EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

PH I/COM-71/38
31 August 1971

PROPOSAL TO STUDY THE REACTION $\pi^- p \rightarrow \pi^0 \pi^0 n$ AT SERPUKHOV ENERGIES

W.D. Apel, H. Müller, D. Schinzel,
G. Sigurdsson and H.M. Staudenmaier,
Institut für Experimentelle Kernphysik,
Universität und Kernforschungszentrum, Karlsruhe.

E. Bertolucci, I. Mannelli, G. Pierazzini,
A. Scribano, F. Sergiampietri and M.L. Vincelli,
Istituto di Fisica dell'Università, Pisa,
and INFN, Sezione di Pisa.

G. Leder, R. Oberparleiter and M. Steuer,
Institut für Hochenergiephysik, Wien.

1. INTRODUCTION

In 1970 the Pisa-Karlsruhe Collaboration finished data-taking on the reaction $\pi^- p \rightarrow n$ + neutrals at 3.8, 6.0, 8.0 and 12.0 GeV/c. An earlier CERN-Karlsruhe experiment was done at 0.57 and 1.77 GeV/c. One of the aims of these experiments was the study of the $\pi^0\pi^0$ system up to 1.7 GeV $\pi\pi$ mass. The possibility to extend the mass range and to look for the existence of resonances in the series 0^+, 2^+, 4^+, ... at Serpukhov was indicated in the Letter of Intention PH I/COM-70/52.

In a discussion with physicists at Serpukhov, it came out that a Serpukhov group is considering a high-statistics precision experiment on the reaction $\pi^- p \rightarrow \pi^0 n$ with an apparatus which could also be used in part (beam, γ-detector, target) for the $\pi^0\pi^0$ experiment. In particular the γ-detector, which has to be constructed for the charge-exchange experiment, is a complex and expensive instrument. Therefore it seems reasonable to combine the experimental programs. The two experiments could run alternately, each group participating in the experiment of the other. The following reactions will be measured :

1) $\pi^- p \rightarrow \pi^0 n$ at the range of energies available at Serpukhov. The aim is to perform a high-statistics measurement of $d\sigma/dt$. This is a continuation of a present experiment at Serpukhov(10). A digitized γ-detector which makes it possible to measure the angle and energy of each γ will be constructed at Serpukhov and will replace the currently used optical spark-chambers.

2) $\pi^- p \rightarrow \pi^0\pi^0 n$ in the energy range from 25 to 45 GeV. The gammas and the neutron are detected. This reaction

falls under the responsibility of the K-P-V Collaboration. We propose also to perform a test on the feasibility of measuring $K^-p \rightarrow K^0n$ without a magnet.

As the planning of (1) rests with the Serpukhov group, we will elaborate (2) only.

2. MOTIVATION

The ππ interaction has been studied extensively in bubble chambers and also using counter-spark chamber techniques. The series of resonances $\rho(1^-)$, $f(2^+)$, $g(3^-)$ is well estiblished. The mass, width and spin of these ππ resonances are well measured. Also the existence of a wide $\varepsilon(0^+)$ resonance is proved although its exact mass and width is not well known. Above the g meson, no clear information on ππ interaction is available, as no specific experiments for that ππ mass range have been performed. It is still an open question whether the series of resonances ε, ρ, f, g is continued with sharp resonances of spin 4^+, 5^-, 6^+, ..., or whether ππ interaction above the g mass will show a more smooth behaviour. The resonances above the g meson could also be wide objects.Because of the high q-values of the decay products, the angular momentum barrier does not effectively inhibit the ππ decay while the presence of many open channels is likely to give rise to large width.

To clarify the question of ππ interaction above the g meson, it is necessary to get quantitative information by measuring the mass dependence and to perform an angular momentum analysis on the ππ system.

The best feasible way of doing this is to measure the reaction $\pi^- p \rightarrow \pi^0 \pi^0 n$ at Serpukhov energies and to use the OPE exchange model with Dürr-Pilkuhn or Benecke-Dürr off-shell correction factors [1,2] to extract the information on the $\pi\pi$ interaction. The application of their correction factors for the penetration of the angular momentum barrier has allowed a quantitative description [to at least 5% accuracy for $|t| < 1$ (GeV/c)^2 [3,4]] of reactions which can proceed via OPE including, of course, ρ, f, g, production, too.

From a quantitative measurement of the above reaction, one can thus deduce $\sigma(\pi^- \pi^+ \rightarrow \pi^0 \pi^0)$ which gives the $\pi\pi$ scattering at the even angular momenta 0^+, 2^+, 4^+, ... This is exactly what one wants, because the next partial wave after $g(3^-)$ is 4^+. Moreover, in $\pi^0 \pi^0$ one gets this information without the complications from odd waves 1^-, 3^-, 5^-, ..., which drastically increases the number of parameters because also all interferences have to be considered.

Also from the experimental side, the reaction $\pi^- p \rightarrow \pi^0 \pi^0 + n$ is favourable because it allows a selective trigger. A veto system against charged particles around the target will select the reaction $\pi^- p \rightarrow$ neutrals + n in which the largest part of the interactions in the hydrogen target is already rejected. The cross-section for all neutrals is below 100 μb at Serpukhov energies. This has to be compared with a cross-section of several mb if one cannot veto against charges particles.

All outgoing particles, γ's from π^0 and the neutron, can be measured. The topology of the events is very characteristic : always two gammas from the same π^0 close together and well separated from the other pair. Purification of the events by kinematical fit (2C if only γ directions are used and 6C using information on γ energies, too) will work very well and will give an almost uncontaminated sample of $\pi^o\pi^o n$ events.

Finally, Serpukhov energies are the best for performing the experiment. In this set-up, beam momenta of 25 - 45 GeV/c are just high enough to reach the wanted $\pi\pi$ mass region also at small t-values. This is important because the OPE reaction is dominant at small t-values. On the other hand it is not reasonable to go to higher beam momenta because then the p_{lab}^{-2} dependence of the cross-section will make the experiment unnecessarily more difficult.

It is obvious that the main aim of the experiment is this study of $\pi\pi$ interaction. But as a by-product, there will be information on cross-sections of neutral objects. Clearly a differential cross-section for f^o production will come out at all beam momenta and will be used as a further cross-check of the OPE model with Benecke-Dürr form factors. Also π^o and η production at large t is in the accepted kinematics interval. Furthermore, one can hope to get the cross-section for ω production from an analysis of the events where ω goes to $\pi^o\gamma$.

3. EXPERIMENTAL APPARATUS.

The incoming particles will be labelled by three threshold Cerenkov counters to give π^-, K^-, $\bar{p}$ signals, whereas their position and direction will be determined by Charpak chambers. It is foreseen to have a 40 cm H_2 target, where the interaction point can be determined by the pulse-height associated with the Cerenkov light of the incident particle. This target has already been used successfully in the Pisa-Karlsruhe experiment and has proved to be able to determine the interaction point position within ± 3 cm [5]. The target will be surrounded by a set of anticounters similar to the one used in the above-quoted experiment.

Neutrons with momenta above 200 MeV/c will be detected in 16 plastic scintillators of dimensions (240 x 16 x 16) cm^3. The time resolution is ± 1.5 nsec and the position resolution is ± 4 cm. Owing to space limitations, the neutron counters will be mounted on the same side in two layers of eight elements each. One set of these counters was already used in the experiment mentioned; the second one is completely equipped and presently under test.

The γ-detector will consist of Pb converters interspaced with scintillators and, for maximum spatial resolution, three planes of Charpak chambers. These planes are positioned behind 4 radiation lengths of Pb and are followed by scintillator hodoscopes (60 elements of 100 x 1.5 x 1 cm^3) alternating with 1 radiation length of Pb. There are six hodoscope planes, two in X, two in Y, one in U, and one in V (45^0 to X and Y) close to the shower maximum. These will give information about the energy and the position of the shower in all three coordinates. The detector is completed by further 20 radiation lengths of Pb, interspaced every 1 radiation length with a scintillator plane to get a good overall energy resolution.

The pulse height of all scintillators is measured via ADC's and scalers. The scaler contents, together with the other electronics information, will be recorded on magnetic tapes through an on-line computer. The CERN IBM 1800 computer equipped for data-transfer via CAMAC, which is presently at Serpukhov, is appropriate for this purpose.

4. RUNNING CONDITIONS.

4.1 Kinematics.

It is intended to study the reaction $\pi^- p \rightarrow \pi^0 \pi^0 n$ at different beam momenta and, if running time allows, also at different angle settings of the neutron detector to cross-check the experimental findings and to see the dependence of the phenomena on lab. momentum.

At least in the first runs we want to have control of the performance of the set-up by observing an established resonance. The kinematics for runs at the lowest beam momentum 25 GeV/c and the highest momentum 45 GeV/c are shown in figs. 2 and 3. The neutron detectors are at a distance of only 5 m and cover the angular range of 51^0 to 77^0 and 55^0 to 81^0, respectively.

As already outlined in section 2, it is essential for the research on $\pi\pi$ interactions to cover also small $|t|$ values. We will accept neutrons with momenta down to 200 MeV/c, which corresponds to $|t| > 0.04 (GeV/c)^2$ and $T_n > 20$ MeV. This is the lowest neutron energy for which we are confident our detectors can be used reliable. There is no such limit at high $|t|$ values, but the missing-mass resolution becomes bad above $p_n > 600$ MeV/c, equivalent to $|t| > 0.33\ (GeV/c)^2$. At 25 GeV/c we cover, for all $|t|$ values, the mass range from the f^0 mass to 2.2 GeV, and at 45 GeV/c from f^0 to 2.8 GeV. It is possible at both energies to get higher masses accepted by shifting the neutron detectors to smaller angles, but then we lose the control by the f^0. The missing-mass resolution is typically 80 MeV FWHM at 25 GeV/c. This is adequate because the known $\pi\pi$ resonances ρ, f, g are wider. At 45 GeV/c the resolution will be around 110 MeV FWHM, which is still good enough.

4.2 Angular acceptance.

The set-up is designed to allow angular momentum analysis of the $\pi\pi$ interaction. As we want to get higher momenta from the $\cos \Theta_{\pi\pi}$ distribution, a large solid-angle acceptance of the γ-detector is needed. A Monte Carlo program has been written to calculate its performance. The first hodoscope of the γ-detector was placed at 2 m distance, and 1.6 cm spacing of the hodoscope elements was assumed . At 25 GeV/c this is sufficient to see even the γ's of the fastest π^0's separately. For 45 GeV/c the γ-detector will be placed at a proportionally larger distance. The detection probability for γ's of different energy in a set-up with scintillators behind a 4 radiation length Pb converter has been taken, for the Monte Carlo calculation, from the tables of Messel and Crawford [6]. They give the probability that at least one electron with energy above 10 MeV is present after the converter.

In figs. 4a,b,c, the results of the Monte Carlo calculations for the $\pi\pi$ scattering angular distribution are shown for the accepted events. The calculations are done for a $\pi\pi$ effective mass of 2.2 GeV. The curve a corresponds to isotropic decay and curves b and c to maximum possible polarization of a 2^+ and 4^+ resonance. Events with $0 < |\cos \Theta_{\pi\pi}| < 0.6$ are almost uniformly accepted. The different angular momentum states can be clearly distinguished.

4.3 Rates.

For the established $\pi\pi$ mesons ρ, f, and g, a good description of the dependence of the production cross-sections on lab. momentum and momentum transfer is given by the OPE model with Dürr-Pilkuhn or Benecke-Dürr penetration factors for the angular momentum barriers. We use this model and known f^o cross-sections for an estimate of the production cross-section of a 4^+ $\pi\pi$ resonance. For this resonance we use the symbol h.

For a $\pi^o\pi^o$ resonance of spin j produced in $\pi^- p \to \pi^o\pi^o n$, one has

$$\frac{d^2\sigma}{dtdm} = \frac{f^2}{\pi} \frac{m^2 q}{p^2_{lab}} \frac{t}{(t+\mu^2)^2} \cdot F_j(t) \cdot \sigma_j(\pi^-\pi^+ \to \pi^o\pi^o).$$

$F_j(t)$ is a correction which gives the dependence of the penetration factor of the angular momentum barrier for off-shell momenta; f is the pion-nucleon coupling constant, μ the pion mass, t the invariant momentum transfer, m the effective $\pi\pi$ mass, q the momentum of the π in the $\pi\pi$ system, p_{lab} the momentum of the π^- beam particle, and $\sigma_j(\pi^-\pi^+ \to \pi^o\pi^o)$ the $\pi\pi$ charge exchange cross-section at the $\pi\pi$ mass m. In the case of a resonance of mass m_r, it is given by

$$\sigma_j(\pi^-\pi^+ \to \pi^o\pi^o) = (2j+1) \times \frac{2}{9} \times 4\pi\lambda^2 \frac{\Gamma_{el}^2}{4(m_r-m)^2+\Gamma^2}$$

The cross-section for f^o production is known up to 16 GeV/c and follows the p^{-2}_{lab} law well. An extrapolation of the compiled data of Ballam et al.[7] to 25 GeV/c gives $\sigma(\pi^- p \to f^o n) = 18\ \mu b$.

For the ratio of the h to f^o cross-section, the OPE formula gives :

$$\frac{\sigma(\pi^- p \to h\, n) \atop \quad \hookrightarrow 2\pi^o}{\sigma(\pi^- p \to f^o n) \atop \quad \hookrightarrow 2\pi^o} = \frac{F_4(t)}{F_2(t)} \cdot \frac{\eta_h^2}{\eta_{f^o}^2} \cdot \frac{9}{5} \cdot \frac{\Gamma_h}{\Gamma_f} \cdot \frac{m_h}{m_f} ,$$

where $\eta = \dfrac{\Gamma_{el}}{\Gamma} = \dfrac{\sigma(2\pi)}{\sigma(all)}$ = elasticity of resonance.

Owing to the high q-values in the decay, the factors $F_j(t)$ are near to 1 if we restrict ourselves to $t < 0.4 (GeV/c)^2$, which already contains most of the cross-section and is the maximum t for which we have reasonably good mass resolution The momentum of the pions is so high that the angular momentum barriers are well penetrated, assuming a standard interaction radius of 0.6 fermi [see Wolf (4)].

The elasticity η is essentially 1 for the f^o meson, as no other decays except 2π are known. The crucial point in the calculations is η_h. At this high mass, clearly other channels are open. In addition to the elastic one

$h \to$	2π with	$\ell = 4$		(1)

the most likely channels should be :

$h \to$	$\rho\rho$	$\ell = 2$		(2)
$h \to$	$A_3\pi$	$\ell = 1$		(3)
$h \to$	$f\varepsilon$	$\ell = 2$	but q small	(4)
$h \to$	$K\bar{K}$	$\ell = 4$		(5)

The angular momentum barriers play only a small role, as is shown by the penetration factors $v_l(Rq)$ of Dürr Pilkuhn [1] as tabulated in Lax and Feshbach [8]. Therefore reactions (2) and (3) should not go faster than the wanted one $h \to 2\pi$. Reaction (4) probably contributes only a little because of the small q-value, and the decays into K's as in reaction (5) are inhibited because strange particles are involved. From these arguments we conclude that a good guess is $\eta \approx 1/3$ giving equal weight to the decays (1) to (3).

This value fits the situation at the g meson where similar channels are open and $\eta \approx 0.4$ is indicated by the ABC collaboration [9].

The cross-sections which we estimate are given together with the expected rates and peak-to-background ratios in table 1. With the neutron detector at 5 m, the number of events per hour of useful running-time is

$$N_{ev}/h = 3 \times 10^{30} \times \varepsilon_\gamma \times \int_{t_{min}}^{t_{max}} \frac{d\sigma}{dt}\, dt.$$

ε_γ is the probability that all four γ's are detected and is 0.36 for a 4^+ meson of mass 2.2 GeV and 0.39 for the f^0 meson. The worst case of full polarization has been assumed. The range of momentum transfer $0.04 < t < 0.4$ GeV^2 which we accept includes, for peripherally produced resonances, about 2/3 of the total cross-section. With these values we get for f and h production the estimate :

$$N_{ev}/h \approx 0.7 \times 10^{30} \times \sigma_{tot}$$

The formulas are based on the following running conditions : 40 cm hydrogen target, 20% efficiency for the detection of neutrons which reach the counter array, 5×10^5 π^-/pulse, and 400 pulse/h.

For the background estimate, we obtained useful information during our visit to Serpukhov. The group which is measuring charge exchange observed 5×10^{-5} interactions per incoming pion with a veto against charged particle in a 20 cm hydrogen target at 30 GeV/c. This means that the cross-section for $\pi^- p \rightarrow$ neutrals is around or below 60 μb at 30 GeV/c, which corresponds to about 80 μb at 25 GeV/c assuming a $p_{lab}^{-1,5}$ dependence; 20 μb of this cross-section can be subtracted for π^0 and η production. The rest should distribute about equally in the produced mass^2 interval of 0 to 6 GeV^2, which means that we have to expect only a background of neutrals triggers with more than two γ's of about 1 μb/0.1 GeV^2. The peak-to-background ratios should therefore be quite good. The estimated values are also given in table 1.

In summary, the conclusion of the rate and background considerations is as follows. If the $\pi\pi$ interaction at high mass leads to a 4^+ resonance of width similar to ρ, f, g then this resonance could be seen clearly even for an elasticity $\eta = 0.3$. If, instead, above g the $\pi\pi$ interaction leads only to a broad structure, one has still enough events to measure the interaction quantitatively including an angular momentum analysis.

5. ORGANIZATIONAL ASPECTS.

The major part of the experiment should be installed during the Summer shutdown 1972, and it seems possible to have the equipment ready at that time. The beam most suited is the 4V beam, whose energy ranges from 20 to 45 GeV with a very good focus and sufficient (~ 10^6 π^-/burst) intensity. For the data-taking, two running periods (about three weeks each) at 25 GeV/c plus the same amount at 45 GeV/c is necessary. Some weeks with an inferior beam are also needed for running in.

The use of the CERN IBM 1800 with the associated electronics currently installed is needed for the experiment. For convenience, also the Charpak chambers currently installed in the beam should be taken over.

Moreover, because of a lack of liquid helium at Serpukhov, the liquid H_2 target must be adapted to work with a refrigerator. The CERN refrigerator already existing at Serpukhov is needed and CERN support is required in the adaptation work.

In view of an effective collaboration it is intended that part of the participants will stay during the full experiment at Serpukhov.

HM/ea

REFERENCES

1) H.P. Dürr and H. Pilkuhn, Kinematical form factors in the peripheral model, Nuovo Cimento 40 A, 899 (1965).

2) J. Benecke and H.P. Dürr, A relativistic model for kinematical form factors, Nuovo Cimento 56 A, 269 (1968).

3) P. Schlein, Kπ scattering and normal parity K*'s, Informal Meeting on Experimental Meson spectroscopy, (eds. C. Baltay and A.H. Rosenfeld) (W.A. Benjamin Inc., New York, 1968), p. 161.

4) G. Wolf, Single and double-pion production by one-pion exchange and a comparison with experimental data between 1.6 and 20 GeV/c, Phys.Rev. 182, 1538 (1969). Many further references can be found therein.

5) E. Bertolucci et al., $X^0 \to 2\gamma$ and other results from $\pi^- p \to$ neutral meson + neutron at 3.8 GeV/c, contribution to International Conference on Elementary Particles, Amsterdam (1971).

6) H. Messel and D.F. Crawford, Electron-photon shower distribution function tables for lead, copper and air absorbers, (Pergamon Press, Oxford, 1970).

7) J. Ballam et al., A study of the reaction $\pi^- p \to \pi^- \pi^+ n$ at 16 GeV/c, Phys. Letters 31 B, 489 (1970).

8) M. Lax and H. Feshbach, Absorption and scattering for impedance boundary conditions on spheres and circular cylinders, J. Acoust. Soc. Am. 20, 108 (1948).

(9) J. Bartsch et al., The g-meson, Nuclear Phys. B 22, 109 (1970).

(10) V.N. Bolotov et al., Measurement of $\pi^- p \rightarrow \pi^0 n$ reaction cross-section in the momentum range up to 50 GeV/c, Contribution to Int. Conf. on Elementary Particles, Amsterdam (1971).

TABLE 1

Table of expected cross-sections and rates

	25 GeV/c	45 GeV/c
f^0		
σ_{tot} for $f^0 \to 2\pi^0$	6 μb	2 μb
events/period (200 h effect. running	840 events	280 events
ππ from resonance relative to neutral triggers in the same mass region	1 : 1	1 : 1.5
h^0 $m_h = 2.2$ GeV, $\Gamma_h = \Gamma_f$, $\eta^2 = 0.1$		
σ_{tot} for $h \to 2\pi^0$	2 μb	0.6 μb
events/period	280 events	90 events
ππ relative to triggers	1 : 4	1 : 6
wide object around 2.2 GeV, $\eta^2 = 0.1$		
σ_{tot}/100 MeV for $\pi^0\pi^0$	1.5 μb	0.5 μb
events/period	200 ev./100 MeV	70 ev./100 MeV
background in trigger (before reconstruction)		
$\sigma_{neutrals}/GeV^2$	10 μb/GeV^2	4 μb/GeV^2
events/period	1400 ev./GeV^2	600 ev./GeV^2

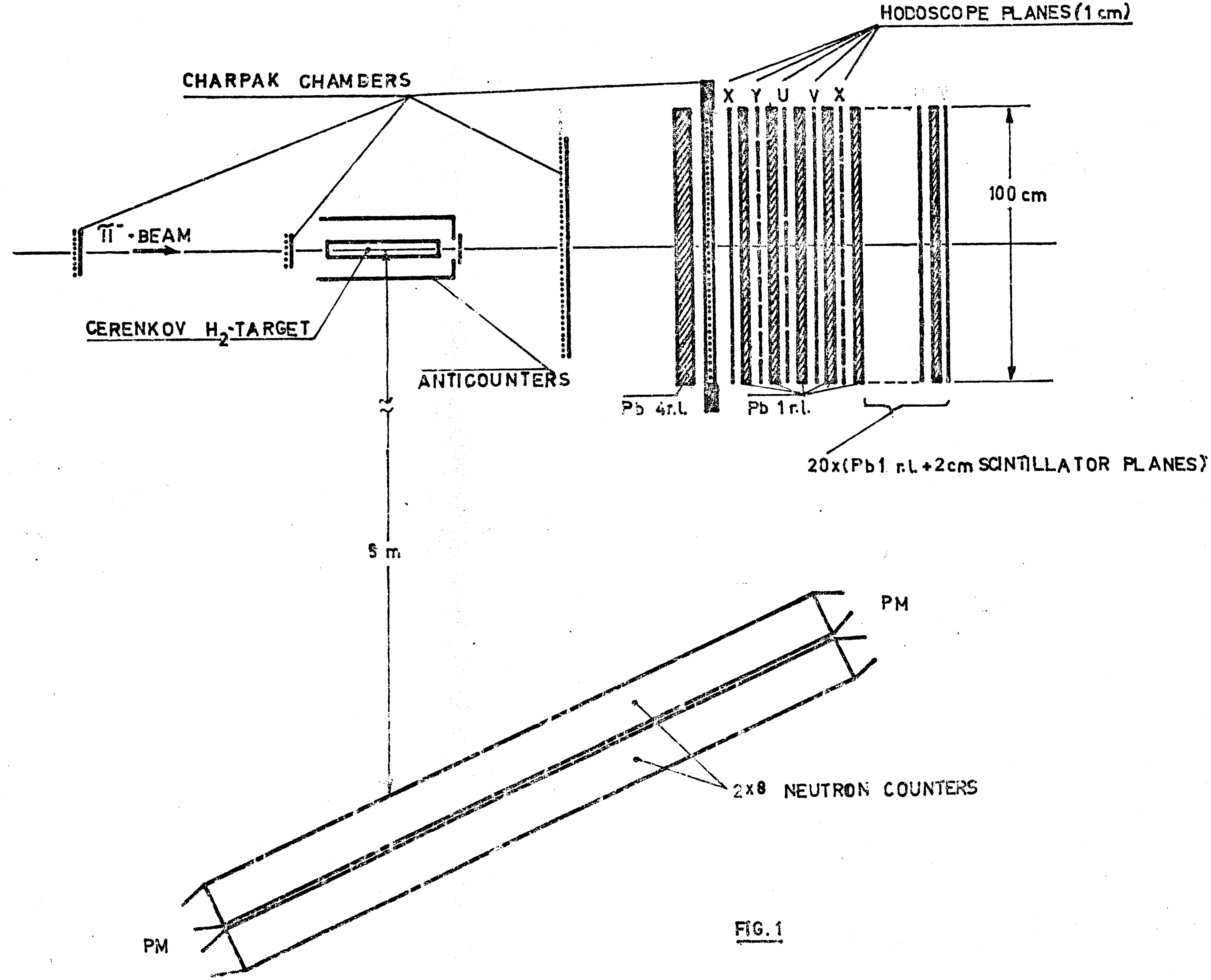

HODOSCOPE PLANES (1 cm)
CHARPAK CHAMBERS
X Y U V X
π⁻-BEAM
100 cm
CERENKOV H₂-TARGET
ANTICOUNTERS
Pb 4 r.l.
Pb 1 r.l.
20x(Pb 1 r.l. + 2cm SCINTILLATOR PLANES)
5 m
PM
2x8 NEUTRON COUNTERS
PM

FIG. 1

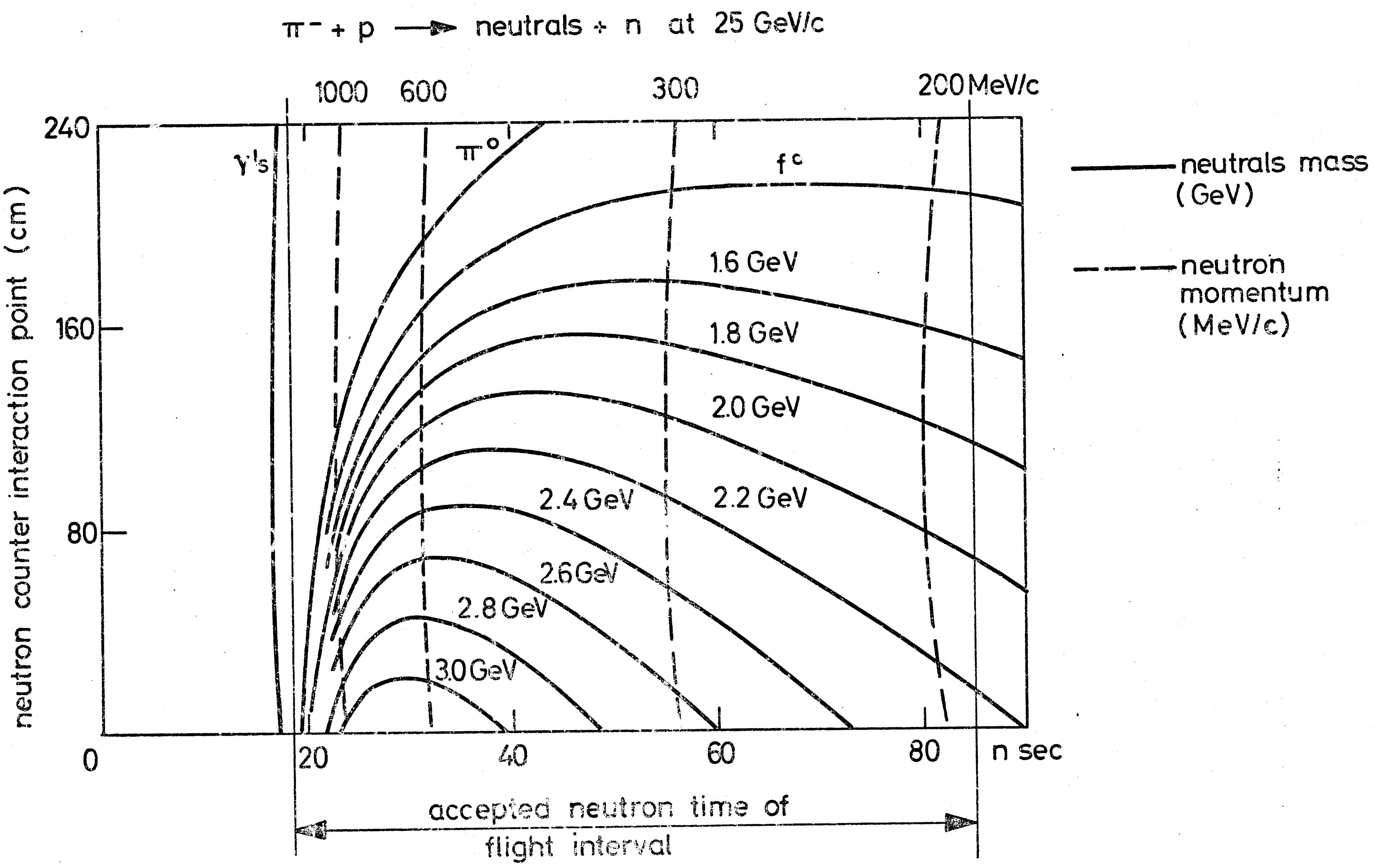
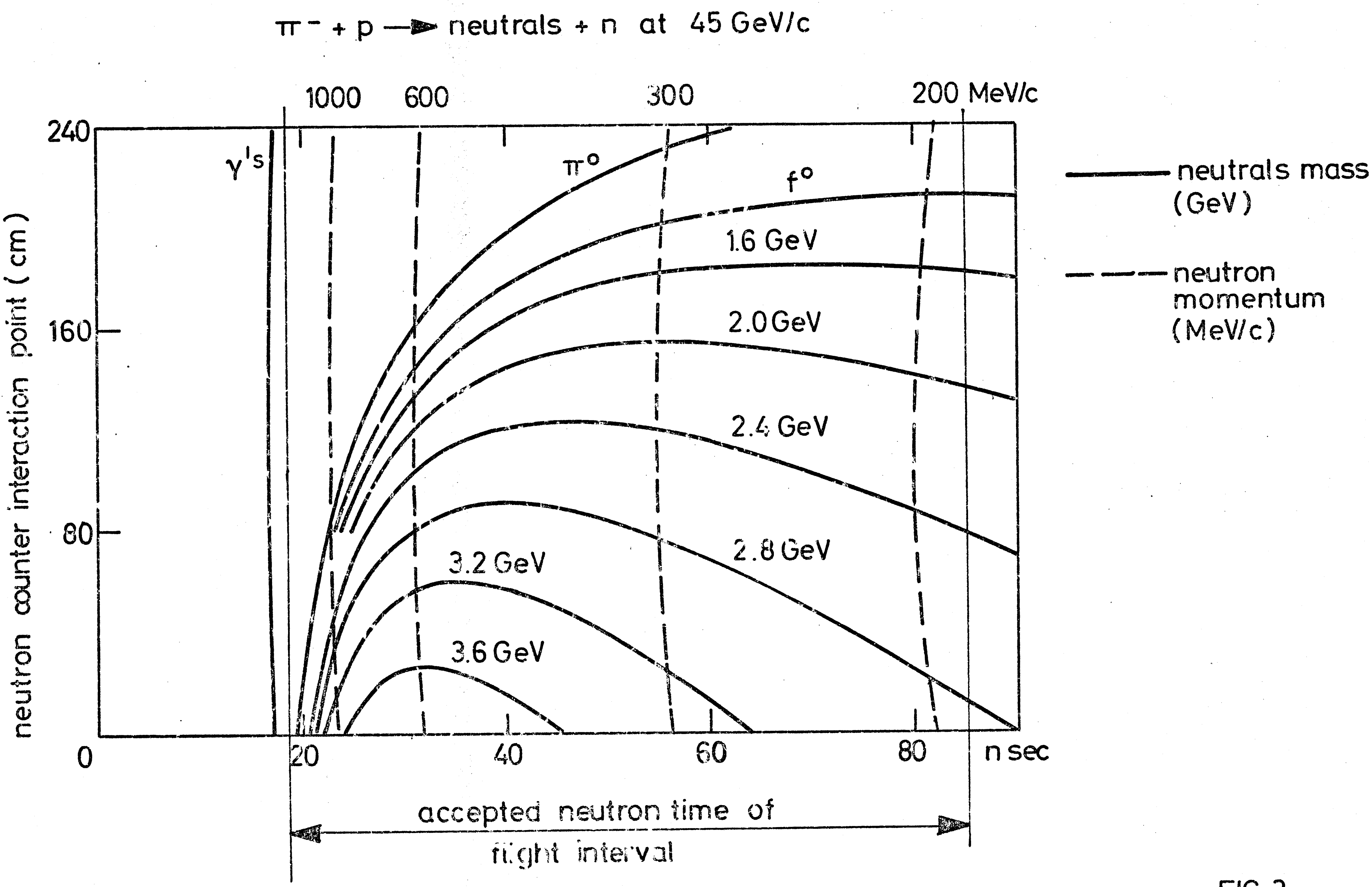

π⁻ + p → neutrals + n at 25 GeV/c
1000
600
300
200 MeV/c
240
160
80
0
20
40
60
80
n sec
γ's
π°
f°
1.6 GeV
1.8 GeV
2.0 GeV
2.2 GeV
2.4 GeV
2.6 GeV
2.8 GeV
3.0 GeV
neutron counter interaction point (cm)
accepted neutron time of flight interval
neutrals mass (GeV)
neutron momentum (MeV/c)

FIG. 2



π⁻ + p → neutrals + n at 45 GeV/c
1000
600
300
200 MeV/c
240
160
80
0
20
40
60
80
n sec
γ's
π°
f°
1.6 GeV
2.0 GeV
2.4 GeV
2.8 GeV
3.2 GeV
3.6 GeV
neutron counter interaction point (cm)
accepted neutron time of flight interval
neutrals mass (GeV)
neutron momentum (MeV/c)

FIG. 3

$\pi\pi$ scattering angular distributions
10 000 events generated by Monte Carlo program
25 GeV/c, $m_{\pi\pi}$ = 2.2 GeV/c, detector at 2 m,
curves are distributions for 100% acceptance and full polarisation

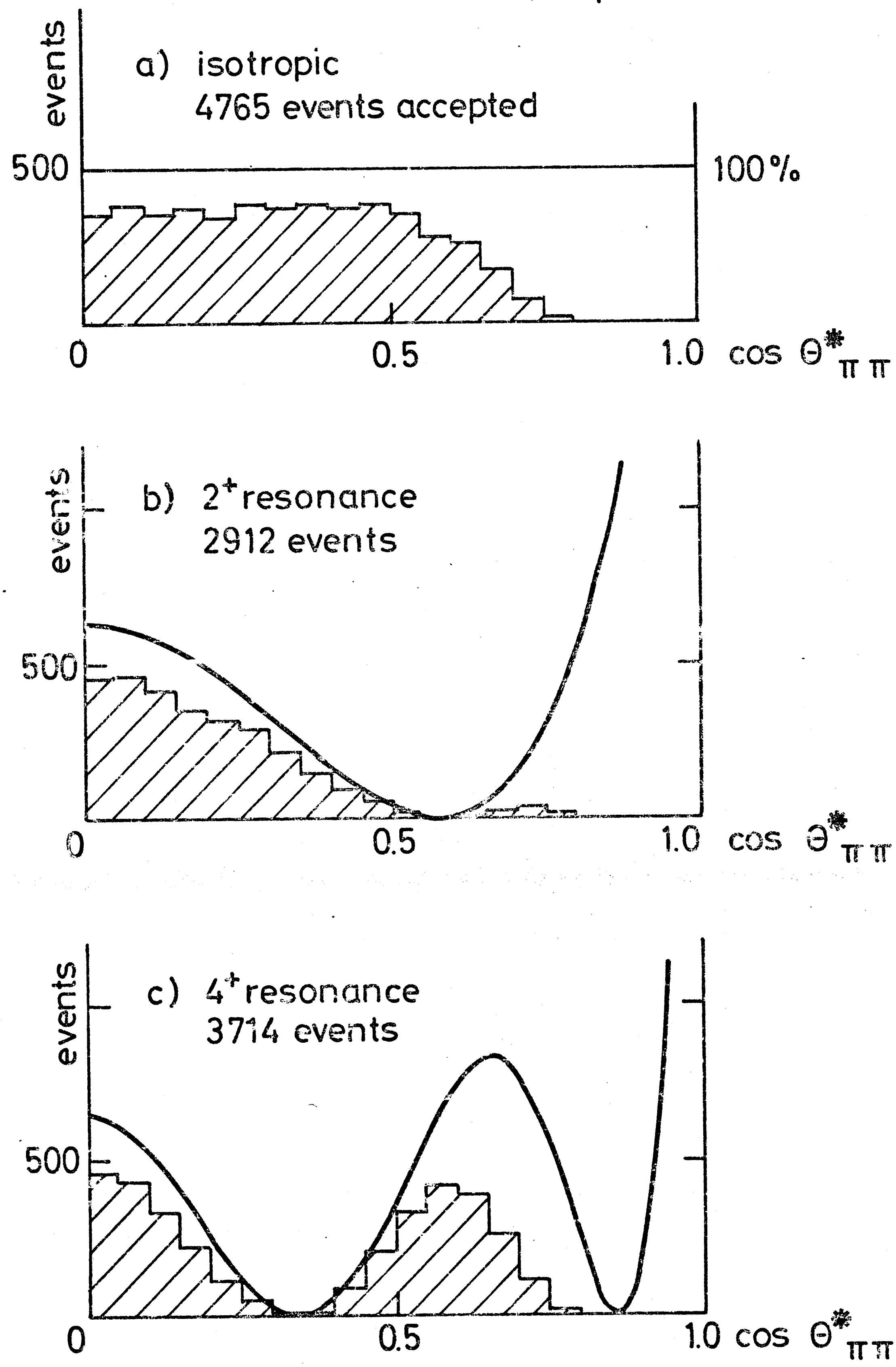


FIG.4