of the beam but also on its distance from the point of origin, i.e; the internal target in the accelerator. The last three are stable particles but the pions have short lifetime and decay on their way through the beam focussing elements causing the beam composition to be a function of the distance travelled from the internal target. But over a small distance far from the internal target the beam composition would remain practically constant. Therefore, a measurement of it just before the hydrogen target was sufficient for the required purpose.

Particles in the beam have the same momentum, but different masses, due to which their velocities are different. In order to separate them a device sensitive to the velocity of a charged particle is needed. Such a device is the threshold Cerenkov counter.

A 90 cms. long Cerenkov counter, C, filled with the gas "Arcton 13" and placed just before the target

(figure 2:4) was used to determine the composition of the beam. Two small beam defining scintillation counters, C_1 and C_2 were placed near each end of the Cerenkov counter so that particles that went through both C_1 and C_2 also traversed the entire length of the Cerenkov counter near its centre. The counters were so arranged that their perspex light guides did not overlap ensuring that no particles would be detected by the simultaneous production of Cerenkov light in both light guides.

The counting rate($C_1.C.C_2/C_1.C_2$) versus gauge pressure curve obtained is shown in figure 2:4.

If the threshold of the discriminator detecting Cerenkov pulses is $\ll 1$ photoelectron the efficiency for detecting a particle, at a pressure "p", is given by,

$$\text{Eff.} = 1 - \exp(-L.(p - p_0)) \dots\dots\dots(2:1),$$

where L is a constant and p_0 is the threshold pressure for the given particle. This formula may be derived as follows:

The refractive index "n" of a gas depends on its pressure, p, and is given by,²⁵

$$n = 1 + k.p \dots\dots\dots(2:2),$$

where k is a constant characteristic of the radiator gas.

The number of photoelectrons, N, emitted from the photocathode is connected with the refractive index of

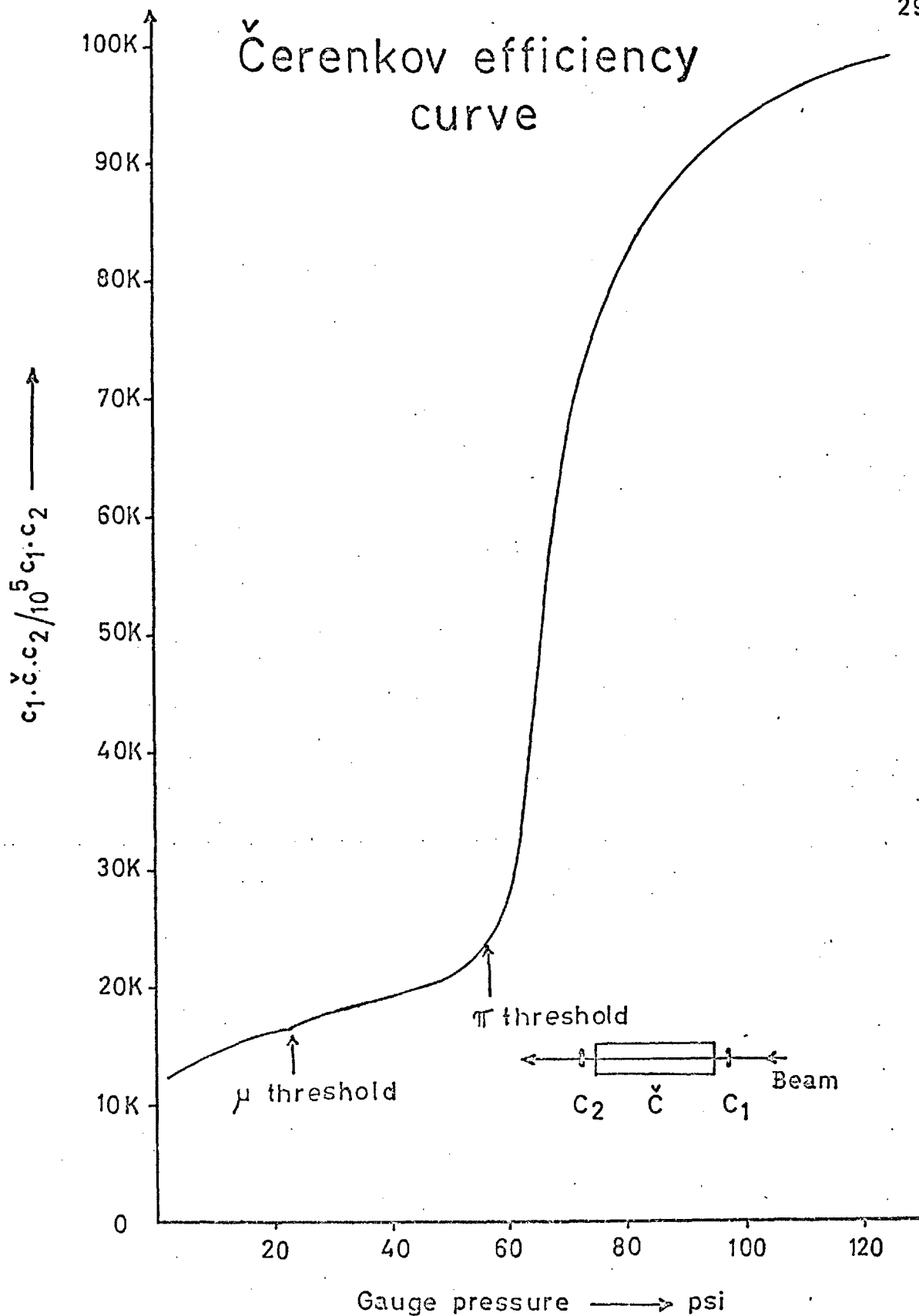


Fig. 2:4

the gas by,

$$N = K.(1 - c^2/(nv)^2) \dots\dots\dots(2:3),$$

where v is the velocity of the particle and c is the velocity of light; K is a constant that includes light collection and quantum efficiencies.

At the threshold pressure p_0 we have the relation,

$$0 = 1 - c^2/(v^2(1 + k.p_0)^2), \text{ or,}$$

$$v^2/c^2 = 1/(1 + k.p_0)^2 \dots\dots\dots(2:4).$$

Substituting (2:2) and (2:4) in equation (2:3) we get,

$$N = K.(1 - (1 + k.p_0)^2/(1 + k.p)),$$

$$= 2k.K.(p - p_0)/(1 + k.p)^2.$$

As $(1 + kp)$ changes very slowly compared with $(p - p_0)$, we can write,

$$N = L.(p - p_0) \dots\dots\dots(2:5),$$

where L is a new constant replacing $2k.K/(1 + kp)^2$.

Assuming now a very low level discrimination the inefficiency will arise only because of the chance of no photoelectron emission. When the mean is N this chance is given by, $\exp(-N)$, using Poisson statistics. Therefore,

Eff. = $1 - \exp(-N) = 1 - \exp(-L(p - p_0))$, which is equation (2:1).

The above law was found to fit the data above the pion threshold quite well, whence it was concluded that the efficiency for detecting a particle, independent of its mass, rose from 0 to 80% at a pressure of (27.5 ± 2.5) p.s.i in excess of its threshold pressure, where the error allowed us to cover departure from the law.

The threshold for electrons is very nearly zero p.s.i. Thus at a gauge pressure of $(27.5 \pm 2.5) - 15$ (1 atm.), i.e; at (12.5 ± 2.5) p.s.i, the efficiency for electrons was 80%. The delta ray contribution to the counting rate was found to be negligible. From the counting rate at this pressure, after subtracting the accidental background, the value of (0.16 ± 0.007) was estimated for the fraction of electrons in the beam. The fraction of muons was determined in the same way and turned out to be (0.06 ± 0.02) .

The proportion of pions was then obtained by subtracting the electron and muon fractions from unity. This was valid because the kaons and antiprotons were less than one per cent.

Thus the percentage of pions in the beam was (78 ± 4) . The estimated error of 2% was increased to 5% in order to include other uncertainties as well.

2:3 Missing Mass Spectroscopy.

(a). General.

The neutron time-of-flight technique used in this experiment belongs to the general method of missing mass spectroscopy. In our experiments we study the production of the system of particles, X^0 , produced in the reaction,

$$\pi^- + p \longrightarrow n + X^0 \quad \dots\dots\dots(2:6).$$

Using four-momentum conservation the effective mass of X^0 system is given by,

$$M_X^2 = (E_\pi + E_p - E_n)^2 - (P_\pi - P_n)^2 \dots(2:7).$$

It can be seen that if the proton is at rest in the laboratory this mass can be evaluated merely by making measurements on the momentum vectors of the pion and neutron. This method of measuring M_X is called the "missing mass" method as it is not necessary to make measurements on the constituent particles of the X^0 system itself. The method is especially suited for counter experiments as the momentum of only one particle has to be measured in the final state, and several resonances have already been detected by this technique.²⁶

The missing mass method is to be contrasted with the "effective mass" method widely used in Bubble

chamber experiments where the mass of an unstable particle is determined from measurements made on its decay products. It has the advantage that the unstable particle can be produced along with two or more particles but it would fail if the number of neutral particles in the final state were more than one.

Equation (2:7) can also be written as,

$$M_X^2 = (E_\pi + M_p - E_n)^2 - p_\pi^2 - p_n^2 + 2p_\pi \cdot p_n \cos \theta_n \dots\dots\dots(2:8),$$

where θ_n is the angle between neutron and pion in the laboratory in which the proton is taken to be at rest.

There are two kinematic regions of particular interest where a missing mass study of the reaction(2:6) can be made with high mass resolution. One is the region of the maximum neutron laboratory angle for a given missing mass and the other is the region near the threshold of this reaction. This can be proved by writing down the partial derivatives of M_X^2 . We have,

$$\partial(M_X^2)/\partial p_n = -2B_n(E_\pi + M_p) + 2p_\pi \cdot \cos \theta_n \dots\dots\dots(2:9),$$

$$\partial(M_X^2)/\partial \theta_n = -2p_\pi \cdot p_n \cdot \sin \theta_n \dots\dots\dots(2:10),$$

$$\text{and, } \partial(M_X^2)/\partial p_\pi = -2B_\pi(E_n - M_p) + 2p_n \cdot \cos \theta_n \dots\dots\dots(2:11).$$

There exists a maximum value of θ_n which

depends only on the incident momentum and the value of M_X (provided it is greater than the mass of the incident particle). The Jacobian,

$$J = \partial(\cos \theta_n^*) / \partial(\cos \theta_n),$$

where θ_n^* denotes the neutron angle in the π -p centre of mass, tends to infinity as this maximum angle is approached. Thus, a peak in the missing mass distribution will give rise to a peak in the neutron angular distribution. In this region the missing mass is sensitive to the angle measurement but is not sensitive to the neutron momentum measurement.

Extensive missing mass studies of the reaction,



have been carried out by Maglic et al using this method of "Jacobian Peaks".²⁷

High mass resolution can also be achieved without the need of accurate angle measurement if one works near the threshold of reaction (2:6). The derivatives, (2:9) and (2:10) both vanish when $\theta_n = 0$, and $B_n = P_\pi / (E_\pi + M_p) = B_{\text{cms}}$, the velocity of the centre of mass of the π -p system. Thus the missing mass measurement does not depend critically on the accuracy of measurement of either θ_n or P_n . In the present experiment we have used the latter technique with great advantage.

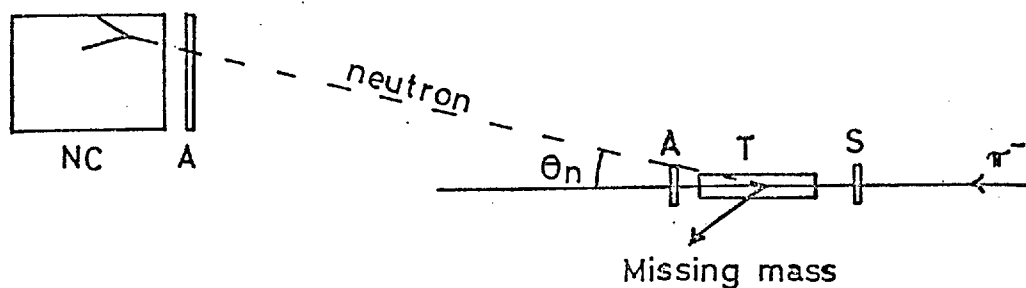
The Lorentz invariant phase space density of states factor(R_2) that enters the expression for the cross section for reaction (2:6) is equal to $\pi p^*/E_c$, where E_c is the total centre of mass energy. As the other factors governing the cross section vary slowly compared to p^* , just above threshold, the cross section is proportional to p^* and rises linearly from zero at exact threshold. For this reason the ideal conditions for high mass resolution determined by equations (2:4) and (2:5) cannot be realized in practice, as the yield from the signal would be negligibly small. As a compromise, therefore, one has to work at a very small but finite angle using a momentum slightly above threshold.

The low p^* range covered implies that the nX^0 final state is produced predominantly in an S-wave angular momentum state. This can be seen on a simple impact parameter model given that the nuclear forces extend only over a pion Compton wavelength.

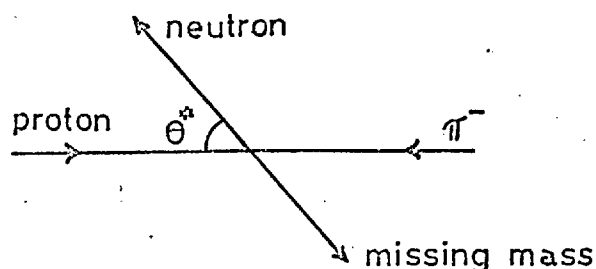
(B) The principles of our missing mass apparatus.

We shall discuss the important features of our basic apparatus with reference to the counter arrangement shown in figure (2:5). The c.m. momentum, p^* , of the neutron can be expressed as a function only of P_π and M_x . This can

The basic missing mass apparatus using neutron time of flight



(a) The situation in laboratory



(b) Centre of mass situation

A,A = Anti - counters

S = Timing - counter

T = Hydrogen target

NC = Neutron counter

Fig. 2:5

be seen from the following two equations:

$$E_c^2 = (M_p + E_\pi)^2 - p_\pi^2 \dots\dots\dots(2:13),$$

and,
$$p^{*2} = (E_c^2 - (M_n - M_x)^2) \cdot (E_c^2 + (M_n - M_x)^2) / 4E_c^2 \dots\dots(2:14).$$

The c.m. momentum is an important quantity, for, it largely determines the behaviour of the apparatus and the shapes of the time-of-flight spectra. Figure(2:6a) shows the relationship between the c.m. momentum and the c.m. angle, θ^* , of the neutron for the inner(θ_1) and outer(θ_2) angles subtended by the counter at the centre of the hydrogen target. Only those neutrons whose kinematical coordinates (θ^*, p^*) are represented by points lying between these two curves are detected by the counter. Two characteristics are obvious:

(a). At low p^* values(26 to 80 Mev/c) neutrons with a wide range of c.m. angles around 90° are collected by the neutron counter; those with very small or very large c.m. angles have Lab. angles smaller than the inner angular limit and, therefore, are not detected;

(b). At high p^* values(greater than 80 Mev/c), angles much smaller or much greater than 90° contribute. Neutrons having c.m. angles over quite a wide region around 90° now have Lab. angles larger than the outer angular limit and, therefore, are not detected. As a result of this the efficiency

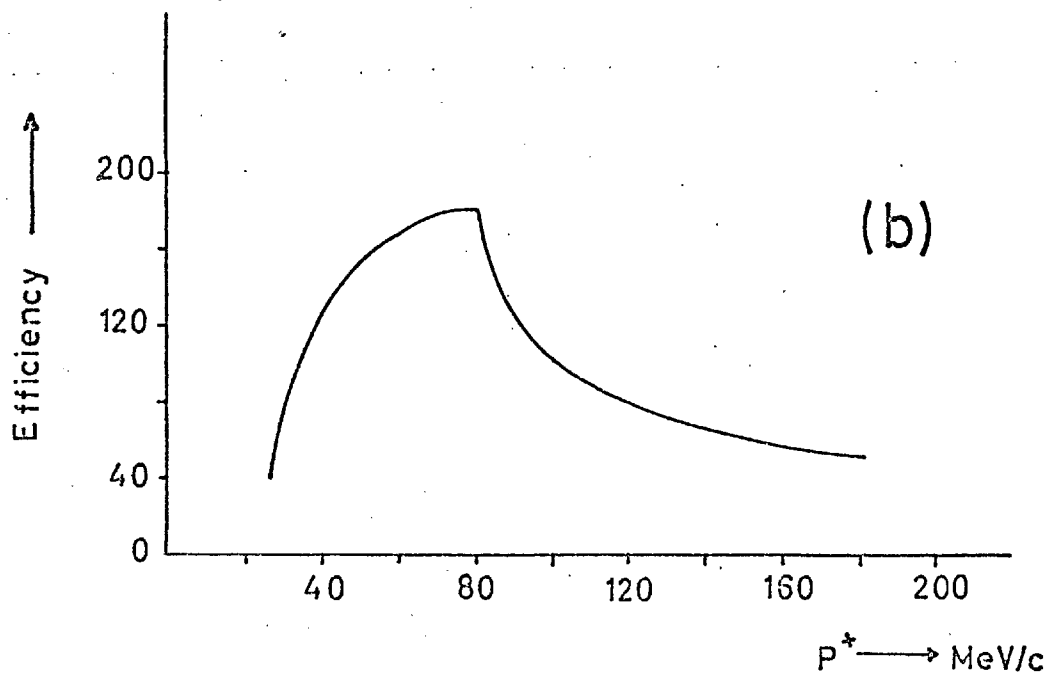
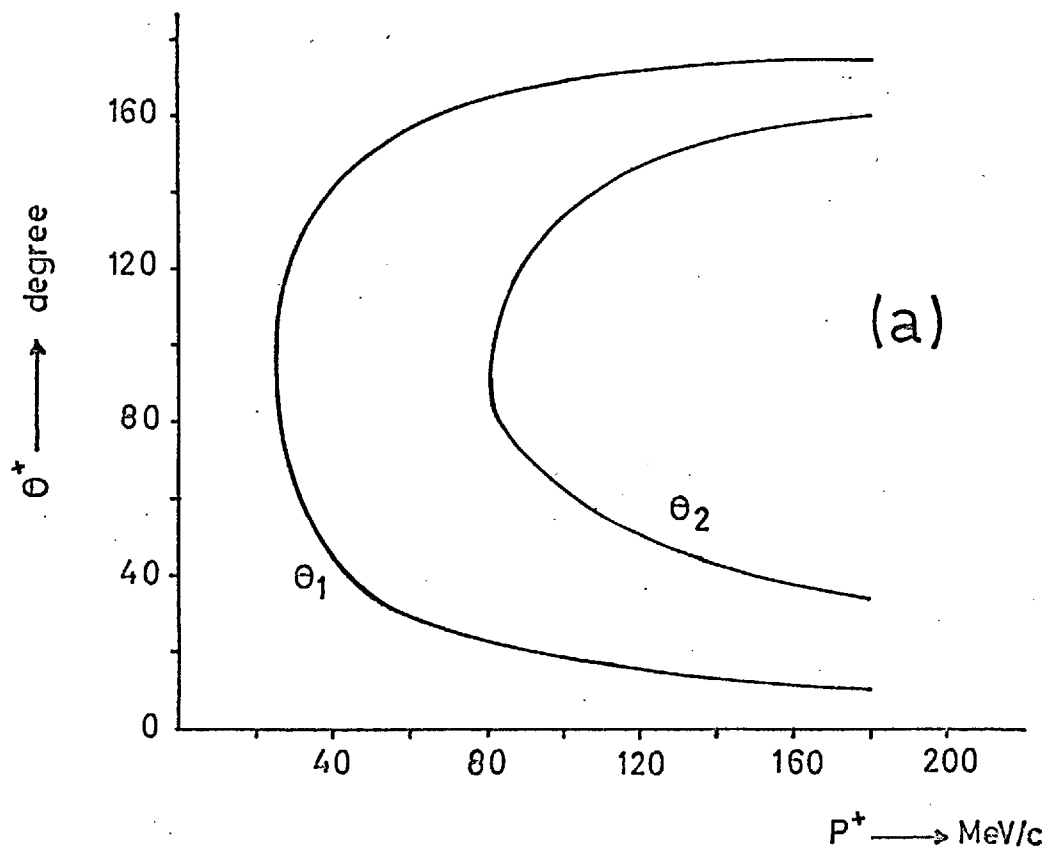


Fig. 2:6

at high p^* 's is low. Figure(2:6b) shows the efficiency for detecting neutrons as a function of p^* assuming a uniform production angular distribution.

Figure(2:7a) shows how the neutron time-of-flight, t_n , is related to p^* . Each p^* gives rise to a range of t_n values which separate into two bands of small and large times of flight when p^* is sufficiently high. The two bands correspond, respectively, to neutrons going forward and backward in the c.m. system.

In figure(2:7b) the ordinate has been changed from p^* to P_π , the incident momentum. These curves express the relationship between t_n and P_π for a fixed mass M_x (1019 Mev/c²), and for the inner and outer limits of the counter. The time t_c corresponds to the velocity, B_{cms} . The threshold momentum $P_{\pi t}$ for this mass is indicated by a dashed line. In order that the neutrons may just reach the inner limit, the incident momentum has to be slightly higher than the threshold value (corresponding to a p^* of about 26 Mev/c). Further increase in P_π enables the neutrons to gain more and more energy in the centre of mass. This gives rise to slow and fast neutrons in the Lab. (going backward and forward in the centre of mass, respectively), and causes the splitting of the time of flight spectrum.

Several factors other than the finite size of

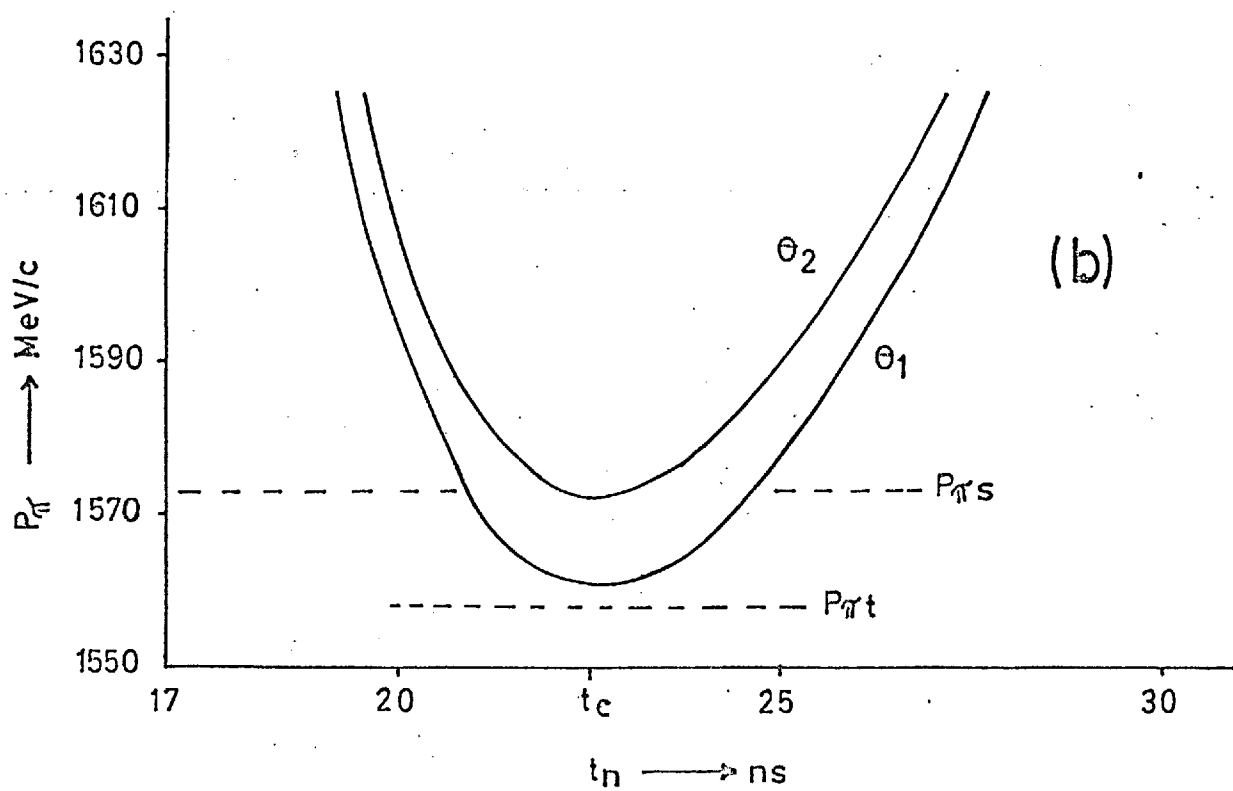
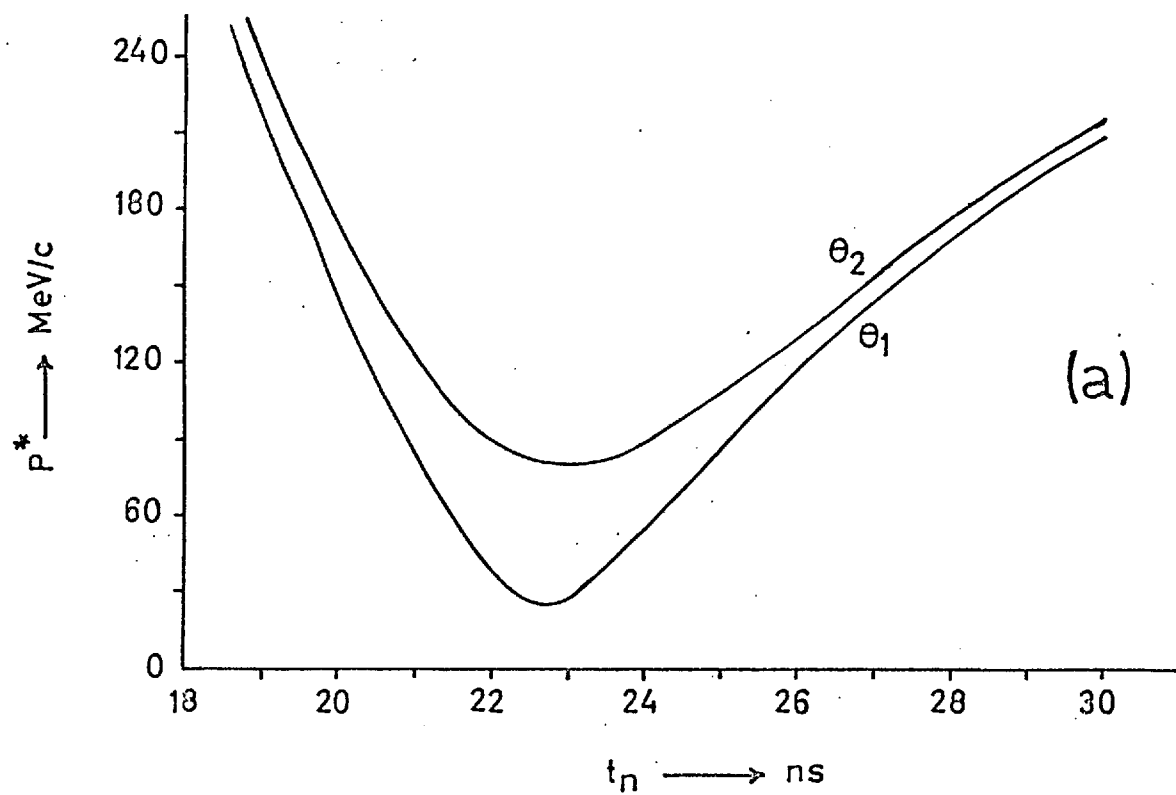


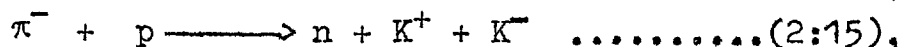
Fig. 2:7

the neutron counter influence the time of flight spectrum observed experimentally. Some of them affect the p^* distribution of the produced events while some directly affect the time of flight distribution. These are as follows:

- 1). ΔP_π , the spread in the incident momentum distribution,
 - 2). length of the hydrogen target (energy loss of beam particles in the target causes additional spread in momentum),
 - and, 3). Δt_n , the uncertainty in the timing of events(timing resolution) caused by spreads in the output pulse height distribution of the timing counters(see section 3:2).
- The result is that the timing spectrum for a fixed mass spreads out beyond the limits indicated by the parabolas in figure (2:7b), and the structure is lost to some extent. The consequence of this smoothing effect is that the splitting referred to earlier occurs at a higher momentum than indicated by the dotted line(P_{π_s}) in this figure.

The effect of the first two causes is to broaden the p^* distribution of the produced events. The p^* distribution and hence the time of flight distribution is also broadened if we consider contributions from a finite mass range instead of from a fixed mass only. This factor can become so dominating that the splitting in the time of flight spectrum may not be observable. This can happen in

the case of reactions with more than two bodies in the final state. For example, in the case of the 3-body direct(phase space) reaction,



no splitting can be observed even far from threshold. The reason is that the splitting in the time of flight spectrum due to the low K^+K^- masses (high p^* 's) is lost due to the contribution from high K^+K^- masses which produce low p^* events.

Four theoretical spectra obtained by the Monte-Carlo technique (described in chapter 4) are shown in figures (2:8) and (2:9) for comparison. The first two belong to the reaction,



for a resonance mass of $1019 \text{ Mev}/c^2$ (and a width of 4 Mev) and the other two to reaction (2:15). Although (2:8a) and (2:9a) are very similar, (2:8b) and (2:9b) are not. The spectrum in figure (2:8b) shows two peaks _____ a forward and a backward peak _____ the backward peak being smaller in size due to the availability of a smaller solid angle .

These spectra are characteristic of the apparatus shown in figure (2:5a), angles $\theta_1(2^\circ)$ and $\theta_2(6^\circ)$ being small. Thus near their thresholds reactions (2:15) and (2:16) would give rise to very similar spectra. And if

Monte Carlo neutron time-of-flight spectra from the reaction $\pi^- + p \rightarrow n + \phi$

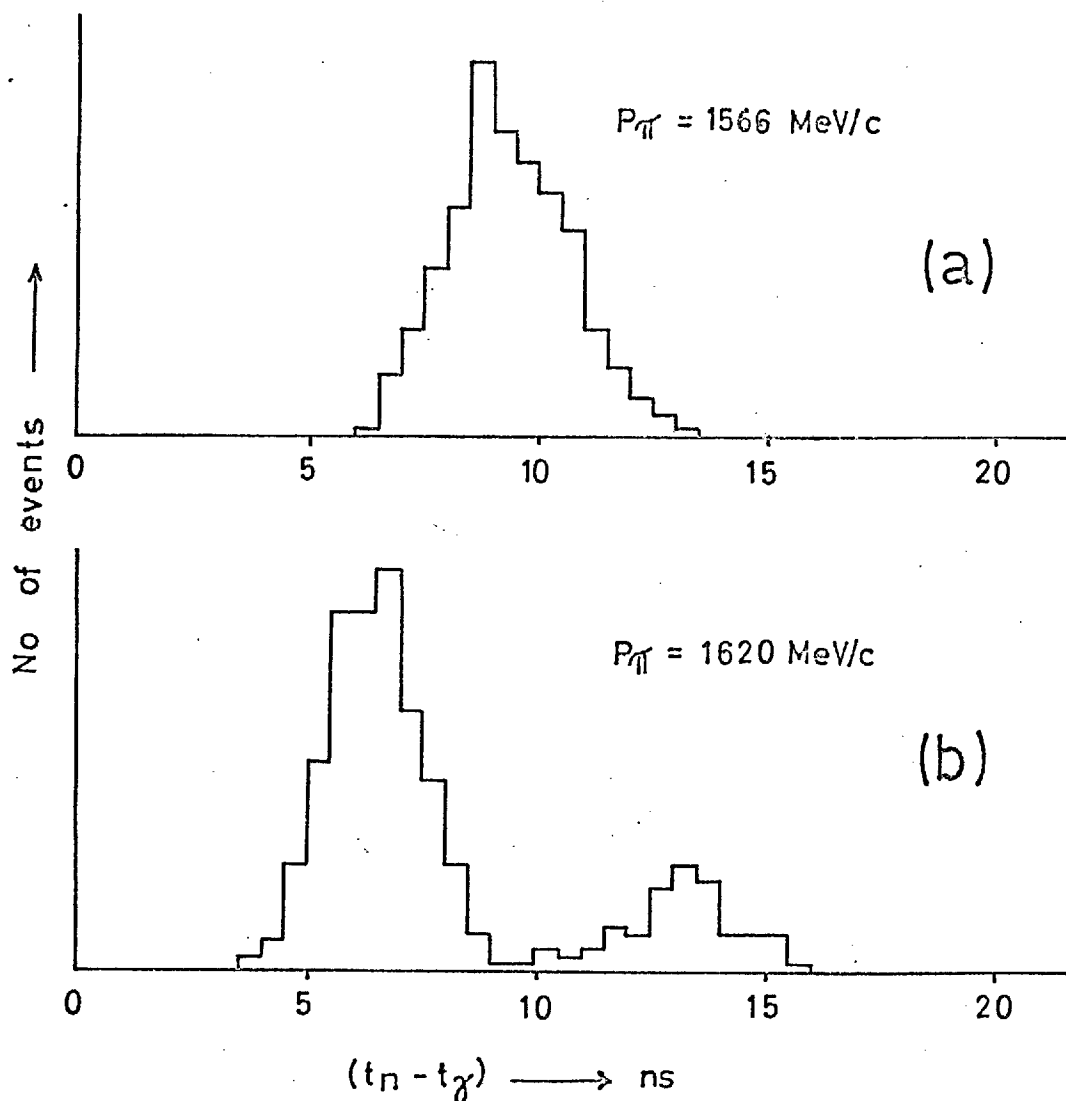


Fig. 2:8

Monte Carlo neutron time-of-flight spectra from the direct reaction

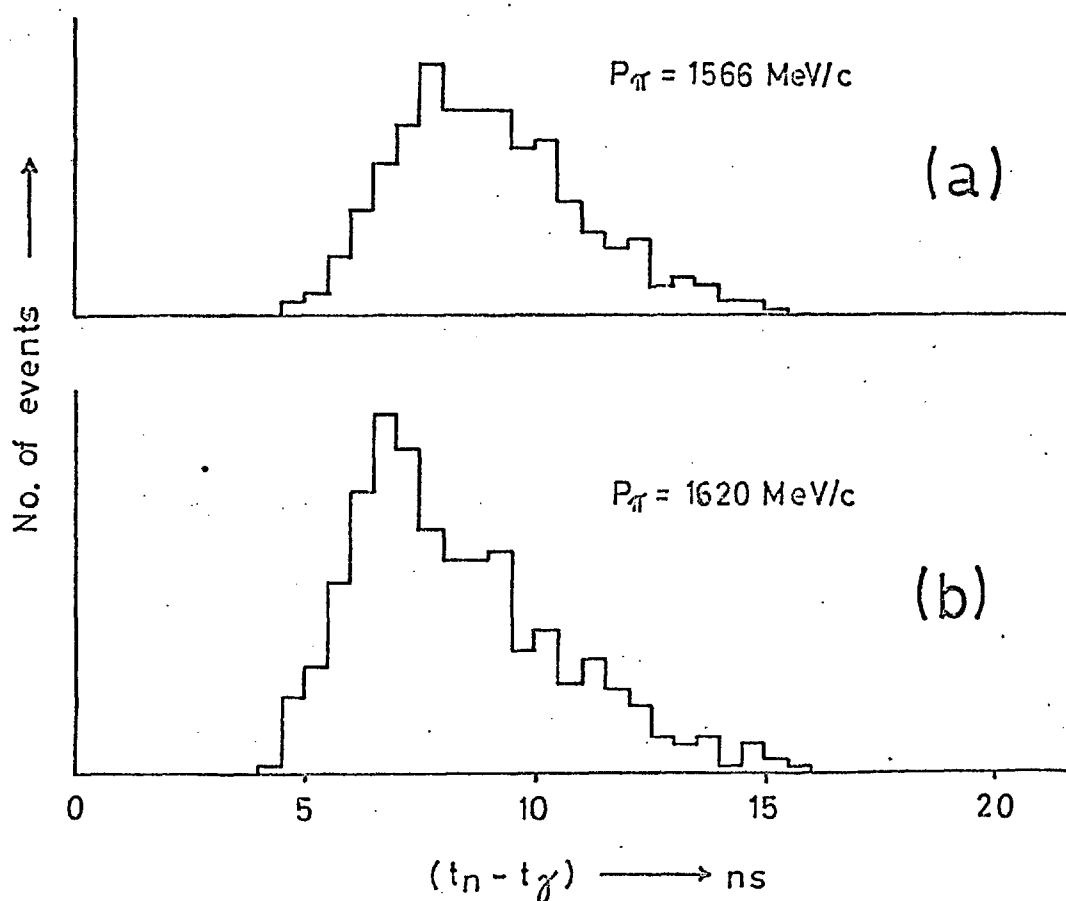
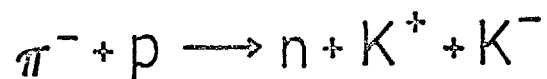


Fig. 2:9

their thresholds happen to be close to each other a peak in the neutron time of flight spectrum near threshold would not be enough to prove the existence of a resonance. This applies to the Phi meson because of the presence of the K^+K^- backgrounds which will be discussed in section 2:4. The splitting of the peak, if it can be observed, is a definite indication.

The Mass Response

The mass response of our apparatus is shown in figure (2:10). Obviously a very narrow range of masses is accepted at any one incident momentum. This is a consequence of the fact that the efficiency falls down rapidly for high p^* events. There are thus strong biases in the missing mass selection made at a fixed incident momentum, and to make a wide ranging missing mass search neutron time of flight spectra would have to be obtained at a large number of different incident momenta.

Mass Resolution.

Factors that broaden the timing spectra (ΔP_π , length of the target, Δt_n) also worsen the mass resolution of the apparatus. We define the mass resolution as the full width at half height of the "yield curve" for a fixed mass:

Mass response of the
apparatus at various
incident momenta

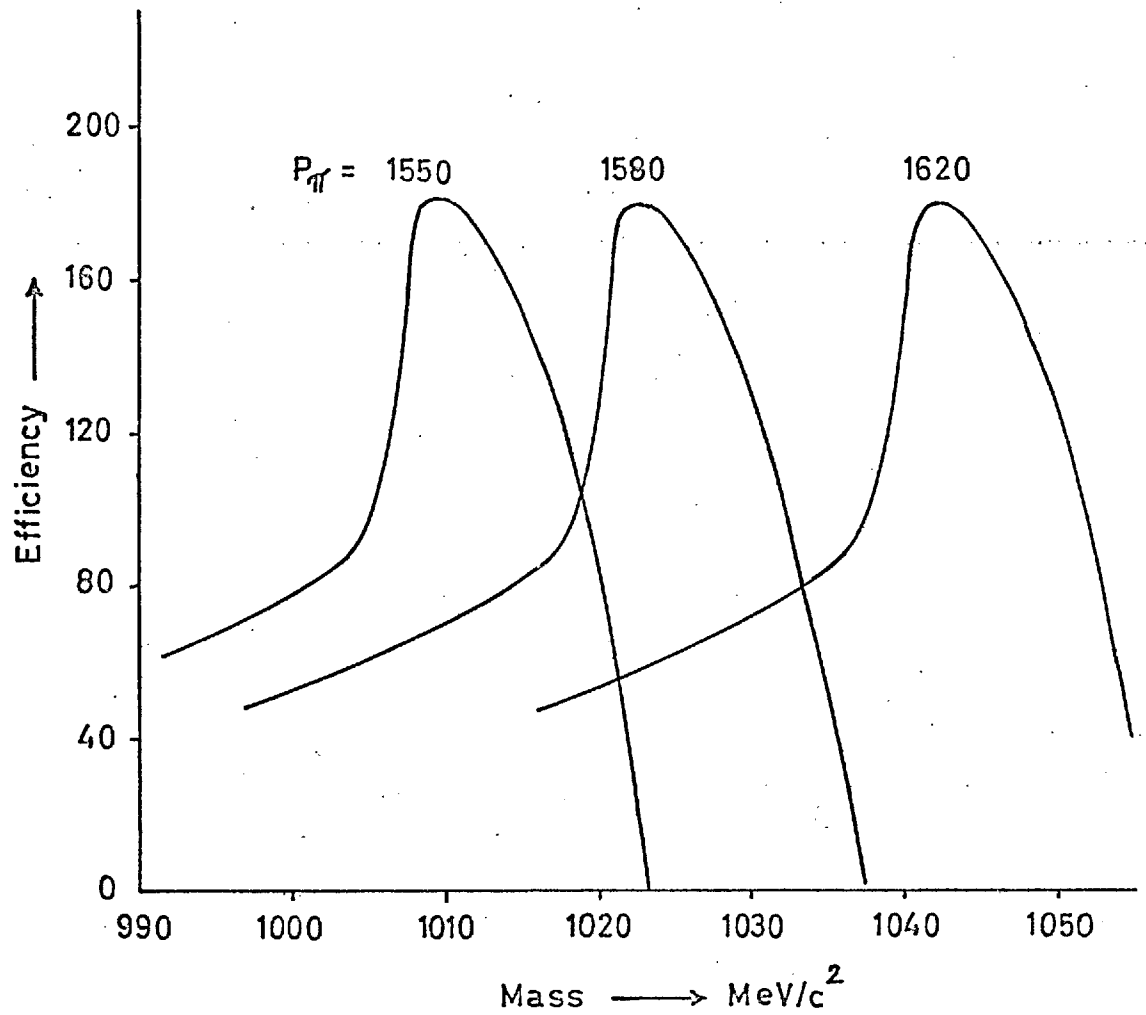


Fig. 2:10

the smaller the width the better the resolution. By "yield" we mean the number of events detected by the apparatus, in a given time of flight range, for a given number of incident pions.

The mass resolution of our apparatus is shown in figure (2:11). This includes the effects of spread in the incident momentum($\Delta p/p_0 = 0.55\%$) and a finite length (32.2 cms.) of the hydrogen target, and, of course, the effect of the angular acceptance of the neutron counter. Figure (2:11a) shows the yields for a "wide timing gate" encompassing all the events in the spectrum from the particular missing mass. These curves indicate that the resolution is about 30 Mev/c in terms of P_π or 15 Mev/c² in mass($\Delta P_\pi \simeq 2. \Delta M$ in this region). The resolution can be improved if one plots the yield from only low p^* events. These events lie near and around the c.m. channel(time t_c in fig. 2:7b) in the time of flight spectrum. To do this one uses a suitably "narrow" timing gate around the c.m. channel for counting the events instead of counting their total number. Figure (2:11b) shows for comparison the "narrow gate" yields for the same masses as in (2:11a). The full width now is only 20 Mev/c in P_π or 10 Mev/c² in mass indicating an improvement in the resolution.

Neutron yields for various missing masses
in the reaction $\pi^- + p \rightarrow n + \text{missing mass}$

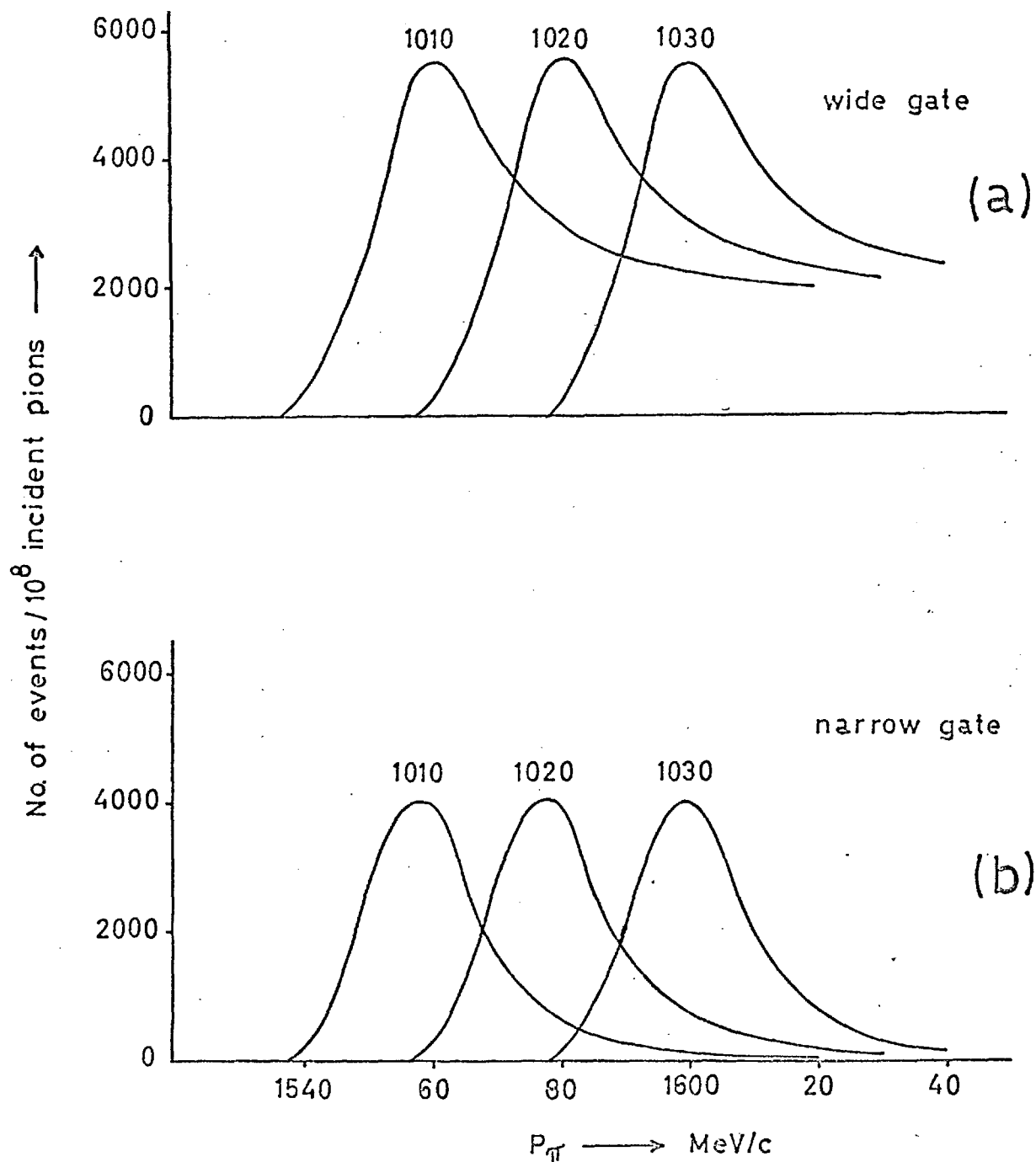
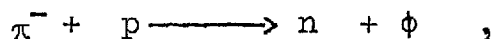


Fig. 2:11

2:4 Background Problems.

The background to the reaction,



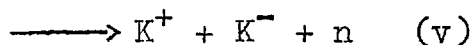
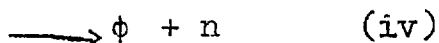
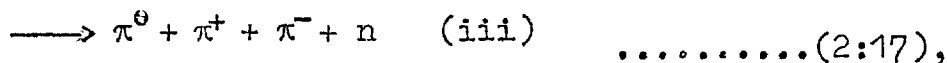
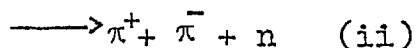
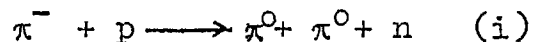
can be divided into two categories, namely,

- (a) The pi-meson background, and,
- (b) The K-meson background.

We shall first discuss the pi-meson background as in order to reduce this, more information about the final state was demanded in the selection of the signal.

(a) Pi Meson Background.

The following final states in the $\pi^- p$ reaction are important from our point of view:



where $m \geq 4$.

Since the cross section for reaction 2:17(iv) is negligible compared to the total cross section for the above processes, almost every event would belong to the

background if simply a neutron were demanded in the final state to give the missing mass.

A neutron time of flight spectrum from this pion background is shown in figure 2:12. The large peak at the left is due to the accumulation of triggers from gamma rays and fast neutrons. The counting rate falls more or less exponentially as we go from the "gamma peak" towards higher times of flight. Our calculations showed that counts from the signal, i.e; reaction 2:17(iv) would accumulate in the region AB although more than 80% would lie in the region CD. The background counts in CD are equivalent to an effective cross section of 0.1 mb. (The total counts in the spectrum shown are only about 0.2% of the total π^-p interaction rate at 1580 Mev/c incident momentum because a neutron is being demanded for trigger and also because of the low collection and detection efficiencies of the neutron counter). The number of counts expected from the signal, assuming $\sigma(\pi^-p \rightarrow n\phi) \simeq \sigma(\pi^-p \rightarrow n\omega)/60$, were equivalent to an effective cross section of only about 2 micro-barns. The amount of the background was thus about 50 times the expected signal. This meant that in order to observe a significant enhancement due to Φ production, above background, the experiment would have to run at a

Time of flight spectrum of
neutrons and gamma rays from
background reactions(2:17)

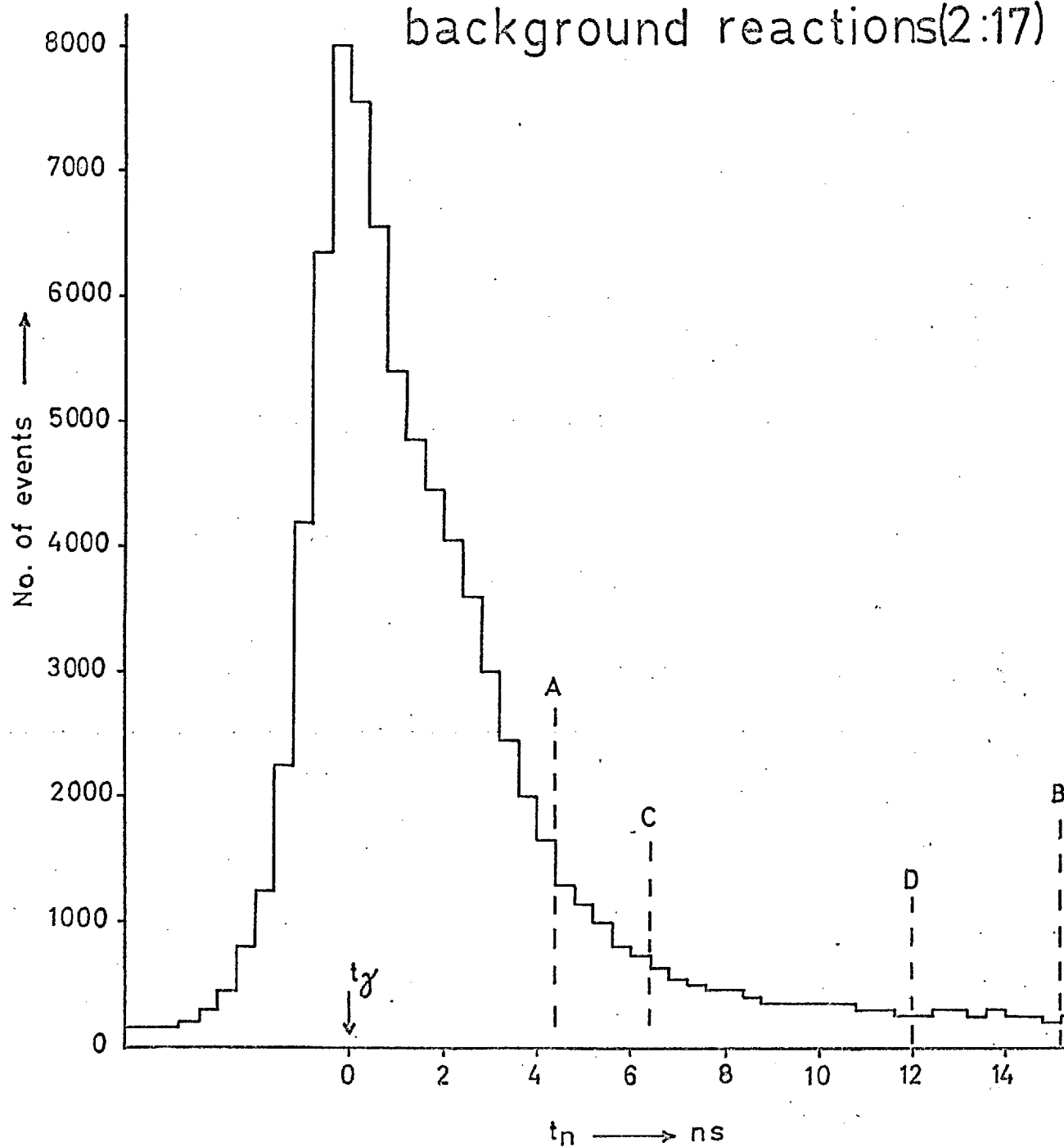


Fig. 2:12

stretch for about 24 hours. This period was so long that the electronics would not remain without suffering from instabilities which could severely distort the signal peaks by altering the timing of events recorded. It would thus be extremely difficult to see a peak due to Φ production in the neutron time of flight spectrum without suppressing the immense π -meson background in some way. The reduced background would not only make small timing drifts less important but would also enable a statistically significant peak to be built up in a much shorter time. The background was reduced by the imposition of additional constraints on the selection of events as is explained in the following paragraphs.

The threshold for the reaction $2:17(v)$ is near the Φ threshold. The K mesons from Φ decay therefore do not travel very fast nor do they make large angles to the beam in the laboratory. In figures 2:13(a and b) are shown the opening angle distributions for k^+k^- pairs from Φ decay and $\pi^+\pi^-$ pairs from the reaction $2:17(ii)$. The kaons have a much smaller opening angle (peaked at 32°) than the pions (peaked at 150°). This gave us a method for separating the signal from the pion background by just demanding that two charged particles should go at small angles in the Lab. along with a neutron. This selection,

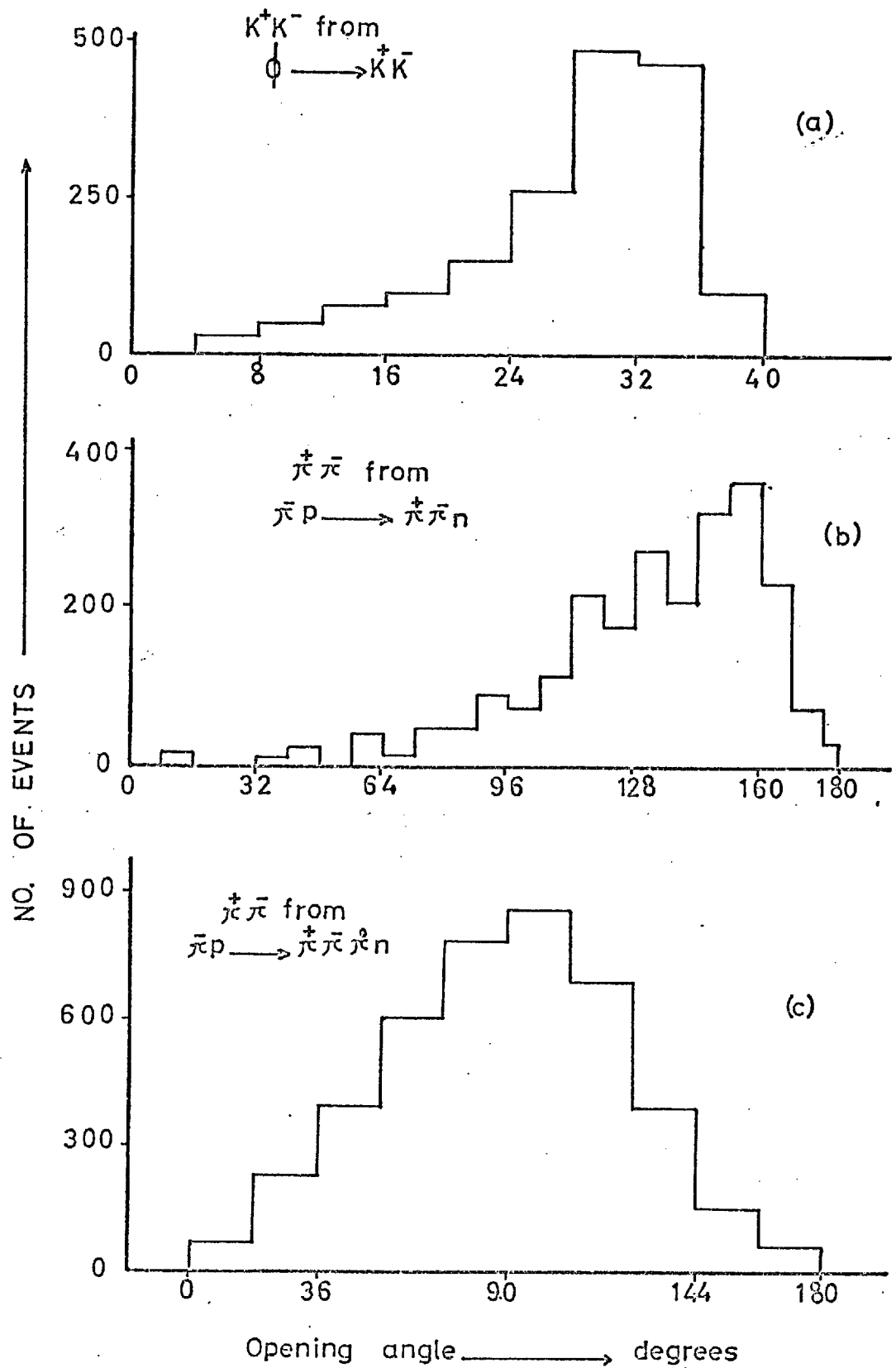


Fig. 2:13

of course, was possible only because the Φ has a large branching ratio (0.48^2) for decaying into K^+K^- .

A set of four scintillation counters (fig. 2:14) was included in the selection system, the duty of which was to provide a coincidence signal whenever any two of the counters were simultaneously triggered by two charged particles coming from the target. The maximum angle subtended at the target by these E-counters, in the experiment, was 33° thus virtually eliminating background 2:17(ii). The requirement of two charged particles, of course, also eliminated background 2:17(i).

Reduction of 3π background.

The reaction 2:17(iii) involves the production of three pions two of which can have any opening angle and so it was not possible to reject this component of the background completely by the requirement of two charged particles triggering the E-counters, although it would be reduced by a large factor by this demand (see fig. 2:13 c). Possibilities of reducing this and other multipion reactions were considered and ultimately a Cerenkov counter was also incorporated in the selection system. The momentum spectrum of K-mesons (fig. 2:15a) shows that very few of them have velocities exceeding 0.75 times the velocity of light. Water

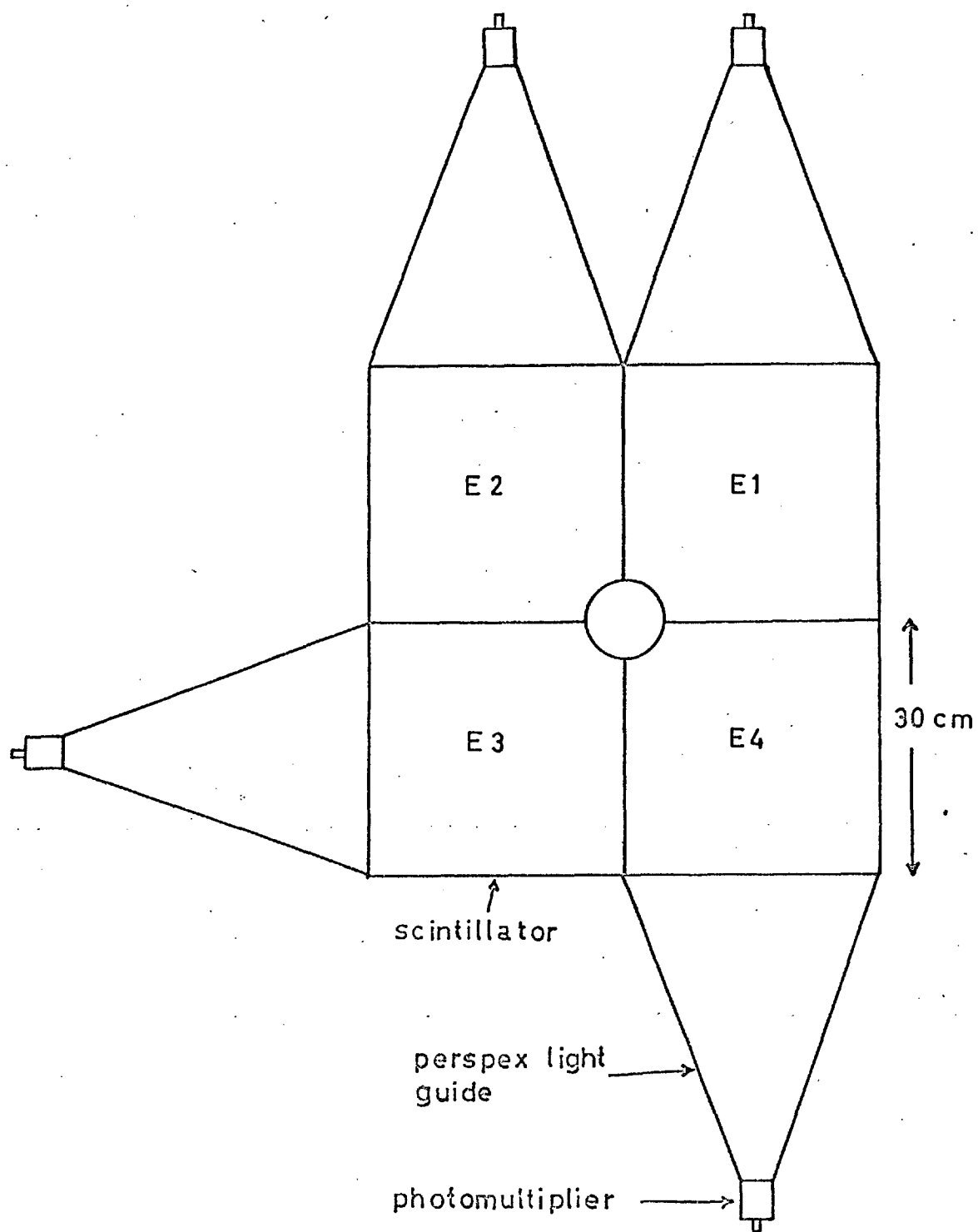


Fig. 2:14 E - Counters

Laboratory momentum distributions of kaons from Phi decay and
pions from the $3\pi n$ final state

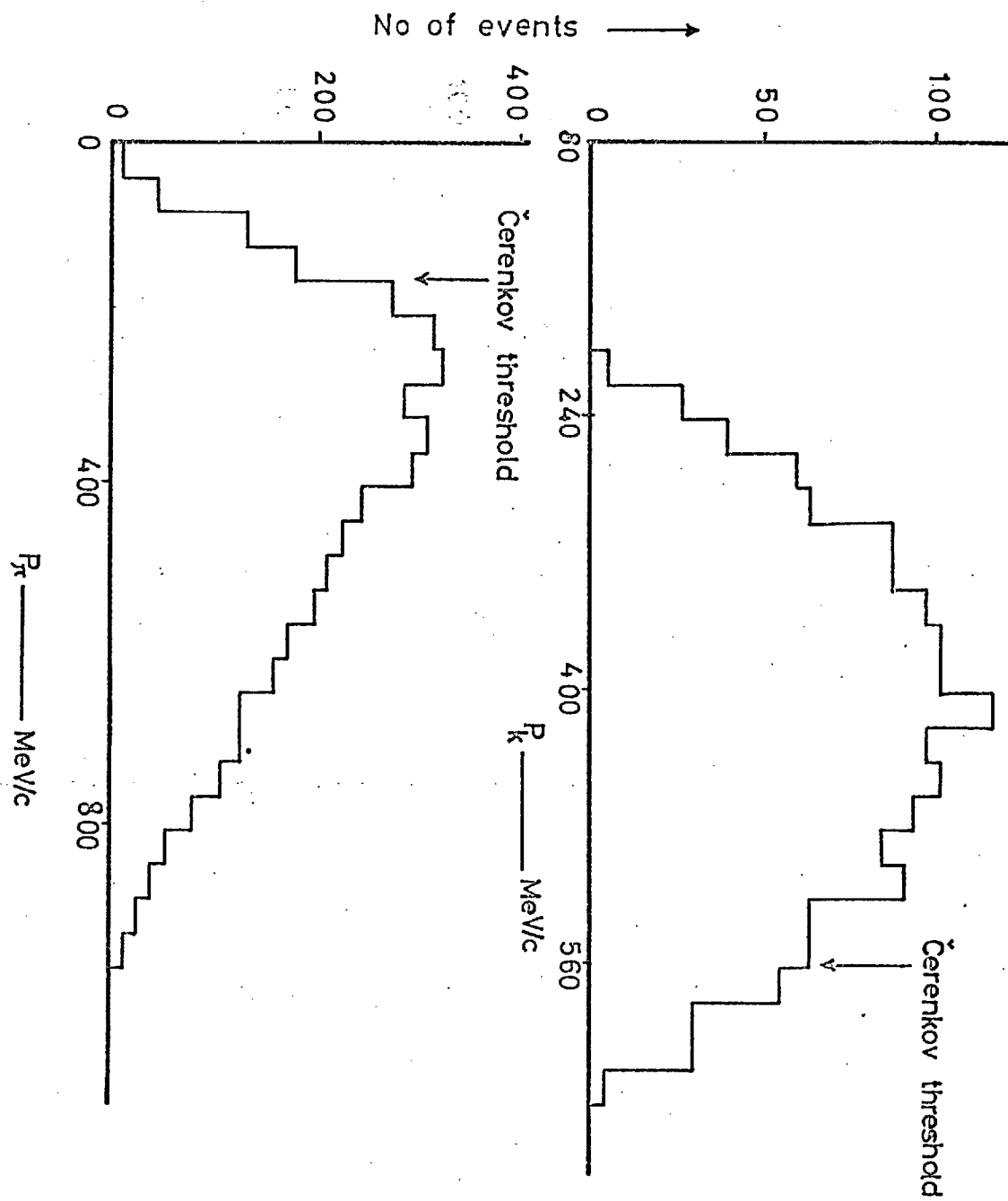


Fig.2:15

with its refractive index of 1.33 was thus a very suitable material as the radiator, as it provided a threshold at about the same velocity. Most of the pions in background reactions would have velocities greater than this (figure 2:15b) and could be rejected efficiently by using the Cerenkov counter in veto.

In order to augment the efficiency of the Cerenkov counter for vetoing multi-pion backgrounds a system of veto counters was designed and placed around the target. This consisted of four scintillation counters (A_8 to A_{11} in figure 2:20) lined inside with one radiation length (0.6 cm.) of lead to convert gamma rays from π^0 decay into electrons; the electrons subsequently triggering the scintillation counters. A smaller lead plate with a 6 cm. hole in the middle was also placed behind the target and in contact with an already existing veto counter (A_7) in a bid to cover as much solid angle as possible.

2:4(b) K^+K^- Backgrounds.

(i). K^+K^- Phase Space. The selection for the Phi demanded a K^+K^- signal as part of the logic and so the non-resonant (phase space) reaction,



was a natural background. As near their thresholds reactions

2:17(iv and v) would give rise to very similar neutron time of flight spectra, and also owing to the presence of several other factors that broaden the timing spectra, their spectra would overlap, making the estimation of the contribution from the resonant reaction rather more difficult and unreliable.

(ii) $\bar{K}\bar{K}$ S-Wave Enhancement. In the reactions,

$K^- + p \longrightarrow \lambda + K + \bar{K}$, and, $\pi^- + p \longrightarrow n + K + \bar{K}$, several groups^{6,7,28-30} have observed a broad enhancement in the $K_1^0 \bar{K}_1^0$ system near threshold. This could appear in the $K^+ K^-$ mode as our background. The S-wave enhancement, however, cannot be explained in terms of a Breit-Wigner resonance. Chew and Low⁴³, using the one-pion exchange model, have shown that the cross section for this enhancement, in the low Δ^2 region, is given by,

$$d^2/(d\Delta^2 \cdot dM^2) = (f^2/2\pi) \cdot (M \cdot k_\pi) / (M_\pi^2 \cdot p_\pi^2) \cdot \Delta^2 / (\Delta^2 + M_\pi^2).$$

$\sigma(\pi\pi \longrightarrow \bar{K}\bar{K})$, where M is the effective mass of the $\bar{K}\bar{K}$ system, k_π is the momentum of the pion or the kaon in the $\pi\pi$ c.m. system, and 'f' is the π -N coupling constant. Taking into account only the channels, $\pi\pi \longleftrightarrow \bar{K}\bar{K}$ and $\bar{K}\bar{K} \longleftrightarrow \bar{K}\bar{K}$ and using the zero effective range approximation, the cross section for $I = 0$ initial and final states can be written as,

$$\sigma_0(\pi\pi \longrightarrow \bar{K}\bar{K}) = 4\pi k_K/k_\pi^2 \cdot 2b_0 / ((1 + b_0 k_K^2) + a_0^2 \cdot k_K^2),$$

where $A_0 = a_0 + i \cdot b_0$, is the scattering length.

⁶Alexander et al found a best fit to their data using the value of $A_0 = (4-6) + (\sim 1.0)F$. Hess²² et al get good fits to their data with $a_0 = (1.5 \text{ to } 10)F$, if b_0 is chosen so that the

expression, $(a_0^2 - 4.65 a_0 + 16.7)/b_0$, is between 50 and 100 F.

(iii) The S* Resonance.

In experiments above 5 GeV/c the reaction, $\pi^- + p \longrightarrow n + K + \bar{K}$ yields a peak in the $K_1^0 K_1^0$ mass distribution near 1050 MeV/c², with $\Gamma \approx 50$ MeV/c², suggesting a Breit-Wigner resonant state. This has been called the S* resonance. It could also appear in the $K^+ K^-$ mode as our background.

2:5 Response of the Apparatus to Signal and Backgrounds.

The presence of the above-mentioned K-meson backgrounds necessitated a study of the behaviour of our apparatus towards both the signal and the backgrounds.

If events over a wide range of mass values around the resonance mass are collected, then with a flat mass response, the resonance stands out as a peak in the observed mass spectrum. To collect masses over a sufficiently wide range it was imperative to work at several momenta starting from slightly above the $K^+ K^-$ threshold (1500 MeV/c) and working our way upwards to 1630 MeV/c (70 MeV/c above the ϕ threshold), thus ensuring that a range of about 20 MeV/c² on either side of the ϕ mass, was covered with more or less the same efficiency.

It was mentioned in section (2:3b) that a peak in the time of flight spectrum alone is not sufficient to prove the existence of the resonance. It is also insufficient for measuring its cross section in the presence of such backgrounds. However, given good mass resolution, the yield when plotted as a function of the incident momentum, gives more information. The yield curve has the advantage that it does not include the poor timing resolution of the neutron counters while if we wanted to plot a mass spectrum we would have to know the time of flight accurately. Besides this, comparison of the basic experimental data with the corresponding data calculated by the Monte-Carlo technique is more convenient because no intermediate quantities have to be evaluated.

Figures 2:16(a and b) show the "wide gate" and the "narrow gate" yield curves for missing masses of 1010, 1020, and 1030 Mev/c². The curves also include decay constraints, i.e; only those events where both K mesons, from the decay of the K^+K^- system, went through the Cerenkov and E-counters, have been plotted. A comparison of these curves with those in figure(2:11) shows that no noticeable bias is introduced by the Cerenkov or E-counters.

Figure (2:17) shows the yields from the production of the Phi meson. The mass and width are assumed to be

Neutron yields from the reaction
 $\pi^- + p \rightarrow n + M_{K^+K^-}$ including decay
 constraints

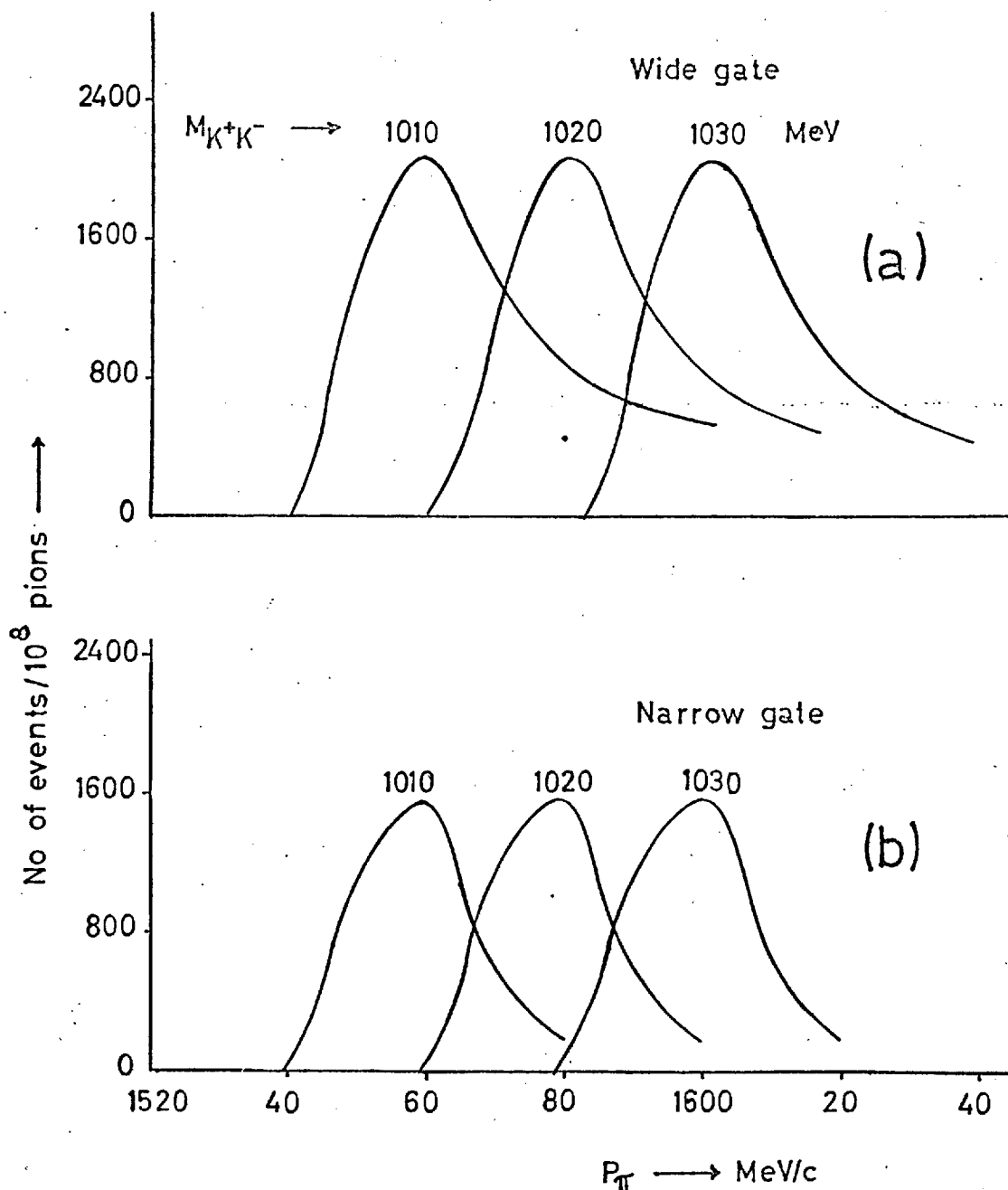


Fig. 2 :16

Neutron yields from the
reaction $\pi^- + p \rightarrow n + \phi$ for

$$\tau\phi = 4 \text{ MeV}/c^2$$

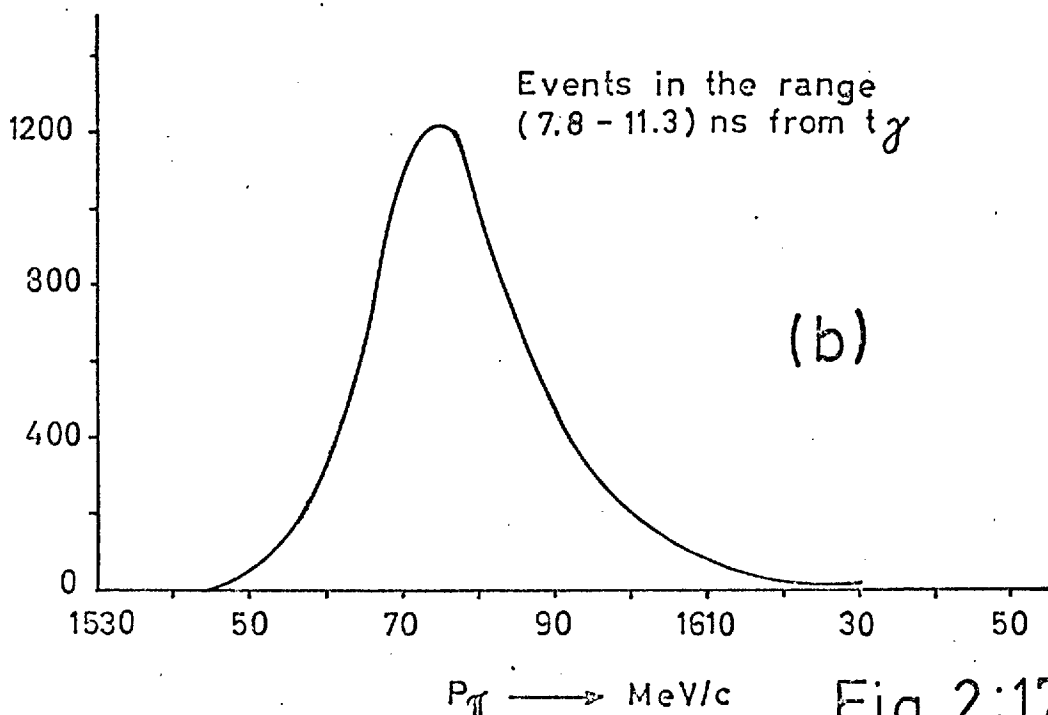
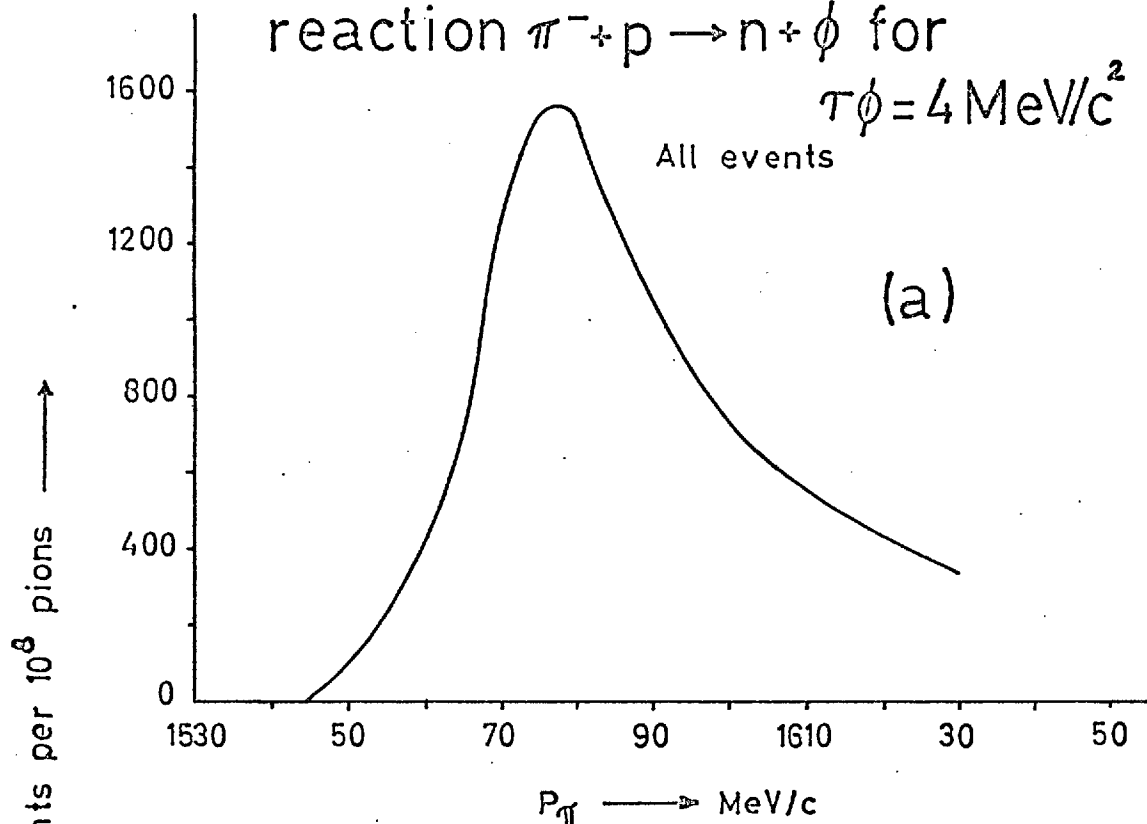
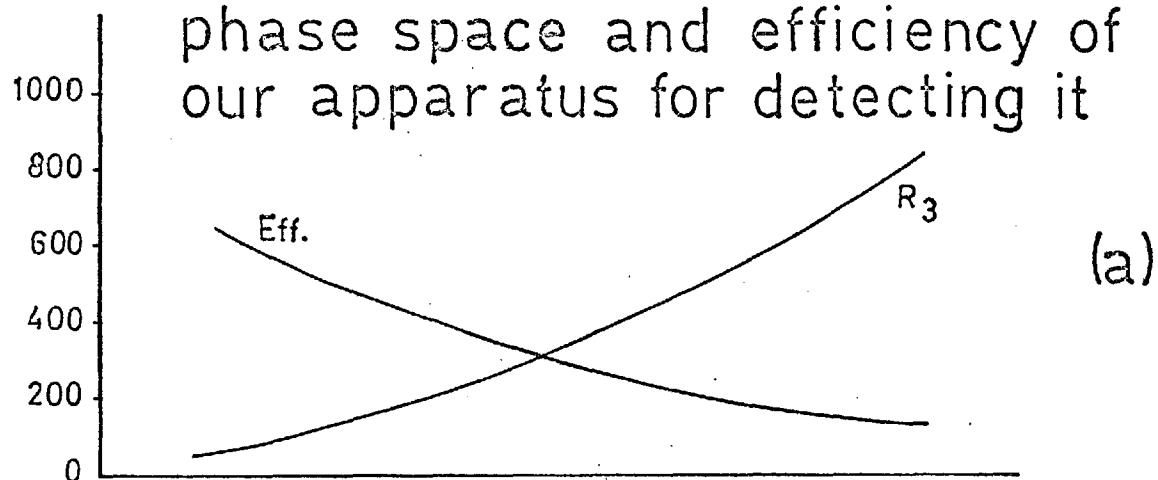


Fig 2:17

respectively, $1018.6 \text{ Mev}/c^2$ and $4 \text{ Mev}/c^2$. The angular distributions are supposed to be uniform and the cross section is assumed to be proportional to p^* throughout. The effect of a finite width is to smear out somewhat the rising edge of the yield curve.

The yield is a product of two functions of the incident momentum, namely, (a) the efficiency of the apparatus that is largely a function of the produced p^* distribution, and, (b) the cross section. Figure (2:18a) shows the efficiency of the apparatus for collecting neutrons from the pure phase space reaction 2:17(v). Starting from about $1530 \text{ Mev}/c$ it falls more or less exponentially as the momentum increases. The second curve shows how the cross section for phase space events changes with momentum. The cross section is proportional to the density of states factor for this 3-body reaction and was calculated at each momentum for which the efficiency had been calculated. If the two curves are now folded together the resultant curve (2:18b) gives us the behaviour of the phase space yield. This has a linear rise for most part of the momentum range but flattens off at higher momenta. If events in a narrow timing gate are plotted the curve becomes almost horizontal in the region where the yield from the Φ is large. The phase space yield thus behaves in a manner markedly different from the Φ yield.

Density of states for nK^+K^-
phase space and efficiency of
our apparatus for detecting it



Yield from nK^+K^- phase space

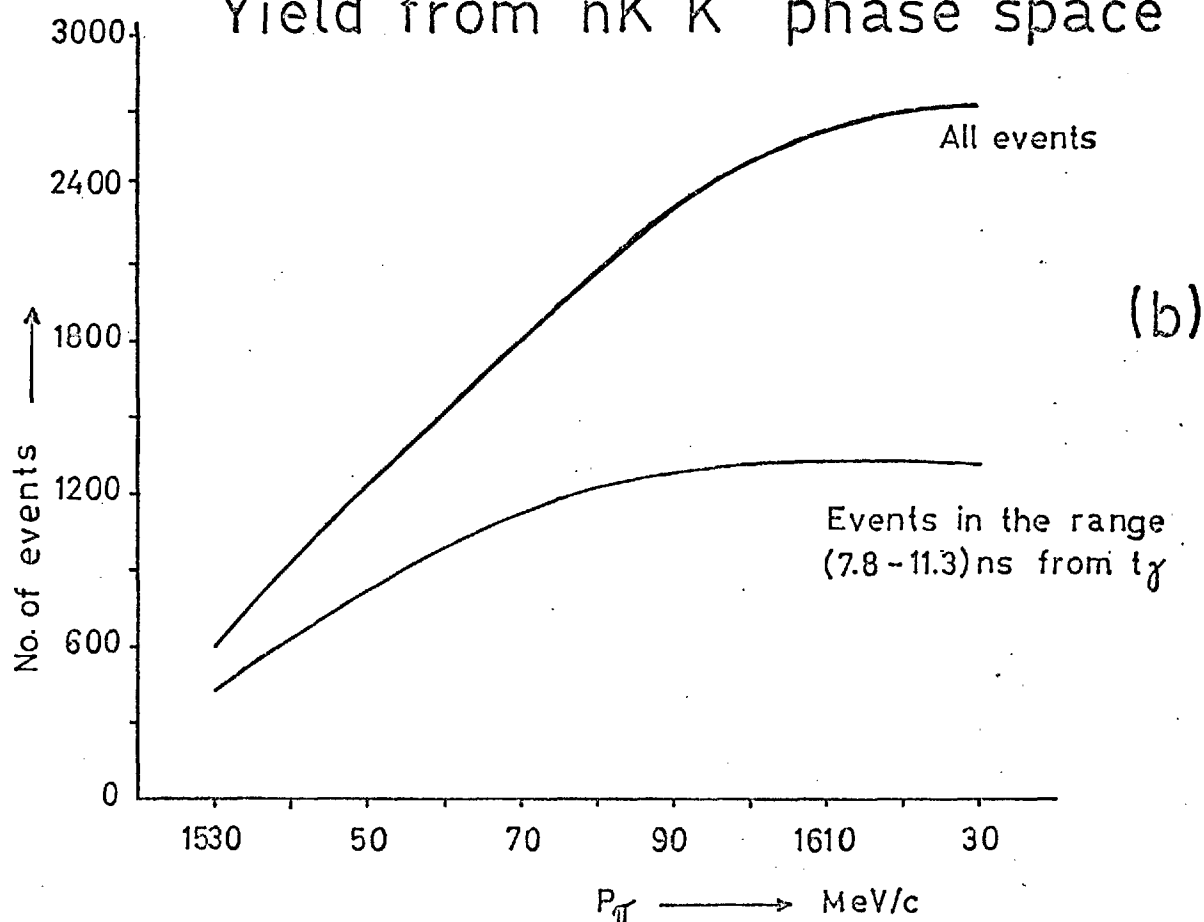


Fig: 2 : 18

In figure (2:19a) are shown the yields against momentum from the S-wave Enhancement, including decay constraints, both using a wide as well as a narrow timing gate. This is again quite different from the Phi yield curve. This yield was calculated assuming that one-pion exchange is the dominant production mechanism which is not a good approximation near threshold. Figure(2:19b) shows yields from the production of the S^* resonance again including decay constraints. An S-wave production of the resonance is assumed with a Breit-Wigner shape having a width of $50 \text{ Mev}/c^2$, peaked at $1050 \text{ Mev}/c^2$.

The three background yields discussed above have completely different momentum dependences compared with the Phi meson yield. The resolution of the apparatus was thus quite adequate for looking for a narrow resonance such as the Phi meson in the presence of these backgrounds.

Non- K^+K^- Background. The momentum dependence of the residual pion background is another factor that merited investigation. The only known resonance in the 3π system close to the Phi meson is the A_1^{32} (mass $1058 \text{ Mev}/c^2$, width $80 \text{ Mev}/c^2$). If the multi-pion final state were not suppressed by our selection system, it could well make a continuously increasing and significant contribution to the background. However due to the small mass range covered at any one momentum

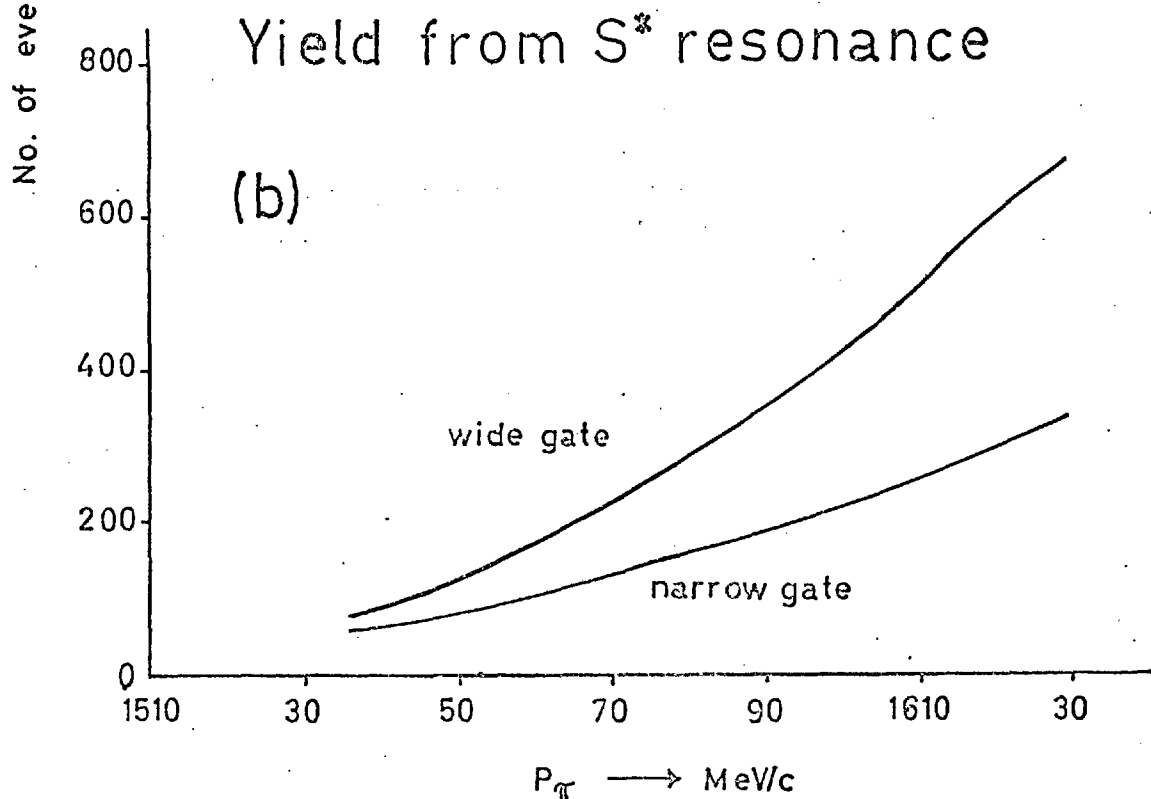
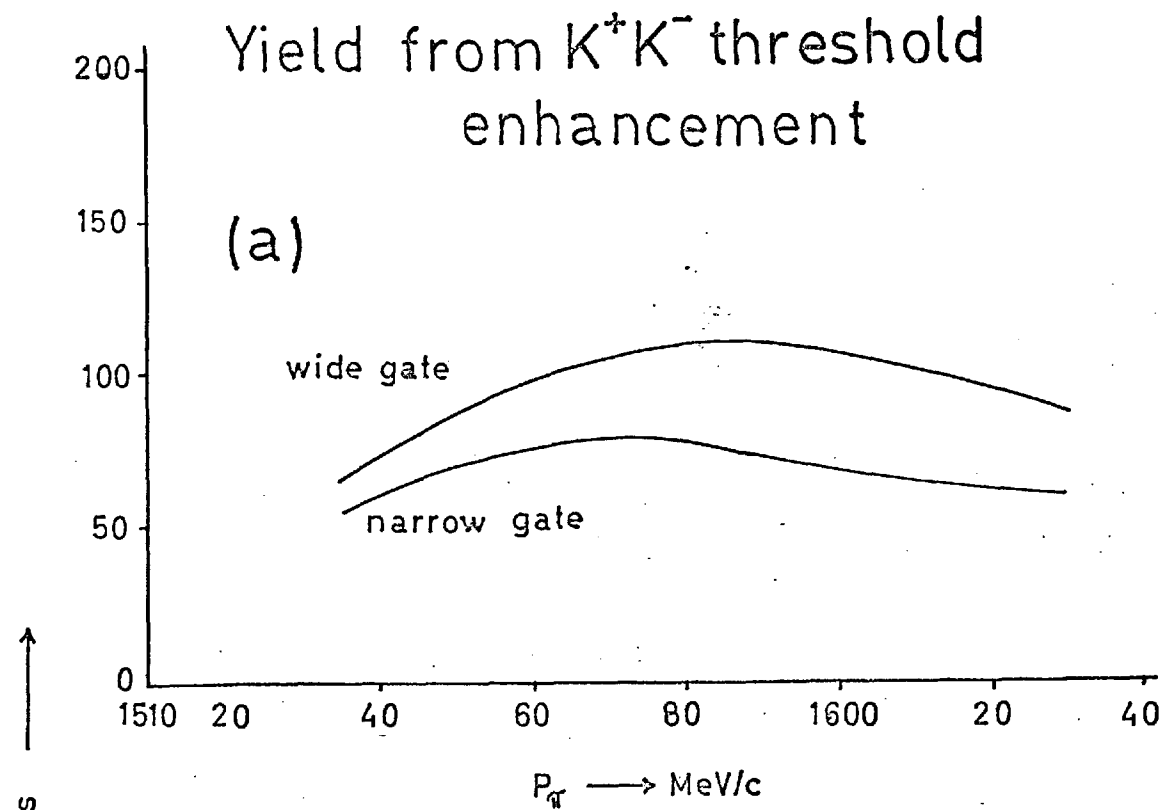


Fig. 2:19

and due to the attenuation imposed by the apparatus neither the phase space(multi-pion) nor the A1 would cause any significant variation in the pion background yield. In fact ²⁴ it turned out that 80% of our residual background resulted from interactions taking place in the apparatus downstream of the target. We, therefore, expected our non- k^+K^- background yield to exhibit no significant variation over the required incident momentum range.

2:6 The Experimental Lay-out.

A few other important features of the design and the lay-out of the counters will now be discussed with reference to figures(2:20) and (2:21).

The liquid hydrogen was contained in a 0.01" thick melinex cylinder of length 32.2 cms. and diameter 6.5 cms. This cylinder had slightly curved end caps. The cylinder was contained in a vacuum vessel made of 1/16" thick duralumin with melinex end windows each 0.005" thick. The space between the inner(target) and the outer(vacuum vessel) cylinders was filled with several layers of thin aluminium foil which, in conjunction with the high vacuum that was maintained in this space, thermally insulated the target.

The timing counter S_2 was 8 cms. in diameter

Apparatus used for detecting the reaction $\pi^- + p \rightarrow n + K^+ + K^-$

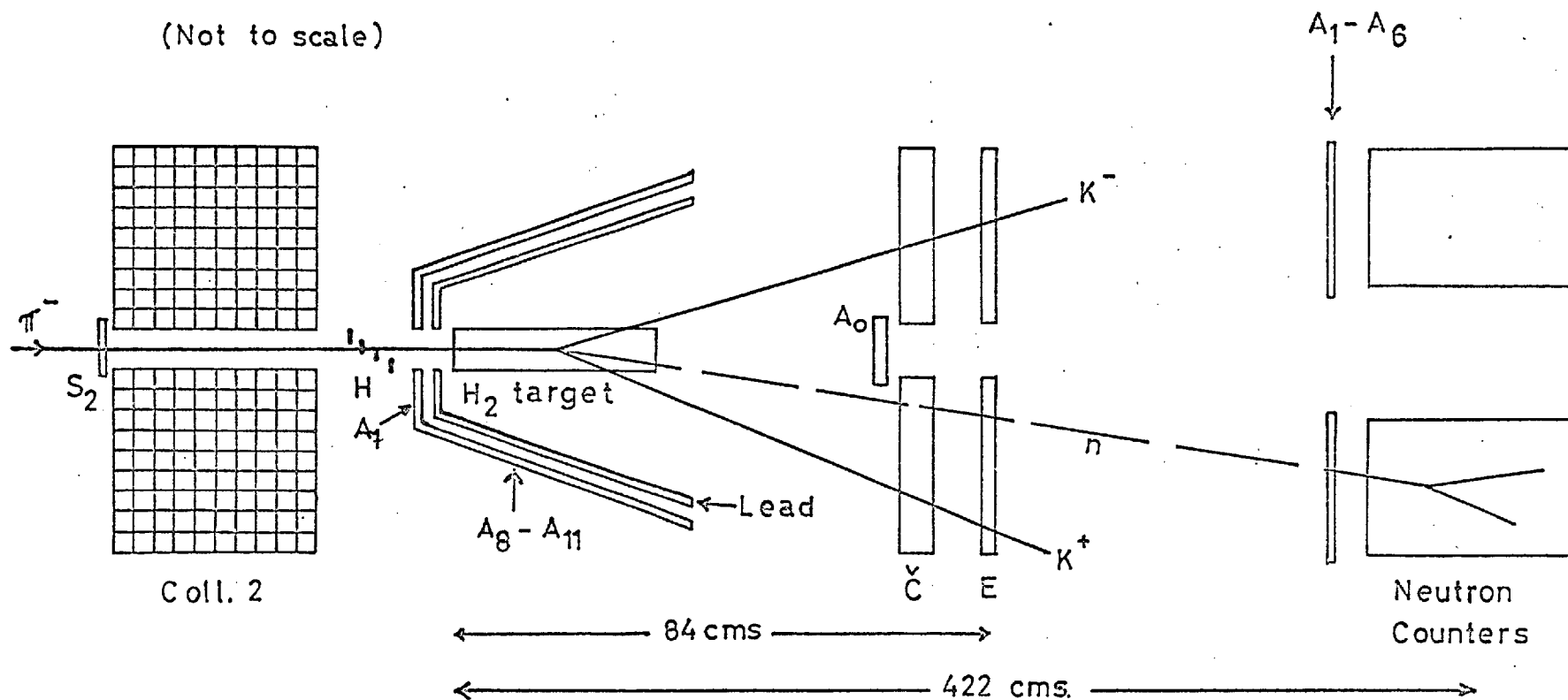
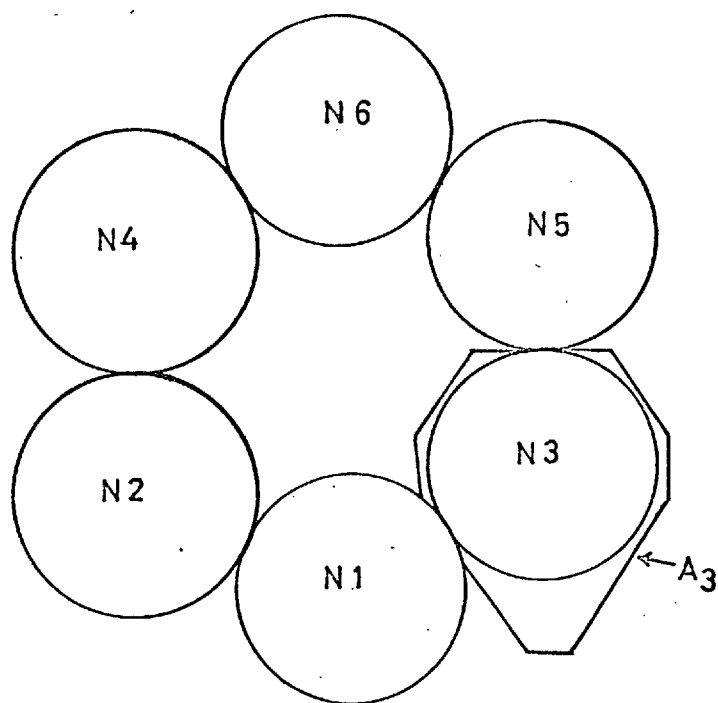
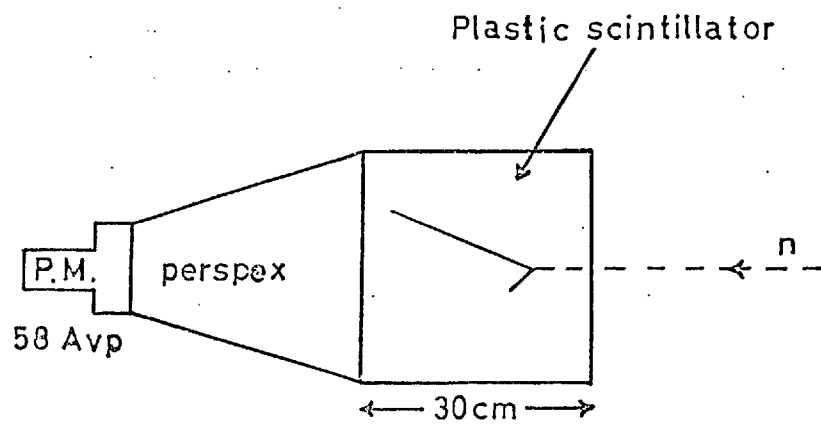


Fig. 2:20



Arrangement of neutron counters



Side view of a neutron counter

Fig. 2:21

and 0.5 cm. thick. It was placed just before the second collimator, and thus away from the target, so that interactions taking place in it were not counted as interactions in the target.

The veto counter A_7 had a 6 cm. hole in it to allow the useful beam to go through. Thus good beam particles were those that satisfied the logic, $S_2 \cdot \bar{A}_7$, along with producing a hodoscope signal.

The A_0 veto counter was 9 cms. in diameter and 2.5 cms. thick. It was placed away from the target in order not to veto the K mesons that would go forward at small angles in the Lab. By putting it just before the Cerenkov counter it was made to stop the beam interacting in the aluminium ring, at the centre of the Cerenkov counter, from increasing our background.

The dimensions of the E-counter scintillator were, 30 cms. by 30 cms. by 2 cms.(thickness). The corners of the counters were removed so that when the four were placed together an 8 cm. hole resulted at their centre. This was done in order to allow the beam to go through and so random coincidences between beam pulses from different E-counters were reduced which otherwise would have greatly increased our background. Four counters were chosen as, in

this case, the ~~size~~ of each counter was small enough to make the chance of both K mesons going through the same counter negligibly small.

The efficiency for detecting the pair of K mesons from Phi decay was an important factor in the overall efficiency of the apparatus. An optimum position for the counters was found by using the Monte Carlo programme. The relationship between the efficiency for collecting K mesons and the distance from the upstream end of the target is shown in figure 2:22. The efficiency is less than one, not only because of a small solid angle, but also because many kaons would decay before reaching the counters. It peaks at about 70 cms. However, due to unavoidable reasons the actual distance in the experiment was 84.0 cms., with a consequent loss in efficiency.

Neutron Counters.

In the experiment a ring of six identical neutron counters (fig. 2:21) was used to provide good azimuthal coverage. All counters in the ring being kinematically identical, if their electrical efficiencies are also equal, the detection efficiency of the whole ring would be six times the efficiency of a single counter.

Each counter was a cylinder of plastic scintill-

Efficiency of E-counters, as a function of their position, for detecting K^+K^- decays of the ϕ -meson.

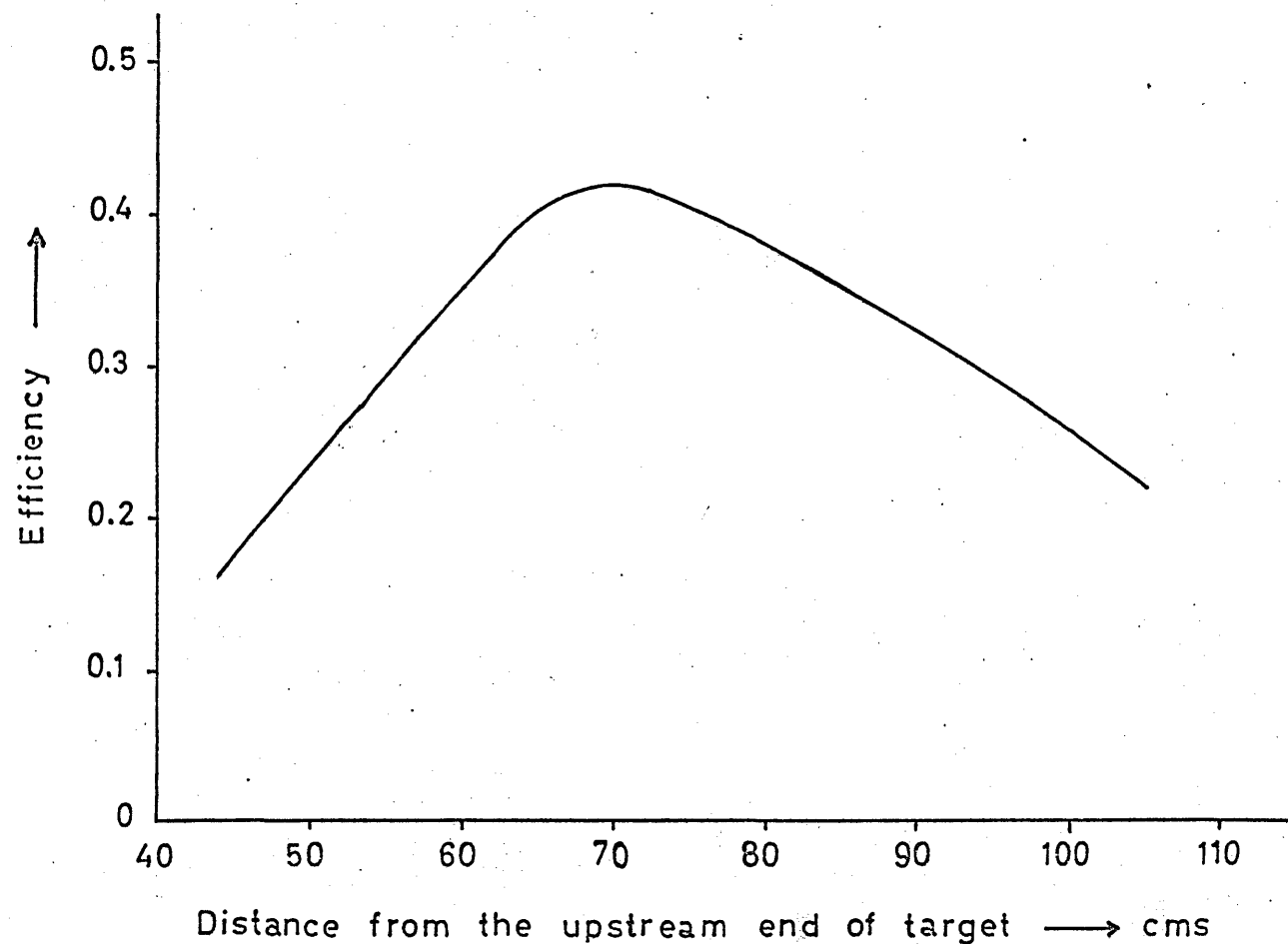


Fig. 2 : 22

ator (NE 102A) 30 cms. long and 30 cms. in diameter viewed parallel to the incident beam direction. The convergence angle of the perspex light pipe was small (17°) so that a big fraction of light from the scintillator would reach the photocathode after only one reflection. The scintillator was viewed by a 58-AVP photomultiplier which has a large photocathode area (11 cm. diameter) and a short rise time. The ring of counters was arranged upon a trolley which enabled their distance from the target to be easily varied.

The known timing resolution (0.83 ± 0.2 ns, measured in an earlier experiment), and the neutron detection efficiency (about one-third) of these counters were adequate for the needs of the present experiment. The requirements of a large solid angle ($\Omega \propto 1/L^2$) and high mass resolution ($\Delta M \propto 1/L$) conflict and, therefore, a compromise has to be made between the two. A distance of about 4 metres from the target was chosen as then the error introduced in the missing mass measurement due to the uncertainty in the time of flight measurement and the neutron angle measurement was well-matched to that due to the uncertainty in the incident momentum. The mass resolution and the solid angle were both adequate for our purpose.

The Cerenkov counter.

This counter was a rectangular box made from

0.2 cm. thick aluminium, and the dimensions were 30 cms. X 30 cms. X 5 cms. The thickness of the water column had to be sufficient to yield a large number of Cerenkov photons from pions of velocity greater than $0.75c$, but not so big as to cause an unbearable loss of kaons by such processes as delta-ray formation or by interactions with water molecules or by stopping in water. The thickness was made 5 cms. to give about 800 photons from a pion. A six cm. hole was made in the centre to allow the unused beam to pass through without triggering the counter unnecessarily.

The column of water was viewed by 12 56-AVP photomultipliers, six of which were above the counter and six below. The inside walls were painted with a white diffusing paint so that light travelling initially in any direction would spread out isotropically and a large solid angle could be covered by the photocathodes. The detection efficiency for beam particles going straight through (traversing 5 cms. of water) was measured using the lowest bias on the discriminator to which the Cerenkov photomultiplier pulses were applied. This turned out to be about 97% which was reasonably high for our purpose. The efficiency was also reasonably uniform over the entire area of the counter. A diagram of the Cerenkov counter is shown in figure 2:23.

The water Čerenkov counter

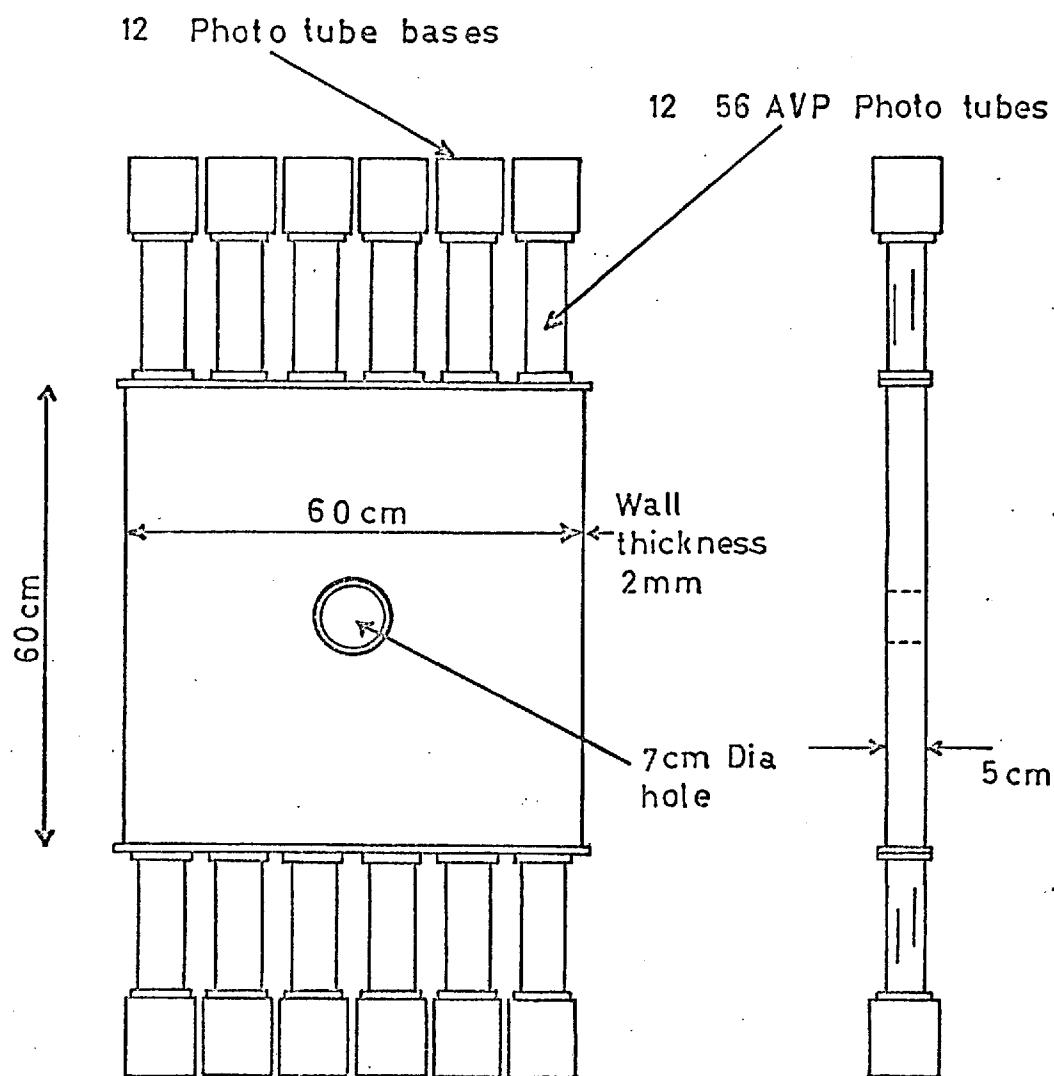


Fig. 2 : 23

CHAPTER IIITHE ELECTRONICS3:1 Introduction.

Each scintillation counter (and a Cerenkov counter, above threshold) supplies a current pulse, on the passage of a charged particle through it, by means of the light produced that actuates the attached photomultiplier. This pulse also contains the useful timing information as the time that elapses between its appearance and the passage of the charged particle through the counter is well fixed. A wanted event would give rise to a certain set of pulses from the system of counters. The duty of the electronics, then, is to make use of this pulse-information and provide an output signal implying the production of the event. Unwanted background events that succeed in producing the same set of pulses also get recorded but they can be eliminated in various ways afterwards. Of course, the electronics must be designed so that it can reject as much of the background as possible. The efficiency for detecting the signal must be high and preferably constant.

The electronic logic in our experiment was responsible, mainly, for doing the following jobs: the infor-

mation so obtained being necessary and sufficient to measure production cross section.

- 1). To record the number of beam particles of known momenta in each hodoscope channel, and,
- 2). to record the time of flight spectra of the events produced by particles of the required momenta.

The need for accuracy in the cross section measurement requires that both of these duties be performed efficiently. Effects that can alter the efficiency, and the corrections applied for them are discussed in section 3:3.

3:2 The Master Logic.

A block diagram showing the basic logic of our selection system is given in figure (3:1). A more detailed diagram appears in figures (3:2) and (3:3). Ready made Rutherford Lab. logic units (discriminators, OR gates, AND gates, etc), were employed in building up our electronic logic. The Master Coincidence, Co4, was represented by the logical requirement,

$$Co4 = (Co3. \sum_4^7 P_{\pi}). \bar{A}_0. (Co2). (delayed Co1).$$

The logical units in brackets above are labelled in the diagram and will be discussed below.

The coincidence Co3, or $S_2. \bar{A}_7$, served as our timing signal. Combined with one of the hodoscope signals

Basic selection logic

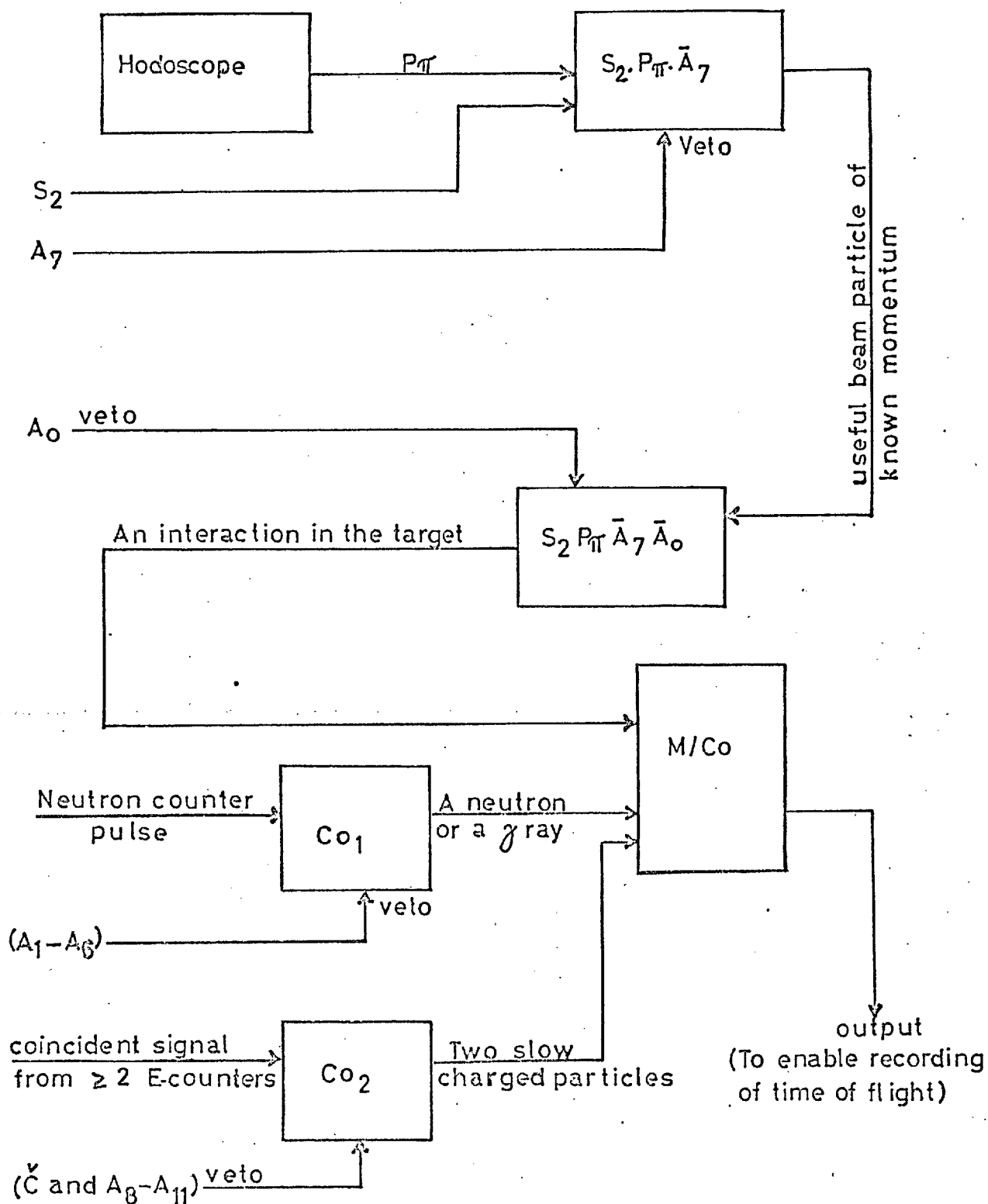


Fig. 3:1

Electronic logic (continued)

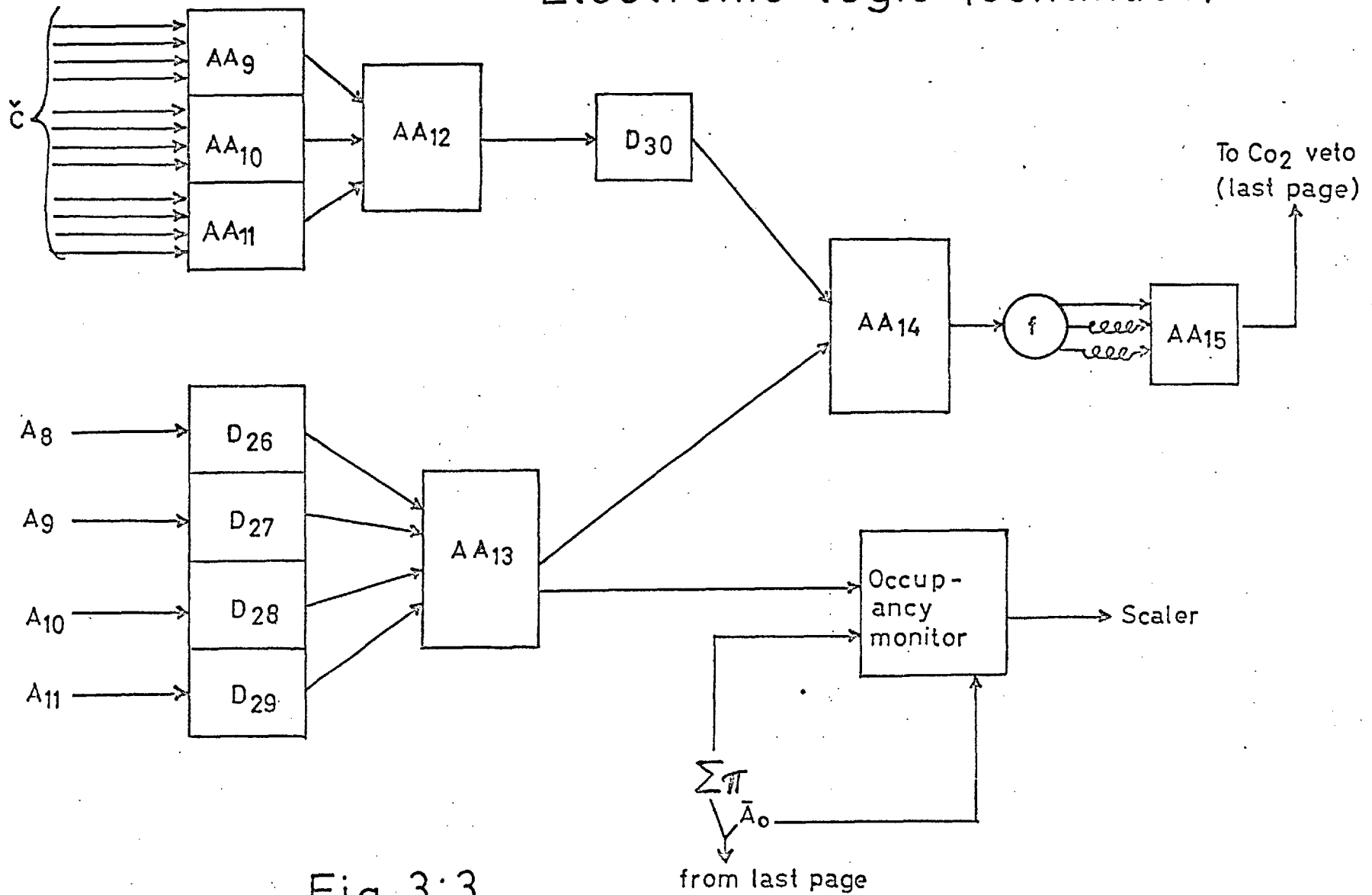


Fig. 3:3

$P_{\pi i}$, that is, in the form $S_2 \cdot \bar{A}_7 \cdot P_{\pi i}$, it represented our flux in the i th momentum channel. The logic Co3. $\sum_4^7 P_{\pi}$, was our useful beam flux in the four hodoscope channels combined.

The Co2 signal representing the logical output,

$$S_2 \cdot \sum_{\substack{i=1 \\ i \neq j}}^4 E_i \cdot E_j \cdot \bar{C} \cdot (\overline{A_8 + A_9 + A_{10} + A_{11}}),$$

indicated the detection of two slow charged particles emanating from the target, triggering two different E-counters, but giving no signal in the Cerenkov counter or in any one of the $A_8 - A_{11}$ counters surrounding the hydrogen target. Pulses from E-counter discriminators (D_{16} to D_{19}) were attenuated by a factor of two before they entered the analogue adder (linear adder) AA_7 . The discriminator D_{22} preceding Co2 was adjusted to have a threshold of about 22 ma. Thus at least two pulses had to coincide in AA_7 in order to trigger this discriminator. An S_2 pulse in Co2 was also demanded in order to reduce the number of accidental coincidences in its output rate.

A_0 veto was demanded in the coincidence circuit labelled $\sum \pi \bar{A}_0$, i.e; $S_2 \cdot \bar{A}_7 \cdot \sum_4^7 P_{\pi} \cdot \bar{A}_0$. The output signal from this implied an interaction in the hydrogen target.

The Co1 signal was supposed to indicate the

detection of a neutral particle (neutron or gamma ray) by one of the six neutron counters and the absence of a signal from any one of the six anti-counters, $A_1 - A_6$, placed in front of them. The logic for this was,

$$\frac{(Nc_1 + Nc_2 + \dots + Nc_6) \cdot (Nd_1 + Nd_2 + \dots + Nd_6) \cdot (A_1 + A_2 + \dots + A_6)}{\dots + A_6},$$

where Nc_i stands for an anode pulse and Nd_i for the corresponding last dynode pulse. The Nd signal was used to help improve the timing resolution as explained below.

The time of flight was recorded by converting the overlap between, essentially, an S_2 and a Co1 pulse, into a positive pulse whose height was proportional to the time of overlap. This pulse was generated by the Time-to-Pulse-Height-Converter (T.T.P.H.C.) gated by the Master coincidence pulse, and caused a count to be stored in one of the memories (or channels, one channel equalled 0.39 ns in width) of the Multi-channel Pulse-height Analyser (Kicksorter).

The spread in height of pulses from the Neutron counters was the chief source of timing error. As small pulses cross the discriminator level later than do large pulses, this caused variations in the delay through the discriminator (D_{20}) causing variations in the timing of the Co1 output. It will be seen from figure(3:4) that if the

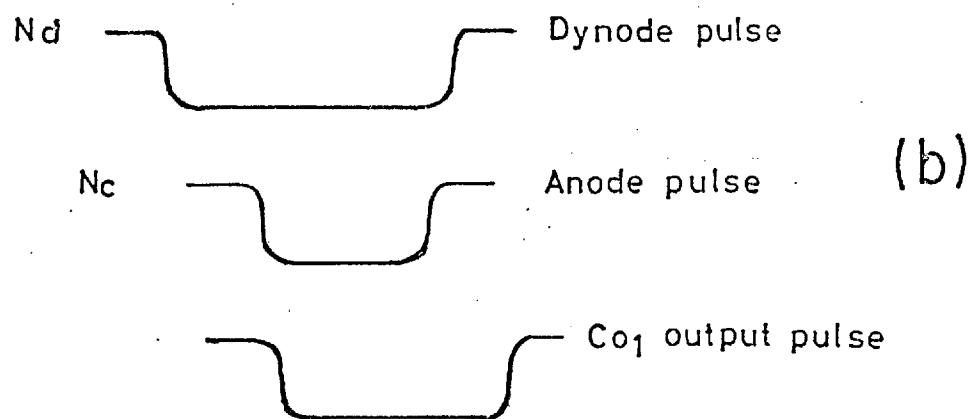
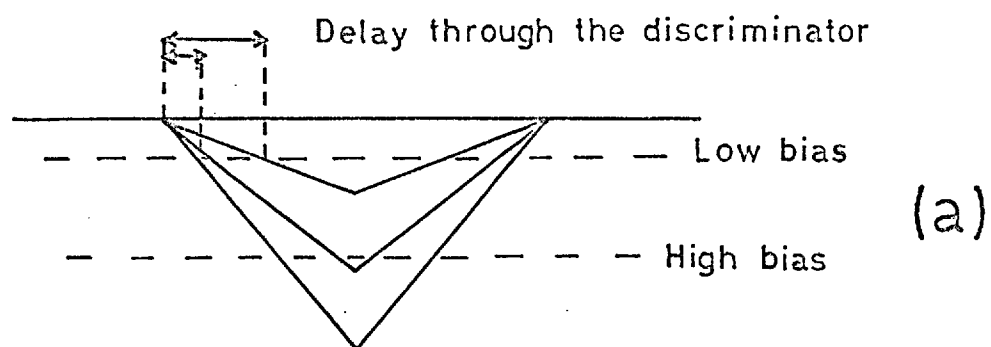


Fig. 3:4

discriminator threshold were very low and the input pulses always large only very small timing errors would occur. This was accomplished by using, in a double discriminator system,³⁴ the last dynode as well as the anode pulses from each of the six photomultipliers.

The former pulse, after inversion, was discriminated at a higher bias level by D_{21} whose threshold was adjusted to be about 10 ma in order to select large pulses. The anode pulse, however, was discriminated at the lowest bias level of 5 ma. By making it arrive later than the dynode pulse (figure 3:4), the instant of arrival of the N_c pulse was made to determine the timing of the $Co1$ output. A considerable gain in the timing accuracy was achieved in this way with a very little loss in neutron detection efficiency.

3:3 Efficiency of the Logic.

Several effects can interfere with the smooth working of the electronics causing an excess or a deficit in the true number of events. For example, a change in the efficiency of the Cerenkov counter or some other veto counter could change the amount of background collected. Similarly at high beam rates casual vetoing of events by anti-counters can result in the reduction of both signal and background; accidental coincidences between other channels have an

opposite effect, i.e.; an increase in the counting rate. Important factors in this connection are the following:-

- 1). Variations in the electrical efficiencies of counters,
- 2). high beam rates that increase dead-time losses in counting, give rise to "casual" triggers and also result in occupancy losses due to veto counters,
- 3). variations in the effective spill time, and,
- 4). other effects peculiar to the equipment used.

The electronics must aim at eliminating these effects or else monitor their contributions continuously. We shall discuss these effects one by one below.

(a) Efficiency of Counters.

The electrical efficiency of a scintillation counter for charged particles depends on the amount of light produced (minimum ionizing particles lose about 2 Mev of their kinetic energy per cm. of the scintillator traversed and this gives rise to about 20,000 photons), the light collection efficiency, the quantum efficiency of photoelectric emission, the E.H.T. supplied to the photomultiplier, and on the discrimination level of the electronic detector into which its pulses are fed. The pulse height distribution available from the counter is determined mainly by the first three factors. At suitably high E.H.T. values a good counter

will have a plateau in its efficiency vs. E.H.T.(or discriminator bias) curve. Efficiency curves for one of our counters are shown in figure(3:5). The plateau signifies that the smallest pulse has attained an amplitude sufficient to overcome the discrimination level. Figure(3:5) also shows the procedure for measuring counter efficiencies. The counter C, whose efficiency is required is placed in the beam between two small scintillation counters, C_1 and C_2 , so that any particle traversing C_1 and C_2 also goes through C. The efficiency of C is then simply the ratio of the coincidence rates, $(C_1.C.C_2)/(C_1.C_2)$.

If the E.H.T. is set in the region of the plateau then one can be reasonably sure that the electrical efficiency will remain constant in spite of small fluctuations in the supply voltage or the discrimination level. In this way one guards against instability in the Power supplies and in the electronics itself. Consistent with this requirement a low value of E.H.T. is to be preferred due to the low associated noise rate and the lesser danger of tube saturation at high counting rates.

No continuous monitors for the electrical efficiencies of our counters were used but all counters were, before the start of the experiment, checked for plateaus in

TYPICAL EFFICIENCY CURVES FOR A SCINTILLATION COUNTER

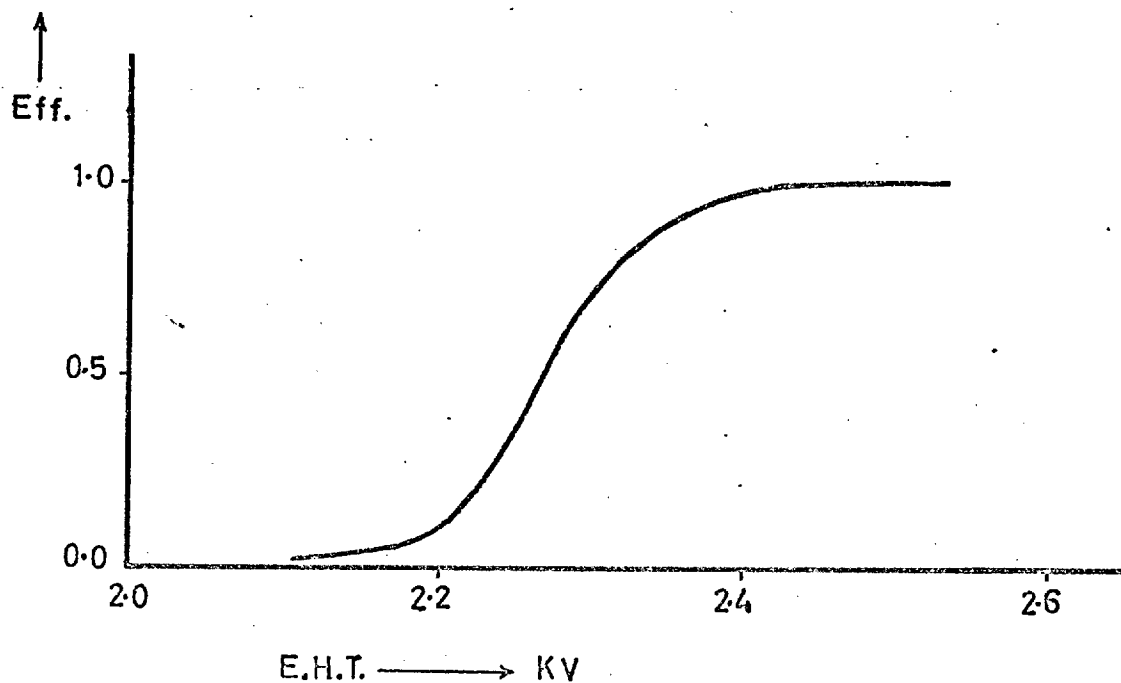
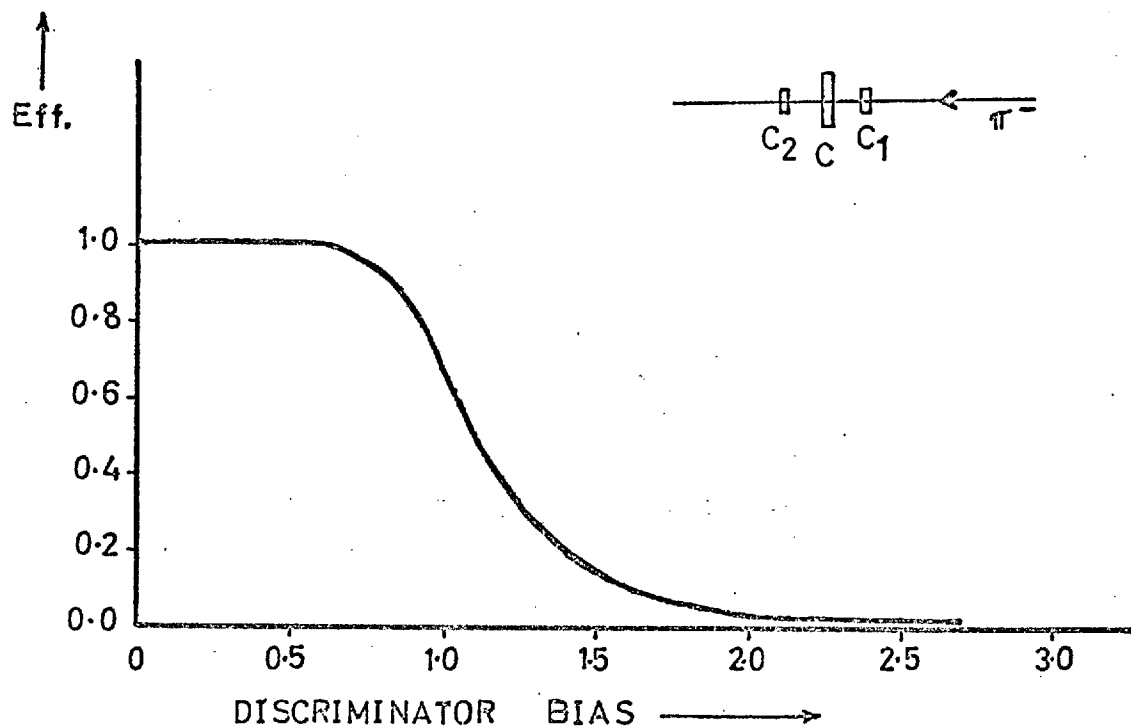


FIG. 3:5

their efficiency curves and the best operating E.H.T's were recorded for future reference. All counters were found to have fairly long plateaus except the six anti-counters A_1 - A_6 , that were only 95 to 98% efficient. This was probably due to their poor light collection efficiency. This small inefficiency, however, was not disturbing as at the worst it could only raise, slightly, the number of accidental background counts. The efficiency of the Cerenkov counter was checked from time to time.

(b) High Beam Rate Effects.

(i). Dead Time. Electronic circuits (e.g; discriminators, OR gates, etc) that re-shape and stretch pulses coming from photomultipliers suffer inherently from a characteristic dead time. During its dead time a circuit ceases to work and will not provide an output on the application of an input pulse, resulting in a loss of that pulse. The source of this dead time is found usually to be the finite time constant of an R-C component. The Rutherford Lab. discriminators have a dead time equal to the output pulse length(t_p). Thus after supplying a pulse of 50 ns a discriminator would become insensitive for the next 50 ns. Effectively the discriminator is dead for 2×50 ns. If during this insensitive time one or more pulses appear at the input no additional output

is produced. Since beam particles that give rise to pulses in scintillation counters arrive quite randomly in time the chance that a certain fraction of pulses would appear in a given interval is the same for all such intervals of equal length. Let us consider a simple case. Supposing that during an interval T , N particles arrived, N pulses would reach the discriminator. Let the output pulse length of the discriminator be t_p , so that its dead time is $2t_p = t_d$ ns (say). Now if ' n ' pulses are given out by the discriminator, $N - n$ are lost. Since the discriminator was triggered n times it presented a total dead time of $n \cdot t_d / 10^9$ second. One can then argue that at the rate of N/T particles per second, $N \cdot n \cdot t_d / (T \cdot 10^9)$ must have been lost. Hence,

$$N - n = N \cdot n \cdot t_d / (T \cdot 10^9) \quad \dots\dots\dots(3:1),$$

The fraction of particles lost is thus,

$$(n - n)/N = n \cdot t_d / (T \cdot 10^9) \quad \dots\dots\dots(3:2).$$

From (3:2) it follows that the dead time loss is inversely proportional to the length of the "spill time", T , and directly proportional to the output rate at which particles are being counted. Thus at high counting rates and/or when the spill time is small these losses assume large proportions and allowance has to be made for them.

If the veto channel of a coincidence circuit

suffers from dead time this can result in additional background, for the dead time would hamper the vetoing efficiency.

In our electronic logic dead time losses were kept to a minimum by employing the smallest pulse lengths (about 10 ns) circuits could work with, especially in branches of the logic where rates were high. Besides this, for counting beam particles, fast 100 Mc/s scalars were used that could work off the discriminator output directly. (Slower 10 Mc/s scalars at Rutherford Lab. need an intermediate 'type II' generator for amplifying and stretching discriminator pulses, with the consequent dead time loss). As the circuits feeding the scalars had dead times of 20 ns no dead time correction was necessary for the scalars.

To achieve zero dead time in veto channels two techniques were used:

- 1). A triad was constructed by fanning-out the output pulse of a discriminator (pulse length t_p ns, say) along three branches into which delays of zero, t_p and $2t_p$ ns were inserted before they combined again in an analogue adder. The output pulse from the analogue adder was then three times t_p as shown in figure (3:6a) and this was applied to the veto input. Since the length of this pulse now

Addition of pulses in a triad

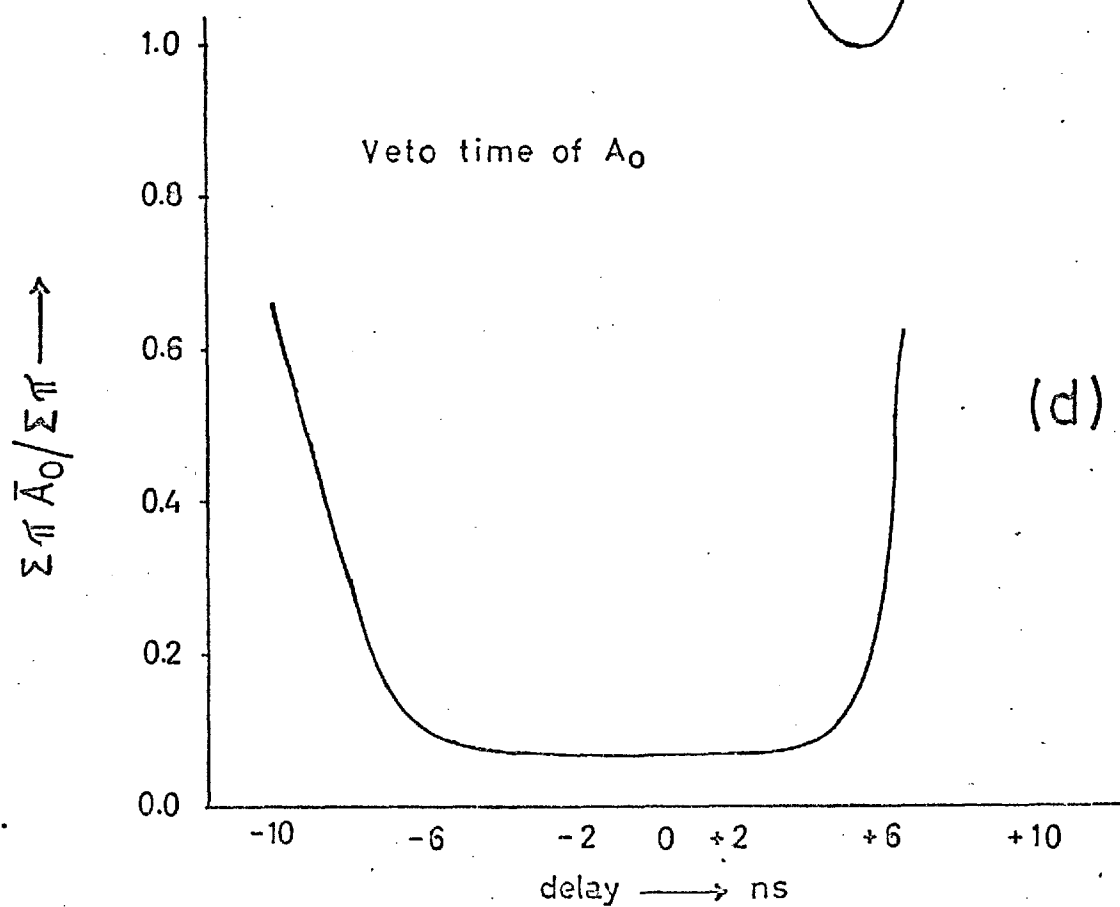
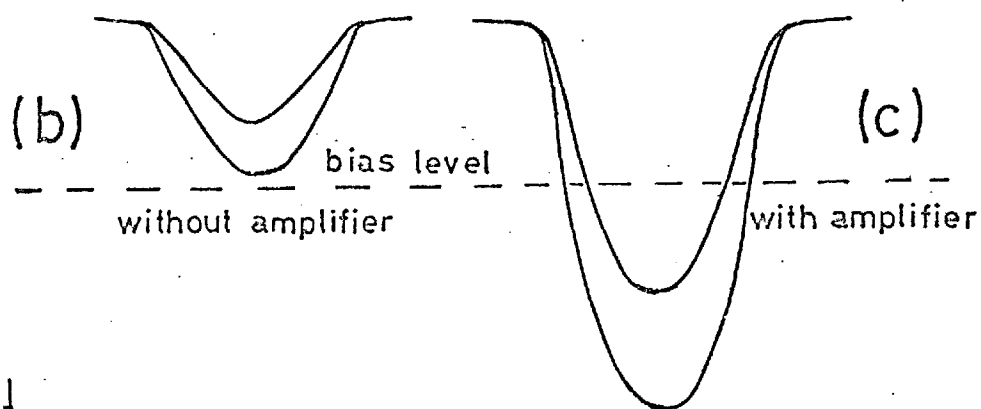
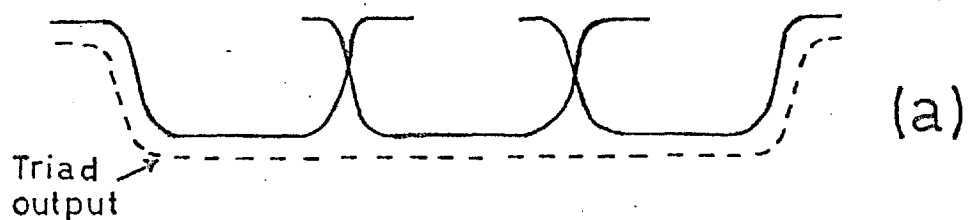


Fig. 3:6

was 1.5 times the dead time of the discriminator it is obvious that an output from the analogue adder would always be present when needed.

2). In the other scheme no discriminator was used at all but instead pulses direct from the photomultiplier, which has practically no dead time, were used after passing them through an amplifier. A high value of E.H.T. could not be used as sagging of the photomultiplier pulses took place particularly at high beam rates resulting in variations in the effective veto length especially as the veto threshold is not well-defined. This necessitated the use of a low E.H.T. but the pulses were not big enough, without an amplifier, to cross the veto threshold as shown in figures 3:6 (b and c).

The second method with its smaller veto time was used only in case of A_0 since it had the highest counting rate due to being in the beam, while triads were used for other veto counters having smaller rates in them. A one - inch thick scintillator was used for A_0 in order to achieve a small spread in pulse height. The resolution curve for this veto counter is shown in figure (3:6d). It has a full width at half-height of only 16 ns. The curve has a wide flat bottom and steep edges which are very desirable features.

(ii). Casuals. In a cross section measurement one is interested in counting the number of beam particles as well as the number of interesting events that satisfy a certain logical requirement. This requirement usually takes the form of a coincidence between two or more counter pulses, and the absence of a veto pulse from some others. For example, as shown in figure (3:7 b) a coincidence between C_1 , C_2 and B and no pulse from A would indicate a typical nuclear interaction. Coincidences between C_1 and C_2 alone could be used to count beam particles.

The rates associated with different counters are different and due to diverse causes. For example, some particles going through C_1 may not pass through C_2 while some passing through C_2 may not have come from C_1 and may be due to parasitic background. The rate through B is partly due to interactions in the hydrogen target and partly due to beam particles scattering into it. Beam particles that interact in the target and then send interaction products into B produce correlated pulses in C_1 , C_2 and B. Those which do not interact produce correlated pulses in C_1 , C_2 and A. A coincidence circuit is supposed to produce an output pulse whenever two or more counters feeding it produce correlated pulses (that are arranged beforehand to coincide) in the coincidence box. However, due to the finite

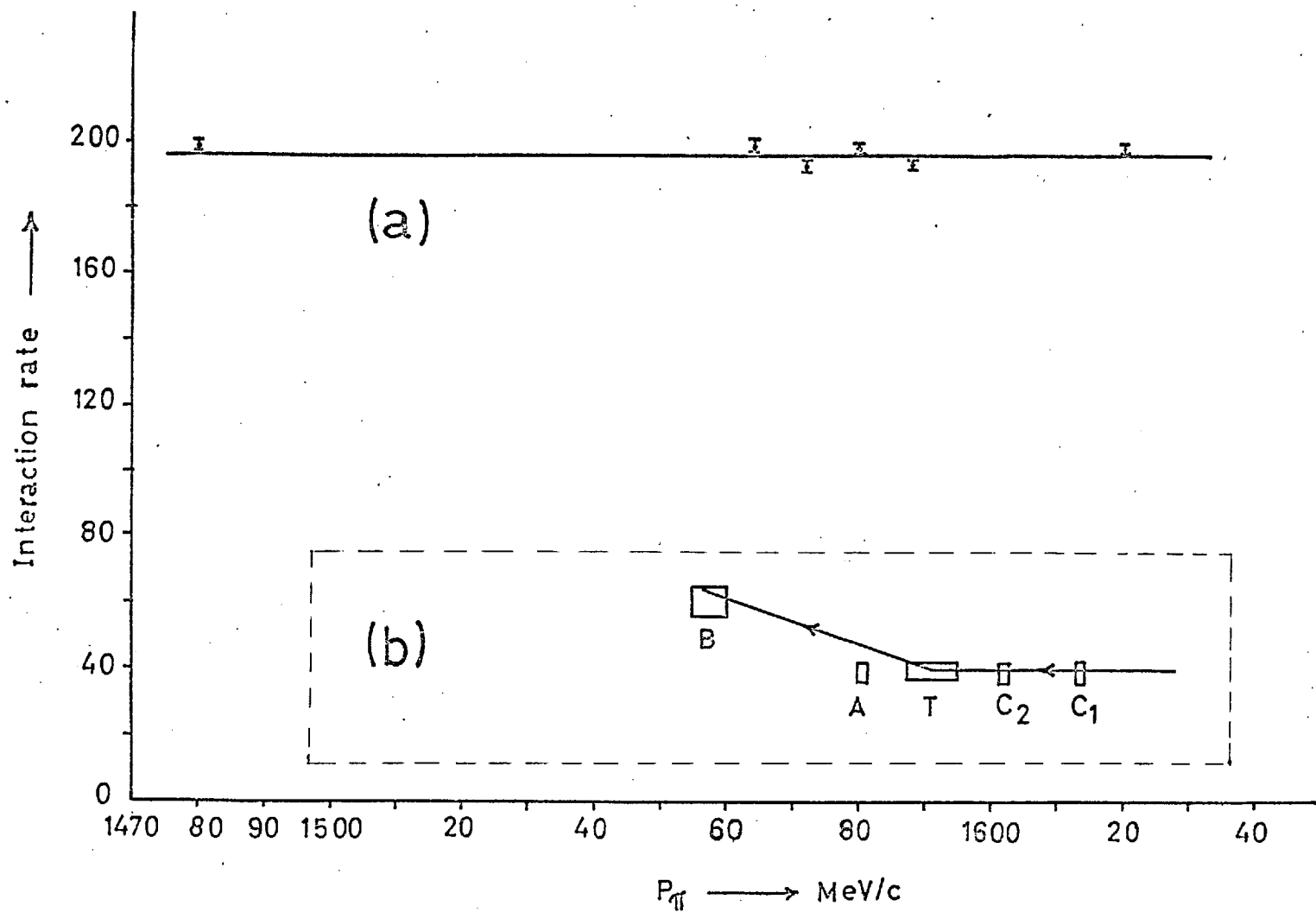


Fig. 3:7

resolving time, τ , of this circuit uncorrelated pulses also have a finite chance of coinciding and providing a spurious output signal called a "casual" coincidence. An important property of such coincidences is that their rate is independent of the delays present in the feeding channels (save when the beam has some kind of modulation on it, to be discussed later), but depends only on the product of the counts (N_1, N_2) going into the two channels, the resolving time τ , and inversely upon the effective spill time T , during which the above counts are recorded. Thus,

$$\text{Number of casuals, } N_{c1} = N_1 \cdot N_2 \cdot \tau / T \dots\dots\dots (3:3).$$

The usual way to measure casuals contributing to a coincident rate is to delay one of the input signals by a large enough amount so that genuine coincidences cannot occur. The output then would be due only to casuals. The number of casuals thus measured can, in fact, be used to evaluate T , the effective spill time. For,

$$T_{\text{eff}} = N_1 \cdot N_2 \cdot \tau / N_{c1} \dots\dots\dots (3:4).$$

The output rate of a coincidence circuit thus always contains a contribution from casuals which can be quite large at high rates. This must be measured and then subtracted from the total rate to get the true coincidence rate.

The task of subtracting casuals in this way

becomes more difficult when, (a). a coincidence circuit has more than two input channels under use, and, (b). the spill time is not constant. In such a case measuring the casual background at one time would not suffice, for it can vary widely from time to time.

(iii). Occupancy. The pulse rate going into the veto channel of the coincidence box has its casual effect as well, for some wanted events can get vetoed simply because a veto pulse happened to be present, accidentally, at that time. This can happen due to two reasons, namely, either a stray particle (or noise pulse) happened to trigger the counter at that time, or the previous beam pulse in the anti-counter was too close in time to a good event. This results in a loss of the signal as well as of any background process being counted. The fraction "k" of the events thus lost is known as the occupancy of the veto counter. Supposing the true coincidence rate to be "m", if the total rate from the anti-counter be N_a and t_p be its pulse length, then the veto is operative for a time $N_a \cdot t_p$. Since 'm' events would have been recorded in T second, those lost in $N_a \cdot t_p$ second are given by, $m \cdot N_a \cdot t_p / T$. The fraction lost = $m \cdot N_a \cdot t_p / (mT)$ = $N_a \cdot t_p / T$. Hence,

$$\text{the occupancy, } k = N_a \cdot t_p / T \quad \dots\dots(3:5).$$

As before, for a given number of beam bursts the occupancy can be measured by delaying the pulses from the anti-counter by a suitable amount. If the total coincidence rate without the veto be 'p', and that with the veto signal delayed be 'p₁', then the required occupancy is given by the ratio, (p - p₁)/p. Here we have neglected the small contribution to the output rate due to casuals between the two (or more) coincidence channels of the circuit. The true occupancy is thus slightly higher (true p₁ is slightly smaller) than that obtained from the above relation. Using the value of the resolving time indicated in figure (3:6d) for A₀ and its counting rate, the value of its occupancy using formula (3:5) was calculated. This tallied almost exactly with the value measured by the ratio of the counting rates,

$$\left(\text{Co3.} \sum P_{\pi} \cdot (A_8 + \dots + A_{11}) - \text{Co3.} \sum P_{\pi} \cdot (A_8 + \dots + A_{11} \text{ . delayed } \overline{A}_0) \right) / \left(\text{Co3.} \sum P_{\pi} \cdot (A_8 + \dots + A_{11}) \right).$$

This procedure is useful only if a quick idea of the occupancy is required during a few beam bursts, but the result cannot be relied upon to hold over extended periods of time, as the beam rate as well as the spill time can fluctuate widely. This calls for continuous monitoring

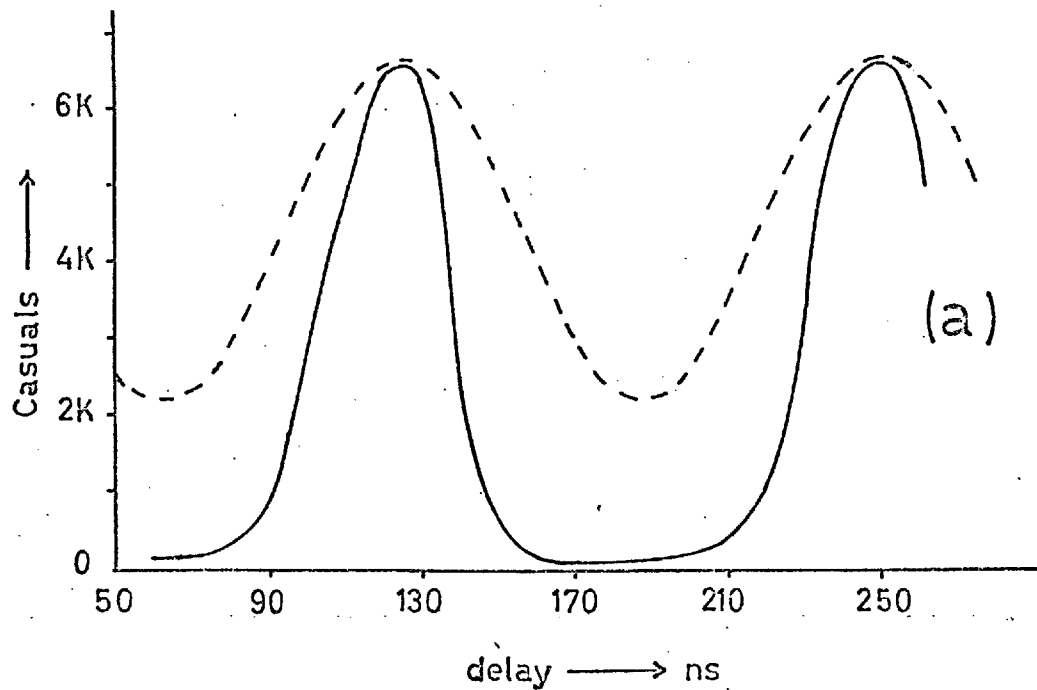
of the occupancy of the veto counter. The same applies to any important accidental background.

Casuals and Occupancy Monitors. Two sources of casuals were important in our Master coincidence rate:

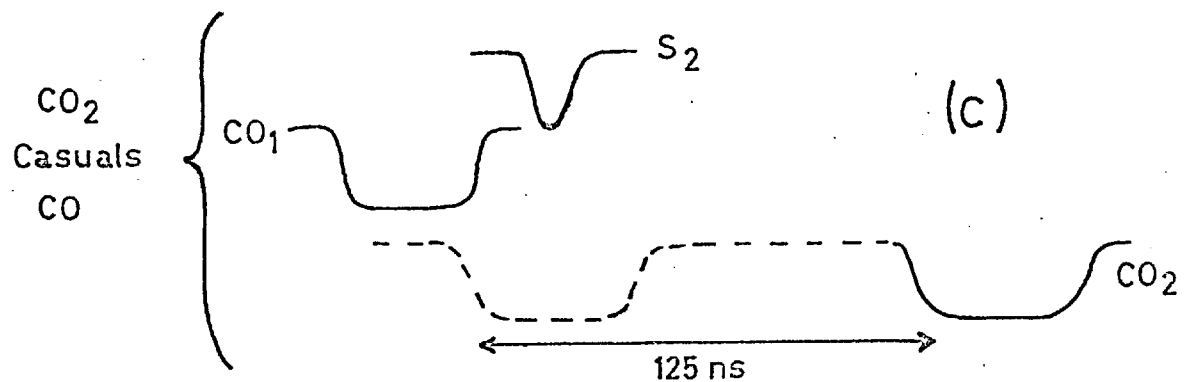
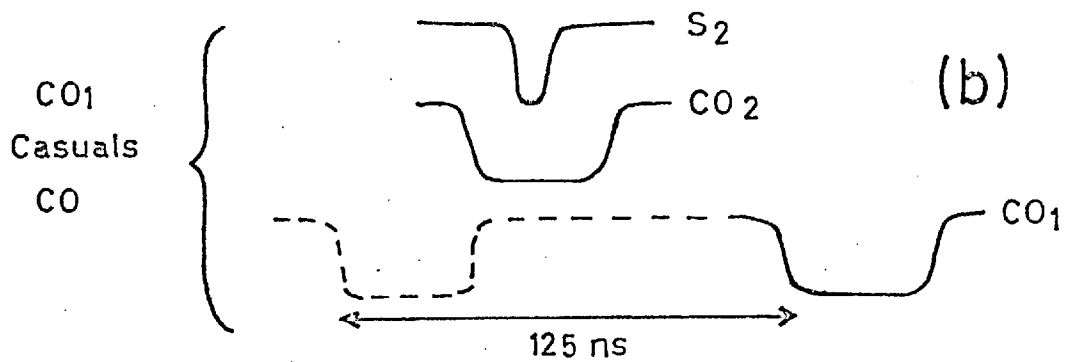
(a). "Neutron or Co1 casuals", in which case a genuine Co2 and Co3. $\sum P_{\pi}$ coincidence happened to coincide in Co4 with a random pulse from one of the neutron counters(through Co1), and, (b). "E-counter or Co2 casuals", where a genuine Co1 and Co3. $\sum \bar{P}_{\pi}$ coincidence occurred simultaneously with a random pulse from Co2. The purely random background due to all the three signals coinciding by chance would, of course, be negligible as it involves the product of two extremely small resolving times.

Two coincidence circuits were set up especially to monitor continuously these casuals during every data run. Co1 and Co2 pulses were delayed by 125 ns each from their normal time in Co4 (figure 3:8) in view of the RF modulation present on the beam(see next section). The length of the Co1 pulse determined the range of time of flight covered. This length, in the Master Co., was made about 25 ns long in order to collect a wide spectrum of neutrons starting from the gamma-ray time of flight. For the purpose of measuring casuals, however, a smaller length of 5.5 ns

Fig. 3:8



Timing positions of pulses in:



was chosen to cover only the region (CD in fig. 2:12) where most of the signal accumulated. By using a number of AND gates (not shown) the sum of the two types of casualls(Co1 + Co2) was monitored for each of the four momentum channels.

The Occupancy Monitor. In our selection system three sources of occupancy were present viz; one due to A_0 , another due to $(\check{C} + A_8 + \dots + A_{11})$, and the third due to $(A_1 + \dots + A_6)$ veto counters. However, only A_0 occupancy was monitored continuously as it was the highest of all due to practically the whole beam passing through A_0 . Towards this end a well-defined interaction rate that required no veto signal from A_0 was continuously scaled during every data run. A_0 veto was, however, added in order to study the effect of its occupancy on the rate. The logic for this rate was thus,

$$Co3. \sum_4^7 P .(A_8 + \dots + A_{11}). \bar{A}_0 ,$$

that is, we demanded an interaction in the target from which at least one product went at a large angle into one of the counters surrounding the target.

The same rate was also measured at a very low beam intensity(occupancy negligible) as a function of the beam momentum from 1480 to 1630 Mev/c and was found to be practically constant. This is plotted in figure 3:7(a).

Any variation in the output rate of this circuit, in the main experiment, could only be due to variations in the occupancy of A_0 caused by changes in beam rate and/or changes in the spill time. Thus at the end of a data run an average value of the occupancy due to A_0 could be obtained by simply comparing the true interaction rate, I_0 , with the one (I , say) measured in course of the run. A small contribution to the rate I could arise from casuals between the two coincidence channels (fig. 3:3) which was measured once for all as a fraction of the A_0 occupancy, as it is expected to be proportional to it. If the contribution from casuals be ' $b k I_0$ ' when the occupancy is ' k ', we have,

$$I = (I_0 + b k I_0) \cdot (1 - k) \quad \dots\dots\dots(3:6),$$

or,
$$b \cdot k^2 + (1 - b) \cdot k + (I/I_0 - 1) = 0,$$

whence ' k ' can be easily evaluated.

(c). Variations in the Effective Spill Time.

R.F. Modulation. During the operating time of each individual accelerator cycle, the intensity of particle emission can, for different reasons, be variable. In particular under the influence of a high-frequency field, the so-called fine-structure (or R.F. structure) occurs. The intensity gets modulated with the frequency of the given field, and extremely short pulses can be formed. The modulation para-

meters depend upon the type of accelerator as well as on the system of operations and the method of obtaining the particle beam.

In the proton-synchrotron at Rutherford Lab. a π^- beam is obtained by the scattering of high energy protons by a metal target placed inside the accelerator. The frequency of the high frequency field is about 8 Mc/s. The π^- beam was found to be modulated in intensity with this frequency. This was verified by measuring, as a function of delay, the rate of accidental coincidences between two scintillation counters placed in the external beam. Solid curve in figure (3:8a) shows how the casuals varied with delay. The dashed curve shows what one expects as a result of 100%, pure sinusoidal modulation, of this frequency.

The effect of modulation is to change the effective spill time; the higher the modulation the smaller the spill time becomes. Assuming perfect sinusoidal modulation it can be proved(see appendix C) that the effective spill time is given by,

$$T_{\text{eff}} = 2T/(2 + M^2) \dots\dots\dots(3:7),$$

where T is the apparent length of the beam spill as seen on the oscilloscope when looking at a counter placed in

the beam, and M is the intensity of modulation. Thus when M is 1(100% modulation) the effective spill time would be two thirds of the apparent spill time. As a result any accidental coincidence rate would go up by a factor of 1.5. The above formula was derived assuming that the resolving time of the coincidence circuit is very much smaller than one R.F. period.

Another interesting effect of the R-F modulation is to invalidate the usual procedure for measuring casual coincidences occurring in a coincidence circuit. The probability of a chance coincidence now does depend upon the delay used, and to measure the correct casuals rate a delay equal to one R-F period has to be used, because regions of equal intensity are now separated by this time interval. It is shown in appendix C that the number of casuals when the relative delay between the coincidence channels is δ , is given by,

$$N_{c1} = N_1 N_2 \tau (1 + M^2 \cos \omega \delta / 2) / T \dots\dots\dots(3:8),$$

where τ is the resolving time of the coincidence unit ($\tau \ll T$), N_1 and N_2 are the counting rates per burst going into the two channels and M is the intensity of modulation. If a delay equal to one R-F period is used the formula becomes,

$$N_{c11} = N_1 N_2 \tau (2 + M^2) / 2T \dots\dots\dots(3:9).$$

Similarly, if $\delta = T/2$, we have,

$$N_{c1\frac{1}{2}} = N_1 N_2 \tau (2 - M^2)/2T \dots\dots\dots(3:10).$$

The ratio of these two casuals rates, i.e;

$$N_{c11}/N_{c1\frac{1}{2}} = (2 + M^2)/(2 - M^2) \dots\dots\dots(3:11),$$

which directly gives the intensity of modulation of the beam.

If one assumes Square-wave modulation the spill time can be quite small depending upon the "mark to space" ratio (m/s). Given 100% square-wave modulation, the shape of the casuals vs. delay curve is expected to be triangular with a full-width at half-height equal to "m" second, the peaks being separated by (m + s) second. Our observed curve can be better understood if we assume 100% square-wave modulation where the beam particles are concentrated in a region of about 40 ns duration. In figure (3:8) the dashed curve shows what one expects from 100% sinusoidal modulation but the agreement with the observed curve is not good.

The dead-time loss increases under conditions of modulation simply because the spill time goes down. If the spill times under conditions of "no modulation" and "modulation" be T and T' respectively, then the dead time losses per second, would be in the ratio, T'/T.

In our experiment as the beam was modulated with a frequency of about 8 Mc/s, a delay of 125 ns was always used whenever a measurement of casuals between two channels was required. Spill times and the intensity of modulation were measured by setting up two coincidence circuits, one measuring N_{c11} and the other $N_{c1\frac{1}{2}}$, using a resolving time of 10 ns in each circuit. A knowledge of the intensity of modulation provides an independent check on the condition of the spill.

We now discuss other miscellaneous high rate effects.

P π Doubles Veto.

At high beam rates there was quite a big chance of two particles arriving very close in time in two different hodoscope channels. The distribution of intervals between successive beam particles follows the exponential law. If the mean interval (reciprocal of mean rate per second) be t_0 , then the probability that no particle will arrive for t second after a given particle, is given by, $\exp(-t/t_0)$. The chance that a particle will arrive is, $(1 - \exp(-t/t_0))$. Thus the higher the beam rate the greater is the chance of two particles arriving within a certain interval t . In case of four hodoscope channels counting

at nearly the same rate the second particle would, 75% of the time, arrive in a different channel. If one of them produced an event, a Master Co. and two P_π signal would arrive at the Routing box (figure 3:2). This circuit was responsible for providing a logical signal to the kicksorter to store the event in the right momentum block. But in the case of two P_π pulses the box would usually provide a wrong signal to the kicksorter. This would have caused a complication for which a correction could not be easily applied. Hence it was decided to veto all such events where two beam particles arrived in two different P_π channels within 10 ns of each other, and also to discount these particles. The simplest way of doing this was to generate a pulse whenever this happened and to use it to veto the S_2 pulse in Co3. The veto pulse was generated by the discriminator D_1 whose threshold was set at about 30 ma so that it could trigger only when two or more pulses overlapped in the preceding analogue adder AA_1 fed by the four hodoscope signals.

If two particles arrived in the same P_π channel within 10 ns of each other one of them would not be counted causing a loss of beam particles. This loss was calculated using the known beam rate and the resolving time.

Kicksorter Busy Time.

The kicksorter had a dead time of about 100 micro-seconds. If another event were produced during this time it would not have been recorded. One could either apply a correction to the data accumulated in the kick-sorter or else stop counting beam particles as well as inhibit the Master Co. during the kicksorter busy time. The first method requires a knowledge of the spill time which cannot be measured accurately; therefore, the second method was employed. The kicksorter provided a positive "busy" pulse during its dead time. This was inverted in polarity and used as a veto in Co3 along with A_7 and P_π - doubles vetos by combining them all in the Analogue adder AA_2 .

3.4 Data Taking.

The experiment was performed in November, 1966, when Nimrod was operating at its full energy of 7 Gev and at a pulse repetition rate of 25 pulses per minute. A flat-top targeting arrangement with the R-F field left on was used. The time structure of the spill was continuously monitored on a slow-sweep oscilloscope in addition to using the spill time monitors already described.

Neutron time of flight spectra were accumulated

at 9 different settings of the current in the bending magnet BM2 and the other beam line elements, thus yielding spectra for 36 values of the incident momentum spanning the range from 1478 Mev/c (below ϕ threshold) to 1680 Mev/c (above ϕ threshold). This range was enough to cover a 20 Mev/c^2 mass range on both sides of the ϕ mass and also to yield the necessary information about the backgrounds. Spectra were produced by 200-500 million incident beam particles and took about 6 to 8 hours to accumulate.

It was important to have an accurate relative measurement of the incident momentum because of the very rapid changes of the time of flight spectra with momentum. To this end the magnetic field in the bending magnet was measured and monitored with a nuclear magnetic resonance device (N.M.R.).

As a check on the stability of the apparatus several intermediate prints-out of the kicksorter memory were made during the accumulation of each spectrum. These prints out were checked for consistency with each other. In addition rates in various parts of the logic were continuously monitored. Before starting a data run these rates were measured and compared with their previously accepted values. Any significant change in one or more of these rates would be the manifestation of a fault in the part or parts

of the logic concerned which could then be easily located and the fault set right. These rates were also checked when the intermediate prints-out were taken. The rates that were monitored are as follows:-

- (1). The flux in each hodoscope channel as well as the total flux. The flux was compared with the coincidence rate, MM , of a telescope of two thin scintillation counters placed near Nimrod. The rate MM was a measure of the intensity of the circulating proton beam and our flux was expected to be proportional to it. All other rates were compared with the beam flux.
- (2). $Co3. \sum P_{\pi} . \bar{A}_0$, or the total interaction rate of the incident pions with liquid hydrogen in the target;
- (3). $Co3. \sum P_{\pi} . \bar{A}_0 . Co1$, that is the rate of production of neutrons and gamma rays that triggered the neutron counters and had times of flight of upto 30 ns greater than the gamma ray time;
- (4). The $Co2$ rate or the rate of production of two slow charged particles.

The details of the measured background rates and of the corrections to the counting rates that were made are described in the next chapter.

CHAPTER IV

ANALYSIS OF THE EXPERIMENTAL DATA

4:1 Consistency Checks on the Data.

The complexity of the apparatus and the electronic logic demanded that frequent checks be made on the data for consistency to ensure that, (a) no faults had developed in any part of the logic, and (b) the rest of the system(counters,etc) was also in good order. Accordingly, the key rates, that were monitored continuously in the experiment, were checked in the middle and at the end of each momentum run to see if they were reasonable and also agreed with their previously accepted values. In addition counts in the gamma peak and those in the large time of flight region(where there are no nKK events), from each t-o-f spectrum, were normalized to 10^8 beam particles, corrected for occupancy, and compared with each other, respectively, and with those obtained from the previous spectra.

The gamma counts were produced by π^0 decay and fast neutrons from the reaction (2:17(iii)) taking place in the target and also by gammas and fast neutrons produced by secondary interactions in the apparatus downstream of the target. For reasons discussed in section 2:4 the yield of these counts should vary very slowly with momentum. If, for some reason,(e.g; occupancy, scaler dead time,but not a

change in the Cerenkov counter efficiency) the normalized number of counts in the gamma peak showed a significantly large fluctuation, one expected the entire spectrum to be affected accordingly. Thus a check on our normalization was afforded by the rate, γ/π .

The data comprising the t-o-f spectra and other rates, obtained in the first six($S_4 \rightarrow S_9$) momentum settings, were found to be quite consistent internally. For instance, the occupancy values of A_0 , deduced from the measured interaction rates, were quite reasonable and agreed well with their expected values at the beam rates and the spill time values concerned. γ/π from these data, after occupancy correction, are plotted in fig. 4:1, and are peaked around the same value with a very small spread. A least squares fit(see sect.5:2) using the hypothesis, $\gamma/\pi = m \cdot P_\pi + C$, yielded a χ^2 -probability of 28%, the value of 'm' being 0.06 which, incidentally, connotes a negligibly small change in γ/π over our range of momentum. The rate $\sum \pi \bar{A}_0$ was found to be flat against P_π , as expected, and is plotted in fig.4:3. Similarly, the rate $\sum \pi \bar{A}_0$. Co1, was also found to be fairly constant with momentum. In addition, the normalized rate of nK^+K^- events obtained, after occupancy correction, from spectra taken at different times but at almost the same momentum agreed with each other within statistical errors.

A very significant drop in the rates, $\sum \pi \bar{A}_0$ and

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Counts in the 'gamma peak,' per 10^8 beam particles
 $(S_4 - S_9)$

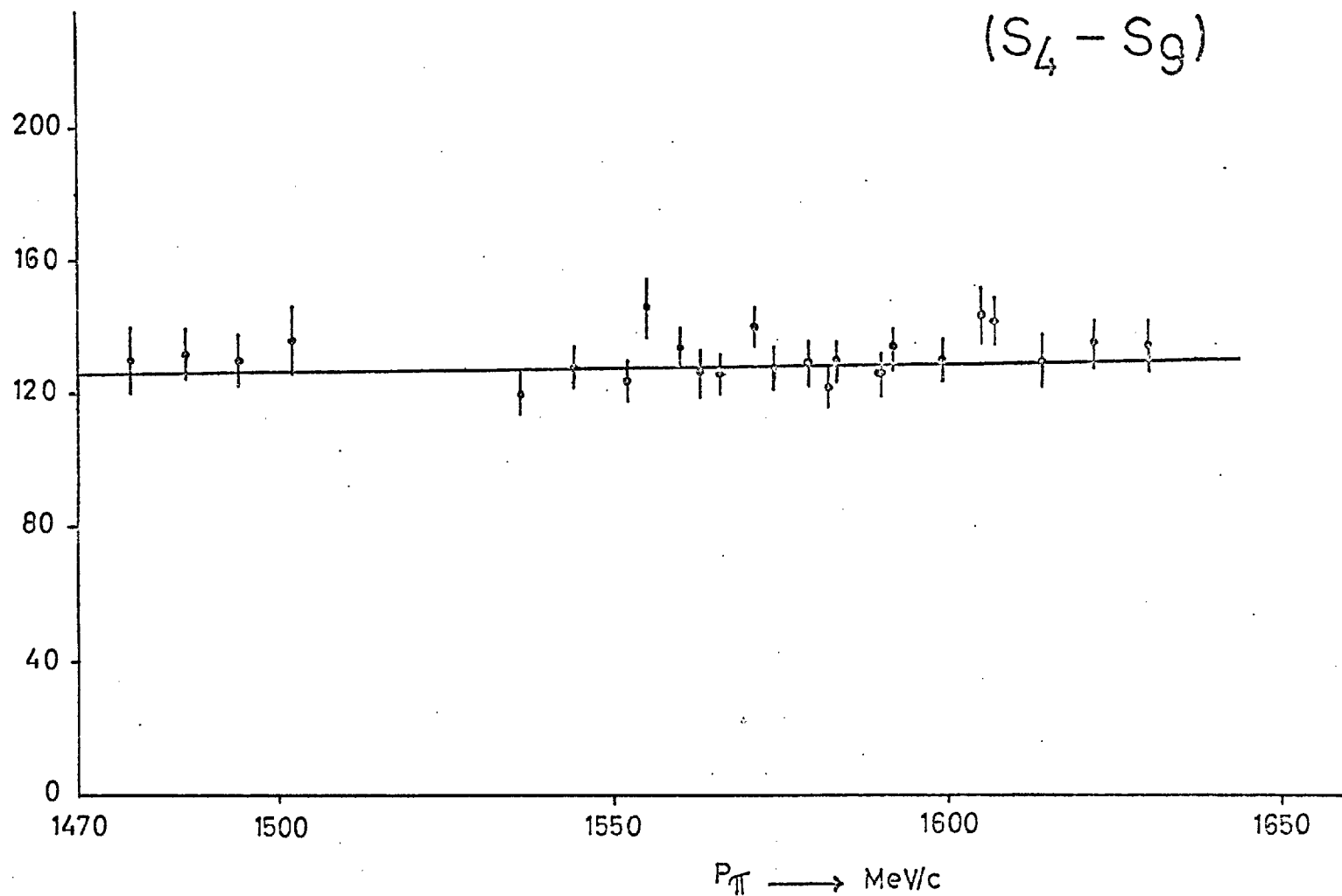


Fig. 4:1

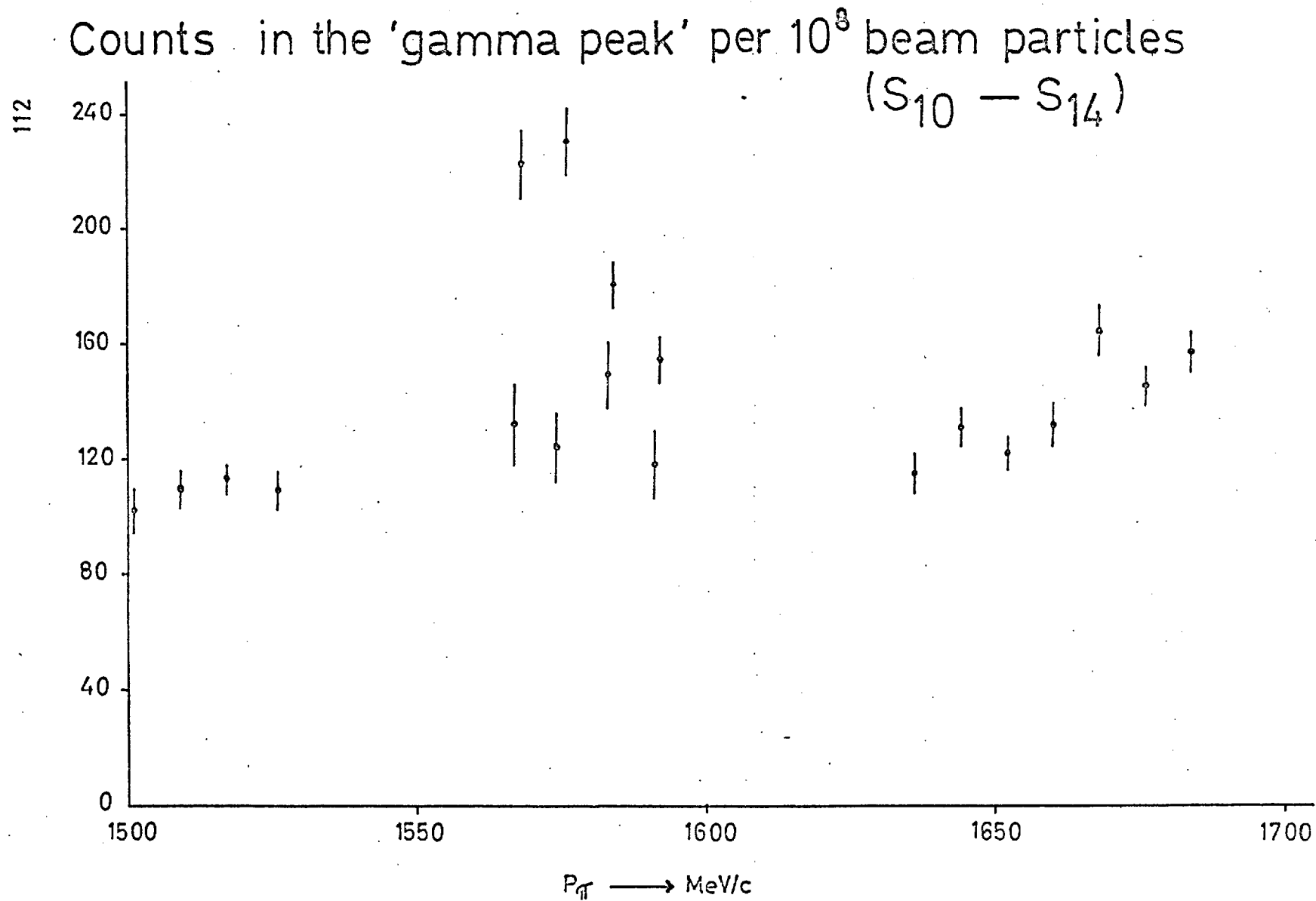


Fig. 4 : 2

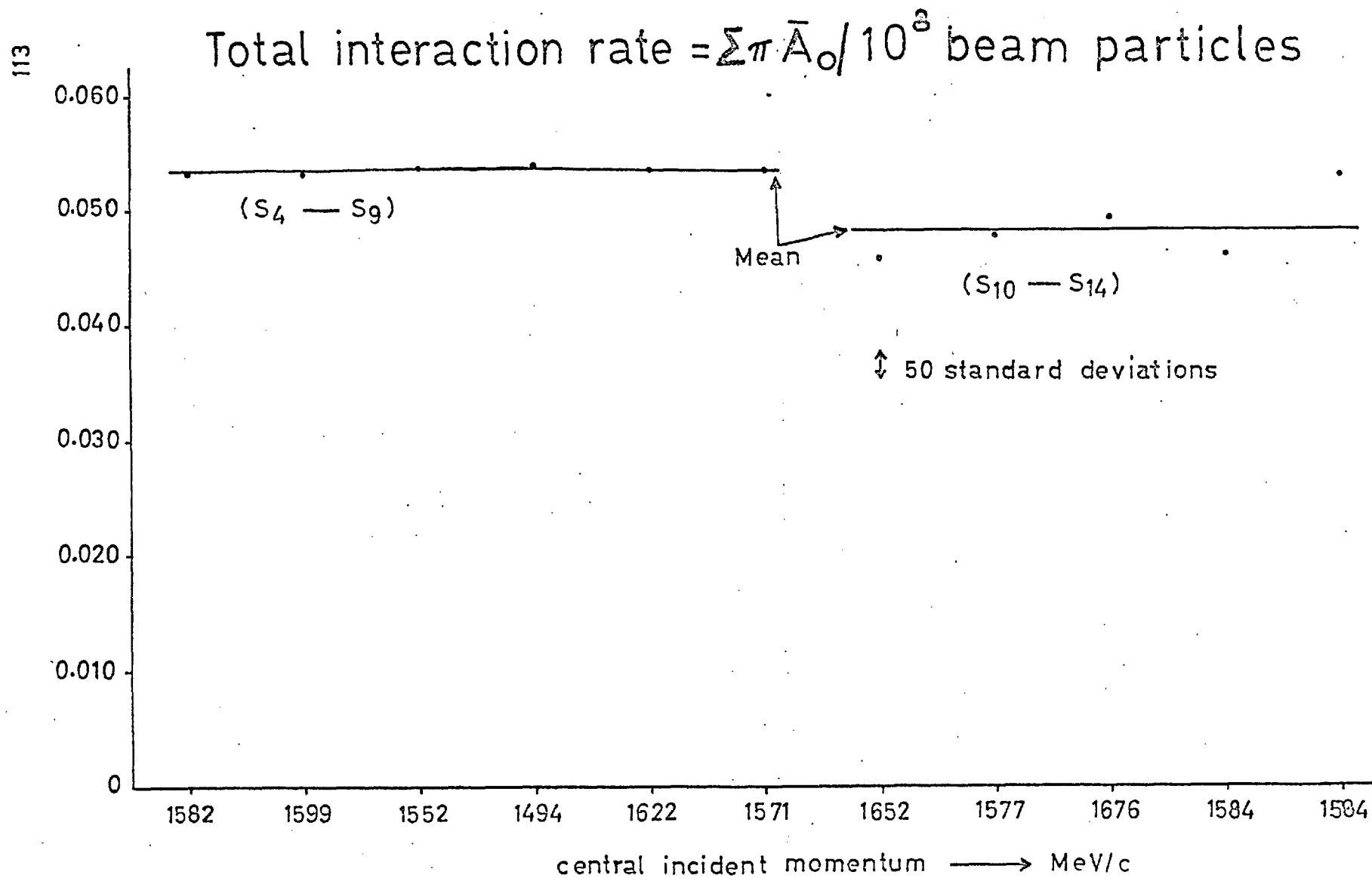


Fig. 4:3

$\sum \pi \bar{A}_0$. Co1, however, took place in the data taken after S_9 (i.e; $S_{10} - S_{14}$). The low rates could not be accounted for by the lack of hydrogen in the target, nor due to an increase in the A_0 occupancy which was now also much higher (15 to 20%) than expected. The rate $\sum \pi \bar{A}_0$, for S_{10} to S_{14} after occupancy correction, is plotted in fig.4:3. It is not only low but is characterized by great fluctuations. γ/π corrected for occupancy are plotted in fig.4:2; the χ^2 -probability concerning the hypothesis, $\gamma/\pi = m.P_\pi + C$, was found to be zero.

An attempt was made to make these data useful by normalizing the counts in the nKK region to the counts in the gamma peak. Unfortunately, this did not help as the normalized rates belonging to the same momentum turned out to be significantly different. As no plausible explanation could be found for the inconsistencies present in these data, they were discarded.

4:2 Positioning of the Timing Gate.

In order to count the number of events in a given t-o-f spectrum, the position of the timing gate has to be accurately known. Near the threshold the phi peak is situated at the time of flight (t_c) corresponding to the c.m. velocity, B_{cms} . The time corresponding to the velocity of light is obtained from a knowledge of the position of the gamma peak. Then with the help of the known calibration (channels/ns) of the kicksorter, any timing gate can be easily located on the time of flight spectrum.

Table 4-1

Kicksorter print-out	Central momentum (MeV/c)	$\Sigma \pi / 10^8$	$\Sigma \pi \bar{A}_0 / 10^6$	Interactions/ 10^6 (occupancy monitor)	$\Sigma \pi A_0 \cdot Co_1 / 10^6$	Casuals	
						Co ₁	Co ₂
S ₄	1580	15.5	76.0	34.6	1.7	16	42
S ₅	1597	16.4	80.2	36.4	1.8	19	56
S ₆	1550	16.9	83.6	37.8	1.9	18	40
S ₇	1492	5.7	28.9	12.9	0.65	8	15
S ₈	1620	8.4	42.6	19.2	0.97	15	24
S ₉	1569	10.8	54.1	24.5	1.25	18	33

Experimental neutron time of flight spectra (i)

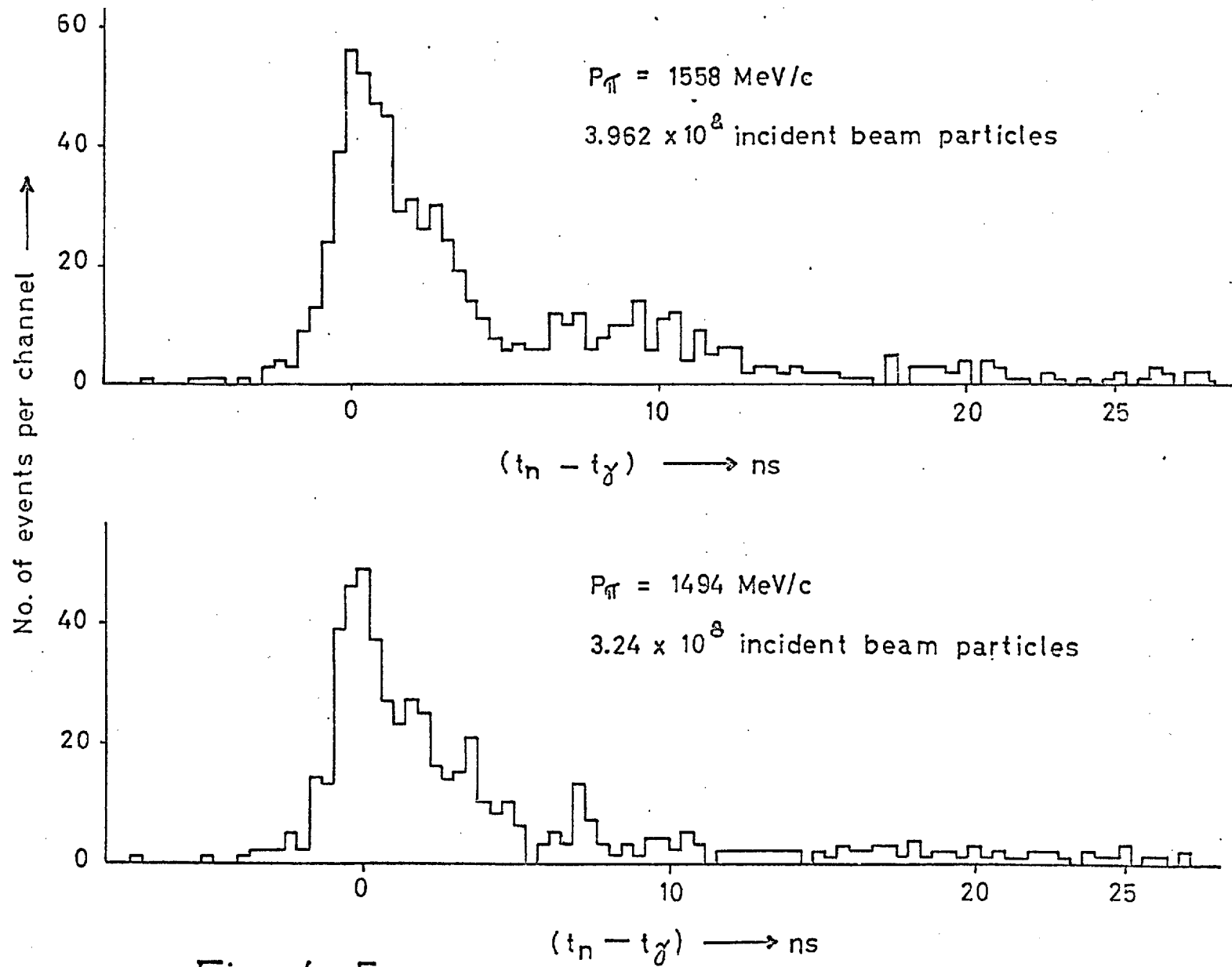


Fig. 4 : 5

Experimental neutron time of flight spectra (ii)

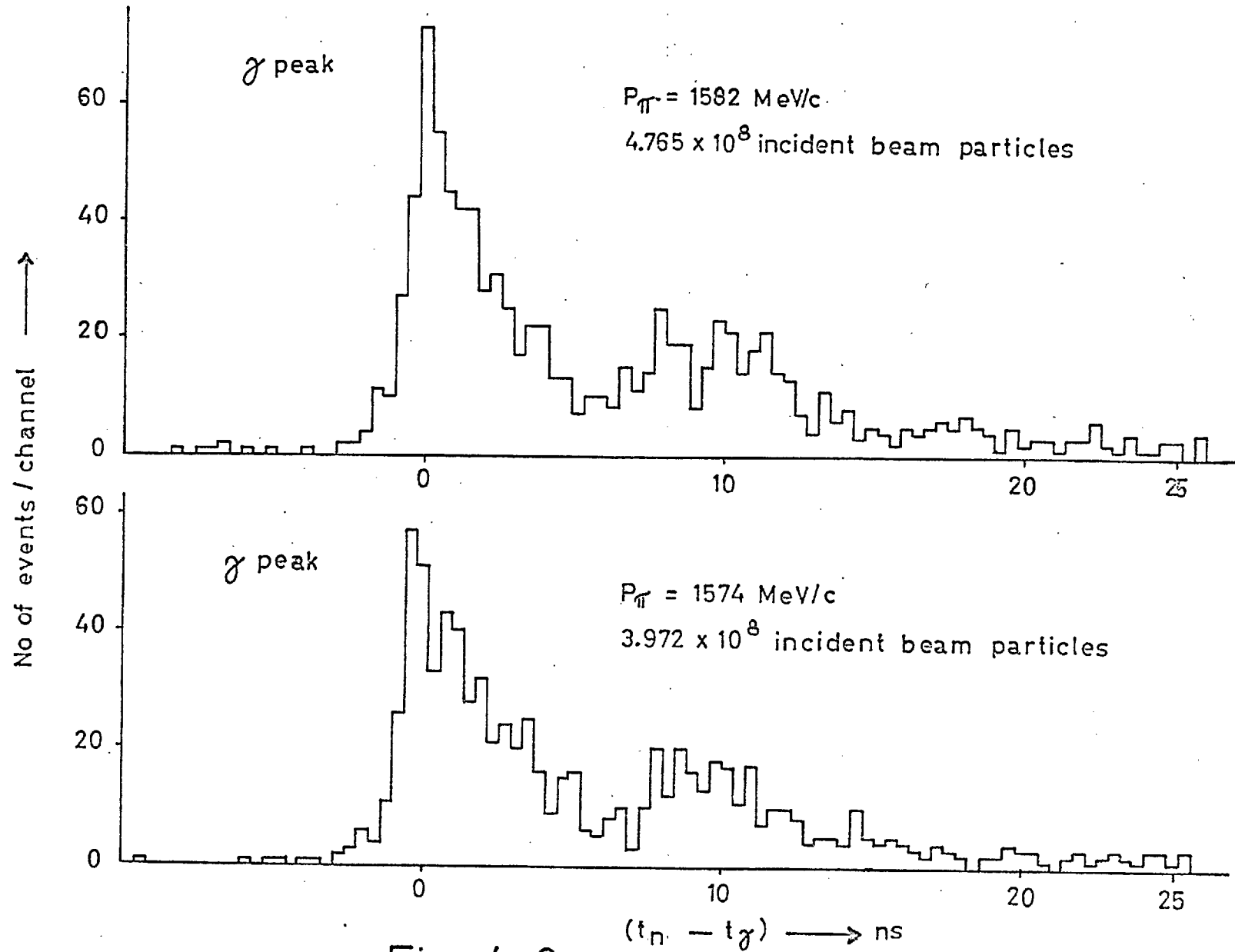


Fig. 4:6

Experimental neutron time of flight spectra (iii)

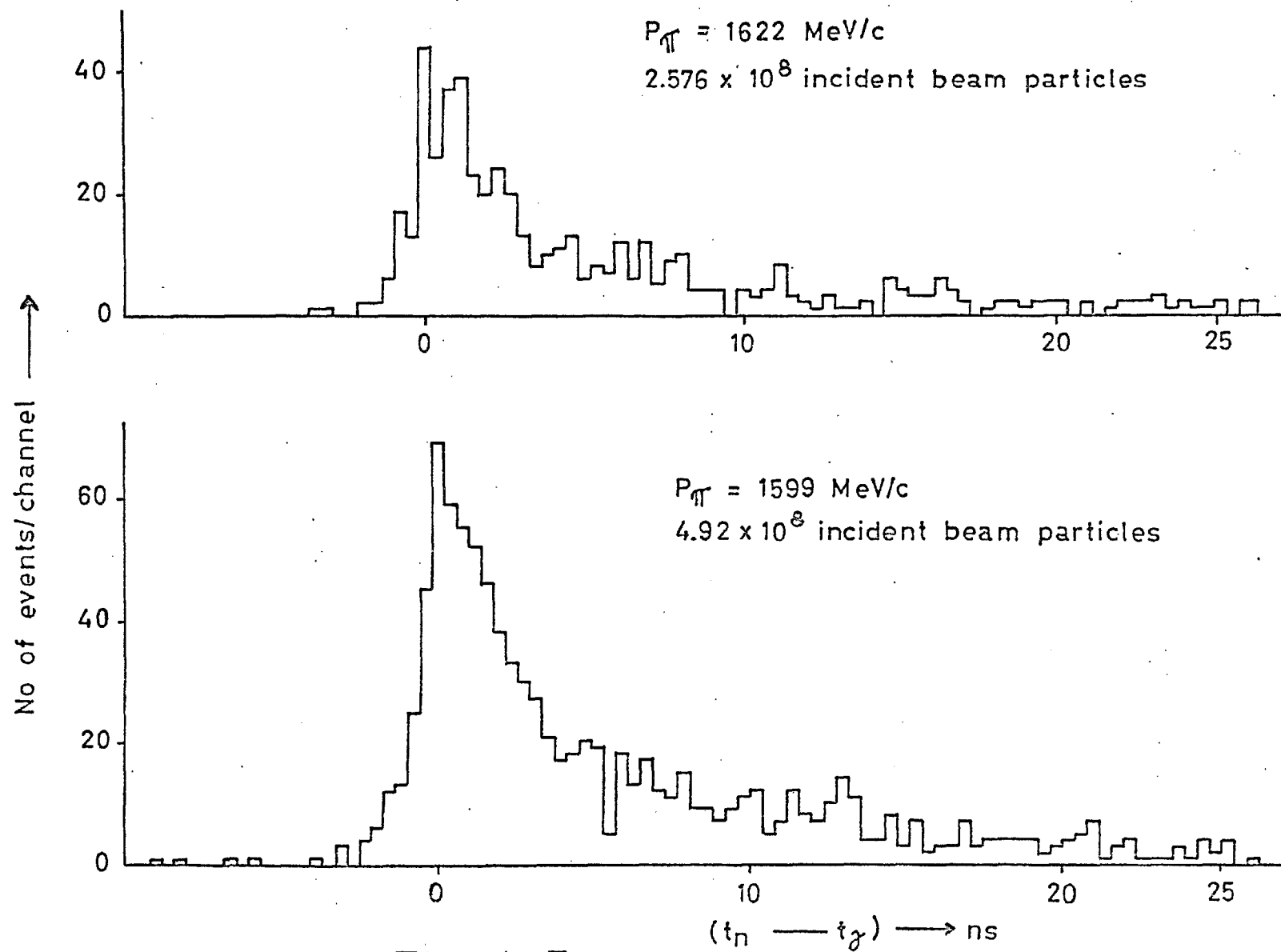


Fig. 4:7

To overcome the lack of statistics, all the four spectra obtained at each momentum setting were added together to determine the position of the gamma peak. The time($t_c - t_o$) depends only on the distance of the neutron counters from the target and the velocity, B_{cms} . The interval, $t_c - t_o$, when measured from the experimental time of flight spectra turned out to be somewhat longer than expected. Since the position of an event on the timing spectrum is directly proportional to the delay between the neutron counter and S_2 pulses, it was obvious that pulses from gamma rays were being detected somewhat too early.

The most likely explanation of this effect seems to be that gamma rays, unlike neutrons, are detected by the production of electron pairs. These travel faster than light, producing Cerenkov light in the scintillator(besides scintillation light) and in the light guide into which they are likely to go due to their small opening angle. Thus not only more light is produced in the case of gamma rays but it is also likely to reach the photocathode earlier than light due to neutrons. As large pulses trigger the discriminator earlier than small pulses both of the above causes can shift the gamma peak towards a smaller time of flight. The same should be true of the fast charged particles in the beam. And in fact the positions of the gamma peaks obtained from the experimental spectra agreed within ± 0.2 ns(half a kicksorter channel)

with the corresponding positions of the beam particle peaks that were recorded before every new momentum setting. The beam particle peak was produced on the kicksorter by recording the t-o-f of the beam particles scattering in the target and then entering the neutron counters.

The systematic error in the time of flight mentioned above was determined by a comparison of the Monte Carlo and the experimental time of flight spectra for 1580 Mev/c incident pion momentum. At this momentum the ϕ yield is the highest and, therefore, the error could be determined more accurately. This error was found to be 1.0 ± 0.3 ns.

Having determined the gamma peak positions for all the six sets of the time of flight spectra, $S_4 - S_9$, and the above timing error a suitable timing gate was chosen to count the number of events for the purpose of analysis. The required positions and widths of the timing gates were found from a study of the Monte Carlo spectra which had the timing resolution of 0.83 ns folded in.

4:3 Background Subtraction.

(a). Casuals. The next step in the treatment of the kick-sorter data was to subtract the non- K^+K^- background and the sum of the Co1 and Co2 casuals mentioned in section 3:3. The subtraction of the latter did not present any difficulty as it had been monitored during the experiment for each and

every time of flight spectrum, and could be directly subtracted if exactly the same timing gate were used in the analysis as had been employed in the casuals monitoring circuits. For gate widths other than this the number of casuals was taken to be proportional to the gate width. This was valid because due to the dominance of "Co1" casuals the shape of the time of flight spectrum of the (Co1 + Co2) casuals that was obtained in the experiment did not have any structure in the region over which counts from the nK^+K^- final state extend.

(b). Non- K^+K^- (pion) Background.

As mentioned in section (2:4) any variations in our non- K^+K^- backgrounds are supposed to be smooth and slight. Therefore we do not expect the shape of the background spectrum to change as we proceed from 1480 Mev/c to 1630 Mev/c incident pion momentum.

It has been shown already in a previous section that the yield of events lying on the low time of flight side of the phi peak, i.e; the yield of the fast neutrons and the gamma events, does not change significantly as we go from 1480 Mev/c to 1630Mev/c beam momentum. Figure (4:8) shows a plot of the yield of events lying on the high time of flight side of the phi peak. The best fit

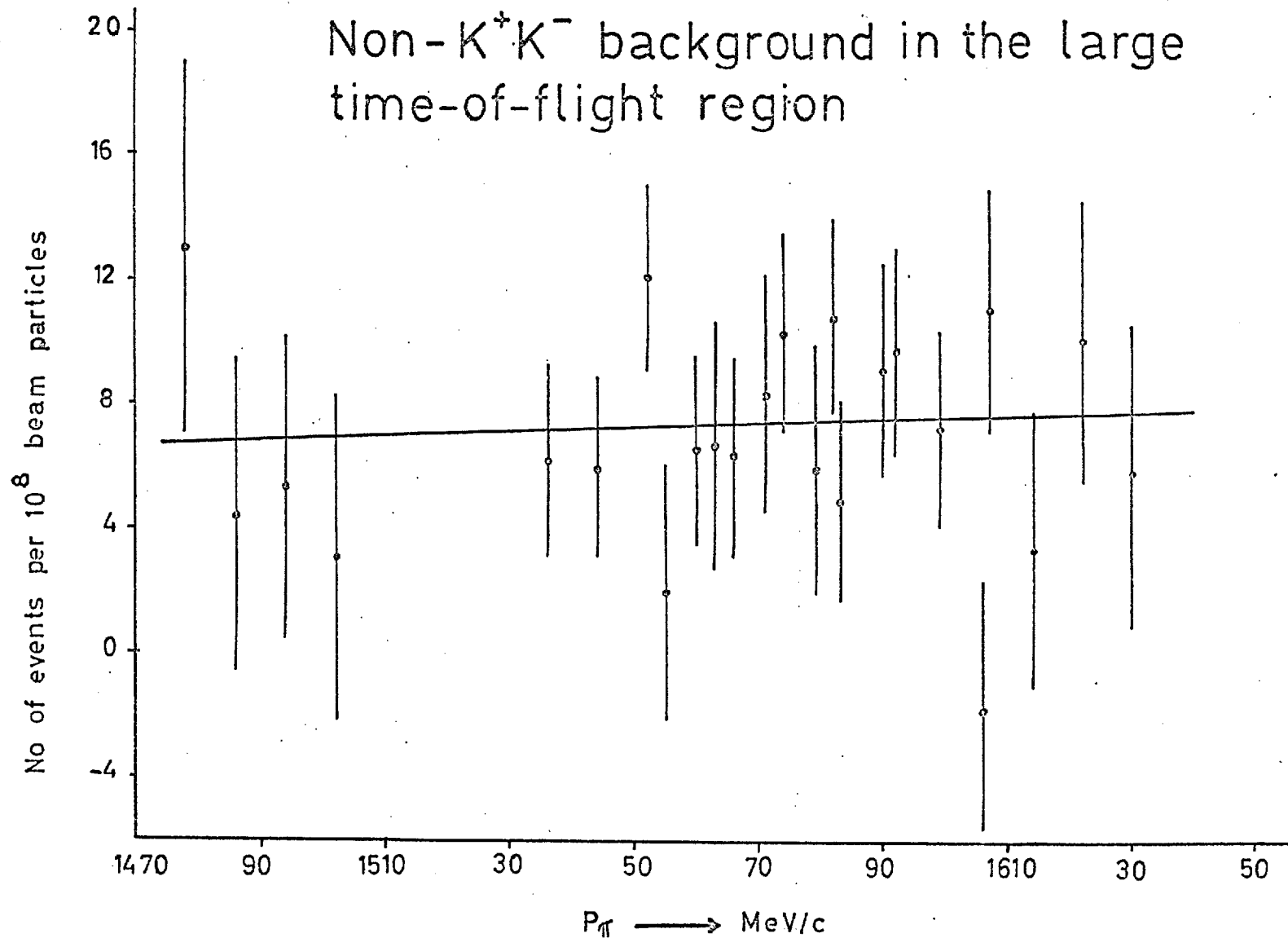


Fig. 4:8

to this, using the hypothesis, $\text{background} = m.P_{\pi} + C$, yielded an extremely small value of 'm' (= 0.006). We are thus reasonably justified in supposing that the background fluctuations inside our timing gates, would also not be statistically significant and we can assume this background to remain constant with momentum.

Four time of flight spectra taken below the nK^+K^- threshold (S_7), after being corrected for casuals and the veto counter occupancies, were used to give an estimate of this background inside a timing gate and this was subtracted from the yields from all the remaining spectra to obtain the number of nK^+K^- events. As a result of the process of background subtraction the statistical errors on the yields increased by 20 to 30 %.

4:4 The Systematic Error in Beam momentum and the Phi Mass.

The momentum settings were done in the experiment with the help of the floating wire calibration and the readings of the N.M.R frequency. The N.M.R enabled us to overcome the effect of hysteresis in the bending magnet, the current being adjusted until the correct frequency was obtained. Thus any relative momentum errors would be quite negligible.

It was thought that there was a systematic

error in the floating wire calibration which had been estimated to be of the order of 0.3 % of the central momentum (section 2:1). This was investigated by fitting the background subtracted experimental yield with the yield predicted by theory using the known phi mass of $1018.6 \pm 0.5 \text{ Mev}/c^2$. The momentum at which the yield peaks is characteristic of the mass of the resonance produced. Only the first ten yield points (around 1580 Mev/c) were used for this purpose as the K^+K^- background here is small. By shifting the incident momentum scale through 1 Mev/c each time a value of minimized χ^2 was obtained. The result is plotted in figure (4:9a). In figure (4:9b) the ordinate has been changed from χ^2 to $P(\chi^2)$ for 9 degrees of freedom. From this curve the value of the P_π error worked out to be $(4.3 \pm 1.5) \text{ Mev}/c$. A new incident momentum scale was established after allowing for this discrepancy.

In the absence of any error in P_π , an error in the phi mass itself could also account for the result shown in figure(4:9). The relationship between P_π and the resonance mass at our momenta is such ($\Delta M \simeq \frac{1}{2} \Delta P_\pi$) that we would ascribe the above discrepancy to an error in the phi mass of $- 2.1 \pm 2.5 \text{ Mev}/c^2$. Thus our best estimate of the phi mass is $1016.5 \pm 2.5 \text{ Mev}/c^2$, where the error comes mainly from the uncertainty in our floating wire calibra-

Systematic error in beam momentum

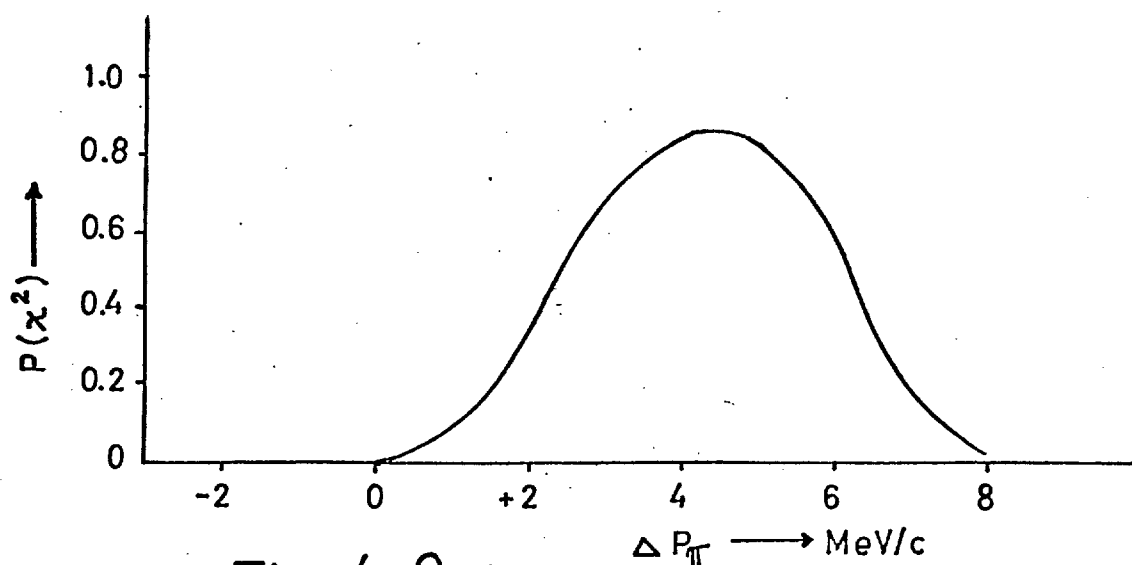
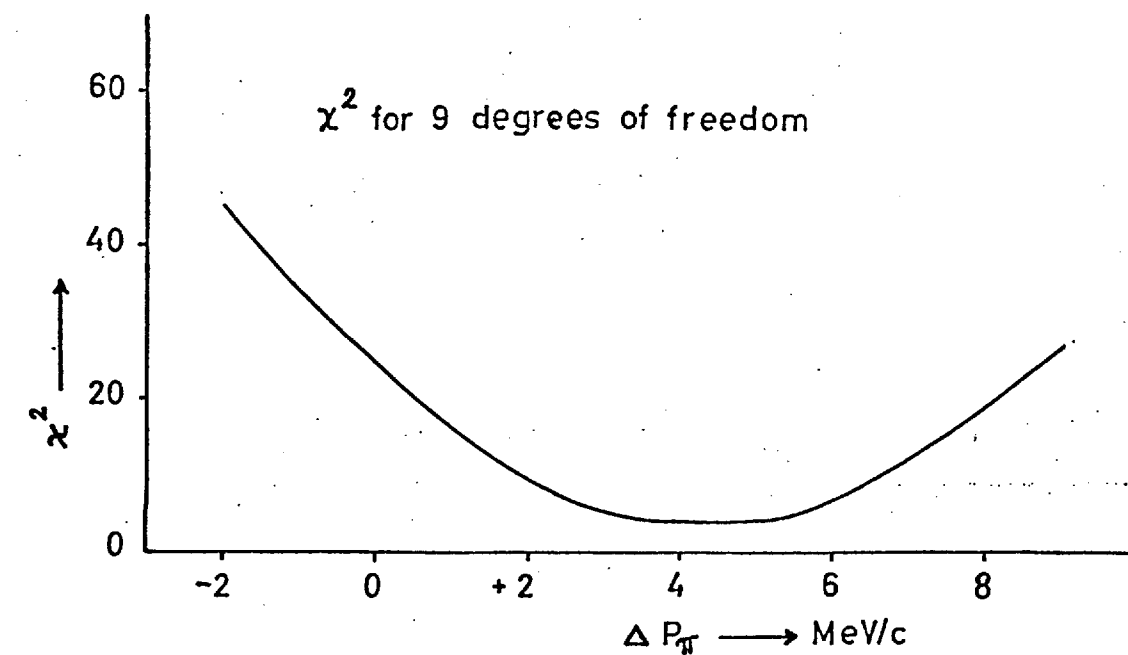


Fig. 4:9

tion. Since the error in our determination of the ϕ mass is 5 times the error in the accepted value, we retained the shifted momentum scale so that the results obtained from the subsequent analysis would be applicable to ϕ mesons having the accepted mass.

4:5 Normalization and Correction Factors.

In the calculation of a cross section the two principal numbers required are, the number of events produced and the number of effective beam particles. Several factors, however, affect the measurement of these numbers; some resulting in a loss of the events and others causing a loss of beam particles. Factors that were either momentum dependent or tedious to calculate by hand were included in the Monte Carlo simulation programme. Several other factors, however, were either determined experimentally or calculated separately. These factors were used to correct the number of effective beam particles.

If the number of beam particles recorded in the experiment be N , then the effective number of pions is given by, FN , where $F = \prod f_i$, i.e; the product of the factors f_i which are now discussed below:-

(1). Degradation of the Beam. The amount of beam received by any part of the target depends on its distance from the

upstream end. Thus the downstream end receives the smallest amount because the beam gets attenuated due to interactions in the target. The total interaction rate was measured to be 4.2%. So the average beam attenuation was 2.1%. The corresponding correction factor is $0.98(f_1)$.

(2). Non-hydrogen events. The small contribution to the signal by the hydrogen present in the melinex end caps of the hydrogen flask was calculated to be $(1 \pm \frac{1}{2})\%$. This gave us a correction factor, f_2 , of 1.01 ± 0.005 . It was consistent with the number of counts observed on a time of flight spectrum taken with an empty target.

(3). Loss of Neutrons. If a neutron interacted anywhere between the point of production and the neutron counters the event would be lost. Interactions taking place in the Cerenkov counter were included in the Monte Carlo programme. However, the loss due to their interactions with the liquid hydrogen in the target, E-counters, 4 metres of air, and in the first $\frac{3}{4}$ thickness of the anti-counters, $A_1 - A_6$, was calculated separately using the values of the geometric cross sections. This gave us a factor, f_3 , equal to 0.93 ± 0.02 .

(4). Beam Constitution. The proportion of pions in our beam was measured in a separate experiment that has been

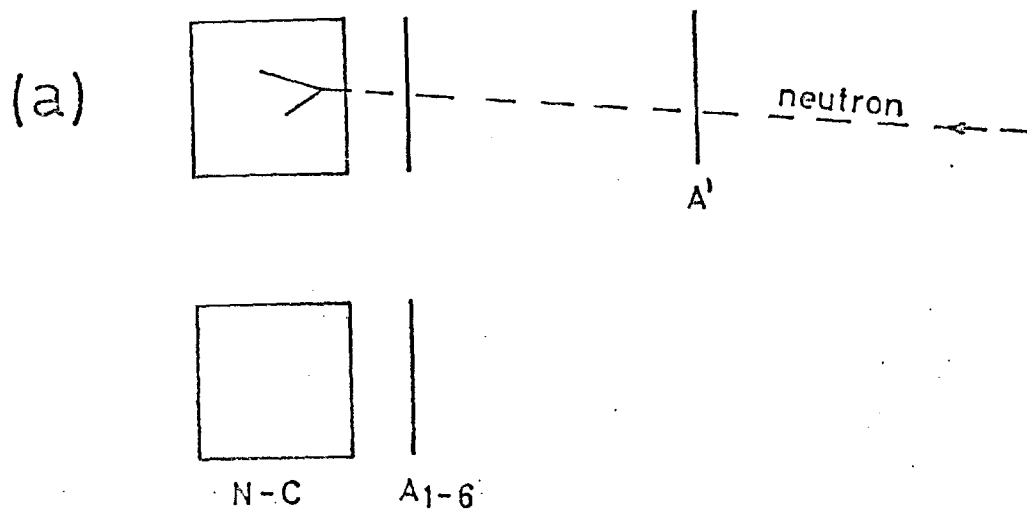
described in section 2:2. This factor (f_4) equalled 0.78 ± 0.04 .

(5). Vetoes caused by the Interaction products of Neutrons.

Loss of an event would occur if one or more charged products from the interaction of a neutron in the neutron counters went back into and triggered one of the anti-counters, $A_1 - A_6$. This loss was measured using an extra veto counter A' (figure 4:10a) for selecting neutrons. This counter was placed far from the neutron counters so that there was little or no chance of an interaction product hitting this counter. The logic selected neutrons accompanied by a pulse in one or more of the six anti-counters. The experiment was performed at a low beam rate to get rid of the casual background. The correction factor (f_5) obtained was, 0.97 ± 0.02 .

(6). Electronic Dead Time Loss.

The dead time losses of both beam particles and neutrons were very small owing to the minimum pulse lengths used in the parts of the logic where rates were high. Also the logic was such that the loss of a beam particle due to dead time of a circuit also resulted in a loss of the event if any, and thus many of the sources of this loss were nullified. The net dead time loss of the events



'Čerenkov window' experiment

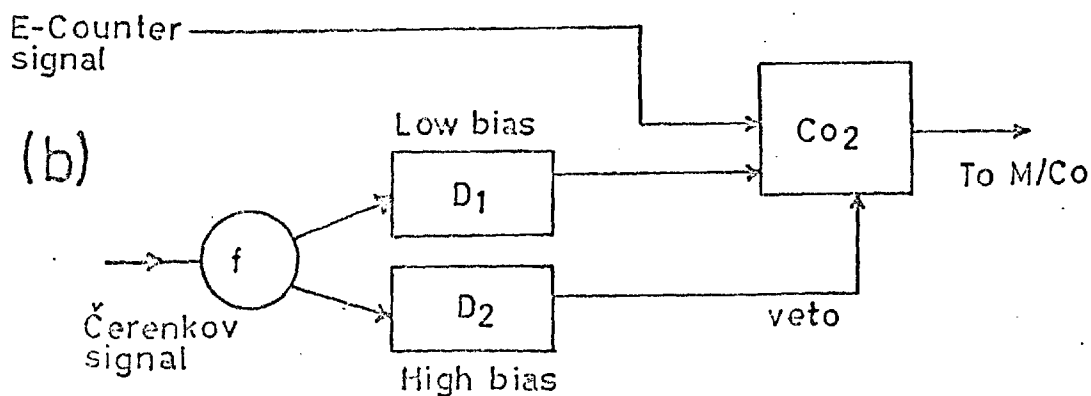


Fig. 4:10

was $1 \pm 1 \%$, giving us a correction factor of 0.99 ± 0.01 .

(7). Loss of events due to delta rays produced by K mesons in the Cerenkov counter.

K mesons could produce a signal from the Cerenkov counter in one of the following ways:

- (a). By stopping and decaying in water, into a fast muon or a pi-meson, or by decaying in flight;
- (b). By interacting with oxygen and hydrogen atoms, in flight, or in case of K^- also at rest;
- (c). By directly producing Cerenkov light if their velocity exceeded the threshold of the counter, and,
- (d). By giving rise to knock-on electrons or delta rays which subsequently produced Cerenkov light.

The first three sources of loss were incorporated in the Monte Carlo programme. The last factor was measured in a separate experiment.

It was calculated that the average number of photoelectrons produced by a K meson via delta rays would lie between 0.1 and 0.2 and thus usually they would give rise to only one photoelectron. The threshold of the discriminator that detected Cerenkov pulses in the main experiment was at about 5 ma(minimum bias) and corresponded nearly to the mean pulse height produced by one photoelectron. Thus almost all events which produced a delta ray

and liberated a photoelectron from one of the photocathodes would have been lost.

In the subsidiary experiment called the "Cerenkov window" experiment only those events were selected that produced a pulse of height greater than the mean pulse height due to one photoelectron but less than or equal to twice this value. The logic for selecting the events in this experiment is shown in figure (4:10b). The threshold of D_1 was set at 5 ma level but the threshold of D_2 in the veto channel was set at 10 ma so as to correspond to twice the mean pulse height due to one photoelectron. This logic, therefore, selected almost all of those events that were being lost in the main experiment, since the kaons would rarely produce 2 photoelectrons via delta rays.

The experiment was performed at a beam momentum of 1580 Mev/c where the signal was the heighest, and from the time of flight spectrum obtained the delta ray loss was estimated to be $(2.5 \pm 2.5)\%$. The correction factor, f_7 , is thus 0.97 ± 0.03 .

(8). An increase in the geometric efficiency for detecting the signal would result if the K mesons decaying between the Cerenkov and the E- counters did not send the muon or the pion back into the Cerenkov counter, but instead the decay product went forward into a suitable E- counter. This

effect turned out to be $(4 \pm 2)\%$. The corresponding correction factor(f_g) is, 1.04 ± 0.02 .

(9). The Efficiency of the Neutron Counters.

Measurements of the efficiency of a plastic scintillation counter for neutrons in the energy range, ³⁵ 20 to 120 Mev kinetic energy, have been made by E.G.Auld at the Rutherford Laboratory, Harwell. The pulses from the counters were discriminated at a bias level of approximately 6 Mev proton energy. His efficiency measurements are shown in figure (4:11).

The energies to be detected in the present experiment fell within the range 150 - 400 Mev neutron kinetic energy but unfortunately no data on efficiency measurements of plastic scintillation counters at these energies were available. However, ³⁶ R.J. Kurz has developed a Fortran programme which uses all the available cross section data to calculate the efficiency for cylinders of plastic scintillator in the neutron energy range 1 - 300 Mev. These calculations have an uncertainty estimated to be $\pm 10 \%$.

Solid lines in figure (4:11) show the efficiencies calculated by the method given by Kurz at various bias levels of the detector. The agreement with the data of

Efficiency of a plastic scintillation counter for detecting neutrons as a function of neutron energy.

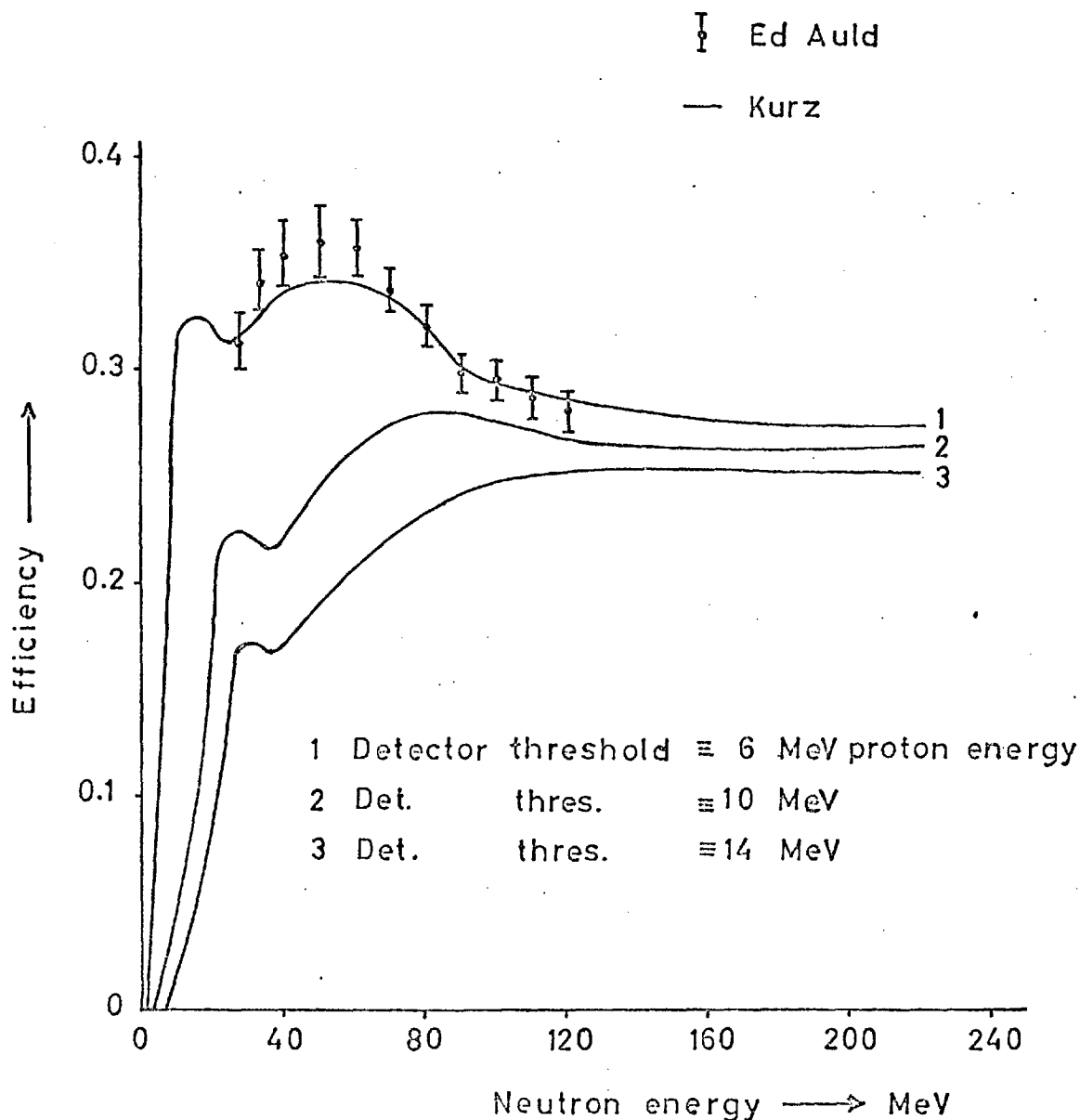


Fig. 4 : 11

Ed Auld is quite good. The conclusions from these curves are that, (a) above 100 Mev neutron kinetic energy the efficiency is almost independent of the energy and, (b) above 100 Mev the efficiency is affected little by relatively large changes in the bias level of the detector.

Our counters were only slightly different from the counters of Ed Auld and our discrimination level determined by the help of the cosmic ray peak was very nearly 10 Mev proton energy. An average efficiency of (0.28 ± 0.03) was deduced for our counters by using the theoretical efficiency value at 200 Mev neutron kinetic energy, corresponding to our bias level. This gave us a correction factor (f_9) of 0.28 ± 0.03

(10). In addition to the above nine correction factors one other factor of importance is the branching ratio for $\phi \longrightarrow K^+ K^-$ decay. The latest value of this is known to be, 0.48 ± 0.04 .

Combining all the above ten factors the value of the factor F turns out to be, 0.094 ± 0.015 .

4:6 The Monte Carlo Programme.

The geometric detection efficiency for a given reaction depends not only on the dimensions and the dispositions of the particle detecting counters and the

properties of the apparatus used but also on several intrinsically unknown parameters that have characteristic statistical distributions as a consequence of the model assumed for the production of the reaction under study. One way of finding the efficiency for a given reaction is to integrate over all these parameters. The integration, for example, should take into account the effect of a finite width in case of a resonance or the effective mass distribution in case of a more than two body final state. It should be carried over the centre of mass production and the decay angular distributions. In addition, the integration should also include effects due to the known spreads in the incident momentum, the length of the target and any other random errors such as those in the measurement of the time of flight.

The integration procedure, however, is extremely tedious even if carried out numerically with the aid of a computer. We, therefore, resort to the Monte Carlo technique which is just another way of performing the above mentioned integration. It may also be regarded as a direct simulation of the experiment.

In the Monte Carlo method of integration, for each event, exact values are assigned to the unknown parameters in such a way that for a large number of events the

distributions of these parameters acquire the correct forms assumed by the model. This is done with the help of a mathematical sequence that generates pseudo-random numbers lying uniformly between zero and one. We consider now an example of the use of such a random number in calculating the c.m. production angles assuming isotropic production.

The first step consists in normalizing to unity the area under the frequency distribution concerned. In our case as $\text{Cos } \theta^*$ is uniformly distributed between -1 and $+1$, the required normalization is obtained from,

$$a \int_{-1}^{+1} d(\text{Cos } \theta^*) = 1, \quad \text{where 'a' is the normaliza-}$$

$$\text{tion constant. Thus, } a = \frac{1}{2}, \text{ and the probability distri-}$$

$$\text{bution is, } P(\text{Cos } \theta^*) = \frac{1}{2}.$$

Now the random number 'R' is properly normalized as it is distributed uniformly between 0 and 1. The next step consists in equating the probabilities, (a) for the unknown parameter $(\text{Cos } \theta^*)$ to lie between $\text{Cos } \theta^*$, and $\text{Cos } \theta^* + d\text{Cos } \theta^*$, and (b) for the random number to lie between R and $R + dR$. Thus,

$$\frac{1}{2} d(\text{Cos } \theta^*) = dR.$$

Integrating and allowing the lower bounds of both distributions to coincide one gets,

$$\frac{1}{2} \int_{-1}^{\cos \theta^*} d(\cos \theta^*) = \int_0^R dR, \quad ,$$

or, $\cos \theta^* = 2R - 1$, which is the required result.

The basic Monte Carlo simulation programme had been written by the author's colleague, G.W.Jones, in connection with the η -width ³³ experiment. This was modified to evaluate the efficiency of our apparatus for detecting neutrons and K^+K^- pairs produced in the reaction, $\pi^- + p \longrightarrow n + \phi$ ($K^+ + K^-$). The programme could also investigate the efficiency for detecting a 3-body direct reaction such as, $\pi^- + p \longrightarrow n + K^+ + K^-$. In addition, the decay of a particle or resonance into 3 particles could be studied.

The major assumptions made about the interactions of the particles with the apparatus were as follows:

- (a). The incident pions were supposed to have a triangular momentum distribution with a full-width at half-height of 4.5 Mev/c.
- (b). The incident particles were taken to be moving along the axis of the target.
- (c). The beam intensity was not supposed to vary along the length of the target. A small correction to the cross section due to this effect was applied separately.
- (d). Neutron counters were supposed to be discs of 100%

efficiency, the plane of the disc passing vertically through the centre of the counter. Any neutron whose trajectory happened to intercept one of these discs was counted as detected, otherwise lost.

(e). For each event a constant error of ± 1 ns and a random timing error with a gaussian distribution of standard deviation 0.83 ns, was added to the true time of flight.

The main assumptions about the nature of the production process were, $\Gamma_\phi = 4\text{Mev}/c^2$, $\sigma_\phi \propto p^*$, and uniform production and decay angular distributions. In addition events were also generated for other phi widths and

$$\sigma_\phi \propto p^{*2}.$$

The normalization procedure for the Monte Carlo generated events can be illustrated by the following example. We can consider N_i pions of the same momentum p_i , entering the target, and then calculate how many of them interact to produce phis in a slice of the target of thickness dx distant x from the front. Due to the energy loss in the target the momentum of the pions after traversing x cms. of the target is, $p = p_i - a.x$, where $a = dp/dx = \text{constant}$. For a fixed phi mass the value of p^* is a function only of x , i.e; $p^* = p^*(x)$.

$$\text{Near the threshold, } p^*(x) = k(p_i - p_t - a.x)^{\frac{1}{2}},$$

where k is a constant and p_t is the threshold momentum for the given mass.

If $\sigma_\phi = A.p^* = A.p^*(x)$, and there are N_p protons/c.c in the target, then the number of pions which interact to produce ϕ is within a thickness dx of the target is,

$$dN = N_i \cdot N_p \cdot A.p^*(x) dx \quad \dots\dots\dots(4:1).$$

Equation (4:1) is a consequence of the 'real model.

In the 'Monte Carlo model' an incident pion is said to produce a ϕ meson within the slice dx if two conditions are satisfied, viz;

(a). $x < R.x_0 < x + dx$, where R is a random number uniformly distributed between 0 and 1, and x_0 is the total length of the target, and,

(b). $R' < p^*(x)/p_{\max}$, where R' is a different random number and $p_{\max}$ is a constant greater than the largest value of p^* that can occur in the experiment.

The combined probability of steps (a) and (b) is, $p^*(x).dx/(x_0.p_{\max})$ and so the number of Monte Carlo events is,

$dN_m = N_{im} \cdot p^*(x).dx/(x_0.p_{\max})$, where N_{im} is the initial number of Monte Carlo pions. If we put,

$$N_i = N_{im}/(x_0.p_{\max}.N_p.A) \quad \dots\dots\dots(4:2),$$

then $dN = dN_m$. Thus the Monte Carlo number differs only by

a normalization constant from the number evaluated using the 'real model'.

It can similarly be shown that for events generated with a cross section proportional to p^{*2} correct normalization is obtained if $p_{\max}$ in equation (4:2) is replaced by $(p_{\max})^2$ and in (b) above, $p^*(x)/p_{\max}$, is replaced by its square.

The way in which the effect of a finite width is incorporated perhaps needs justification, for the mass is fixed before deciding whether or not the ϕ would be produced.

If the production cross section be proportional to p^* then for a resonance having a Breit-Wigner shape the 'real model' predicts for the mass distribution of ϕ s produced x cms. from the front of the target,

$$dN/dM = A \cdot p^*(x, M) \Gamma_{\phi}^2 / ((M - M_0)^2 + \frac{1}{4} \Gamma_{\phi}^2).$$

In the Monte carlo programme events conforming to this distribution are generated by first taking for M , a random number satisfying a Breit-Wigner distribution, calculating p^* for this mass and then, as before, demanding that the random number be less than $p^*/p_{\max}$.

In case of 3-body final states the missing mass was calculated by randomly selecting points inside an

³⁷
 equilateral triangle, the perpendicular distances to the three sides from each point giving the kinetic energies of the three particles in the π -p centre of mass. (Not all points inside the triangle are accessible due to momentum conservation and often more than one attempt has to be made to generate a single event). The missing mass is then just the sum of the masses of the two particles other than the neutron, and their kinetic energies.

The cross section for a pure phase space reaction is proportional to the density of states factor. This factor increases with increase in the incident momentum at several values of which it was calculated separately using the

formula,³⁷

$$R_3(0,E) = \int_0^{p_{3\max}} 4\pi p_3^2 \cdot dp_3 / (2E_3) \cdot \pi ((E^2 + m_3^2 - 2EE_3 - (m_1+m_2)^2)^{1/2} / (2(E^2 + m_3^2 - 2EE_3))) \dots (4.3),$$

where m_3, p_3 were taken to be the mass and momentum, respectively, of the neutron. Again the actual cross section for phase space events and the density of states factor differ by a normalization constant.

Phi mesons (or the di-kaon systems) were allowed to decay uniformly in their own centre of mass frame. From

the c.m. angle and the Lab. momentum and direction of the parent particle the momenta in Lab. and the direction cosines of the K mesons were calculated. Then the effects of their interactions with the rest of the apparatus were investigated. This part was rather complicated. K mesons which did not interact in the H_2 target and would go through the E- counters were assigned 'ages' on a statistical basis using the exponential decay law. If τ be the lifetime of a particle in the Lab. and γ the associated Lorentz factor, then the 'age' is given by the formula,

Age = $\gamma \tau \log_e (1/(1 - R))$, where R is a random number uniformly distributed between 0 and 1. They were then followed through the apparatus. If the time required to reach the plane of the E-counters happened to be greater than the 'age' of any one of the two K mesons, the event was considered lost.

Passage of K mesons through 5 cms. of water in the Cerenkov counter gave rise to interactions with the production of fast pions that could result in a loss of the event by the generation of enough light in the counter. Slow K's stopped in water or in the E-counters and in case of K^+ would then mostly decay into $\mu^+ + \nu$. K^- stopping would produce several kinds of final states involving

hyperons and pions. To calculate the loss of events due to interactions and stoppage in water and the E-counters a survey of the available literature³⁸ was made in order to find out cross sections for various processes as a function of K^+ and K^- momentum. The K^+ was relatively easy to handle as its interactions are more or less energy independent below 700 Mev/c in Lab., the range relevant to our experiment. K^-p and K^-n cross sections for various final states (both at rest and in flight) taken from emulsion and bubble chamber data were used and interactions inside the oxygen atoms were supposed to take place only with single nucleons (as if they were free). The available data on K^- cross sections have large statistical errors. It was, therefore, found quite adequate to fit straight lines to the varying cross sections for various processes in 12-40 Mev and 40 - 300 Mev K^- kinetic energy regions. The fitted values of the cross sections were used in the programme.

The mean number of photoelectrons, M , released from the cathodes of the photomultipliers of the Cerenkov counter was calculated for each event using the known velocities $\beta_{\pi i}$ and the lengths of water (L_{wi}) traversed by the pions produced as a result of the interaction. This is given by,

$$M = \sum m_i = \sum \gamma (1 - 1/(n_{\pi}^2 \beta_i^2)) \cdot L_{wi}/5, \text{ where}$$

γ is a constant that takes care of the light collection and quantum efficiencies. The value of γ was determined from the known efficiency of the Cerenkov counter (at minimum bias level of the discriminator) for beam particles passing straight through it. Since $\beta = 1$ for beam particles and the efficiency was 97% for them, we have,

$$\begin{aligned} 0.97 &= 1 - \exp(-\gamma (1 - 1/(1.33)^2)), \\ &= 1 - \exp(-\gamma (1 - 0.565)), \text{ whence } \gamma = 7.4. \end{aligned}$$

The chance of getting no photoelectron when the mean is 'M' is $\exp(-M)$ and, therefore, an event was considered saved if a random number happened to be less than or equal to $\exp(-M)$. Thus if the Cerenkov counter failed to provide a veto pulse while at least two charged interaction products, or the kaons themselves, happened to trigger two different E-counters the event was saved, otherwise lost. An uncertainty of $\pm 6\%$ was included in the σ cross section due to the uncertainty in the calculation of the above loss.

Scattering of K mesons in water was also taken into account but the resulting loss was small.

A few other losses that were also included in the Monte Carlo programme are as follows:-

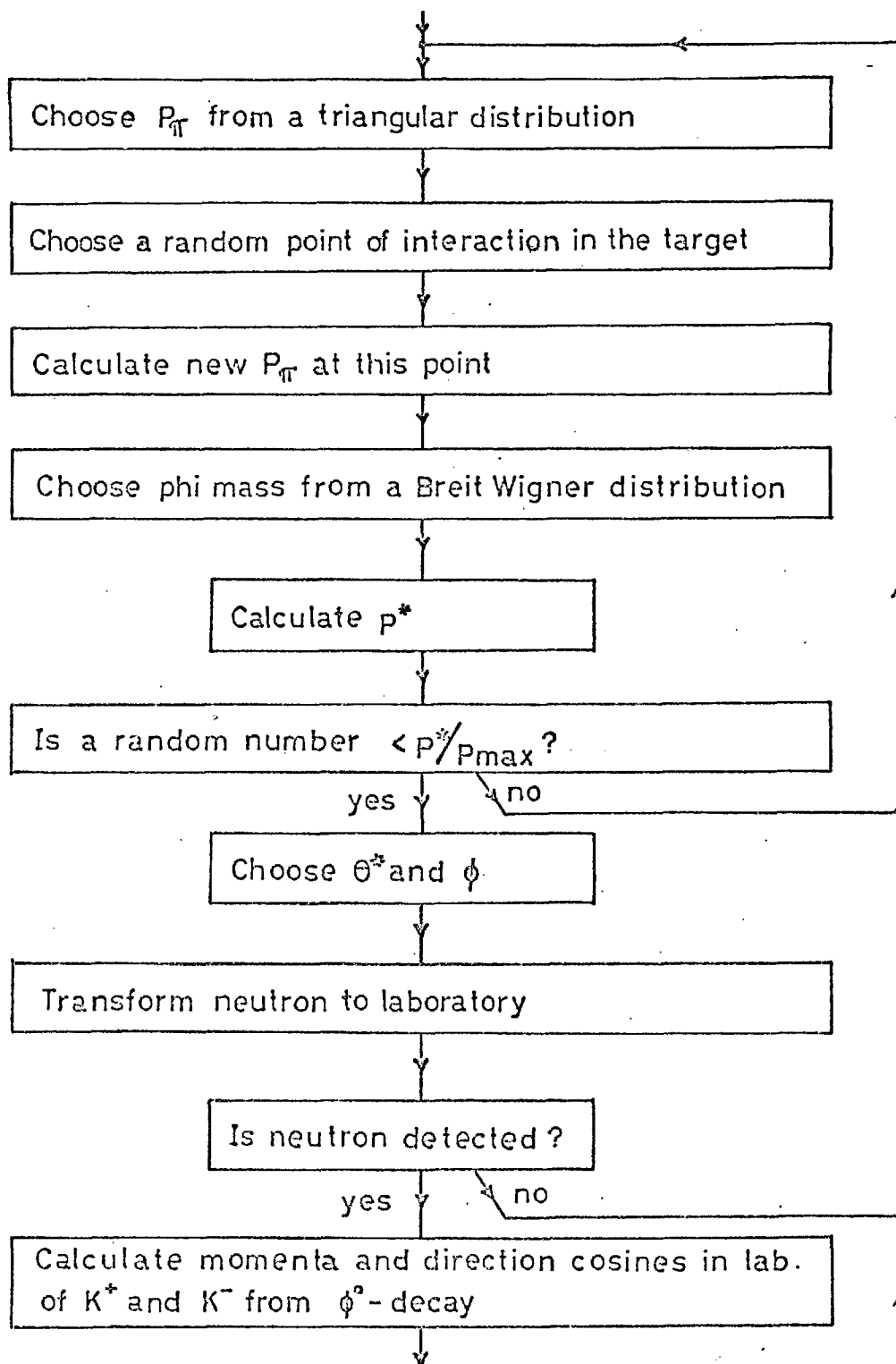
(1). Loss of events due to a $\mu^\pm$ from K^+ or K^- decay, after they had passed through the E-counters, going into one of

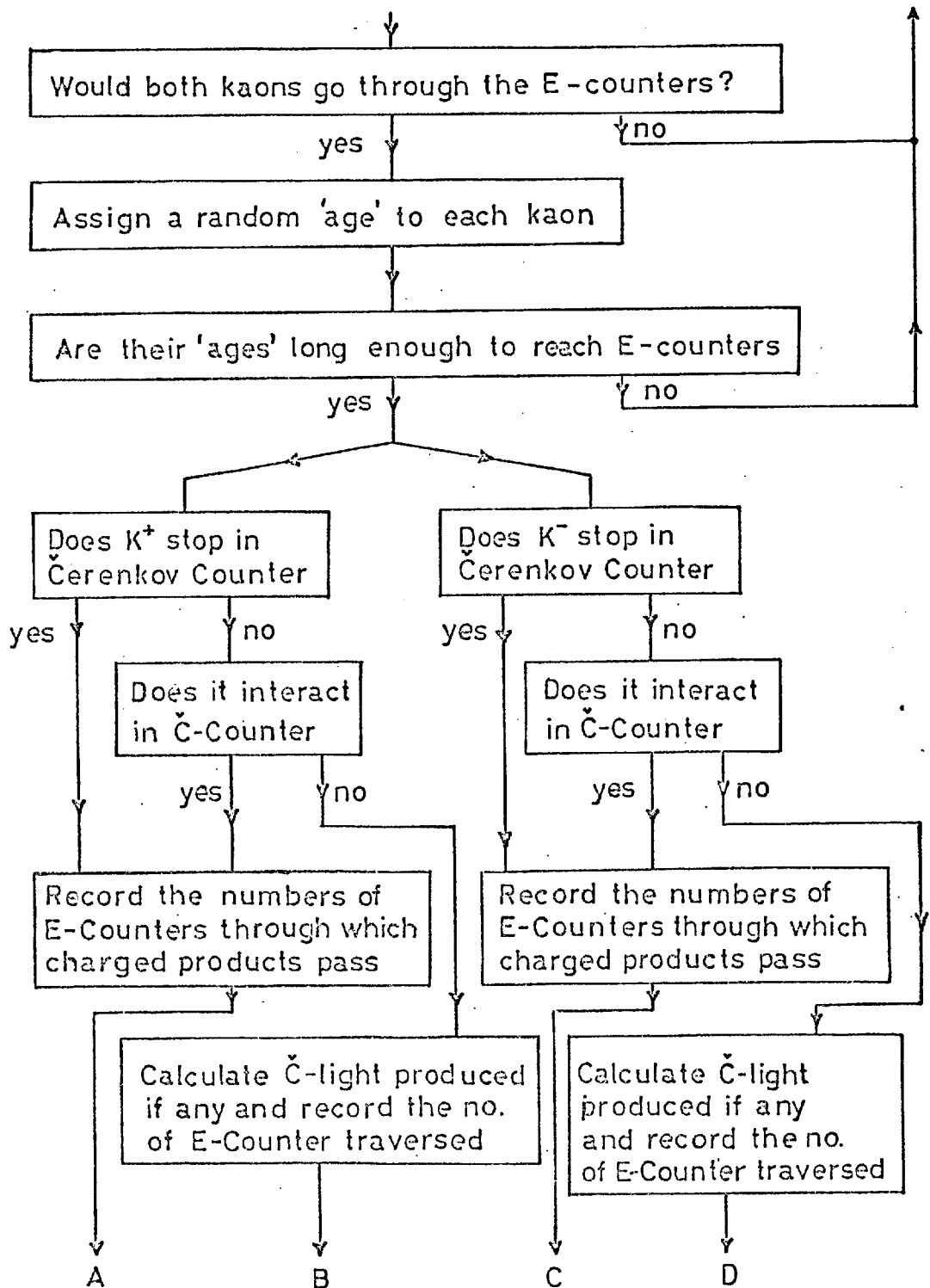
the six anti-counters, $A_1 - A_6$, placed in front of the neutron counters, and (2). Loss of neutrons due to their interactions with water in the Cerenkov counter.

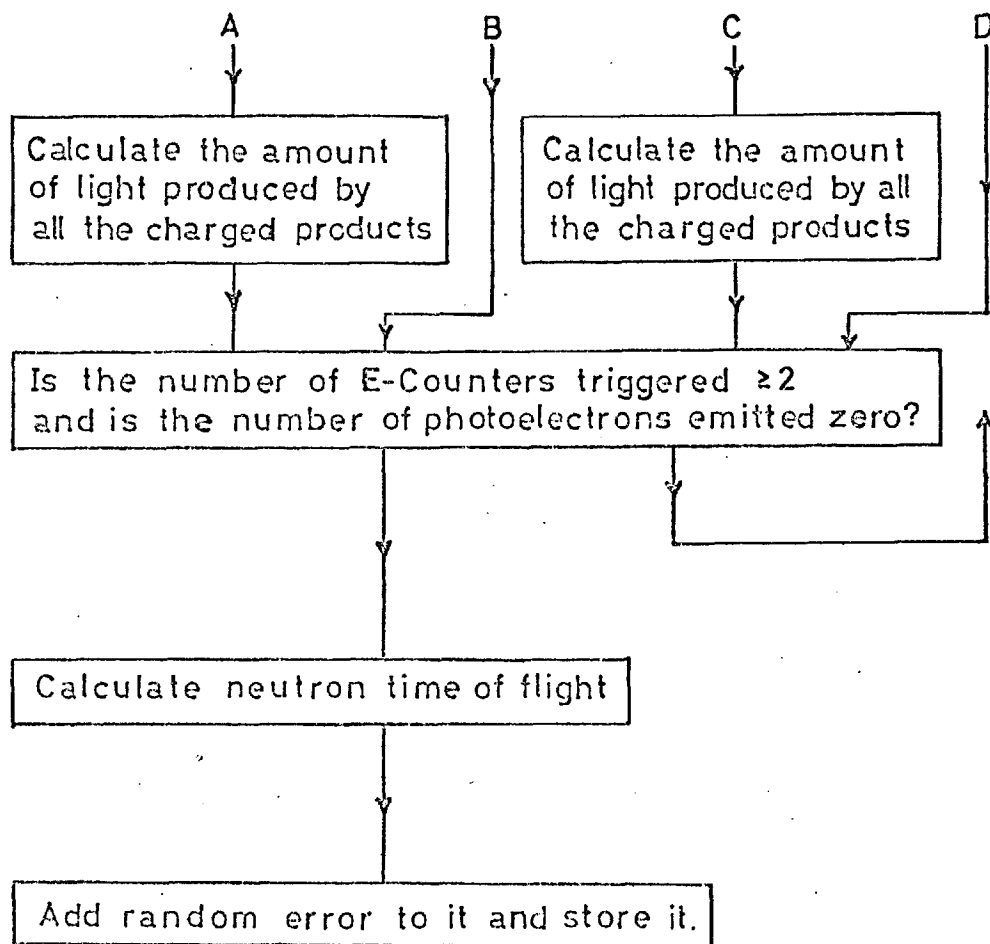
For all events that survived passage of the K mesons through Cerenkov and E-counters, the time of flight of the neutron was recorded as explained before.

A flow diagram of the Monte Carlo programme is given on pages 146 and 147.

Flow diagram of the Monte Carlo programme







CHAPTER VTHE RESULTS AND DISCUSSION5:1 Introduction.

The peaks present in the experimental time of flight spectra shown in the last chapter are not in themselves a sufficient proof of the production of a resonance in the K^+K^- system, although they do indicate the production of the nK^+K^- final state. The existence of a resonance, however, can be ascertained from a study of the yield curve. The peaks we believe also certainly contain contributions from one or more of the processes mentioned in chapter 2. The predicted behaviour of yields from various backgrounds and a resonance in the K^+K^- system, were discussed in section 2:4. We shall make use of those yield curves to unravel the contributions of the different sources of the nK^+K^- final state. In particular we wish to find out the production cross section for the phi meson as a function of its centre of mass momentum and if possible obtain information about its width and the angular distributions.

Our method of analysis is based on a comparison of the basic experimental data with the theoretical(Monte Carlo) data calculated on the basis of various assumptions

about the width, cross section and the angular distributions. The advantages of this method are that the experimental data are used in a very direct way without having to derive intermediate quantities from them, and various experimental factors which have large effects on the data can be reliably taken into account.

There are two ways in which our experimental data could be compared with the theoretical data. One method consists in comparing the experimental time of flight spectra, channel by channel, with the corresponding Monte Carlo spectra. But a difficulty was experienced here due to the K^+K^- background because the background spectra are very similar near threshold to the ϕ spectra and so it would be very difficult to distinguish between the two by such a comparison. Around 1620 Mev/c where due to the splitting of the ϕ spectrum such a comparison is theoretically possible we were prevented from doing so by the lack of statistics. The other method consists in comparing the yield, that is, the number of events for a given number of incident pions, in a given timing gate, with the yield predicted by theory in the same timing gate. To do this we resort to the method of least squares which is described in the following paragraphs.

5:2 The Method of Least Squares.

The general procedure is to **group** the experimental data into a number of bins of experimentally identical events. If the number in bin 'i' be N_{ei} while the predicted number of events in the same bin is N_{ti} then we can define a quantity,

$$\chi^2 = \sum_i (N_{ei} - N_{ti})^2 / \sigma_i^2 ,$$

where σ_i is the error on N_{ei} supposing that N_{ti} have very small errors associated with them. The quantity χ^2 is a measure of the goodness of agreement between the experimental and the theoretical number of events; the smaller the value of χ^2 the better the agreement.

The N_{ti} are functions of two kinds of parameters, a_m and b_m , where a_m are parameters that relate to the width, cross section and angular distributions, and b_m are parameters that describe the properties of the detection system, for example, the beam momentum spectrum and the timing resolution, etc. The set of values of the parameters that gives the minimum value of χ^2 is the best set. Only a_m , however, were allowed to vary in order to obtain the minimum value of χ^2 : the ' b_m ' were not, as we already had reliable information on them. The effect of uncertainties in our knowledge of the b_m was, albeit, taken into account.

It is not always possible to express N_{ti} analytically in terms of the a_m parameters (e.g; Γ_ϕ). Where it can be done the best values of the parameters can be determined by differentiating χ^2 with respect to the a_m , and solving the resulting simultaneous equations, called the "normal" equations. In the other case the minimization can be achieved graphically or by using numerical methods.

If the errors σ_i are Gaussian and if the model used to calculate the N_{ti} correctly describes the processes involved in the production and detection of the real events, then the minimized value of χ^2 has a calculable probability distribution. The value of the probability for getting a value of χ^2 equal to or greater than the observed value can be obtained from standard tables knowing the number of degrees of freedom. If 'k' unknown parameters are simultaneously determined from the data consisting of 'n' independent observations, then the number of degrees of freedom is, $n - k$. One can thus test the validity of the parameterization and place confidence limits on the 'best' values of the parameters. The sensitivity of χ^2 to variations in these parameters governs the accuracy with which they can be determined.

We have already applied the χ^2 minimizing

method to the evaluation of the systematic error in our beam momentum measurement and elsewhere in the last chapter. All the results that we shall obtain in this chapter owe their determination also to this technique.

5:3 Analysis of the K^+K^- Background.

We first analyse the yield from the K^+K^- background alone as this may throw some light on the more important processes contributing to our background. We are in a position to do this without interference from the $\emptyset$ yield by using a narrow timing gate situated from 7.8 to 11.3 ns from the gamma peak. In this gate the number of events from the $\emptyset$ falls rapidly to a very low value above 1615 Mev/c incident momentum (figure 2:17 b). Above this momentum, therefore, the yield in this gate is almost entirely due to the K^+K^- backgrounds. We have two points, viz; at 1622 and 1630 Mev/c in this region. In addition there are 3 points at lower momenta, viz; at 1536, 1544, and at 1552 Mev/c, where the yield from the $\emptyset$ is either zero or negligibly small assuming, of course, that the $\emptyset$ width is less than or equal to 4 Mev/c².

Unfortunately the freedom from contamination from the $\emptyset$ yield achieved by virtue of the narrow timing gate is somewhat offset by the loss of statistical accuracy.

Single parameter least squares fits to these five points were tried assuming that the background was either due to (a) the S-wave enhancement, or (b) direct phase space production, or due to (c) the production of the S^* resonance. The best fits corresponding to these hypotheses are shown by solid curves in figure 5:1. The χ^2 -probabilities respectively are, 85%, 70%, and 20%. Thus both (a) and (b) give excellent fits to this data. The hypothesis (c) with its probability of 20% seems less likely, although it cannot be rejected. This conclusion was further strengthened by the result of our analysis when the data was fitted to a mixture of yields from phase space and the S^* resonance. Although the χ^2 -probability was quite high (75%) but the cross section for S^* (assumed to be proportional to p^*) at a c.m. momentum of 40 Mev/c turned out to be, $-5 \pm 4 \mu$ barn, i.e.; consistent with being zero.

As regards (a) and (b) we are not in a position to say which of the two is a more likely explanation for the behaviour of our yield. Apparently the S-wave enhancement gives a slightly better fit than phase space but this can be due to a statistical fluctuation. Also the cross section for S-wave enhancement, at the beam momentum of 1536 Mev/c, evaluated from the result of the single parameter fit shown

Theoretical fits to the experimental yield from the K^+K^- background

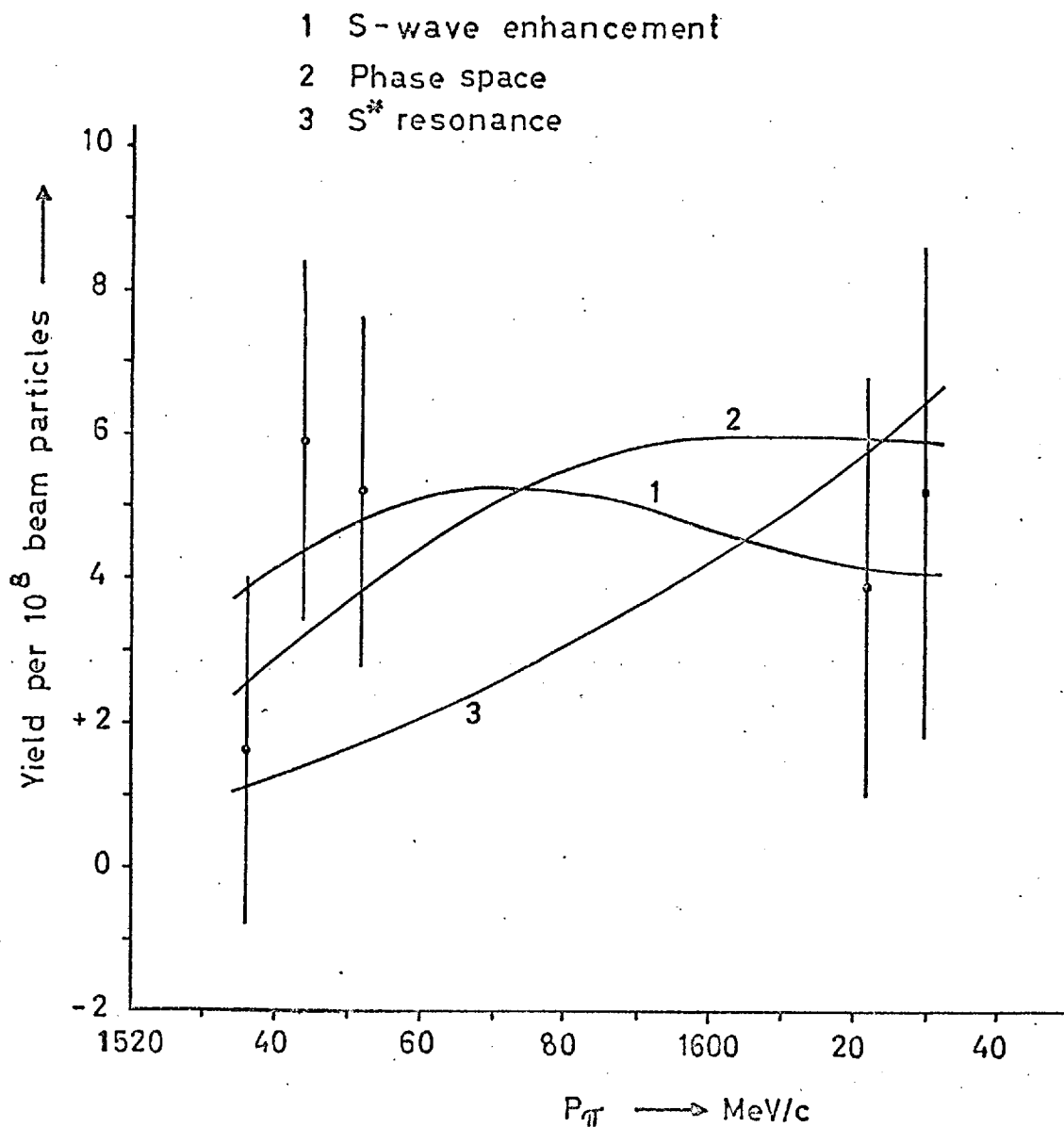


Fig. 5:1

above, turned out to be much higher than measured, for example, by Hess et al at beam momenta above 1600 Mev/c.²² The cross section for S-wave enhancement can be related to the imaginary part 'b' of the scattering length, $a = a_0 + i.b_0$ Fermi. We used a value of $a_0 = 5$ Fermis while the value of b_0 was determined from the fit. Whereas Hess et al using the same value of a_0 find b_0 to be 0.25 ± 0.1 Fermi, we got the value 1.2 ± 0.3 Fermi. The high value of b_0 implies that the background cannot be entirely due to the S-wave enhancement. Thus although the background can be adequately represented by any one of the above two models it is most likely to be phase space with a small contamination from the threshold enhancement.

5:4 ϕ - Width.

The width of the ϕ meson is known at present to³⁹ be 3.4 ± 0.8 Mev/c², which is the latest weighted average of the results of several experiments. We fitted our experimental yield to theoretical yields assuming various ϕ widths in order to (a) study the effect of uncertainties in the width on the measurement of the ϕ cross section, and (b) to deduce the 'best' value of the width from our data.

Our yield is sensitive to the width of the ϕ especially as far as the rising edge of the curve is concerned, because in this region, p^* , that controls the yield

is changing very rapidly. This is shown in figure 5:2 where yields for three different values of the ϕ width have been plotted.

The non- K^+K^- and K^+K^- backgrounds were both subtracted from the data consisting of 19 points above 1536 Mev/c incident momentum. The former was estimated from the 1492 Mev/c yield points and the latter was assumed to be pure phase space for this analysis. The resultant yield was submitted to a χ^2 analysis. The experimental yield (in the wide gate) was fitted to theoretical yield curves for various ϕ widths and each time a value of minimized χ^2 was obtained. The χ^2 values were converted into χ^2 - probability values for 18 degrees of freedom. The result is plotted in figure 5:3. It is apparent from this curve that due to our large errors (enlarged by background subtraction) χ^2 is not very sensitive to the width. The highest probability occurs in the region of 4 Mev/c² which is, therefore, our best estimate of the width of the ϕ meson. The error on this is obviously quite large.

5:5 ϕ -Production Cross Section.

Assuming dominant S-wave production of the ϕ meson near threshold the cross section is expected to be proportional to p^* , the c.m. momentum. In calculating the

Phi yield curves for various
phi widths
(wide gate)

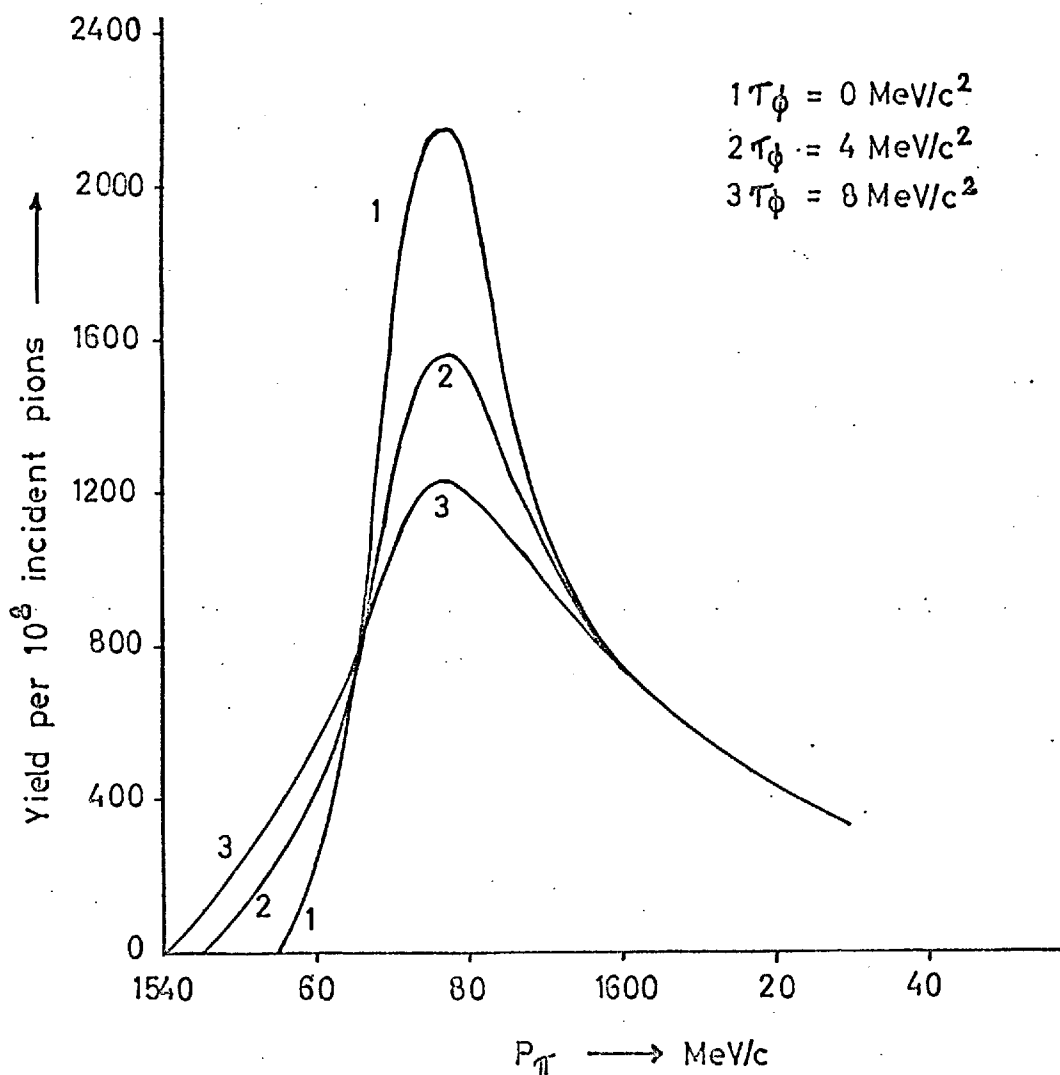


Fig. 5:2

χ^2 probability against ϕ -width

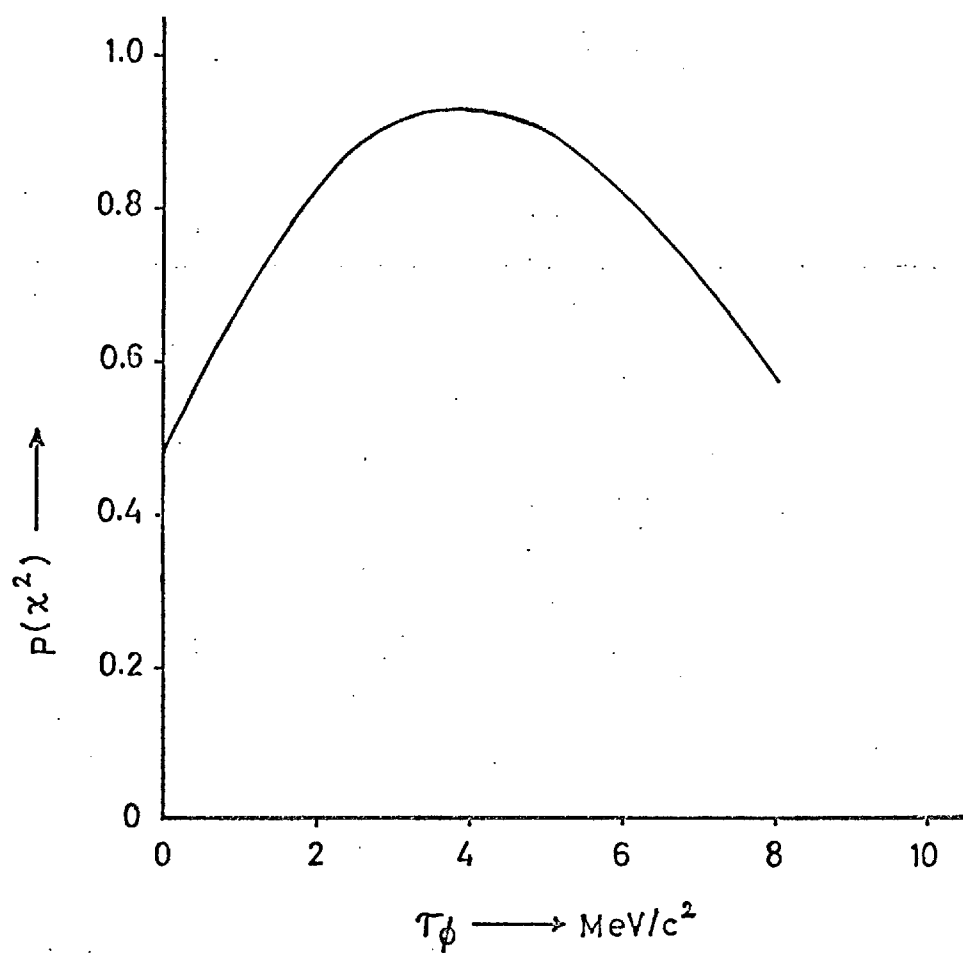


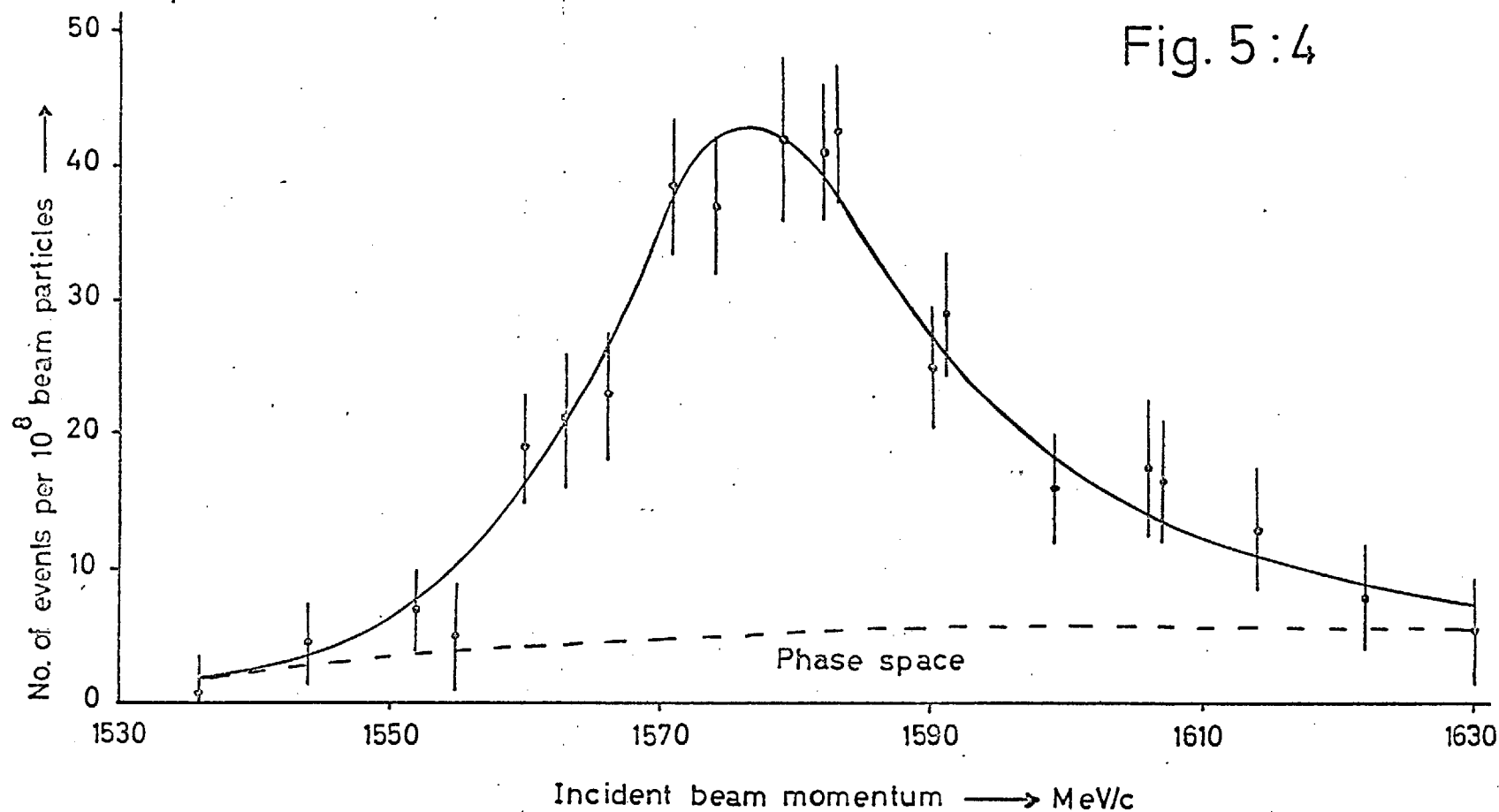
Fig. 5: 3

Monte Carlo yield curves the constant of proportionality was assumed to be 1μ b/Mev/c. The value of 'k' in $\sigma_{\emptyset} = k.p^*$, was then determined by using the experimental yield (after subtracting non- K^+K^- background) in a timing gate extending from 6.2 to 11.7 ns from the gamma peak. This is the region indicated by CD in figure 2:12. The region AB contains 100% of the K^+K^- background and the $\emptyset$ events and was somewhat better suited for this analysis, as in this case the timing resolution becomes unimportant. However, the proximity to the gamma peak, of the wide gate AB introduced a difficulty which compelled us to use a somewhat narrower gate situated relatively farther away from the gamma peak. The main problem is that in a wide gate the amount of background (non-KK) is large, especially near the gamma peak, and so its fluctuations are also likely to be large. Fortunately, as we narrow down the timing gate the amount of signal ($\emptyset$) does not decrease as rapidly as does the background. The uncertainty in our timing resolution (0.83 ± 0.2) has an effect on the predicted yield that is much smaller than the statistical errors and could be easily ignored.

Solid curve in figure 5:4 shows the best fit to the experimental yield assuming, (a) $\sigma_{\emptyset} = k.p^*$, (b) $\Gamma_{\emptyset} = 4 \text{ Mev}/c^2$ (c) isotropic angular distributions, and

Experimental yield of nK^+K^- events vs. beam momentum and the best fit assuming ϕ -production with $\sigma_\phi \propto p^*$, $\tau_\phi = 4\text{ MeV}$, plus nK^+K^- phase space production

Fig. 5:4



that the K^+K^- background was purely from phase space. The dashed curve shows the amount of phase space contribution present in the yield. The fit gave a very high χ^2 -probability, namely, 98%, justifying clearly the above assumptions. The value of 'k' determined by the fit was 0.026 ± 0.0024 . This included the occupancy correction discussed in section 3:3; the error being mainly statistical. The value of the normalization factor obtained in section 4:5 does not include the uncertainty of $\pm 6\%$ arising from the uncertainty in the calculation of the loss of nKK events by interactions and stoppage in the Cerenkov and E-counters. When this is included the value becomes, 0.094 ± 0.016 . The value of 'k' obtained above was then corrected for normalization; the corrected value being, $(0.026 \pm 0.0024)/(0.094 \pm 0.016) = 0.28 \pm 0.05 \mu b / \text{Mev}/c$. Thus $\sigma_{\phi} = (0.28 \pm 0.05) \cdot p \cdot \mu b$.

The effect on the value of 'k' of (a) the uncertainty in the ϕ -width ($\pm 1 \text{ Mev}/c^2$), (b) error in P_{π} and (c) uncertainty in the timing resolution, being small compared with the normalization error, were ignored.

When the S-wave enhancement was also included as a background, a 3-parameter fit yielded a value of 'k' (after correction) $= 0.29 \pm 0.06$. The cross section for S-wave enhancement, however, turned out to be negative, i.e;

the fit had tried to subtract its yield from the other yields. The original simple model comprising $\emptyset$ and phase space was, therefore, retained.

To check if the cross section appreciably departed from linearity or if an anisotropy was present in the production angular distribution a more complicated model was also used. Both of these effects can change our yield at high p^* s. Therefore, a two parameter fit assuming $\sigma_{\emptyset} = k.p^* + k'.p^{*2}$ was tried (other assumptions remaining the same) after subtracting the phase space background from the yield. This did not alter the value of the cross section as the value of k' turned out to be -0.0003 ± 0.0015 , without any change in the value of k or that of the χ^2 -probability.

Cross Section as a Function of p^* .

The cross section for $\emptyset$ production was also evaluated by a second method. If the number of experimental events produced by N_b beam particles at a given incident momentum be N_e , then the cross section σ at that momentum is given by,

$$N_e = N_b \cdot N_p \cdot \sigma \cdot F \cdot L_t$$
, where N_p is the number of protons/c.c in the target, L_t is the "effective length" of the target and F is the correction factor mentioned above. The effective length of the target is the distance travelled, on the average, by pions in the target while still remaining

above the ϕ threshold, and was found at each P_π by the Monte Carlo method. To express the cross section as a function of p^* , the P_π scale was converted into the p^* scale. At each P_π the experimental events have a p^* distribution whose width is determined by the spread in the incident momentum, and the effective length of the target. The width of the resonance ($4 \text{ Mev}/c^2$) had a small effect. The mean value (weighted) of the p^* distribution was obtained at each incident momentum by the use of the Monte Carlo programme. The number of experimentally detected events was converted into the number produced, by dividing the former by the mean geometric efficiency of the apparatus also calculated by the Monte Carlo technique.

The result is shown in figure 5:5. The errors include the error of normalization. For comparison the solid line has been drawn to represent a slope of $0.28 \mu \text{ b}/\text{Mev}/c$.

5:6 Angular Distributions.

It was mentioned in the last section that no noticeable departure from linearity was found in the ϕ production cross section. The Monte Carlo yield curves for $\sigma_\phi \propto p^*$ and $\sigma_\phi \propto p^{*2}$ were calculated assuming isotropic angular distributions. If a significant anisotropy were present in the production angular distribution it is highly

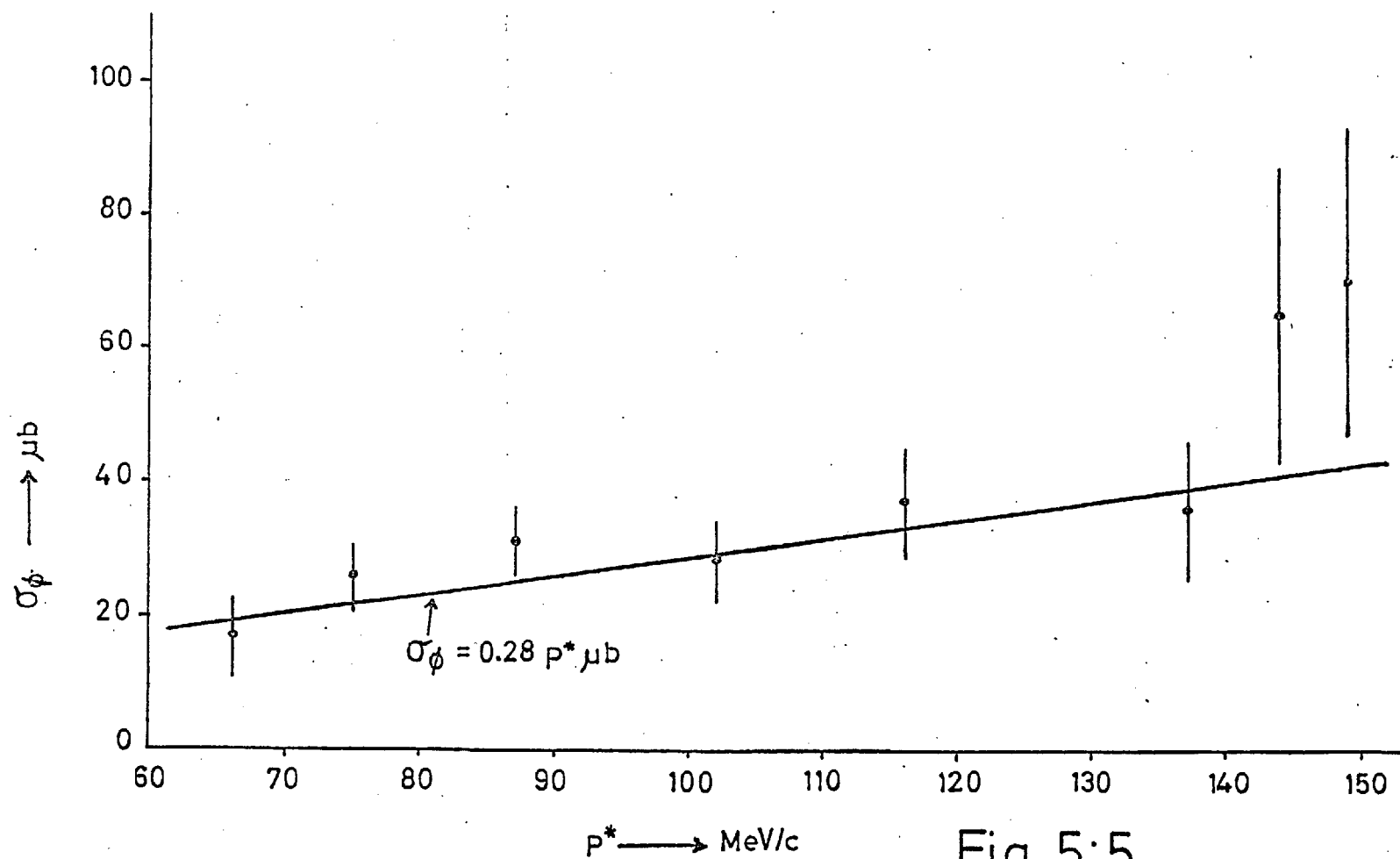
ϕ -production cross section against p^* 

Fig. 5:5

unlikely that its effect could have been exactly cancelled by a non-linearity in the cross section. Our conclusion, therefore, is that the production angular distribution is quite consistent with isotropy.

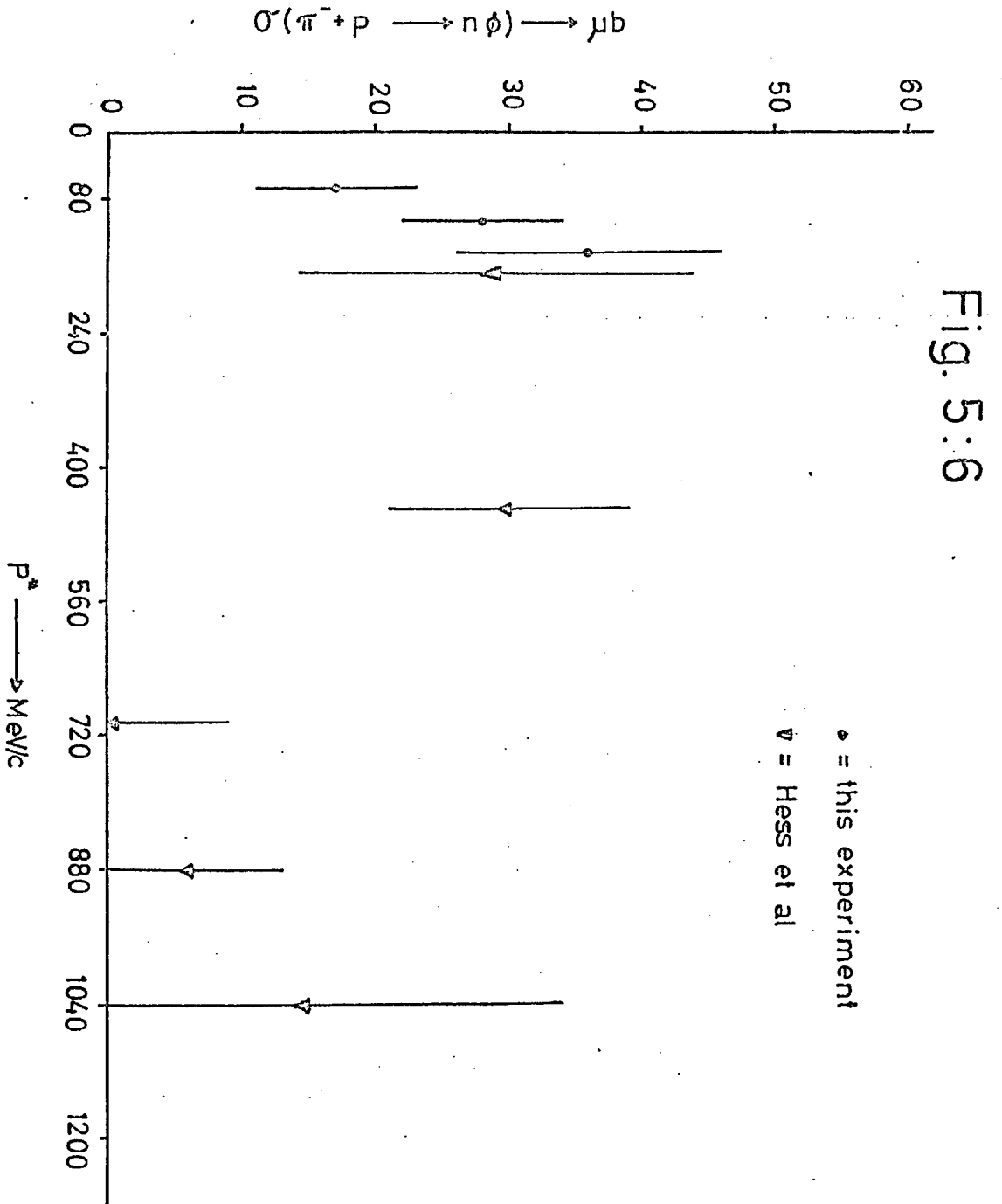
The extremely good fit to the experimental yield also amply justifies the assumption of isotropy that was made regarding the decay angular distribution. By decay angle we mean the angle that the forward going kaon makes, in the $\emptyset$ centre of mass, with the direction of the $\emptyset$ in the laboratory. Additional evidence in support of this was obtained by D.C.²⁴Mason who analysed the angular distributions of the kaons from $\emptyset$ decay using spark chamber photographs of the decay products.

5:7 Comparison and Discussion.

The only experiment with which we can directly compare our results is that of Hess et al. In figure 5:6 we have plotted their measurements of the $\emptyset$ cross section along with ours. Only 3 points from figure 5:5 have been used in this comparison as these are largely independent of each other. There is only one point in the data of Hess near our p^* region and this is quite compatible with our measurements although somewhat low.

M.Abolins have recently⁴¹ reported $\emptyset$ production

Comparison of ϕ -production cross sections from this experiment and that of Hess et al



in the reaction $\pi^+ + n \longrightarrow \phi + p$, and quote a cross section of $23 \pm 10 \mu$ barns, but this has been averaged over a p^* range of 0 - 650 Mev/c.

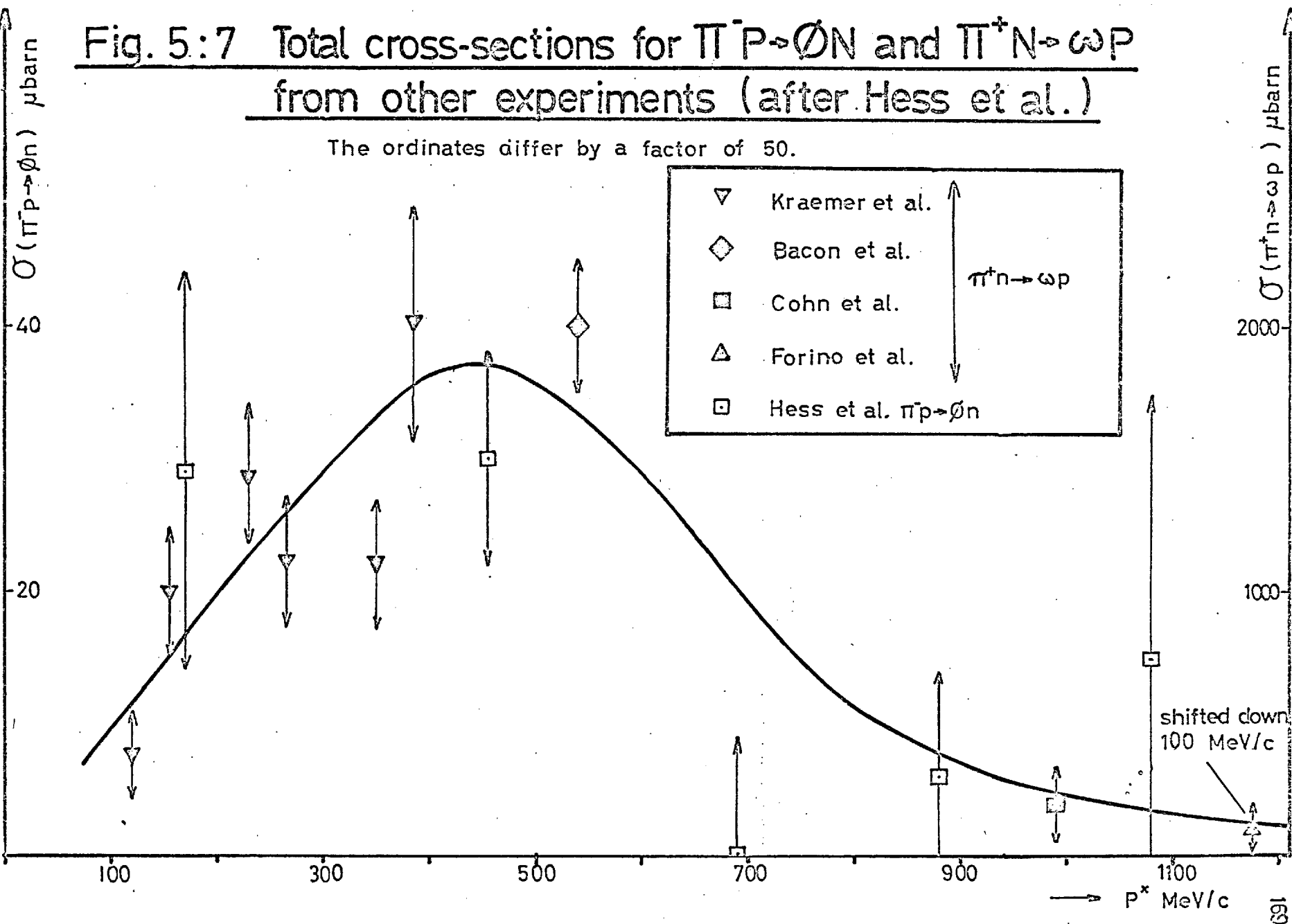
The cross sections for $\pi^- + p \longrightarrow n + \phi$, and $\pi^+ + n \longrightarrow \omega + p$ may be related through SU3 and charge symmetry. Hess et al have compared their results on ϕ production with those of other experiments on ω production in the latter reaction. This is illustrated in figure 5:7. They say that the energy dependences correspond roughly when the ordinate for $\pi^- + p \longrightarrow n + \phi$ is increased by about 50. The agreement between their data and those of others is quite good, but is somewhat worsened if our points are also included in the comparison. This seems to indicate that the peak in the cross section for $\pi^- + p \longrightarrow n + \phi$ occurs at a lower p^* than that for $\pi^+ + n \longrightarrow \omega + p$.

Hess observes that the production and decay angular distributions observed by them are consistent with isotropy and are similar to those reported by Kraemer et al for $\pi^+ + n \longrightarrow \omega + p$. The distribution of the decay angle is expected to be proportional to $\sin^2 \theta$ in the simple mechanism of ϕ (or ω) production by ρ exchange. Hess et al do not find this correlation nor do Kraemer et al from their analysis of the above reaction.

²³
Liu and Singer have shown that important

Fig. 5:7 Total cross-sections for $\pi^- p \rightarrow \phi n$ and $\pi^+ n \rightarrow \omega p$ from other experiments (after Hess et al.)

The ordinates differ by a factor of 50.



contributions to the process $\pi^+ + n \longrightarrow \omega + p$ (near threshold) might be expected from a nucleon pole diagram. It is quite possible that the same explanation might also be true for $\emptyset$ production in $\pi^- p$ reaction near threshold.

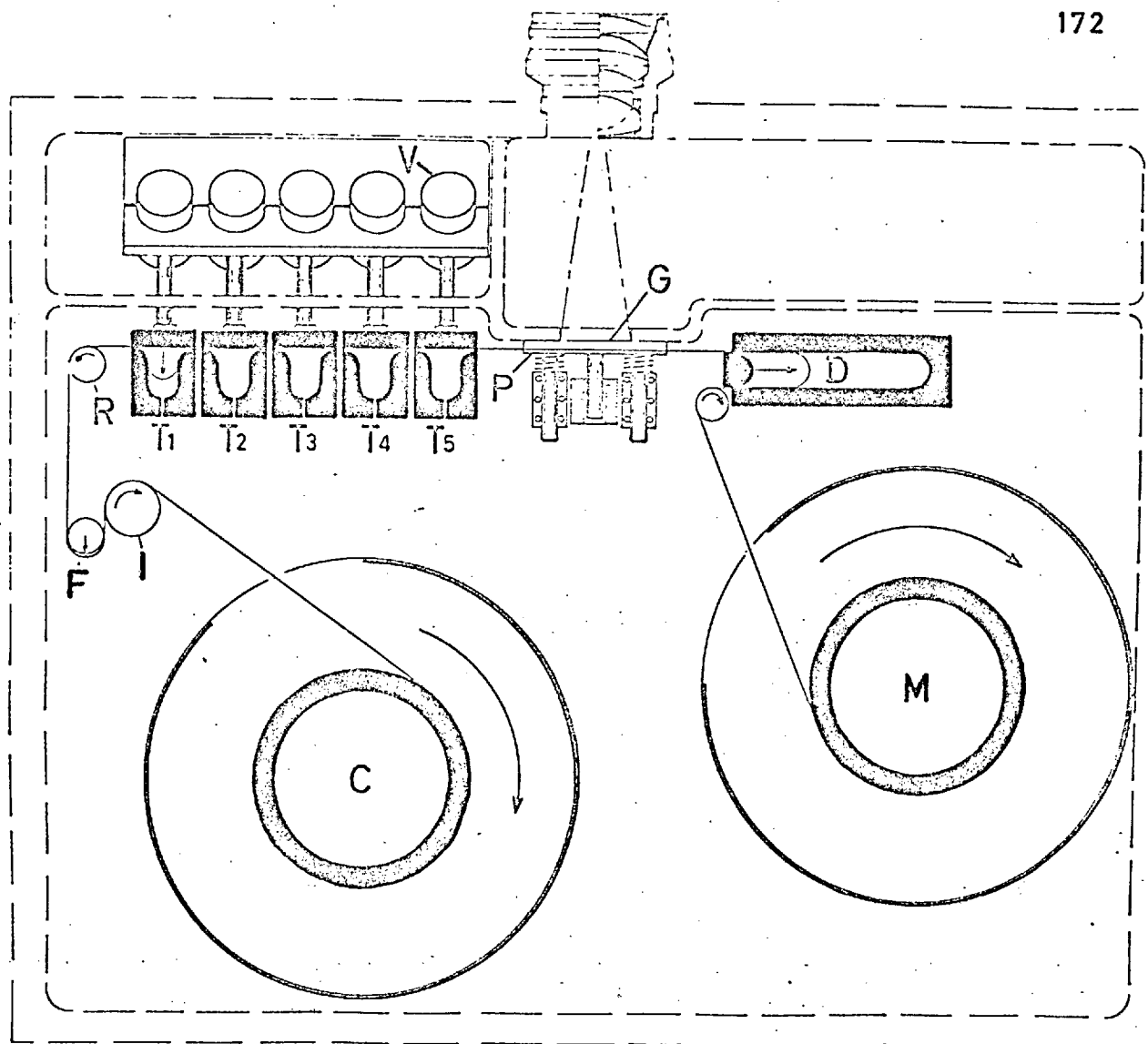
APPENDIX A

DESIGN OF AN ELECTRONIC LOGIC FOR OPERATING A FAST CAMERA USED FOR SPARK CHAMBER PHOTOGRAPHY.

The need for a "fast" camera, which could be pulsed and could take a number of pictures during a beam burst, arose when the $\omega \rightarrow e^-e^+$ decay experiment was being planned. The mechanics of a camera which fulfilled these requirements was designed by R.F. Wilkins, an Engineer in the Physics department, while the necessary electronic logic was designed and built by the writer.

The principle of operation of the camera has been fully described in a paper⁴² by Wilkins and also in the Journal of Photographic Science, vol. 14, page 66, 1966. This will be briefly reproduced here to enable the demands on the electronics to be better understood.

A labelled drawing of the camera is shown in figure (1). Film is stored in a magazine M, follows the path shown in the diagram and is finally wound into a cassette C. The camera is designed to take up to five pictures during the spill time of the accelerator. Its operation can be conveniently divided into two parts ____ a slow cycle that



- M Magazine
- D Delivery pocket
- G Film gate
- P Pressure plate
- V Solenoid valves
- T Transfer pockets
- R Free roller
- F Fixed post
- I Integrating roller
- C Cassette

Fig. 1

is repeated between accelerator bursts and a fast cycle that covers the spill time while photographs are being taken.

During the slow cycle the film exposed during the preceding burst is wound into the cassette. Then a loop of film sufficient for five further photographs is taken from the magazine and held in readiness for the next burst.

During the machine burst, film is moved as required through the film gate but no motion of the heavy spools of film is demanded.

The Fast Cycle.

The movement and metering of a single frame can be followed by reference to figure (1) which shows the film gate G, the pressure plate P used to hold the film in the focal plane of the lens, and the so-called "transfer pockets" T_1 to T_5 .

When the first photograph in a burst has been taken, the pressure plate is drawn back by a solenoid and, simultaneously, a solenoid valve opens allowing compressed air to drive the film into pocket T_1 . The film is prevented from moving from left to right by the capstan action of the fixed post F. It, therefore, moves from right to left and is drawn through the gate. When the movement is complete, the pressure plate returns to clamp the film but the air

supply to pocket T_1 continues open. A second picture can then be taken and the same cycle repeats but, this time, film is forced into pocket T_2 . The cycle can be repeated until all five pockets have been filled.

The Slow Cycle.

At the end of the spill time the air supply to the transfer pockets is cut off. The film can then be drawn into the cassette by a constant torque motor attached to the spool. It passes first round a free roller R, then round the fixed, rubber covered, post F and then round a second free roller I whose revolutions are counted by a photo-electric device underneath the camera. To allow the film to move freely round the post F, compressed air is forced from a hole in the post to form a lubricating air cushion.

After exposed film has been wound into the cassette a fresh loop is taken from the magazine. This is done by blowing the film into a long "delivery pocket" D. This pocket is designed to hold rather more than five frames of film. The large inertia of the spool in the magazine makes the filling of the delivery pocket a slow operation (between 0.5 and 1.0 second depending upon the amount of film in the magazine). The air supply to the delivery pocket is, of course, stopped at the end of the

slow cycle.

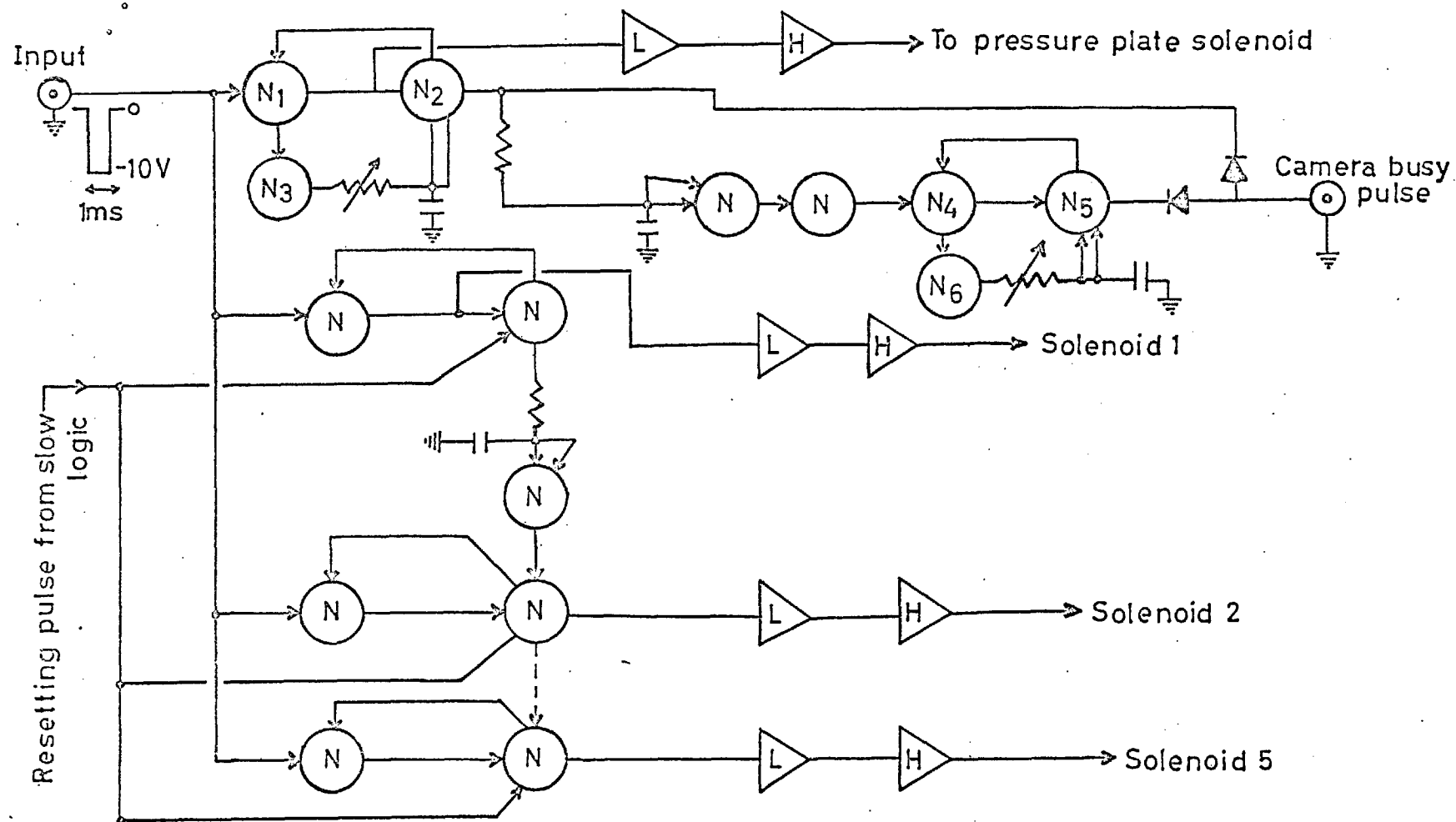
It is worth pointing out that the fast and slow cycles are independent of one another. The slow cycle occurs even when no photograph is taken in the previous accelerator burst but it leads to no movement of the film.

From the above description it follows that the duty of the electronic logic was to supply high current pulses, at appropriate times, to the various solenoids that either opened an air valve or caused the pressure plate to move. In addition a "camera busy" pulse of about 45 ms duration was also demanded every time command to move the film into a transfer pocket was received. This pulse was used as an inhibit to stop the logic in the main experiment from working while the film in the camera was moving. The "camera busy" pulse generator was required to have no dead time.

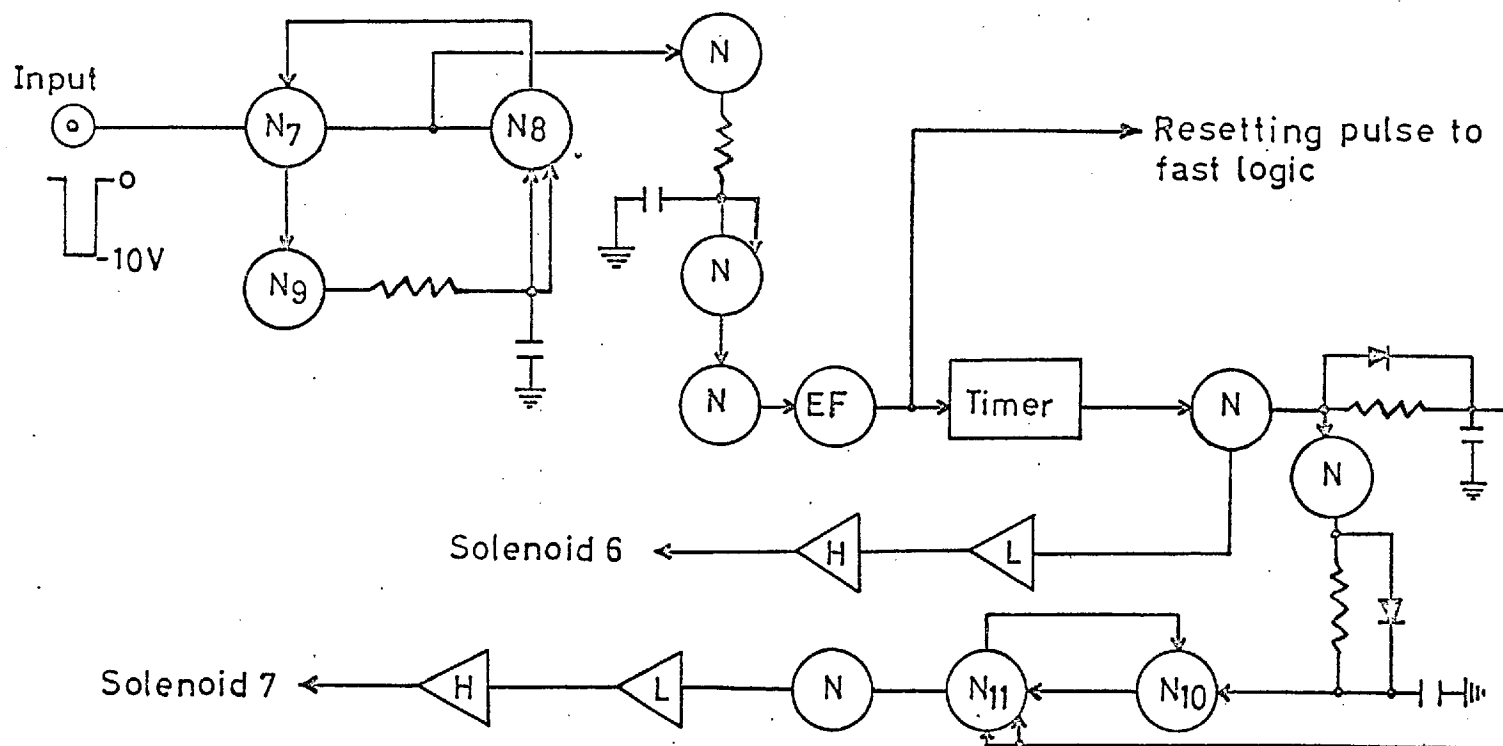
Use was made of the switching elements, Norbits, and Low Power and High Power units supplied by **M.E.L.** Ltd; London, in building the camera logic. The camera electronics was also conveniently divided into two parts, a Fast logic and a Slow logic. We now describe these logics in detail with reference to figure (2).

Camera electronics: Fast logic

Fig. 2a



N = Norbit
EF = Emitter follower
L = Low power unit
H = High power unit



Fast Logic.

This was initiated by a trigger pulse received, essentially, from a M/co. fan-out, during a beam burst. The logic consisted basically of 5 bi-stable circuits each consisting of two Norbits. The bi-stables (or 'memories') were each coupled to a Low power unit which drove a High power unit that had in its load circuit the associated solenoid. Each bi-stable normally inhibited, by means of a Norbit, the next bi-stable below, until it changed its state on the application of a trigger pulse. This was done so as to enable only one bi-stable to work at a time and also to enable the solenoids to be energized in the proper sequence.

The mono-stable comprising 3 Norbits (N_1, N_2, N_3) supplied a 25 ms long pulse to the pressure plate solenoid. In conjunction with another mono-stable (N_4, N_5, N_6) and the OR gate~~x~~ composed of diodes D_1 and D_2 , it provided the camera busy pulse. The two mono-stables in parallel formed a sort of 'di-ad' which had almost no dead time. The lengths and timings of various pulses generated by the Fast logic, at the occurrence of an event, are shown in figure (3).

Slow Logic. The slow cycle was initiated by the trailing

edge of a so-called " ΔB " pulse that marked the end of the beam burst (figure 3).

The mono-stable consisting of N_7 , N_8 , N_9 provided a 50 ms long pulse which, after a delay of about 40 ms, reset all those bi-stables in the Fast logic that had suffered a change of state during the previous Fast cycle. The resetting pulse was delayed in order to enable the transfer pocket, that had 'fired' last, to fill up completely, in case it had done so near the end of the beam burst.

The solenoid S_6 which was associated with a valve in post F, was energized immediately after the resetting took place, by a timer which supplied a one second long pulse. Thus S_6 was kept 'on' for about a second. About half a second later the bi-stable consisting of N_{10} and N_{11} energized the solenoid S_7 which opened the valve associated with the delivery pocket and kept it open for about a second. The lengths and timings of the pulses supplied by the Slow logic are also shown in figure (3).

A modification (not shown) was made subsequently in the Slow logic so that it would operate only if at least one transfer pocket had filled up during the previous Fast cycle. ~~This~~ reduced, to some extent, the heavy demand placed on the compressed air supply.

Timings and lengths of the pulses supplied by the camera electronics

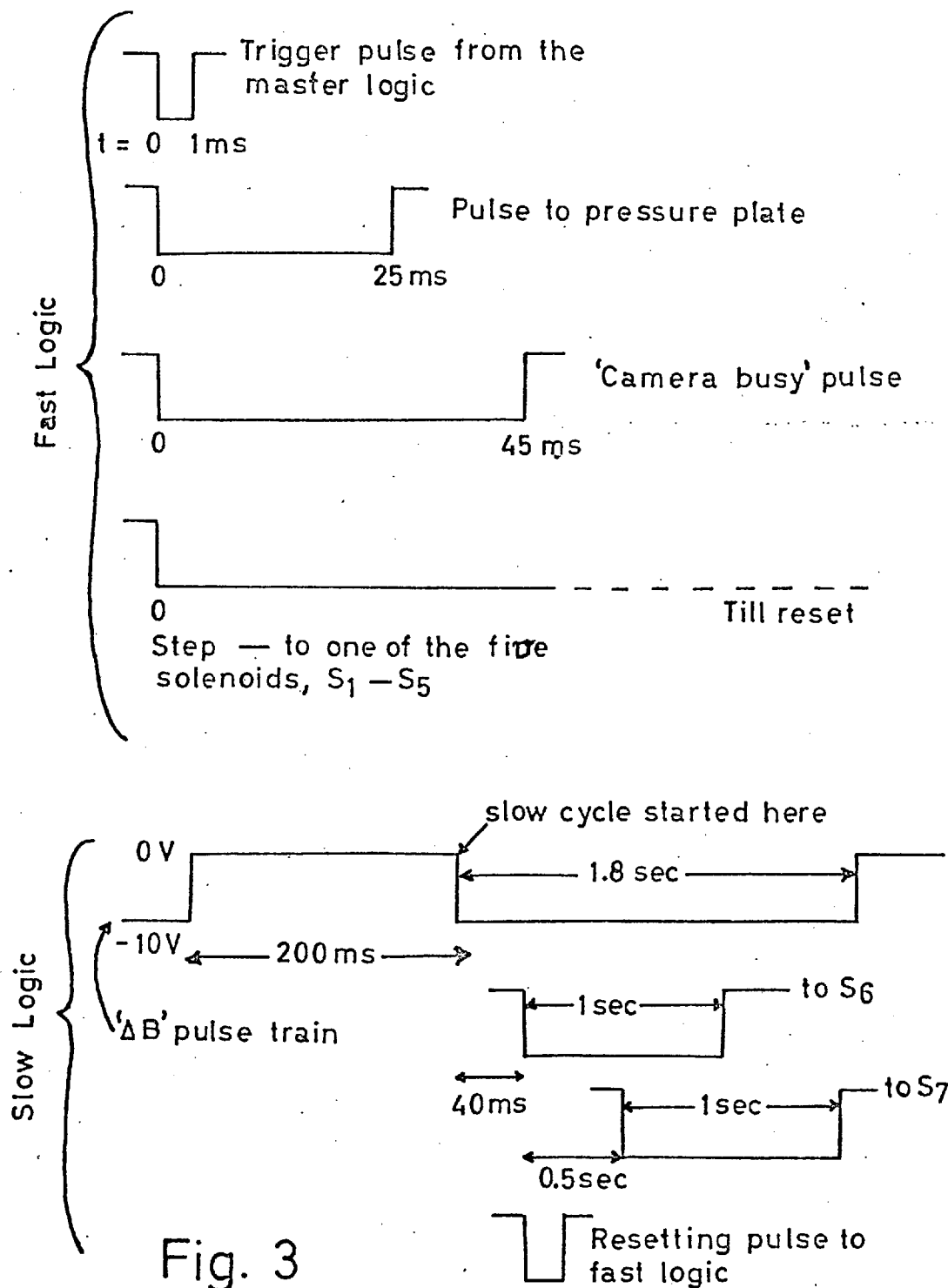


Fig. 3

APPENDIX BSUPPRESSION OF PICK-UP IN NIXIE DISPLAY CIRCUITS

In the $\phi \longrightarrow e^-e^+$ decay experiment it was required to record on the film the number of the neutron counter and the number of the hodoscope channel that was associated with the event photographed. There were 6 neutron counters and 4 hodoscope channels. Ten monostables(pulse stretchers) were built that triggered off the fast logic pulses supplied by AND gates(figure 1b): one channel of each AND gate was connected to a counter discriminator while the other channel received its input from a Master Co. fan-out. Unfortunately, the electromagnetic energy radiated by the spark chambers on firing made simple monostables unsuitable for this work. Unwanted outputs appeared from one or more circuits whenever the chambers fired and a photograph was taken setting at naught the object of the display.

Various attempts, to make the chambers radiate less energy and the circuits less sensitive to pick-up, were made but these always proved futile. For example, reduced E.H.T. was tried on the chambers to realize the first aim also keeping all wires that passed heavy currents during

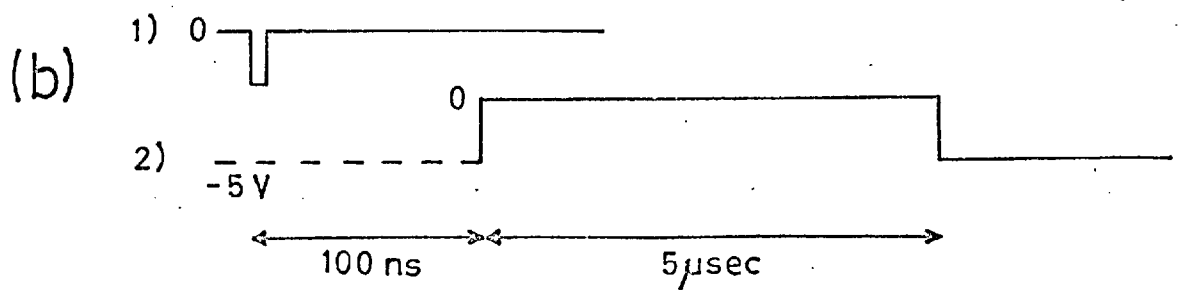
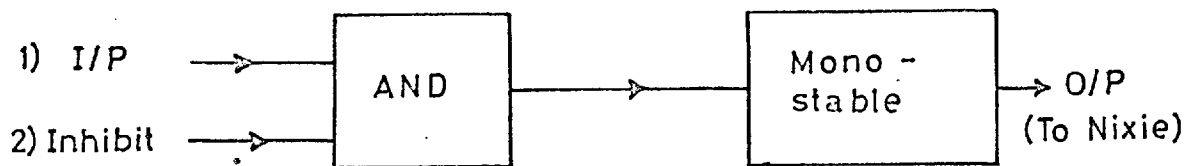
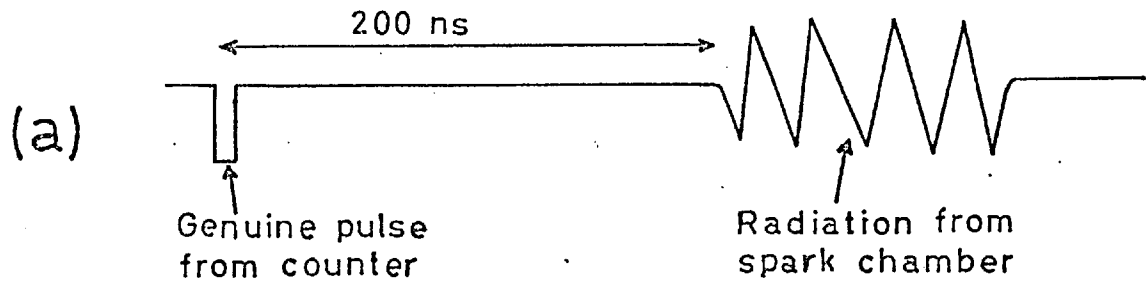
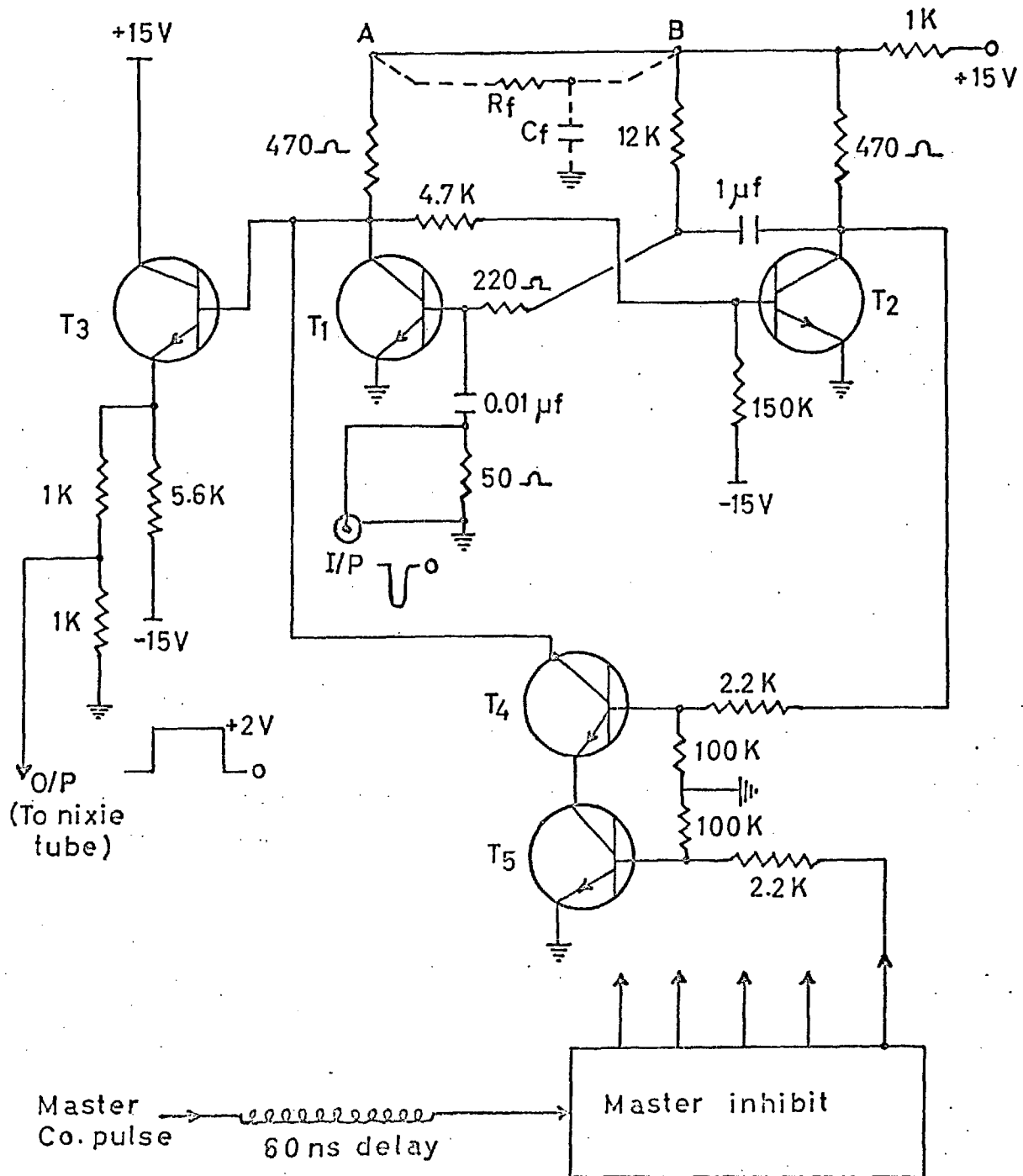


Fig. 1

the firing period as short as possible; low-pass filters were inserted in the power supply lines of the circuits as well as in the path of the outgoing pulses, to realize the second. Probably direct pick-up by the circuit wiring (which was kept quite short) and the circuits feeding the AND gates was responsible for providing the unwanted outputs. The triggering thresholds of the monostables had to be kept low because of the general low level of the fast logic pulses. The failure of these attempts led us to design a circuit which aimed at curing the symptoms rather than removing the cause of this trouble.

Due to the delay introduced by the high tension electronics and partly due to the time taken by the radiation to reach the monostables from the chambers, the radiation arrived at the circuits about 200 ns later than the occurrence of the Master Co. pulse. This is shown in figure (1a). This fact was exploited and it was decided to clamp, in a short time, the output terminals to ground, of all those circuits that had not triggered during the M/co. pulse, so that they would become unable to work even if they happened to receive a trigger pulse when the chambers fired. This scheme worked and the final circuit is shown in figure 2.

Each circuit consists of a flip-flop comprising



(All transistors are type C111)

Fig. 2

two high speed switching transistors, T_1 and T_2 , and an emitter follower T_3 driven by T_1 . When T_1 is switched off by applying a trigger pulse to its base via C_1 , collector of T_2 falls down to zero volt thus switching off T_4 which forms an AND gate with T_5 . Collector of T_1 and hence the base and emitter of T_3 rise upto about 4V positive. This is divided by 2 to provide a +2V pulse to the Nixie tube, the length of the pulse being about 10 ms.

Consider T_2 in a circuit that did not trigger during the Master Co. pulse. Its collector is at about +4V. T_4 is, therefore, on. The 'Master Inhibit' supplies a positive pulse of amplitude 5V and of 5 micro-second duration on the application of the delayed M/Co. pulse. This switches on T_5 . As T_4 and T_5 are both bottomed, collector of T_1 is very near the ground potential and cannot rise above this as long as T_4 and T_5 are both on.

The object of including the AND gate comprising T_4 and T_5 is to enable the Inhibit to "act" only upon that circuit which had not already been triggered by the associated counter pulse.

In another scheme the H.T. supply to T_2 can be switched off by clamping the point A to ground. It will then be necessary to include a filter, $R_f C_f$, between points A and B so that the potential at B does not fluctuate as a result of fluctuations at A.

APPENDIX C

THE EFFECT OF R-F BEAM MODULATION ON DEAD TIME LOSSES AND THE RATE OF CASUALTCOINCIDENCES.

(1). Casuals.

Let the average rates per second in two counters, A and B, placed in the beam, be n_1 and n_2 respectively, and let their instantaneous rates be,

$$n_1(t) = n_1(1 + M \sin \omega t) \dots\dots\dots(1),$$

and,
$$n_2(t) = n_2(1 + M \sin \omega t) \dots\dots\dots(2),$$

where $f = \omega / 2\pi$, is the frequency of modulation of the beam of particles, and M is the percentage modulation defined by 'a/n' as shown in figure (1).

We are interested in measuring the rate of chance coincidences between the pulses from these two counters when they are feeding a coincidence circuit having a resolving time τ ns, where τ is small compared with one R-F period.

Let one channel, say B, be delayed by δ ns. In this situation the instantaneous rates going into the coincidence circuit are respectively,

$n_1(1 + M \sin \omega t)$, and $n_2(1 + M \sin \omega (t - \delta))$. The number of 'casuals' in a small time Δt is given by,

Sinusoidal modulation of the beam intensity

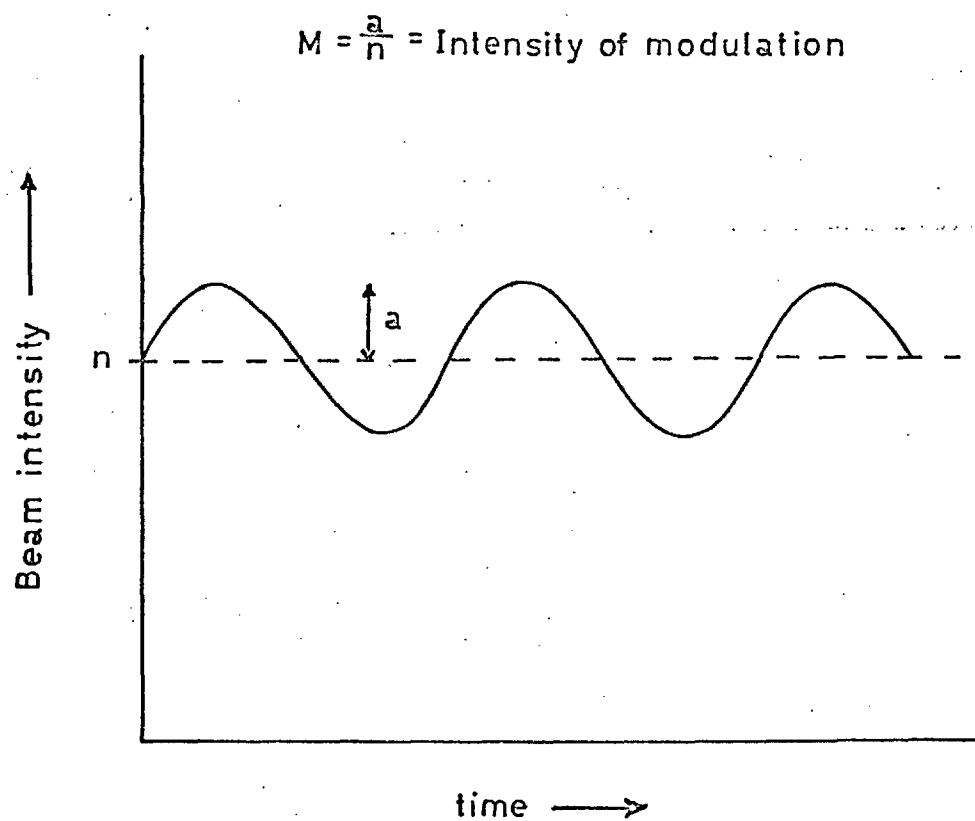


Fig. 1

$$n_1 n_2 \cdot \tau (1 + M \sin \omega t)(1 + M \sin \omega (t - \delta)) dt.$$

The average number of casualties per second can be obtained from this by integration over one R-F period and dividing the result by the length of the period, T_{rf} . Thus,

$$N_{cl(av)} = n_1 n_2 \cdot \tau / T_{rf} \int_0^{T_{rf}} (1 + M \sin \omega t)(1 + M \sin \omega (t - \delta)) dt,$$

$$= n_1 n_2 \cdot \tau (1 + M^2/2 \cos \omega \delta) \dots\dots\dots (3).$$

Equation (3) shows that in case of modulation the rate of casualties depends on the delay δ between the channels.

If the apparent length of each beam burst be T second, then the number of casualties per burst would be,

$$N_{cl(b)} = n_1 n_2 \cdot \tau \cdot T (1 + \frac{1}{2} M^2 \cos \omega \delta) \dots\dots\dots (4).$$

The counter rates per burst are,

$$n_1 T = N_1 \text{ (say), and,}$$

$$n_2 T = N_2.$$

Hence we have,

$$N_{cl(b)} = N_1 N_2 \cdot \tau / T (1 + \frac{1}{2} M^2 \cos \omega \delta) \dots\dots\dots (5).$$

We now consider a few important cases:

(a). In the absence of modulation (a flat beam), $M = 0$, and we get,

$$N_{cl(b)} = N_1 N_2 \cdot \tau / T \dots\dots\dots (6),$$

the well known formula.

(b). In the presence of modulation when the delay is equal to one R-F period,

$$N_{cl1} = N_1 N_2 \tau (2 + M^2)/2T \dots\dots\dots(7).$$

(c). If the delay is equal to one-half R-F period,

$$N_{cl\frac{1}{2}} = N_1 N_2 \tau (2 - M^2)/2T \dots\dots\dots(8).$$

From (7) and (8), by dividing we get,

$$N_{cl1}/N_{cl\frac{1}{2}} = (2 + M^2)/(2 - M^2) \dots\dots\dots(9),$$

from which M may be evaluated.

The effective spill time T_{eff} is obtained from (6) when the number of casuls measured in (7) is substituted, i.e;

$$T_{eff} = 2T/(2 + M^2) \dots\dots\dots(10).$$

When $M = 0$, $T_{eff} = T$, as expected. The minimum value of $T_{eff} = 2T/3$, for 100% modulation.

(2). Dead Time.

Let the average beam rate be n_0 and M be the modulation. Then if a counter having a dead time t_d per pulse is counting at a mean rate of 'n' per second, its instantaneous rate may be assumed to be $n(1 + M \cdot \sin \omega t)$, if t_d is small compared with one R-F period. The instantaneous beam rate is, of course, $n_0(1 + M \cdot \sin \omega t)$. The loss of counts per pulse due to dead time would depend on

time t at which the pulse is generated, and is given by,

$$n_o \int_t^{t+t_d} (1 + M \sin \omega t) dt \dots\dots\dots(11).$$

Also the counter output rate depends on time. Over a small time δt the loss of beam counts is, therefore,

$$\delta t \cdot n_o n (1 + M \sin \omega t) \int_t^{t+t_d} (1 + M \sin \omega t) dt \dots\dots\dots(12).$$

The average dead time loss can be evaluated from the above expression by integrating it over one R-F period and dividing by the length of the period. Thus,

$$\begin{aligned} \text{Dead time loss/sec} &= \frac{1}{T} \int_0^{T_{rf}} n(1 + M \sin \omega t) \left[\int_t^{t+t_d} n_o (1 + M \sin \omega t) dt \right] dt, \\ &= n_o n t_d (1 + \frac{1}{2} M^2 \sin \omega t_d / \omega t_d) \dots(13), \end{aligned}$$

which is the required result. If $M = 0$, we arrive at the usual rate, $n_o n \cdot t_d$.

If $t_d \ll T_{rf}$, we have, $\sin \omega t_d / \omega t_d \longrightarrow 1$, and therefore,

$$\text{Dead time loss/sec} = n_o n t_d (1 + M^2/2) \dots\dots\dots(14).$$

By using eqn.(10) this can be simplified to,

$$n_o n t_d \cdot T / T_{eff} \dots\dots\dots(15).$$

Equation (15) indicates that the dead time loss is inversely proportional to the effective spill time.

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