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Recent Results from the Brookhaven National Laboratory 7' Bubble Chamber*

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In this presentation we will briefly describe the equipment and review the method of analysis used for all events. We will then present new results on the ratio of neutrino cross sections on neutrons to that on protons. We will remind you of the published event indicating an apparent $\Delta S = -\Delta Q$ current. Finally, we present the parameters of all the other charged current events containing at least one strange particle.

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The neutrino beam is sketched in Fig. 1. A proton beam of 5×10^{12} protons per pulse strikes a water cooled sapphire target once every 1.5 seconds. Pions and kaons emerging from the target are focused by a two horn (finger)[1] system and allowed to decay inside a 57 m long tunnel. Muons from the decays are stopped in 30 m of iron and neutrinos pass through this shield to the bubble chamber beyond.

The bubble chamber is approximately 2 m (7 ft.) in diameter and 3 m high with a visible volume of 7 m^3. Inside the chamber there are four steel plates, each 5 cm thick and about 1.5 m x 1.5 m, located on the down stream side of the chamber. They are set on an angle of 30^o to the beam, such as to intersect the maximum number of negative tracks (see Fig. 1). The visible volume in front of the plates is 5 m^3.

The data that will be presented has come from a sample of 62,000 pictures taken with hydrogen in the chamber and 220,000 pictures with deuterium.

Events were initially selected if they contained at least two tracks. Three pronged events representing the reaction $p + p \to p + p$ were removed if they fitted. The vector sum of momenta of all tracks was then computed and its direction plotted in azimuth and dip. Such a plot for a partial sample of the data is shown in Fig. 2. A clear separation is seen between beam related events (azimuth $\sim$ 0, dip $\sim$ 0), and cosmic ray events (dip $\sim 90^o$). A cut was applied requiring the vector momentum to be within 40^o of the beam direction and a further cut required the sum of the vector momenta to be greater than 400 MeV. After these cuts, there remained 95 events from the hydrogen exposure and 476 from the deuterium.

Neutral current events were identified when there was no μ^- track candidate; the flux of antineutrinos that would give events with no μ^- being negligible (1%). The μ^- hypothesis could be rejected whenever a track interacted in the chamber or plates. It was also rejected if the track made a $\pi - \mu - e$ decay or was observed to stop in the chamber with no decay electron. Fig. 3 shows the probability for such negative track identification as a function of the track momentum. For comparison, the dashed curve shows the case had there been no plates. The advantage of the plates is clear. Background for the neutral current sample from beam related neutrons was determined by identifying events that fit the reaction $n + p \rightarrow p + p + \pi^-$. Only three such events were found, indicating a small background from such neutrons and allowing, using known cross sections, an estimate of the magnitude of this background in individual channels. Analysis of the neutral current events is still in progress and will not be further reported on here.

We will now restrict ourselves to the charged current events and report on the ratio of cross sections on neutrons to that on protons. In this charged current sample, the background from neutrons is negligible and the contamination from unidentified neutral current events is sufficiently small as to introduce errors that are much less than those due to statistics. In order to obtain the neutrino energy and other parameters for each event in the sample, each event was examined by a physicist and the tracks identified by ionization or range whenever possible. Events with multiple fits were given appropriate fractional weights in all distributions. In practice, 90% of all events were unambiguously identified so that any smearing of distributions from this cause is small. When the kinematics indicated that one or more π^0's were missing, the event was calculated on the assumption of its being a single π^0. Similarly, if a neutron with or without π^0's was missing, it was assumed that only the neutron was present. Since the number of events falls rapidly as a function of track multiplicity, this treatment introduces little bias to the data. The distribution of the neutrino energy calculated in this way is shown in Fig. 4.

We will now consider the method used to estimate the relative contribution from interactions of the neutrinos on the neutrons and protons. For this purpose we will restrict ourselves to the deuterium data only. If in this data we see a number of events with an even number of prongs (n_{even}), then we identify them as interactions on neutrons in which the spectator protons were not seen. If, on the other hand, we see events with an odd number of prongs (n_{odd}), then they can be interactions on protons, or, alternatively, interactions on neutrons in which the proton spectators were visible. If we define C to be the ratio of seen to unseen spectator protons, then it is trivial to conclude that the number of events on protons (n_p) and on neutrons (n_n) are given by:

$$\begin{aligned} n_n &= n_{even}\,(1 + C) \\ n_p &= n_{odd} - n_{even}\,(C) \quad . \end{aligned} \tag{1}$$

We can determine C by observing the ratio of events that fit the reaction $\nu\ n\ (p_s) \rightarrow \mu^-\ p\ (p_s)$ in which the spectator proton (p_s) is either seen or not seen. The numbers of events observed were 42 and 131 respectively, yielding a value of C:

$$C = .32 \pm .06 \quad . \tag{2}$$

We note that the use of this value of C in equation (1) assumes that C is not dependent on the event type. Large variations are not expected, but some increase in C as a function of multiplicity should occur and is in fact indicated by a study of the reaction $\nu\ n\ (p_s) \rightarrow \mu^-\ p\ \pi^+\ \pi^-\ (p_s)$ with the spectator seen and unseen (12 and 24 events respectively). If this data is used together with the above, we obtain a modified value of C:

$$C = .35 \pm .06 \quad . \tag{3}$$

These two results (equations (2) and (3)) agree within the errors. We will here[2] use the second (equation (3)) since it does, at least to first order, allow for such variations of C with multiplicity.

The observed distribution of charged current events as a function of the number of observed prongs is:

Number of Prongs	Number of Events
2	171
3	249
4	24
5	24
6	2
7	2

We have thus observed 197 events with even prongs and 275 with odd prongs. Using equations (1) and (3) and applying a correction for a 13% contamination of hydrogen in the deuterium used, we obtain[2] for the ratio of neutrino total cross section on neutrons $\sigma(n)$ to that on protons $\sigma(p)$:

$$\frac{\sigma(n)}{\sigma(p)} = 1.48 \pm .17 \quad . \tag{4}$$

This result may now be compared with various parton theoretical expectations. Barger and Phillips[3] obtain $\sigma(n)/\sigma(p) = 2.05$ which does not agree with our result. However, their prediction for the ratio of deeply inelastic electron scattering is also in disagreement with that experiment. McElhaney and Tuan[4] fit the electron data and predict $\sigma(n)/\sigma(p) = 1.72 \begin{smallmatrix}+.60\\-.46\end{smallmatrix}$ where the errors reflect those of the data used. This is clearly in agreement with our result.

It should be stressed at this point that the theories quoted give predictions for this ratio at asymptotic energies, a situation far from that present in this experiment. The only justification for comparing such predictions with this experiment is that other asymptotic predictions, such as those for the total ν and $\bar{\nu}$ cross sections, have been realized at low energies. This situation has been described as "precocious scaling"[5], a concept that further implies that distributions of events at low energies in the variable $x' = q^2/(2M\nu + M^2)$ should approximate the asymptotic distributions in the variable $x = q^2/2M\nu$. (Here q is the 4 momentum transfer between the neutrino and lepton, ν the fourth component of q, and M the nucleon mass.) In order to further test this hypothesis we can plot the distribution of all our events as a function of x' and compare this distribution with the parton theory. Fig. 5 shows this distribution. The smooth line is a parton prediction based on the assumption that there are only p and n quarks in the nucleon. The curve is then obtained directly from the function νW_2(en) and νW_2(ep) derived experimentally from electron scattering[6]. The line is dashed in the small x' region since the above assumption that ignores a "sea" of quarks and antiquarks renders the theory inapplicable to this region. The agreement between the theory and the experimental results as seen in this figure represents further evidence for precocious scaling.

We can now present the ratio of $\sigma(n)/\sigma(p)$ as a function of the variable x' and again compare the result with the asymptotic predictions for x obtained from the parton theory. This is shown in Fig. 6. The line is again obtained assuming no sea, but we have omitted to dash the curve in the small x' region since charge invariance requires that the ratio be 1 at x' = 0, thus assuring that the introduction of the sea cannot have a very large effect on the prediction even for small x'. It is seen that although the trend of the data is in agreement with the prediction, there is a suggestion of a departure in the high x' region.

In the last part of this paper we wish to discuss the charged current events containing strange particles. We will use for this the data from both the hydrogen and the deuterium exposures. Table I gives the event types, constraint class, interpretations, q^2 and x (where $x = q^2/2M\nu$, q and M, are defined as above) of the events.

The first event in the table has been reported in the literature[7] and is shown again in Fig. 7. It represents an apparent $\Delta S=-\Delta Q$ current which would be an expected signature for the production and decay of a charmed baryon. The effective mass of the hadron system in this event is 2426 ± 13 MeV and this represents either the mass or the upper limit on the mass for such a baryon. The probability that this event is a misinterpreted associated production event is calculated to be 3×10^{-5}. This value must be compared to an estimated probability that a charmed baryon be produced and decay in a way such that it would be identified in this experiment. For this purpose we need a cross section for charm production as a function of energy, the branching ratio of the charmed baryon into states with no missing neutral and the probability that at production no other neutral is produced. Obviously such data is unavailable. However, if we assume the charm/noncharm ratio to be of order $\sin^2\theta_c$ (∿ 3%) and constant above threshold (∿ 4 GeV), take the branching ratio of charm into identifiable negative strangeness to be 50%, and further assume that the ratio of charm events with and without neutrals is similar to that observed for associated strange particle production 50%, then we can obtain an estimate for the number of charmed particle events that would be identified by their 3C fits. Since we have 74 events above 4 GeV, we would expect to have identified 0.6 (74 x .03 x .5 x .5) such events[8]. The a priori probability that such events once seen could be ascribed to associated production is estimated to be of the order of a few 10^{-3}. The much lower value of this probability in the event observed arises primarily from the fact that its energy

(13.5 GeV) is near the upper limit of the spectrum. On the basis of these assumptions, we would expect ∿ 10% of identified charm events to have this energy or higher.

Returning now to Table I, we note five other events containing strange particles, one of which (#2) cannot be associated production and is consistent with a $\Delta S=\Delta Q$ current. We note[9] that since a $\Delta S=\Delta Q$ interaction implies in parton theory that the initial interaction occured on a λ quark in the parton "sea," the x of such an event should therefore be low. The observed value of .13 is consistent with this expectation.

Of the remaining four events that are all candidates for associated production, two (#4 and #6) could in principle be $\Delta S=-\Delta Q$. Their hadronic masses on this assumption are less than or equal to ∿ 3.5 and 2.40 ± .04 GeV respectively. The agreement between the second mass and that for the identified $\Delta S=-\Delta Q$ event may be coincidental but is interesting. For the moment, however, we will assume that we have observed one $\Delta S=-\Delta Q$, one $\Delta S=\Delta Q$, and four associated events. The ratios of observed strange particle events to the numbers of nonstrange events are then

Event Type	Number of Events	Ratio Observed Strange to Nonstrange For E > 4 GeV
$\Delta S=-\Delta Q$	1	1.4 ± 1.4%
$\Delta S=\Delta Q$	1	1.4 ± 1.4%
Associated Production	4	5.4 ± 2.7%

REFERENCES

1. R.B. Palmer, Proc. Informal Conference on Experimental Neutrino Physics, CERN, p. 141 (1965).
2. The result actually presented at the conference was based on equations (1) and (2) which gave $\sigma(n)/\sigma(p) = 1.40 \pm .14$, however, the possible bias due to variations of C with multiplicity was stressed. The result given here allows for this bias and is thus more reliable.
3. V. Barger and R.J.N. Phillips, Nucl. Phys. B73, 269 (1974).
4. R. McElhaney and S.F. Tuan, Nucl. Phys. B72, 487 (1974).
5. Bloom and Gilman, Phys. Rev. Lett. 25, 1140 (1974); H. Deden, *et al.*, Nucl. Phys. B85, 269 (1975).
6. G. Miller, *et al.*, Phys. Rev. D5, 529 (1972).
7. E.G. Cazzoli, *et al.*, Phys. Rev. Lett. 34, 1125 (1975).
8. We can apply this same method of estimation to the FNAL bubble chamber experiment. Out of 450 events, we would expect 6 charm events with identifiable negative strangeness, of which one-sixth (6 out of 36 strange particle events) would make 3C fits. Thus we would expect FNAL to observe 1.1 (450 x .03 x .5 x .16) identified charm events.
9. S. Trieman, private communication.

TABLE I

	Event Type	Constraint Class	Neutrino Energy GeV	Interpretations	q^2 GeV/c^2	x
1	$\nu p \rightarrow$ $\mu^- \Lambda\ \pi^+ \pi^+ \pi^+ \pi^-$	3C	13.5	$\Delta S = -\Delta Q$	2.2	.31
2	$\nu p \rightarrow$ $\mu^- \pi^+\ p\ K^0$	3C	5.2	$\Delta S = \Delta Q$	.5	.13
3	$\nu d \rightarrow$ $\mu^- K^+ \pi^- \Sigma^+ p_s$	3C	7.0	Associated Production	7.3	.79
4	$\nu d \rightarrow$ $\mu^- \pi^- \pi^+ p\ K^0 (K^0)(p_s)$	0C	6.5	Associated Production	.4	.05
5	$\nu d \rightarrow$ $\mu^-\ \Lambda\ K^+\ p_s$	3C	3.1	Associated Production	.3	.05
6	$\nu d \rightarrow$ $\mu^- \pi^+ \Lambda\ \left({K^0 \atop \pi^0}\right)(p_s)$	0C	5.8	Associated Production	1.3	.19

FIGURE CAPTIONS

1. The neutrino beam.
2. Distribution of a typical sample ($\sim$ 30%) of events in the dip (λ) and azimuth (θ) of the direction of the sum of all track vector momenta.
3. The efficiency for separating negative pions from muons as a function of their momentum.
4. Distribution of all charged current neutrino events as a function of calculated incoming neutrino energy. Events containing a strange particle are indicated in black.
5. Distribution of charged current events in the variable $x' = q^2/(2M\nu + M^2)$. The line represents a parton theory prediction that ignores the "sea."
6. The ratio of neutrino cross sections on protons to that on neutrons as a function of x'. The curve indicates a parton theory prediction that ignores the "sea."
7. Event #1 which fits the reaction $\nu + p \rightarrow \mu^- \Lambda \pi^+ \pi^+ \pi^+ \pi^-$ and thus represents an apparent $\Delta S = -\Delta Q$ current.

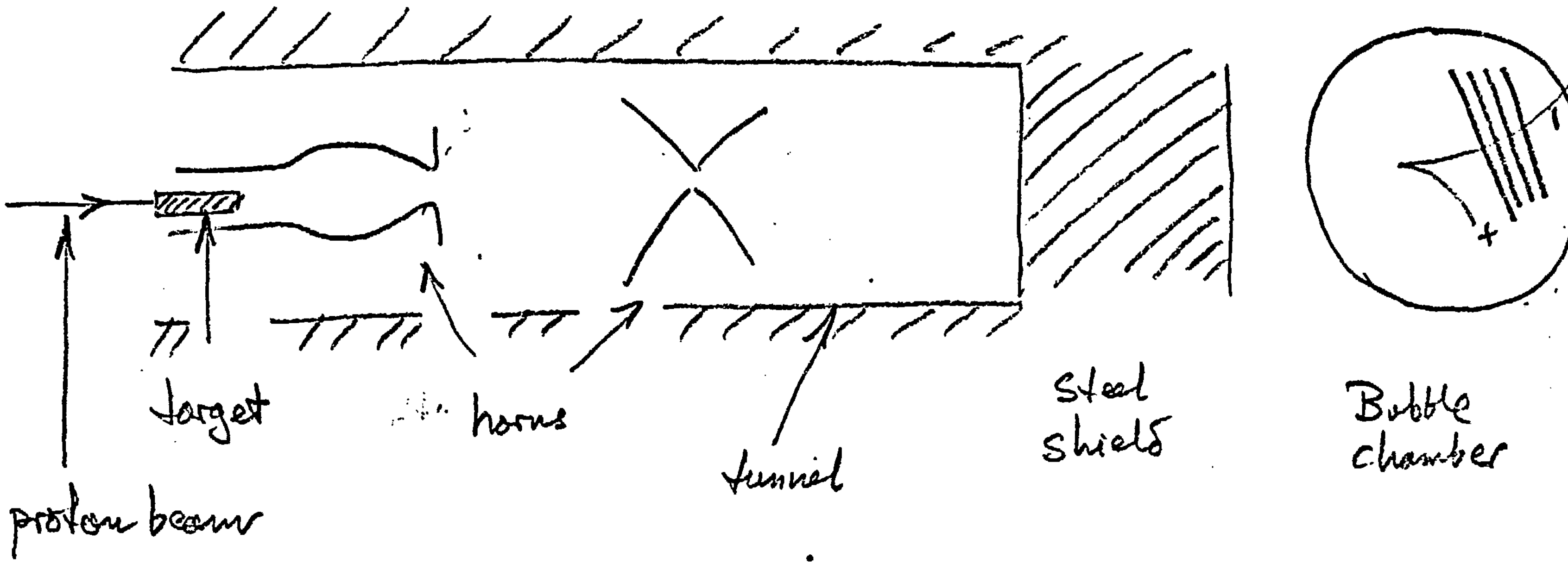

proton beam
target
horns
tunnel
Steel shield
Bubble chamber
+

Fig. 1

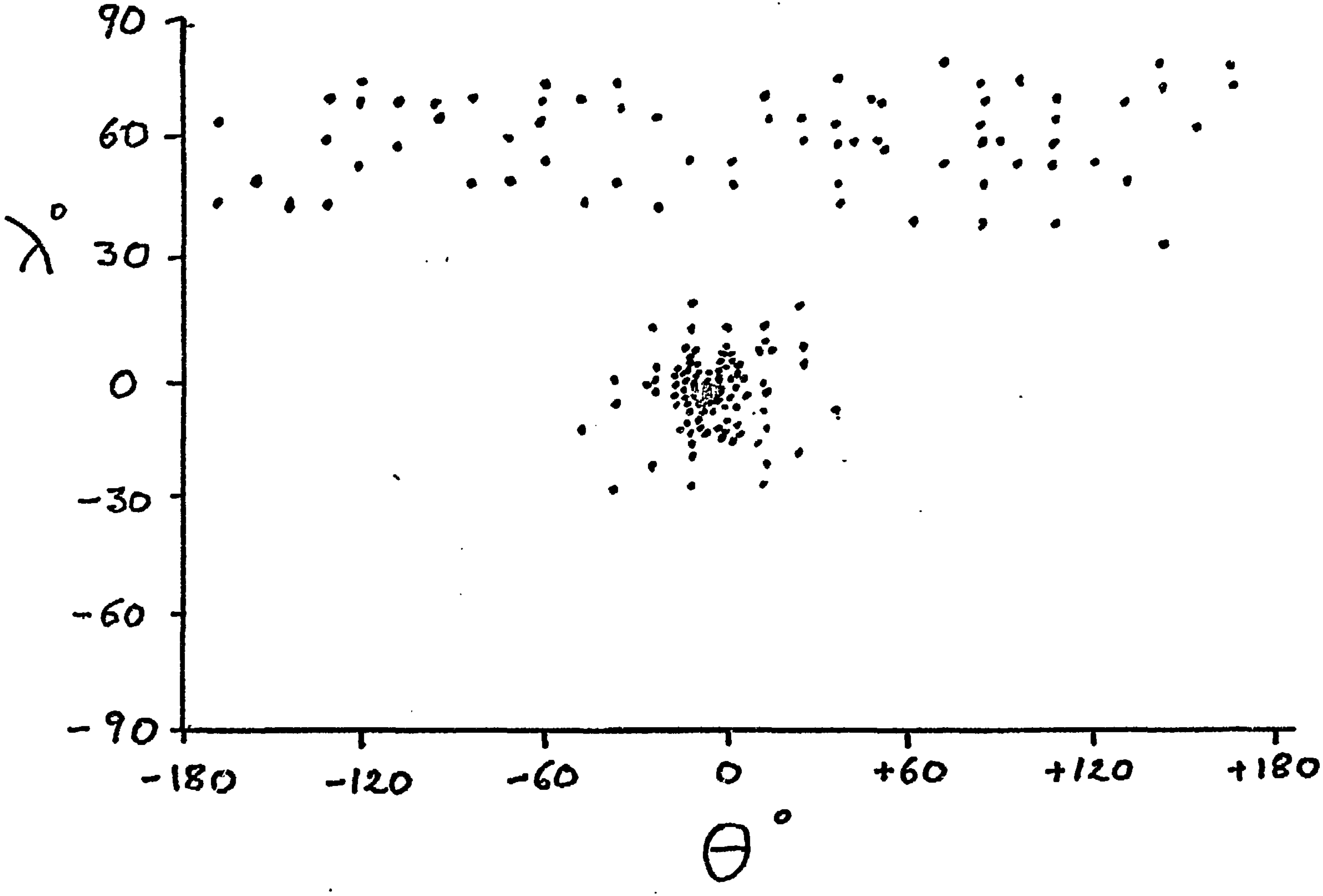


Fig. 2

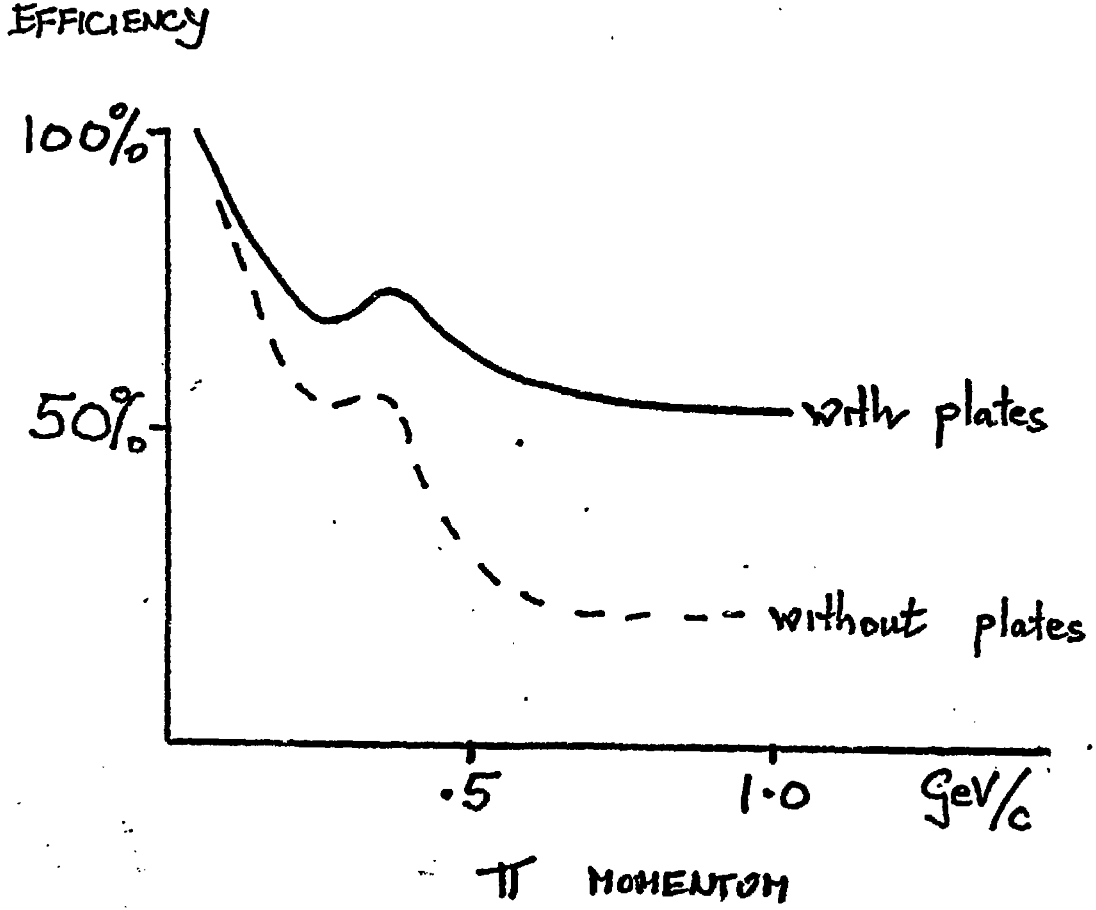
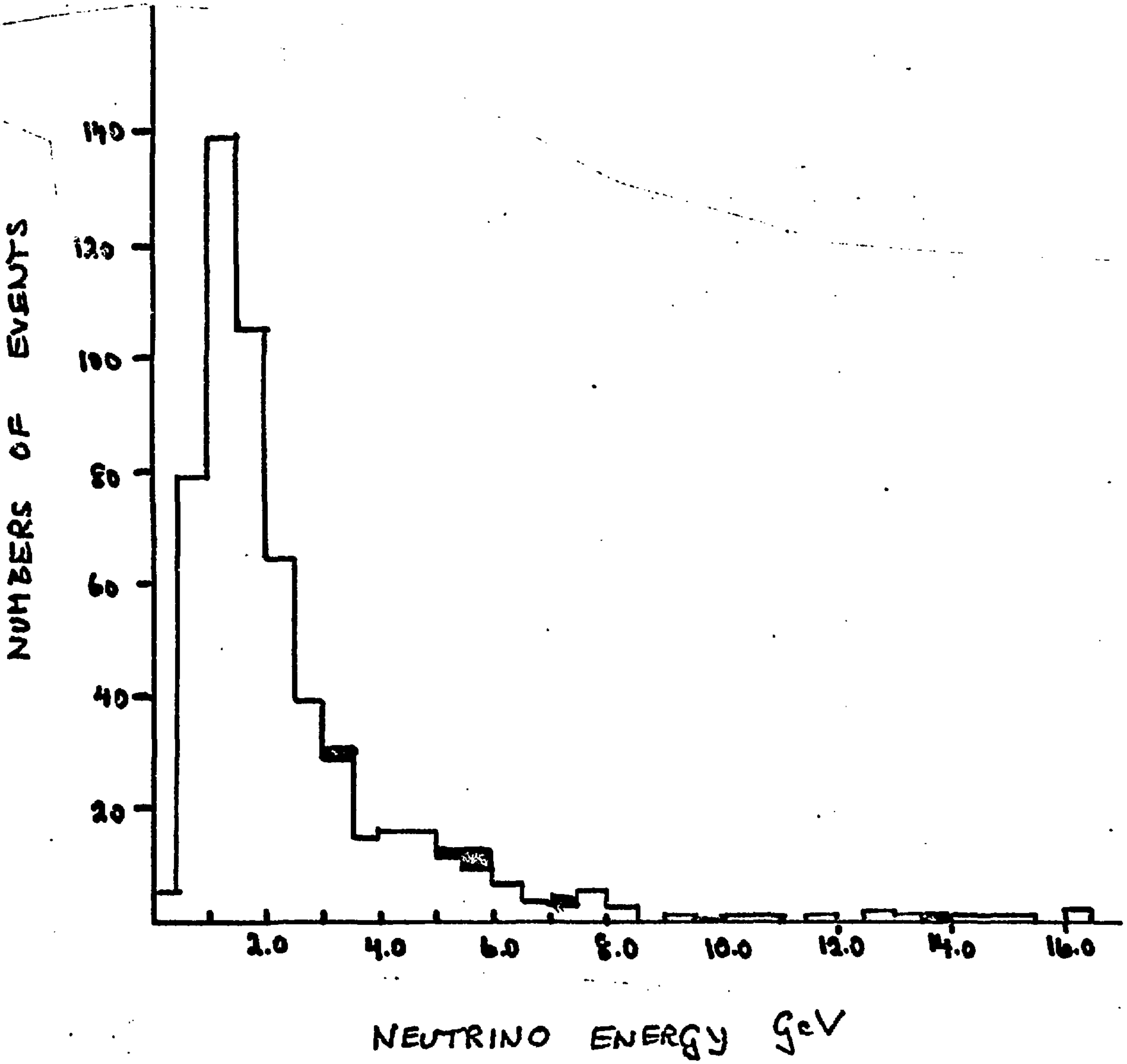

EFFICIENCY
100%
50%
with plates
without plates
·5
1·0
GeV/c
π MOMENTUM

Fig. 3


140
120
100
80
60
40
20
NUMBERS OF EVENTS
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12.0
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16.0
NEUTRINO ENERGY GeV

Fig. 4

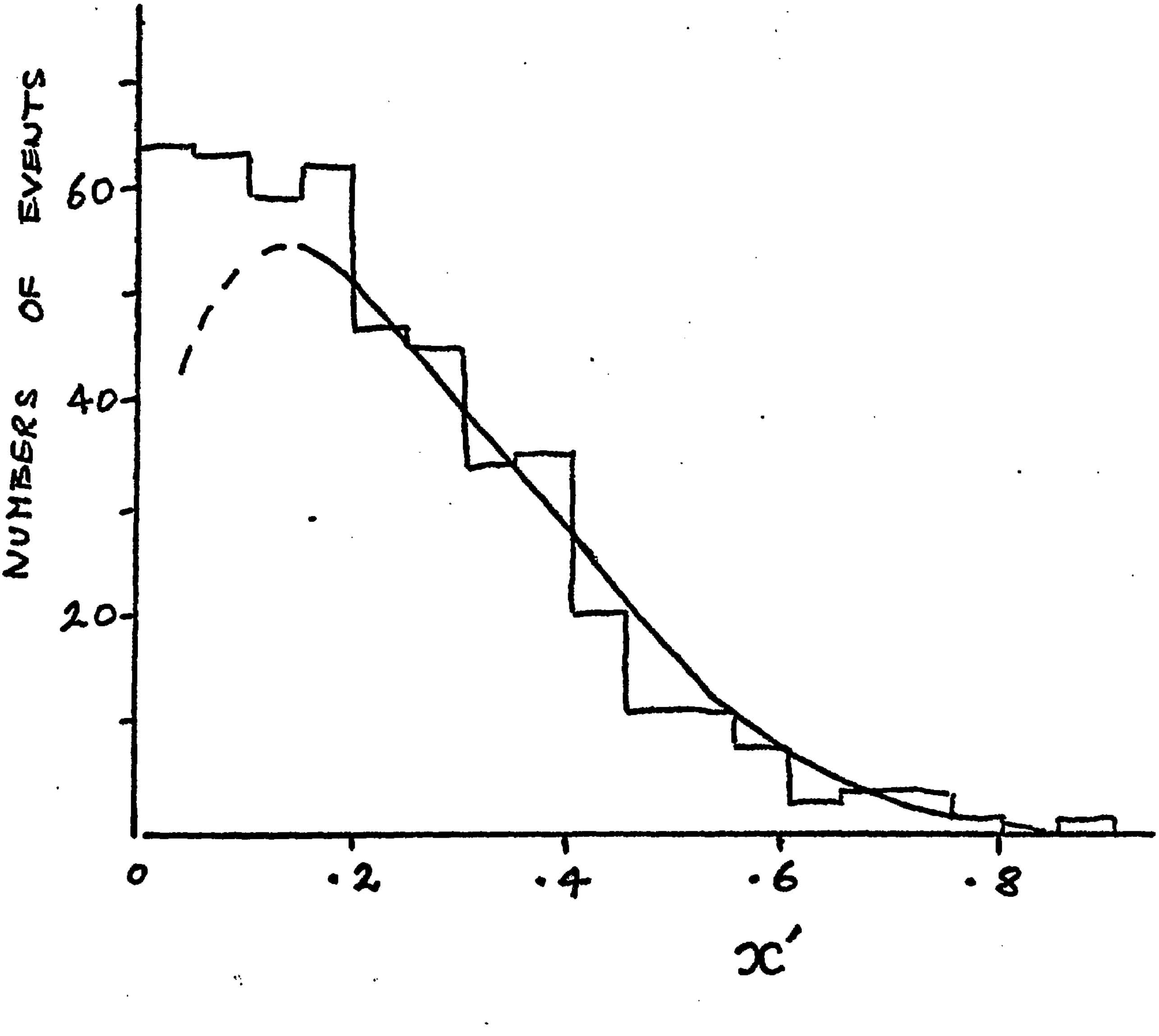

Fig. 5

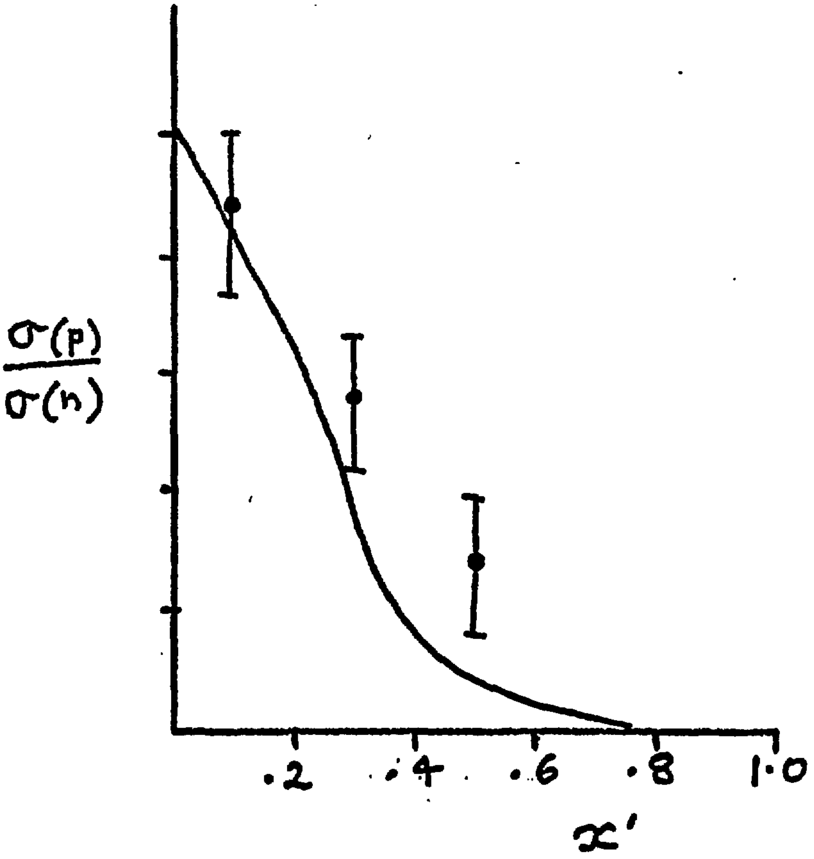

Fig. 6

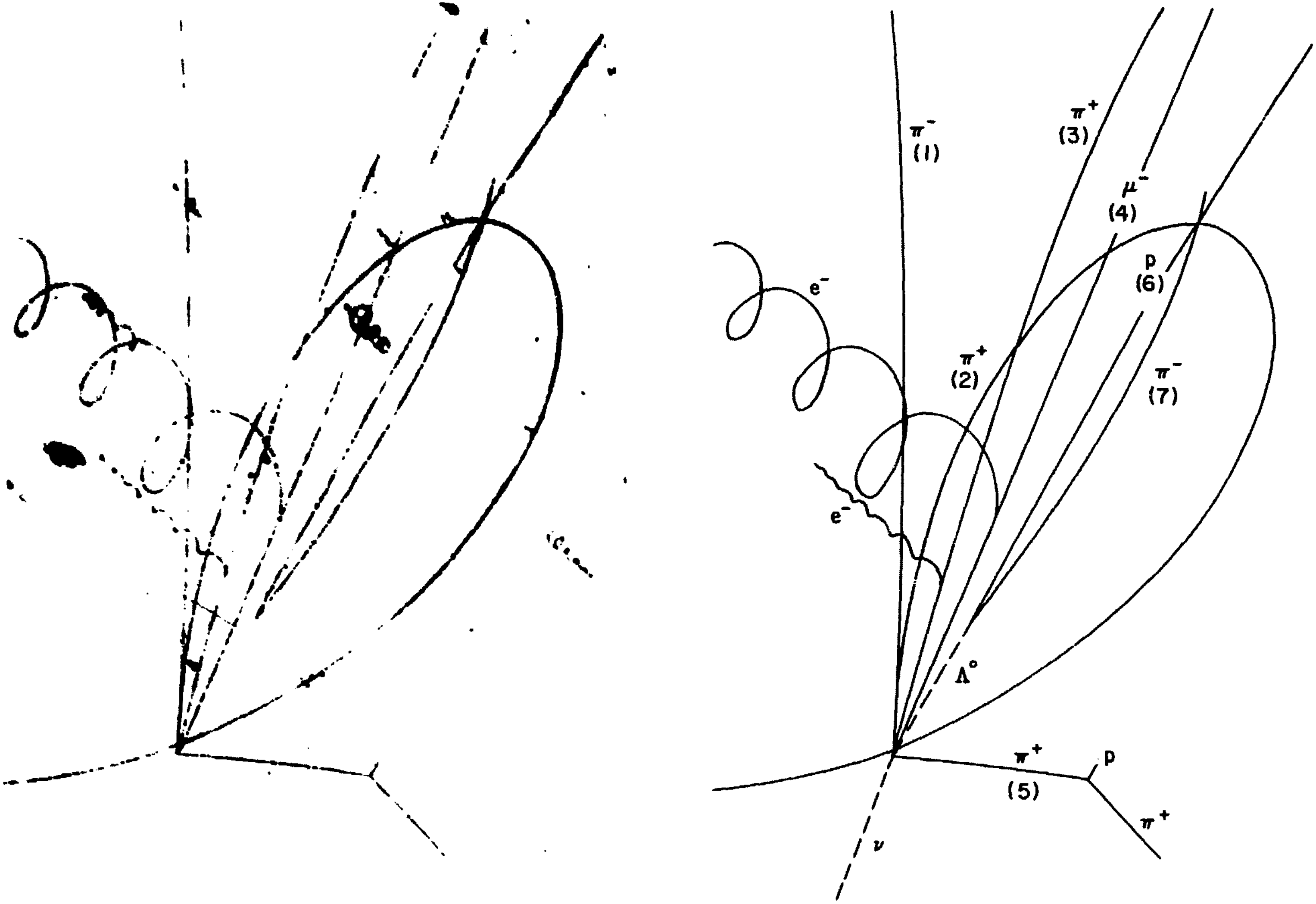

Fig. 7