

THE CHARGE EXCHANGE REACTION

$\bar{P}P - \bar{N}N$ AT 5 AND 8 GEV/C

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A B S T R A C T

An account is presented of a high statistics experiment to measure the differential scattering cross section in the forward region for the process $\bar{p} p \rightarrow \bar{n} n$. Data are presented at 5.0 GEV/C in the range $0 < |t| < 0.55 \text{ (GEV/C)}^2$ and at 7.76 GEV/C in the range $0 < |t| < 0.3 \text{ (GEV/C)}^2$. The experimental technique involved a precise measurement of the antiproton trajectory into a liquid hydrogen target and the detection of the antineutron by its interaction in a copper plate.

The differential cross section at 7.76 GEV/C exhibits a smooth exponential behaviour with a small forward peak in the region $|t| < 0.01 \text{ (GEV/C)}^2$. The 5.0 GEV/C data, although lacking statistics, show a similar structure. An empirical model incorporating reggeized pion exchange with absorption corrections to the pion pole provides a good fit to the 7.76 GEV/C data and indicates the importance of absorption corrections in the non-helicity flip pion amplitude.

P R E F A C E

Research in elementary particle physics often requires the use of a considerable amount of sophisticated equipment, both in the actual data taking as well as the subsequent analysis using large computers. In consequence, experiments involve the participation of a number of people and this experiment was performed at C.E.R.N. by a group of physicists from C.E.R.N., E.T.H., Zurich and Imperial College, London.

The author worked at C.E.R.N. as a visitor from Imperial College from 1968 - 1972 and, although this thesis describes all stages of the experiment, not all that is presented is the author's own work. In particular, much of Chapter 2 concerning the optical spark chambers has been described previously but is included to illustrate the changes to the apparatus that were made specifically for this experiment. The author contributed to the design, preparation and running of the experiment and was responsible for the on-line data collection program and for the off-line analysis of the spark chamber data.

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C H A P T E R 1

INTRODUCTION

The study of high energy particle physics is concerned with the individual and collective behaviour of various elementary particles and the nature of the interactions between them. In the case of the electromagnetic interactions, which govern the field of atomic physics, a complete and highly accurate theory has been derived to explain the observed phenomena. This theory is known as Quantum Electrodynamics. In weak interactions, a similar theory exists although it is somewhat more limited and less satisfactory than that for electromagnetic interactions. However, in the case of the strong interaction, no theories, similar to those above, exist at present. The difficulty arises from the strength of this interaction (~ 2000 times greater than the electromagnetic interaction) which is such that perturbation methods employed in electromagnetic theory are no longer possible.

In spite of this lack of a general theory, a vast amount of ideas and data exist on the strong interaction and these have been used to formulate general principles and models which explain, to some degree, the observed effects. Certainly, it is hoped that eventually such developments will be formed into a comprehensive

theory. However, at the moment, the approach to strong interaction physics is to construct models to provide various predictions and to compare such predictions with experimentally measured data. The experiments that are performed to provide such data are basically all of the same type; they involve a scattering process. The strong interaction, unlike the electromagnetic or gravitational interactions, has an extremely short range and thus one must probe very close to a particle in order to investigate the forces involved. This is realized experimentally by scattering high-energy particles on a target particle or nucleus and observing the resulting effects on some sort of detector system.

1.1 Scattering Process and Crossing Symmetry

Consider the two-body reaction where $1 + 2 \rightarrow 3 + 4$, as shown in Figure 1a.

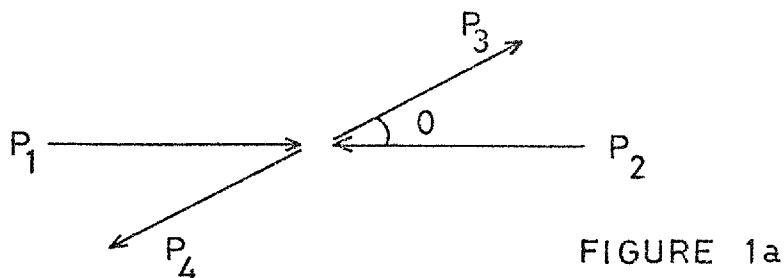


FIGURE 1a

The diagram shows the process in the centre of mass reference frame where the total momentum of the system is equal to zero. The variables used to describe each particle are the four-momenta

P_i where $P_i = (E_i, \mathbf{p}_i)$. E_i is the energy of a particle and $\mathbf{p}_i$ its three-momentum. For convenience, it is found useful to introduce combinations of these basic variables which allow one to see more easily the relevant features of the scattering process from the various mathematical relationships. The combinations, referred to as s , t and u , are called Mandelstam variables and are given below:

$$s = (P_1 + P_2)^2$$

$$t = (P_1 - P_3)^2$$

$$u = (P_1 - P_4)^2$$

The Mandelstam variables, being squares of four-vectors, are invariant under a Lorentz transformation and are reduced to two independent variables by the following relation:

$$s + t + u = \sum_{i=1}^4 m_i^2$$

A description of a scattering process is given by a "Relativistic Scattering Amplitude," $T(s, t)$ which, in the absence of spin effects, can be expressed as a function of s and t alone.

Crossed Reactions

The idea of 'particle-antiparticle correspondence' states that a particle A with momentum P is equivalent to a particle $\bar{A}$ with momentum $-P$, and this idea can be used to generate "crossed" or

"line reversed" reactions. Applying this to the original process, one obtains the following crossed channels:

$$1 + \bar{3} \rightarrow \bar{2} + 4$$

$$1 + \bar{4} \rightarrow 3 + \bar{2}$$

where

$$1 + 2 \rightarrow 3 + 4 \quad \text{is called the direct channel.}$$

Since only particle-antiparticle correspondence is used to generate the three channels, it is postulated that there exists a unique scattering amplitude $T(s, t)$ which describes all three reactions. This postulate is known as "Crossing Symmetry" and is a direct consequence of CPT conservation in Quantum Field Theory. The amplitude $T(s, t)$ is in general a complex function and exists for all values of s and t . In the regions where these variables have values given by a physical process, $T(s, t)$ will represent the amplitude for that particular channel. Physical processes in the S channel are determined by two conditions:

$$(a) \quad s > (m_3 + m_4)^2$$

$$(b) \quad -1 < \cos \theta < +1$$

where s = total C.M. energy squared

and θ = scattering angle.

Figure 1b, the classical s, t, u diagram, shows for particles of equal mass, the regions where physical processes can occur.

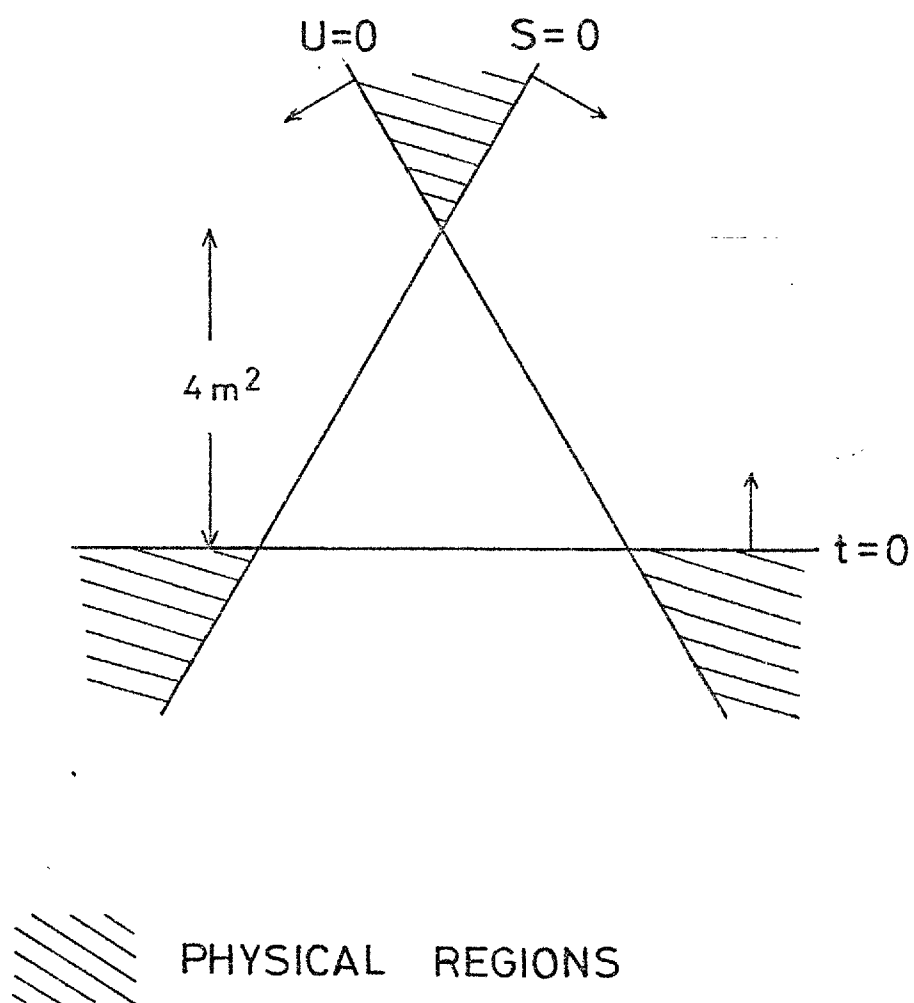


FIGURE 1b

The amplitude $T(s, t)$ is assumed to be an analytic function and thus, if it is known in one channel, it is in principle possible to extrapolate outside the known region and predict the scattering amplitude in the crossed channels. This operation, known as analytic continuation, is not trivial since the physical regions share no common point and singularities exist in the unphysical regions.

Applying the ideas of the previous section to the reaction $\bar{p} + p \rightarrow \bar{n} + n$ (denoted as the 's' channel), the corresponding crossed reactions are

$$p + \bar{n} \rightarrow p + \bar{n} \quad (\bar{p}n \text{ elastic scattering})$$

$$p + n \rightarrow n + p \quad (pn \text{ charge exchange})$$

Crossing symmetry implies that the scattering amplitudes in the separate channels are closely related and that the physical behaviour in one channel directly influences the form of the amplitude in the crossed channel.

1.2 Amplitudes and Cross-Sections

The scattering amplitudes mentioned in the previous section are, in general, complex quantities and, therefore, they cannot be measured directly in a laboratory experiment. However, they are

related to differential cross-sections and polarisations which are measurable parameters. In this section, we shall consider the case of spinless external particles and work in the centre of mass frame. In this frame, the incident beam is represented by a plane wave, wave number $\underline{k}$, and the final state by a modified spherical wave set around the scattering centre.

$$\Psi(r, \theta) = e^{ikz} + f(E, \theta) \frac{e^{ikr}}{r}$$

$f(E, \theta)$ is defined as the amplitude and it contains the angular dependence of the final state.

The differential cross-section, $d\sigma/d\Omega$, can be defined as the number of particles scattered at angle θ , per unit solid angle, per sec., per unit incident flux. Since the scattered particle density at any point is given by $|\Psi_{\text{scatter}}|^2$, it follows that:

$$\frac{d\sigma}{d\Omega} = |f(E, \theta)|^2$$

Frequently, it is found convenient to express the amplitude $f(E, \theta)$ as a partial wave expansion in terms of definite angular momentum states. The incident plane wave is expressed as an expansion in terms of spherical harmonics and is made up of a series of in-going and out-going spherical waves. The effect of the scattering centre is to modify only the out-going components and to represent this, we insert a factor, η_1 , as a coefficient to the out-going wave.

$$\Psi_{\text{total}} = \Psi_{\text{in}} + \Psi_{\text{out}}$$

$$\approx \frac{1}{kr} \sum_{L=0}^{\infty} (2L+1) \frac{1}{2} \frac{L+1}{2} \{ e^{-i(kr - L\pi/2)} - \eta_L e^{i(kr - L\pi/2)} \} Y_L^0(\theta, \phi)$$

where $Y_L^0(\theta, \phi)$ are spherical harmonic functions.

$$\Psi_{\text{scatter}} = \Psi_{\text{total}} - e^{ikz} = f(\theta) e_{\frac{ikr}{r}}$$

Thus, the amplitude $f(\theta)$ can be written as

$$f(\theta) = \sum_{L=0}^{\infty} (2L+1) \frac{\eta_L - 1}{2ik} P_L(\cos \theta)$$

where $P_L(\cos \theta)$ are Legendre polynomials.

The parameter η_L is complex and in general can be written as

$$\eta_L = \rho_L e^{2i\delta_L}$$

where ρ_L is the inelasticity parameter and δ_L is a real phase shift between the in-going and out-going waves.

The amplitude $f(\theta)$ given above can now be used to obtain some useful results concerning cross-sections. The total elastic scattering cross-section, σ_{el} , is given by the squared modulus of the amplitude.

$$\sigma_{\text{el}} = \int_{\Omega} |f(\theta)|^2 d\Omega = \frac{\pi}{k^2} \sum_{L=0}^{\infty} (2L+1) |\eta_L - 1|^2$$

The reaction cross-section, which represents all non-elastic channels, can be found from the difference between the in-going

and out-going intensities.

$$\begin{aligned}\sigma_r &= \int |\psi_{in}|^2 - |\psi_{out}|^2 d\Omega \\ &= \frac{\pi}{k^2} \sum_{L=0}^{\infty} (2L+1) (1 - \eta_L^2)\end{aligned}$$

The total cross-section, σ_T , is the sum of the elastic and reaction cross-sections.

$$\begin{aligned}\sigma_{TOT} &= \sigma_{el} + \sigma_r \\ &= \frac{2\pi}{k^2} \sum_{L=0}^{\infty} (2L+1) (1 - R_e \eta_L)\end{aligned}$$

Optical Theorem

This is a relation between the total cross-section and the imaginary part of the forward scattering amplitude.

$$\text{Im } f(0) = \frac{1}{2k} \sum_{L=0}^{\infty} (2L+1) (1 - R_e \eta_L)$$

$$\text{Thus } \sigma_{TOT} = \frac{4\pi}{k} \text{Im } f(0)$$

Absorption and Diffractive Scattering

Earlier, we introduced the relation $\eta_L = \rho_L e^{2i\delta_L}$ where δ_L was a phase shift and ρ_L , an inelasticity parameter of modulus between zero and one. In the case where $\rho_L = 1$, we have purely elastic scattering. Another interesting example is where ρ_L tends to zero and the scattering centre, being highly absorptive, absorbs all particles which fall upon it. If R represents the radius of the target and k , the incident C.M. wave number, the scattering conditions

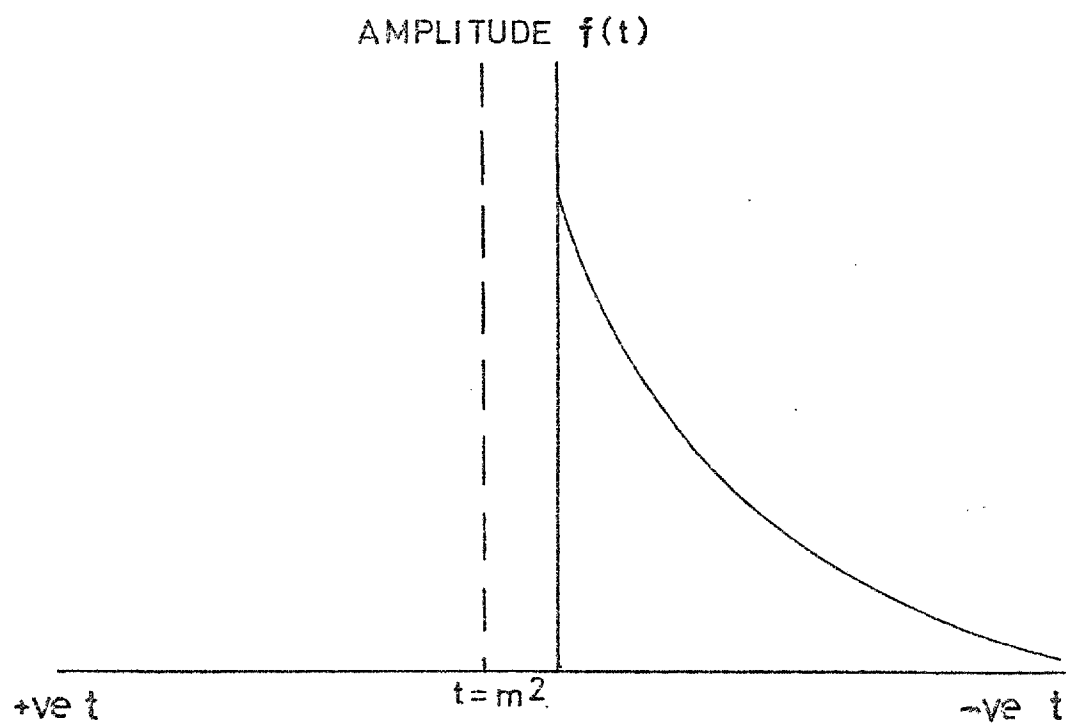


FIGURE 1c

are given by:

$$\rho_L = \eta_L = 0 \quad L < kR$$

$$\eta_L = 1 \quad L > kR$$

For all waves of $L < kR$, complete absorption occurs. Inserting these conditions into the formulae for the elastic and reaction cross-sections, we find

$$\sigma_{el} = \sigma_r = \frac{\pi}{k^2} \sum_{L=0}^{L_{MAX}} (2L+1)$$

$$\sigma_{TOT} = \frac{2\pi}{k^2} \sum_{L=0}^{L_{MAX}} (2L+1) = 2\pi R^2$$

It is interesting to note that the elastic scattering and reaction cross-sections are equal and are the same as the geometrical cross-section of the target disc. The elastic scattering is analogous to diffraction and results from a deformation of the incident plane wave introduced by absorption in the disc. Such effects would not arise with a transparent disc where no absorption occurs. Absorption and elastic scattering are thus highly related processes and the latter is characterized by sharply forward-peaked differential cross-sections.

1.3 Features of Differential Cross-Section Data.

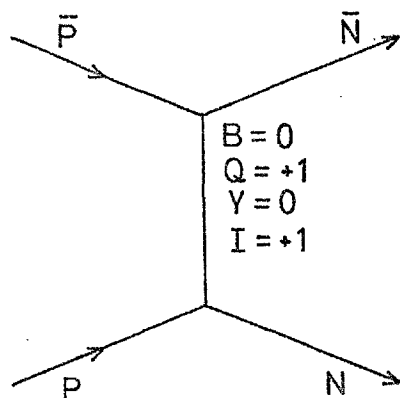
Scattering data at high energies shows that the differential cross-section for a process is greatly enhanced in the forward direction

when the quantum numbers of the 't' channel correspond to those of a known meson. Similarly, a backward peak is seen when the 'u' channel corresponds to a baryon. The dominance of low momentum transfer events in two-body processes can be interpreted in terms of glancing collisions where 'longer-range' forces (higher partial waves) govern the process. Such collisions correspond to the exchange of low mass particles and the 'short-range' forces (low partial waves) are effective mainly in multi-particle final state reactions. This idea is known as the Peripheral Model.

Such features in the experimental data led to consideration of simple particle exchange models in which known particles were exchanged and whose quantum numbers governed the reaction process. Calculations based on such models gave rise to expressions in the amplitude of the form $\{t - m^2\}^{-1}$ where m is the mass of the exchanged particle. The form of the amplitude given by a one-particle exchange model is shown in Figure 1c. A singularity exists at the value $t = m^2$. Physical scattering processes require $t \leq 0$ and thus the singularity does not lie in the physical region. However, such singularities do influence very strongly the form of the amplitude near the forward region, particularly where they lie close to the $t = 0$ axis. In reactions where low-mass particles can be exchanged, this is indeed the case, and such exchanges dominate the amplitude in the forward region.

For antiproton charge exchange, the quantum numbers of the exchanged object are given in Figure 1d shown on the following page. Thus, on the basis of a particle-exchange model, one would expect the pion to give the dominant contribution to the forward scattering amplitude,

with lesser contributions from the ρ and A_2 mesons.



B: Baryon No.
Q: Electric Charge.
Y: Hypercharge.
I: Isospin.

FIGURE 1d

The simple particle exchange model, whilst having many useful qualitative features, is by no means a complete explanation, and it leads to predictions which deviate considerably from the experimental data. In particular, the energy dependence of a differential cross-section where a particle of spin J is exchanged is predicted to have the following asymptotic behaviour:

$$\frac{d\sigma}{dt} \sim S^{2J-2}$$

where S tends to large values for a fixed t value. This implies that for values of J greater than unity, the total cross-section will tend to infinity for large S values. This result is in direct conflict with the "Froissart" bound which states that:

$$\sigma_{\text{Total}} < c \{\ln(s)\}^2$$

where c is a constant. This bound can be derived from very basic principles in Field Theory and is a consequence of the finite range of the nuclear force. Furthermore, the extensive amount of

cross-section data indicate that total cross sections decrease with increasing incident momentum.

In view of the failure of the particle exchange model, we must consider more elaborate models and, in particular, the Regge pole approach.

1.4 Regge Pole Models

The basic idea of Regge poles originates from potential scattering theory where one solves the Schroedinger equation for a potential with a "well-behaved" functional form. For example, a Yukawa potential, $V(r) = g \frac{1}{r} \exp(-vr)$. However, since the Schroedinger equation is non-relativistic, one cannot apply the results of such an analysis directly to high energy relativistic interactions. Nevertheless, ideas and results obtained do provide an extremely useful framework on which to construct more sophisticated models for high energy interactions between elementary particles.

In the Regge pole model, the spin of the exchanged object is no longer quantized but is allowed to become a continuous function of momentum transfer. The high energy limit of the scattering amplitude, can then be expressed in the following form:

$$T(s,t) = \sum_i \gamma_i(t) \left\{ \frac{1 + t \exp(-i\pi\alpha_i(t))}{\sin\pi\alpha_i(t)} \right\}^2 \left(\frac{s}{s_0} \right)^{\alpha_i(t)}$$

where the summation operates over i Regge poles.

The function $\gamma_i(t)$ is called the "residue function" and is assumed to be real in the scattering region ($t < 0$). The expression in parenthesis { } is known as the "signature factor" where $\tau = \pm 1$, according to the signature of the Regge pole defined by $\alpha_i(t)$. This term, $\alpha_i(t)$, defines a Regge trajectory which has well-defined quantum numbers with the exception of spin which is now a continuous function of momentum transfer. It is this Regge trajectory which, in this model, takes the place of the exchanged particle in the simple exchange model. The trajectory function is taken as a linear function of t , $\alpha_i(t) = \alpha_i + \alpha_i' t$, and is represented on the Chew-Frautschi plot shown in Figure 1e. In the scattering region, $\alpha_i(t)$ is always less than unity, whereas in the resonance region it interpolates between particles or resonances with spins differing by two units.

An interesting result that emerges immediately from the Regge model is the form of the amplitude in the high-energy limit. If we fix the value of t , and consider the case of large s values, we see that the reaction will ultimately be dominated by the exchange of a single leading trajectory, $\alpha_L(t)$. The overall amplitude can then be written as

$$T(s,t) = \gamma_L(t) \frac{1 + \tau \exp(-i\pi\alpha_L(t))}{\sin\pi\alpha_L(t)} \left(\frac{s}{s_0}\right)^{\alpha_L(t)} \quad s \rightarrow \infty$$

$T(s,t)$ is related to the amplitude referred to in section 1.3 according to:

$$T(s,t) = 8\pi\sqrt{s} f(E,\theta) \quad \text{where} \quad |f(E,\theta)|^2 = \frac{d\sigma}{d\Omega} \quad (\text{Elastic Scattering})$$

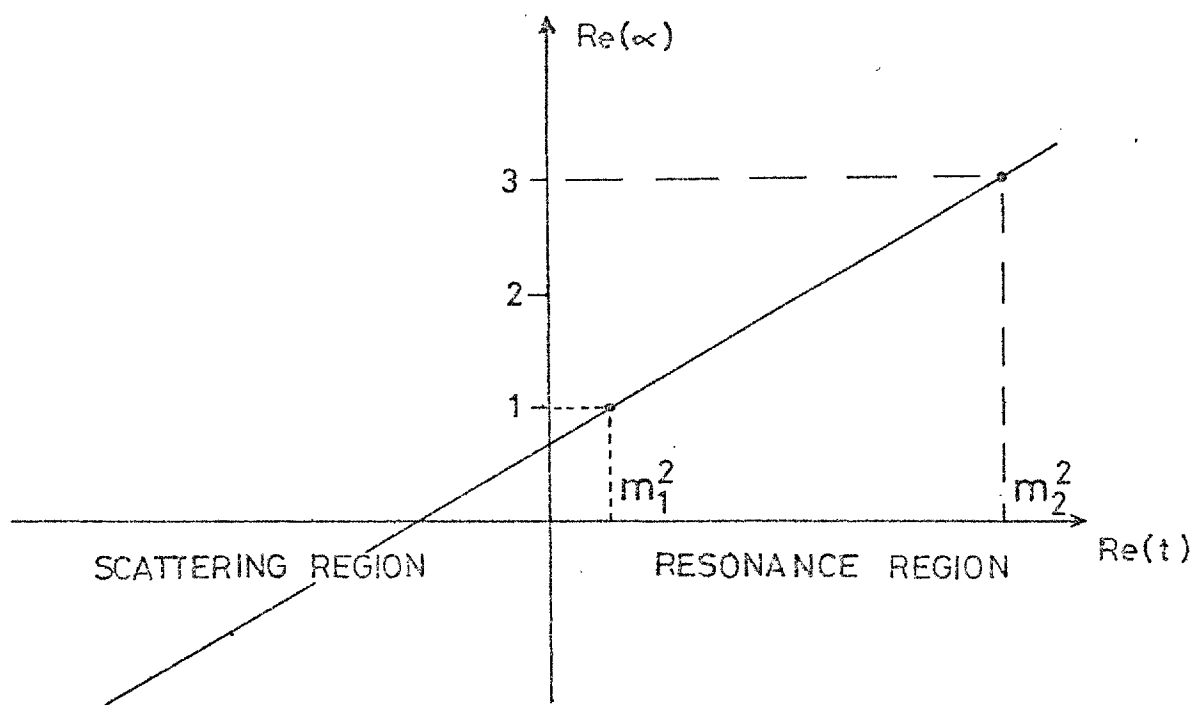


FIGURE 1e

The differential cross-section $\frac{d\sigma}{dt}$ then becomes:

$$\frac{d\sigma}{dt} = \frac{d\sigma}{d\Omega} \frac{d\Omega}{dt} = \frac{|T|^2}{64\pi^2 s} \frac{d\Omega}{dt}$$

The $\frac{d\Omega}{dt}$ term is proportional to s^{-1} since the following relations apply in the case of particles of equal mass.

$$s = 4(p^2 + m^2) \qquad t = -2p^2(1 - \cos\theta)$$

Inserting this in the above equation, we have:

$$\frac{d\sigma}{dt} \propto \frac{1}{s^2} |T(s,t)|^2 \quad \text{as } s \rightarrow \infty$$

and, with the Reggeized form for $T(s,t)$, we find:

$$\frac{d\sigma}{dt} \propto \left(\frac{s}{s_0} \right)^{2\alpha_L(t)-2}$$

The corresponding expression in the case of the one-particle exchange model is $\frac{d\sigma}{dt} \propto s^{2J-2}$ where J is the spin of the exchanged particle. In the Regge model, the leading trajectory function, $\alpha_L(t)$, is less than unity in the scattering region and therefore the cross-section does not violate the "Froissart" bound.

Regge models have been applied with considerable success to many high-energy reactions and one of particular interest is the charge exchange $\pi^- p \rightarrow \pi^0 n$. In this channel, the ρ trajectory governs the Reggeized scattering amplitude. Agreement between Regge theory and measured data is good for the differential cross section, but discrepancies arise with the polarisation. A Regge model, considering ρ exchange alone, predicts zero polarisation for the scattered neutron whereas a small but non-zero polarisation has been measured. (1)

Attempts were made to explain this by the introduction of a ρ' pole, but it is now thought that the non-zero polarisation is associated with Regge "cut" terms in the amplitude.

Another source of difficulty for the straight-forward Regge model are pion exchange reactions: In proton-neutron charge exchange scattering, a sharp forward peak of width $1/m_\pi^2$ has been observed in the differential cross section. This reaction is dominated by π exchange, but a Regge model incorporating π exchange predicts an amplitude falling to zero at $t = 0$. Thus, certain modifications must be incorporated into Regge theory to explain such reactions and we shall now consider some possibilities with particular reference to pion exchange reactions.

1.5 Pion Exchange Reactions

In this and the following sections, we shall deal more or less explicitly with the processes $\bar{p}p \rightarrow \bar{n}n$ and $np \rightarrow pn$. When describing such processes, where particles of non-zero spin are involved, it is found convenient to use the helicity formalism. Each particle is described by its helicity, λ , which is defined as the projection of its spin, $\underline{\sigma}$, along the direction of its motion

$$\lambda = \frac{\underline{\sigma} \cdot \underline{p}}{|\underline{p}|}$$

We can now consider matrix elements between definite helicity states and, for our original process $1 + 2 \rightarrow 3 + 4$, we can write:

$$T(s,t)_{\lambda_3 \lambda_4 \lambda_1 \lambda_2} = \langle p_3 p_4 \lambda_3 \lambda_4 | T | p_1 p_2 \lambda_1 \lambda_2 \rangle$$

where $T(s,t)_{\lambda_3\lambda_4\lambda_1\lambda_2}$ represents the amplitude for scattering between an initial state defined by $\lambda_1\lambda_2$ and a final state defined by $\lambda_3\lambda_4$. If σ_i ($i = 1, 4$) are the spins of the 4 particles, then the number of possible amplitudes is given by:

$$(2\sigma_1 + 1)(2\sigma_2 + 1)(2\sigma_3 + 1)(2\sigma_4 + 1)$$

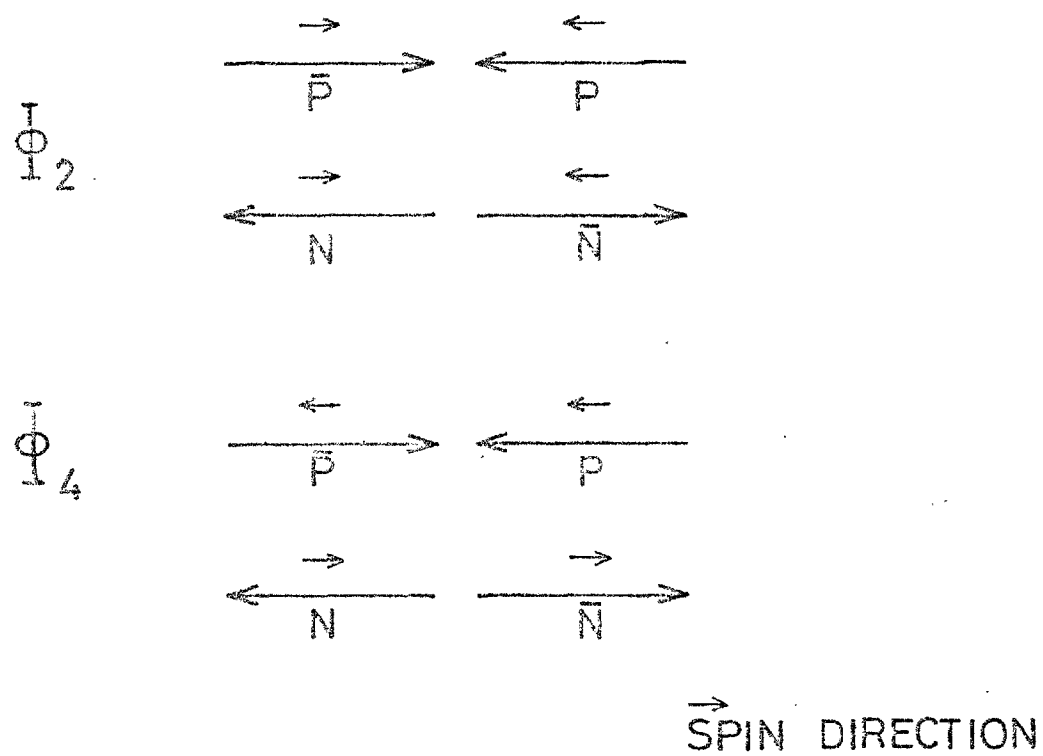
Relating these ideas to $\bar{p}p - \bar{n}n$ and $pn - np$ where only spin $\frac{1}{2}$ particles are involved, we see there exist 16 possible amplitudes which can contribute to the general matrix elements $\langle \bar{n}n | T | \bar{p}p \rangle$ and $\langle np | T | pn \rangle$. However, by applying the principles of parity conservation, time reversal, and G-parity conservation, this number reduces to 5 independent, non-zero amplitudes which are given below:

$$\begin{aligned}\phi_1 &= \langle +\frac{1}{2} +\frac{1}{2} \mid +\frac{1}{2} +\frac{1}{2} \rangle \\ \phi_2 &= \langle -\frac{1}{2} -\frac{1}{2} \mid +\frac{1}{2} +\frac{1}{2} \rangle \\ \phi_3 &= \langle +\frac{1}{2} -\frac{1}{2} \mid +\frac{1}{2} -\frac{1}{2} \rangle \\ \phi_4 &= \langle +\frac{1}{2} -\frac{1}{2} \mid -\frac{1}{2} +\frac{1}{2} \rangle \\ \phi_5 &= \langle +\frac{1}{2} +\frac{1}{2} \mid +\frac{1}{2} -\frac{1}{2} \rangle\end{aligned}$$

The differential cross-section is related to these amplitudes by the relationship:

$$\frac{d\sigma}{dt} \sim |\phi_1|^2 + |\phi_2|^2 + |\phi_3|^2 + |\phi_4|^2 + 4|\phi_5|^2$$

The exchanges of the ρ and A_2 give a contribution to each of the 5 amplitudes given above but, in the case of pion exchange, the contribution is only non zero for 2 of the amplitudes, namely ϕ_2 and ϕ_4 .



HELICITY AMPLITUDES

FIGURE 1f

$$\Phi_2 = \langle \bar{n}(-) n(-) | \bar{p}(+) p(+) \rangle$$

$$\Phi_4 = \langle \bar{n}(+) n(-) | \bar{p}(-) p(+) \rangle$$

These 2 amplitudes can be represented schematically as shown in Figure 1f and we see that Φ_4 corresponds to a net helicity flip whereas in Φ_2 , there is no net helicity flip involved.

In the forward region of the differential cross-section, pion exchange dominates the process owing to the proximity of the pion pole and therefore, in this $|t|$ region, we need only consider the pion contributions, namely Φ_2^π and Φ_4^π .

For the pion, $J^P = 0^-$, and as a result of the unnatural parity, the contributions of the pion to Φ_2 and Φ_4 are equal.

$$\Phi_2^\pi = \Phi_4^\pi$$

A further constraint can be applied by angular momentum conservation which requires that the net helicity flip amplitude, Φ_4 , vanishes in the forward direction. This implies therefore that the total pion amplitude goes to zero as $|t|$ goes to zero.

As one would expect from crossing symmetry, similar arguments apply to np charge exchange and the scattering amplitude should have a similar structure to that of $\bar{p} p$ charge exchange and vanish as $|t|$ goes to zero. The existing data ^(2,3) for both reactions show no evidence of a forward dip and, in the case of pn - np, where high statistics data exist, a sharp forward spike is seen in the differential cross-section.

In an attempt to explain the observed distribution within the framework of Regge theory, it was proposed that ⁽⁴⁾ there existed a doublet of the pion with natural parity. This partner was called a "conspirator" and gave a contribution to the amplitude of a similar magnitude to that of the pion. Thus, the process in the forward direction was governed by the contribution from ϕ_2^π , ϕ_2^C , ϕ_4^π , ϕ_4^C .

As before, the net helicity flip amplitude ϕ_4 must vanish in the forward direction for angular momentum conservation and this can be achieved by choosing:

$$\phi_2^C = \phi_2^\pi \quad (t = 0)$$

and requiring

$$\phi_2^C = -\phi_4^C \quad (\text{Natural parity of the conspirator})$$

We now see that angular momentum can be conserved (ϕ_4 set to zero at $t = 0$) whilst still retaining a finite total amplitude and in this way the combined contributions of the pion and its conspirator are able to explain the observed peaked structure in the differential cross-section. Following these ideas, Sonderegger et al ⁽⁵⁾ looked at the reaction $\pi^- p \rightarrow \pi^0 \pi^0 n$ where a measurement of the polarisation of the neutron gave a direct measure of the relative contributions of the two exchange mechanisms. The results showed that pion exchange dominated the process to more than 95% and gave a forward dip in the differential cross-section. Thus, experimental data tended to rule out the existence of a conspirator and Le Bellac ⁽⁶⁾ in extending the idea to the process $\pi^+ p \rightarrow \rho^0 \Lambda^{++}$, found that the inclusion of a conspirator term gave rise to a forward dip, whereas

a peak was observed experimentally. In the light of these results, it appears impossible to modify the basic Regge model by pole terms alone; one must perhaps include Regge cut contributions and we shall consider cut contributions in the subsequent section.

1.6 Absorption Models

A second method of approach whereby one is able to explain the absence of a forward dip in the pion exchange reactions $\bar{p}p - \bar{n}n$ and $pn - np$ is to incorporate absorptive corrections into exchange models. A qualitative argument for the introduction of such corrections can be seen from the ideas of the peripheral model. In that model, we saw that a large cross-section in the forward direction was related to glancing collisions. Such glancing collisions correspond to large impact parameters and the reaction is mediated by a long-range force implying the exchange of a light particle. We now want to incorporate the idea of "peripheralism" into a reggeized pion exchange model.

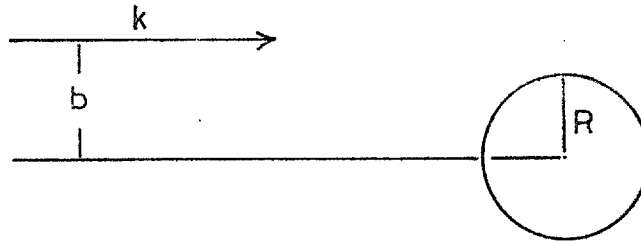
In the case of spinless particles, the scattering amplitude can be decomposed into a set of partial waves according to the relation

$$f(\theta) = \frac{i}{2k} \sum_{L=0}^{\infty} (2L+1) a_L P_L(\cos\theta)$$

where a_L is the L^{th} partial wave amplitude.

The angular momentum quantum number, L , is related to the impact parameter b by the equation:

$$L + \frac{1}{2} = kb$$



The lowest angular momentum components of the amplitude correspond to small values of the impact parameter and thus represent head-on collisions. As a result of this feature, one would not expect the lower partial waves to be effective in a peripheral, two-body reaction whereas in the simple exchange model, all waves were considered as contributing to the amplitude. Thus, the essential ingredient of the various absorption models that have been constructed (7) is that the low partial wave amplitudes are extremely small. Another way of expressing this is to say that where the impact parameter is less than a certain value, the interacting particles are more likely to give rise to a complex reaction as a result of the head-on collision.

Using a relation first introduced by Sopkovich (8), one can show that the absorption of low partial waves is directly related to elastic scattering in the initial and final states. Thus, the total amplitude can be represented diagrammatically as shown in figure 1g. Following Sopkovich, the L^{th} partial wave amplitude for scattering

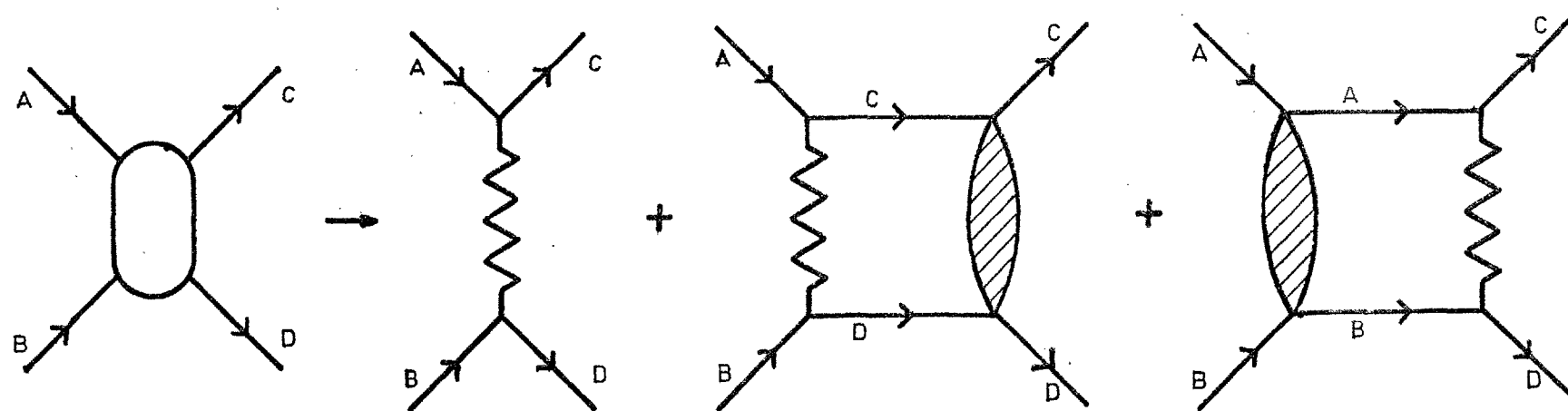


FIGURE 1g



REGGEON EXCHANGE

POMERON EXCHANGE

from a state A into a state B can be expressed as:

$$T_{BA}'^L = (S_{BB}^L)^{\frac{1}{2}} T_{BA}^L (S_{AA}^L)^{\frac{1}{2}}$$

where S_{BB} and S_{AA} are elastic scattering matrix elements in the final and initial states respectively. Making the assumption that $S_{AA} = S_{BB}$, the above expression reduces to:

$$T_{BA}'^L = S_{el}^L T_{BA}^L$$

The elastic scattering term S_{el}^L , which modifies the unabsorbed amplitude, can be written in the form:

$$S_{el}^L = 1 + iT_{el}^L$$

where the "1" represents the unscattered wave and T_{el}^L represents the elastic scattering amplitude for the L^{th} partial wave. Since the amplitude T_{el}^L is largely imaginary, we can write:

$$T_{el}^L \approx i|T_{el}^L|$$

Combining the last two expressions, we find for the S matrix term:

$$S_{el}^L = 1 - |T_{el}^L|$$

The exact form of the expression S_{el}^L , and hence the nature of the corresponding absorption depends upon the parametrisation used to represent elastic scattering. Experimentally, it is found that elastic scattering processes exhibit a sharp peak in the forward direction which can be parametrised by a single exponential.

$$\frac{d\sigma}{dt}_{\text{elastic}} = Ae^{-Bt}$$

A partial wave decomposition of the elastic scattering amplitude for spinless particles can be written as:

$$\frac{T(\theta)_{el}}{8\pi\sqrt{s}} = \frac{i}{2k} \sum_L (2L+1) a_L P_L(\cos\theta)$$

where $a_L = 1 - S_{el}^L$

We now convert the partial wave decomposition into the impact parameter representation by making the transformation:

$$L + \frac{1}{2} = kb$$

The sum over all L states now becomes an integral over b values.

$$\text{i.e.} \quad \sum_{L=0}^{\infty} \rightarrow \int_0^{\infty} kdb$$

Also, the following approximation is made which is valid for small values of θ :

$$P_L(\cos\theta) \approx J_0\{(L + \frac{1}{2})2\sin\theta/2\} = J_0\{b\sqrt{|t|}\}$$

The elastic amplitude then becomes:

$$\frac{T(\theta)_{el}}{8\pi\sqrt{s}} = ik \int_0^{\infty} a(b) \cdot b \cdot J_0(b\sqrt{|t|}) db$$

If we now take $a(b)$ to be a gaussian, we have:

$$a(b) = Ce^{-b^2/R^2}$$

$$\frac{T(\theta)_{el}}{8\pi\sqrt{s}} = ik \frac{C R^2}{2} e^{-R^2/4 |t|}$$

This gives a single exponential for the differential cross-section.

$$\frac{d\sigma}{dt} = \pi \{C R^2/2\}^2 e^{-R^2/2 |t|}$$

R is related to the slope of the diffraction peak according to:

$$R = \sqrt{2B}$$

and C is found from the total cross-section by the optical theorem.

$$C = \frac{\sigma_{TOT}}{2\pi R^2}$$

Thus, we have for $S_{el}(b)$:

$$S_{el}(b) = 1 - Ce^{-b^2/R^2}$$

Hence

$$\begin{aligned} S_{el}^L &= 1 - Ce^{-(L+\frac{1}{2})^2/R^2 k^2} \\ &= 1 - C' e^{-L(L+1)/R^2 k^2} \end{aligned}$$

Inserting the last relation into the Sopkovich formula, we find

for the absorbed amplitude:

$$T_{BA}^{'L} = (1 - C' e^{-L(L+1)/R^2 k^2}) T_{BA}^L$$

From the above equation, we see that the effect of elastic scattering is to give an absorption which is most pronounced for the low partial waves (small impact parameters). In our earlier discussion, it was these waves that were considered to play a small role in a peripheral collision and we can attribute their absorption to initial and final state elastic scattering.

Absorptive corrections of this sort have been applied to antiproton charge exchange both in one-particle exchange models and in reggeized exchange models. Migneron and Moriarty (9) have considered a peripheral model with contributions from ρ and π

exchange plus absorptive corrections from initial and final state elastic scattering. In this model, the ρ contribution is typically 10% of that of the π and the momentum transfer distributions obtained are in reasonable agreement with the known data for the range $0 < |t| < 0.6 \text{ (Gev/c)}^2$. At higher momentum transfers, discrepancies appear between the model and the data as one might expect from a purely peripheral model.

1.7 Regge Cut Models.

In section 1.5, we mentioned that a possible explanation of π exchange processes, within the framework of the Regge model, involved considering Regge cut contributions. Such cuts were closely related to the absorption ideas of the previous section. In potential theory, from which the original Regge ideas evolved, cuts are absent but in the relativistic models, they are believed to be present. However, the mathematics relating to cuts does not lend itself simply to physical applications and no methods exist for calculating cuts directly. The usual method of approach is to use models with some physical basis to generate cuts (i.e. "cut-like" contributions in the amplitude) and although confidence in such models is not complete, they do give us some general properties of cuts.

Amati et al ⁽¹⁰⁾ first considered the existence of cuts and suggested that a cut could be generated from the simultaneous exchange of two Regge poles. Thus, if one considers pion exchange accompanied

by elastic scattering in the initial and final states, a pion-pomeron cut is generated which contributes to the total amplitude. This approach is essentially the absorption model of the previous section.

Two properties of Regge cuts which emerge are (11)

(a) The energy dependence of a cut is given by

$$A^c(s,t) \sim S^{\alpha_c(t)} (\ln(s))^{-n+1}$$

where n is the order of the cut and is given by the number of reggeons which produce the cut.

(b) Cut contributions, as a function of t , fall off less steeply than pole contributions; they are less peripheral.

As a consequence of (b), one normally expects cut contributions to be important in the large t region, where pole terms are small. If, however, the pole term vanishes, as is the case in the forward direction for π exchange, then cuts may again be important. Moreover, since cuts interfere destructively with poles, the overall effect is to make the amplitude more peripheral.

A second model which can be used to generate cut terms is called the Eikonal model (12) and this gives us expressions for the n -particle cut although in most phenomenological applications, only two particle cuts are considered.

Henyei et al (7) have constructed a model which considers Regge

pole exchange together with cut contributions calculated from elastic scattering. Known as the Strong Cut Regge Absorption model, this is the only model which claims to fit satisfactorily both the np and $\bar{p}p$ charge exchange reactions. The pole terms used in the model are structureless functions of t and the cut terms, or absorptive corrections are calculated from the Sopkovitch prescription but are enhanced by a special λ factor ($\lambda > 1$). The justification of such a factor lies in the fact that with the absorption model considered earlier (Figure 1g), only elastic effects were considered. However, it is reasonable to suppose that diffractive dissociation mechanisms are operative producing inelastic intermediate states. The presence of such exchanges, which do not decrease with energy, would be expected to introduce further absorption than that estimated from the Sopkovitch prescription.

Even with the λ factor, the model has difficulties with the $p-n$ data (2). The absorbed waves (low L waves) are still too large so that, although a forward spike is produced, the differential cross-section in the region $-t \sim 0.4 \text{ (GEV/C)}^2$ is too high. More absorption is required to reduce the low partial waves even further.

1.8 Existing Charge Exchange Data.

The Diagrams 1h & 1i show some of the existing data at high energies for the charge exchange reactions $\bar{p}p \rightarrow \bar{n}n$ (antiproton charge exchange) and $np \rightarrow pn$ (pn charge exchange). The differential cross-section for the np channel has been measured to a considerably

higher precision than that for the $\bar{p}p$ channel so that, in the latter case, one is unable to see the exact form of the scattering amplitude near to the forward direction. In view of the importance of this region of the cross-section in distinguishing between various models, it was decided to perform an experiment whose prime aim was to measure the forward cross-section for the $\bar{p}p$ channel to a precision similar to that obtained in the np experiments. With this aim in mind, the following requirements were incorporated into the design of the experiment:

(i) High statistics are required in order to allow a bin size of about 0.002 (GEV/C)^2 in the momentum transfer, t . Thus, about 10,000 charge exchange events are required in the region $0.0 < (-t) < 0.2 \text{ (GEV/C)}^2$.

(ii) In order to allow the fine binning as outlined in (i), it is necessary to measure the scattering angle to an overall uncertainty of better than 2 mrad. Such a requirement involves not only measuring the trajectory of the incident antiproton by means of wire spark chambers, but also locating the antineutron to a spatial precision of a few millimetres by means of its interactions in heavy plate spark chamber.

(iii) The experiment was performed primarily at one incident momentum (7.76 GEV/C) although a certain amount of data was taken at 5.0 GEV/C.

In the next chapter, we shall now see how the various requirements were realized experimentally.

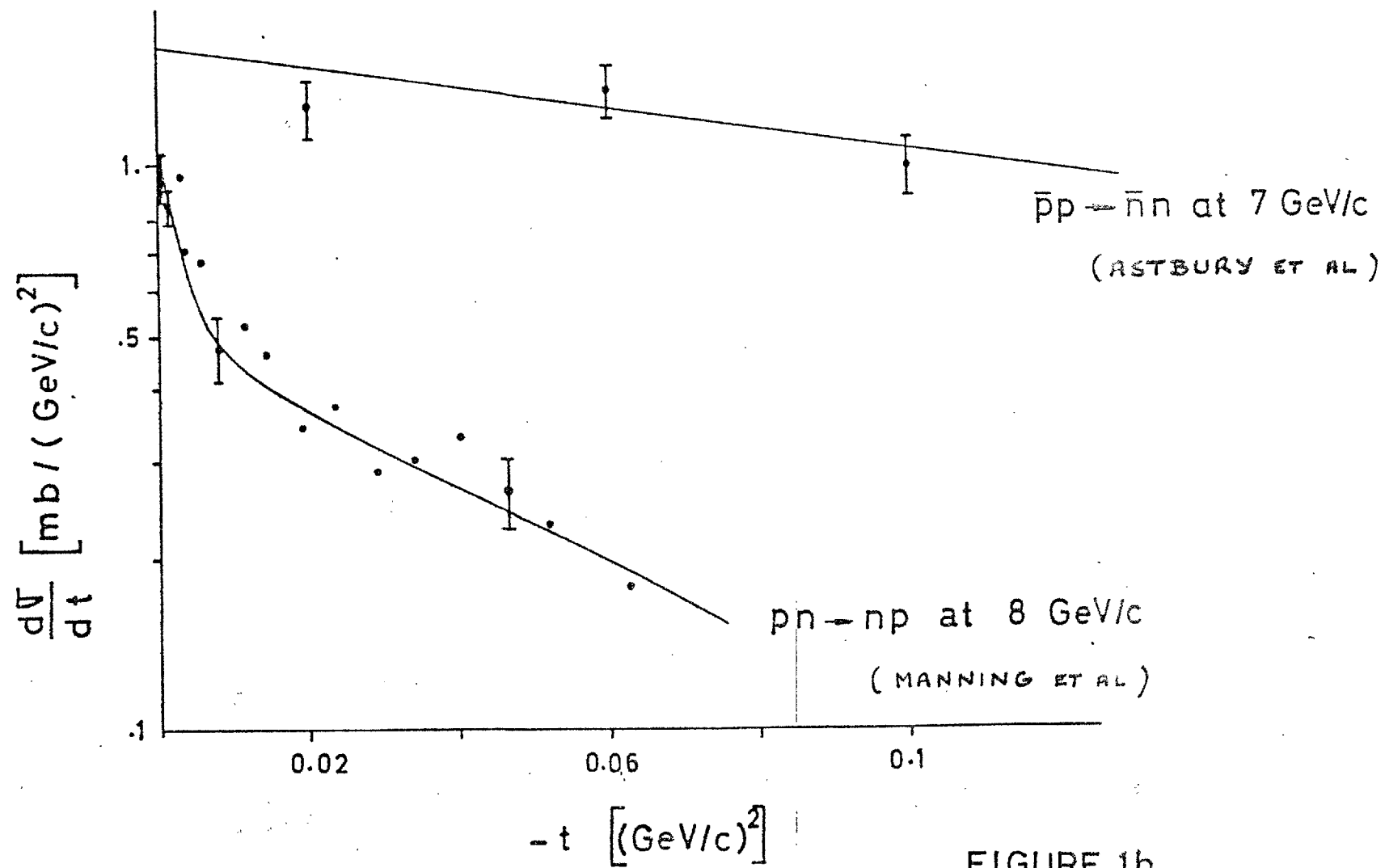
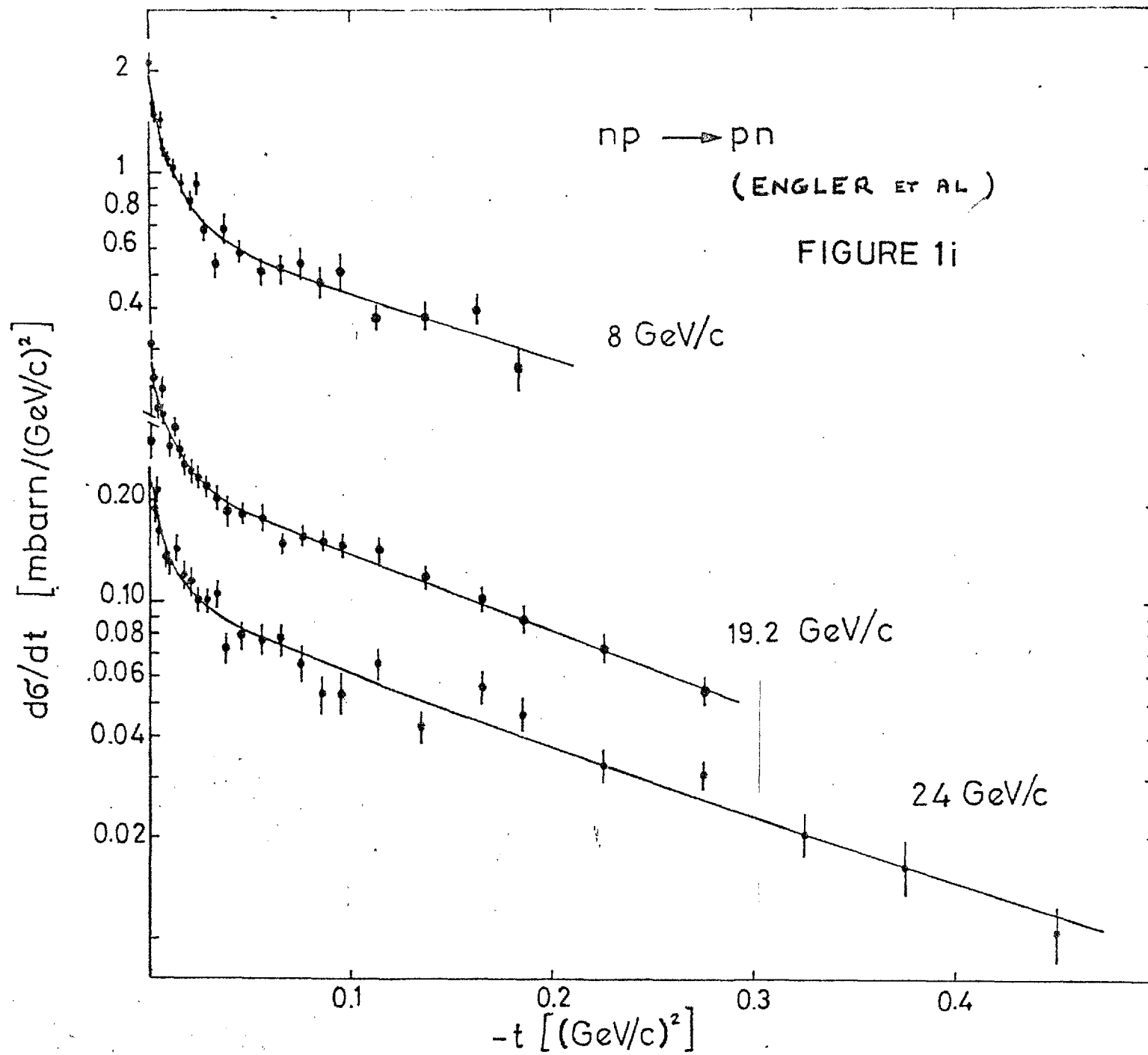


FIGURE 1h



C H A P T E R 2

EXPERIMENTAL APPARATUS

2.1 Beam and Associated Apparatus

The beam used in this experiment, D29, was produced on an internal target at the C.E.R.N. proton synchrotron (P.S.); the relevant parameters for the P.S. operation during the run were as follows:

P.S. Energy	=	24.1 Gev.
Beam Production Angle	=	82.5 mrad.
Spill Time	≈	400 msec.
P.S. Repetition Rate	=	1 burst every 2 sec.
Primary Intensity	≈	10^{12} protons.

With the above parameters, beam D29 had a physical length of 96 metres and a maximum momentum of 12 GEV/C. The beam line, which was not under vacuum, consisted of two sections, the first part being used by another experimental team and the second part, referred to as D29a, being used by this experiment. With this arrangement, the maximum intensity of negative pions in the D29a section was $\sim 250,000$ per burst, and this could be reduced if required by the use of a collimator. Focussing within the D29a section was achieved by means of a doublet system consisting of

1 metre Quadrupole lenses which reduced the beam to a spot 7 cms by 3 cms at the target; the horizontal and vertical divergencies of the beam were then ± 3 mrad and ± 6 mrad respectively.

The composition of the beam was determined by the primary P.S. energy and the production angle and with the figures given above, the percentages were:

Negative Pions	=	95.50%
Negative Kaons	=	3.94%
Antiprotons	=	0.56%

Thus, with a beam intensity of $2.5 \times 10^5 \pi^-$, 1.4×10^3 incident antiprotons were obtained each burst.

The various beam elements in D29a, together with the positions of the target and the primary focus, are shown in Figure 2a for the 5.0 GEV/C run. At 7.76 GEV/C, the primary focus moved upstream some 3 metres and the hydrogen target was displaced upstream 2.5 metres.

2.2 Target and Trigger System

The target, providing the protons for the reaction, consisted of a cell, 41 cms long and 8 cms in diameter containing liquid hydrogen. The main body of the cell was a stainless steel tube of 0.5 mm thickness whilst the end windows were made from 0.19 mm thick mylar, so as to reduce background interactions in the target to a minimum. The cell was supplied with hydrogen from

a larger reservoir situated above it, and the whole system was monitored continuously from the experimental area.

The incident beam of antiprotons was selected by a series of scintillation and gas Cerenkov counters as shown schematically in Figure 2b. Counter S_0 was used as a monitor when setting up the beam whilst counters $A_0 S_1 S_2 A_3 S_3 A_4 S_4$ were collectively assigned as the beam telescope, T. The threshold Cerenkov counters were C_1 and C_2 and the pressure of the ethylene gas was adjusted so as to give an output signal for a pion ^{or kaon} but not for an antiproton. In this way, the antiprotons in the beam could be separated, by the logic electronics, from the pions and kaons present. Symbolically, we have:

$$T_{\pi} = T C_1 C_2$$

$$T_{\bar{p}} = T \bar{C}_1 \bar{C}_2$$

The multi-wire proportional chambers shown in Figure 2b were used to measure the trajectories of the incident antiprotons and these will be described in more detail in the following chapter.

The final trigger, besides demanding an antiproton incident in the target, required that no charged particle and no gamma rays were produced in the reactions. This was accomplished by means of an anticoincidence counter (Figure 2d) consisting of a lead/scintillator sandwich surrounding the hydrogen target (Figure 2c). Neutral pions (π^0) were converted in the lead plates with an efficiency of $\sim 95\%$ and vetoed in the scintillator by detection

of the electrons thus produced. Gamma rays and charged products in the forward direction were vetoed by means of the 3 F counters (Figure 2d) where the thickness of the lead plates could be changed so as to provide a method of correcting for events where the antineutron interacted in the lead plates.

A further constraint on the final trigger was provided by four "star counters" (S_*) which were positioned in two planes, one after the 6th spark chamber unit, the other after the 3rd unit (Figure 2c). These were incorporated so as to reduce the number of empty photographs by demanding at least one charged secondary from the antineutron interaction in the copper plates. The efficiency of the star counters was expected to be high as earlier tests had shown that over 95% of events produced at least one prong which penetrated two spark chamber units.

The final trigger can be expressed symbolically as $T_F = \overline{TC}_1 \overline{C}_2 \overline{R}_i \overline{F}_i S_{*i}$ and the interconnection of the electronic logic units is shown in Figures 2e and 2f. The target monitor count (Figure 2f) served as a check on the level of hydrogen in the target cell and was a coincidence between the antiproton telescope and the R_i counters ($\overline{T}_p \overline{R}_i$). Also recorded on a scaler were the 'accidentals'. The 'accidentals' were events where the final trigger conditions were satisfied but the trigger was killed by a random signal, beam track or otherwise, from either the R or the F counters. The method for correcting for these losses has been described before

(13), the main points being as follows:

Let τ be the time interval during which a signal from R_i or F_i would kill the trigger and let τ_1^{-1} be the mean background signal rate from R_i or F_i combined. Then, the true number of triggers, N_0 , is reduced to N_1 according to the relation

$$N_1 = N_0 e^{-\tau/\tau_1}$$

By choosing a different time interval, τ' , the number of triggers becomes N_2 where:

$$N_2 = N_0 e^{-\tau'/\tau_1}$$

Hence, N_0 can be found from the two relations by extrapolating to zero delay. Experimentally, the parameter N_2 was recorded as the accidental monitor by means of a coincidence between the final trigger and a delayed anti-signal from the combined R_i and F_i counters (Figure 2f).

The data taking was broken up into rolls with a maximum of 770 pictures per roll. At the end of each roll, the contents of all scalars were punched out onto paper tape so as to provide a subsequent check on the experimental conditions.

2.3 Sweeping Magnet

The beam intensity through the hydrogen cell could be varied using the collimator up to a maximum of about 250,000 pions per burst. With maximum intensity, the trigger and detection systems were by

no means saturated but the high flux of pions passing through the spark chambers, particularly in the presence of the copper plates, would have led to many unwanted background tracks on the photographs. These tracks not only made the manual scanning more difficult but also the subsequent measurement and track matching procedures.

It was therefore decided to incorporate a bending magnet, situated after the target (Figure 2c) to deflect the beam outside the spark chambers so the maximum beam intensity could be utilised. The magnet, whilst not limiting greatly the acceptance defined by the chambers, was required to deflect the 8 GEV/C beam through an angle of about 130 mrad. This was accomplished by using a C.E.R.N., 2-metre "C" type magnet⁽¹⁴⁾ which, at the nominal current of 850 amps, had a bending power of 3.48 wb/m. The magnet was modified by the addition of several steel shims to the upstream sections of the pole pieces and these produced an increase in bending power of about 25%. The acceptance of the magnet was only slightly changed by the introduction of the shims.

The presence of the magnet between the target and the chambers introduced a possible source of background events: such events arise when the antineutron suffers a small angle scatter on the magnet iron before being detected by its star in the copper plates. In order to estimate the effects of this background, it was necessary to take a certain amount of data without the sweeping magnet in place.

2.4 Detection System

The basic system of optical spark chambers has already been described by Astbury et al (15), and we shall give only parameters and modifications made that are relevant to the present experiment. The magnet shown in Figures 2g and 2h was not active in the experiment and was only present to provide a mounting for the spark chambers and a support for the optical tower and camera situated above.

The spark chambers themselves were made up of 6 units, each unit consisting of a gas-tight box containing 13 plates, each separated by a gap of 0.8 cms. The face of each plate was 25 micron thick aluminium foil and each unit was supplied with a Neon-Helium gas mixture at a controlled rate. The aluminium foil, together with the gas and mylar windows attached to each unit, gave rise to a radiation length for the chambers of 34 metres. In order to detect the antineutron produced in the charge exchange reaction, it was necessary to introduce an interaction medium, namely a number of copper plates, into the spark chamber system. The plates, whilst providing a reasonable detection efficiency, were required to be sufficiently thin so that multiple scattering of secondaries from the antineutron stars did not significantly reduce the experimental resolution. Furthermore, the separation of the copper plates had to be such that the secondaries had an adequate length for subsequent track-following and event-reconstruction.

The arrangement chosen is shown in Figure 2c. In each of the 1st, 3rd and 5th units, the 8th thin foil plate was removed and replaced by a copper plate of thickness 20 mm and connected to earth. The detection efficiency of the three plates combined was about 36% whilst multiple scattering of the secondaries was typically 20 mrad. The distance between each plate was 22 active spark chamber gaps which allowed the apex reconstruction to be performed using only the chamber regions adjacent to the plate containing the interaction. An output signal from the final coincidence unit, after being passed through a discriminator, was used to trigger the high voltage thyatron pulse system. This, in conjunction with the slave units (Figure 2g) delivered a 12 kilovolt negative pulse to alternate spark chamber plates. The pulse rise time was ~ 50 nsec. The clearing field was provided by a 50 volt D.C. level of polarity opposite to that of the high-voltage pulse. The multi-track efficiency was 98% for one track falling to 68% for seven tracks and this proved quite adequate as the mean prong multiplicity for an antineutron "star" was 4-5 tracks. In the absence of a magnetic field, there was no staggering of the tracks and the electric drift of the sparks introduced a correction of ~ 1 mm.

The upper face of each chamber unit was perspex allowing the events to be photographed by a camera system incorporated in the optical tower above the chamber (Figures 2g and 2h). Light rays emitted parallel to the gaps were deflected, so as to enter the camera, by a series of accurately machined prisms placed in a plane above the chambers. Events were recorded on unperforated 70 mm film

in the form of two adjacent stereo views so as to allow subsequent reconstruction into three dimensions. Reference marks for this reconstruction were provided by 10 fiducial crosses positioned in a plane above the chambers; this plane denoted the zero of the vertical (Z) axis and was called the Fiducial Plane. The fiducials were flash tubes placed behind a masking cross and were fired from the final discriminator. The demagnification of the optical system was 24 and, with an optic axis separation of 58.2 cms, the stereo constant (the parameter relating the vertical position to a coordinate difference in the fiducial plane) was 4.7 . A data box, comprising a series of flash tubes in B.C.D. format was used to record the event number and other useful information at the end of each photograph. The camera which was used in the experiment had been specially designed and built at C.E.R.N. to permit photography at a high event rate. Film passing to and from the take-up and supply spools was buffered so that an individual frame could be fed into position, exposed, and ejected in a time of about 50 msec.

Systematic optical distortions that were introduced by the prism, mirror and camera systems were corrected in the analysis programs; these will be discussed in more detail in the section on geometrical reconstruction, Chapter 4. Photograph 2i shows a typical event at a momenta of 7.76 GEV/C, and photograph 2j shows the hydrogen target and neighbouring apparatus.

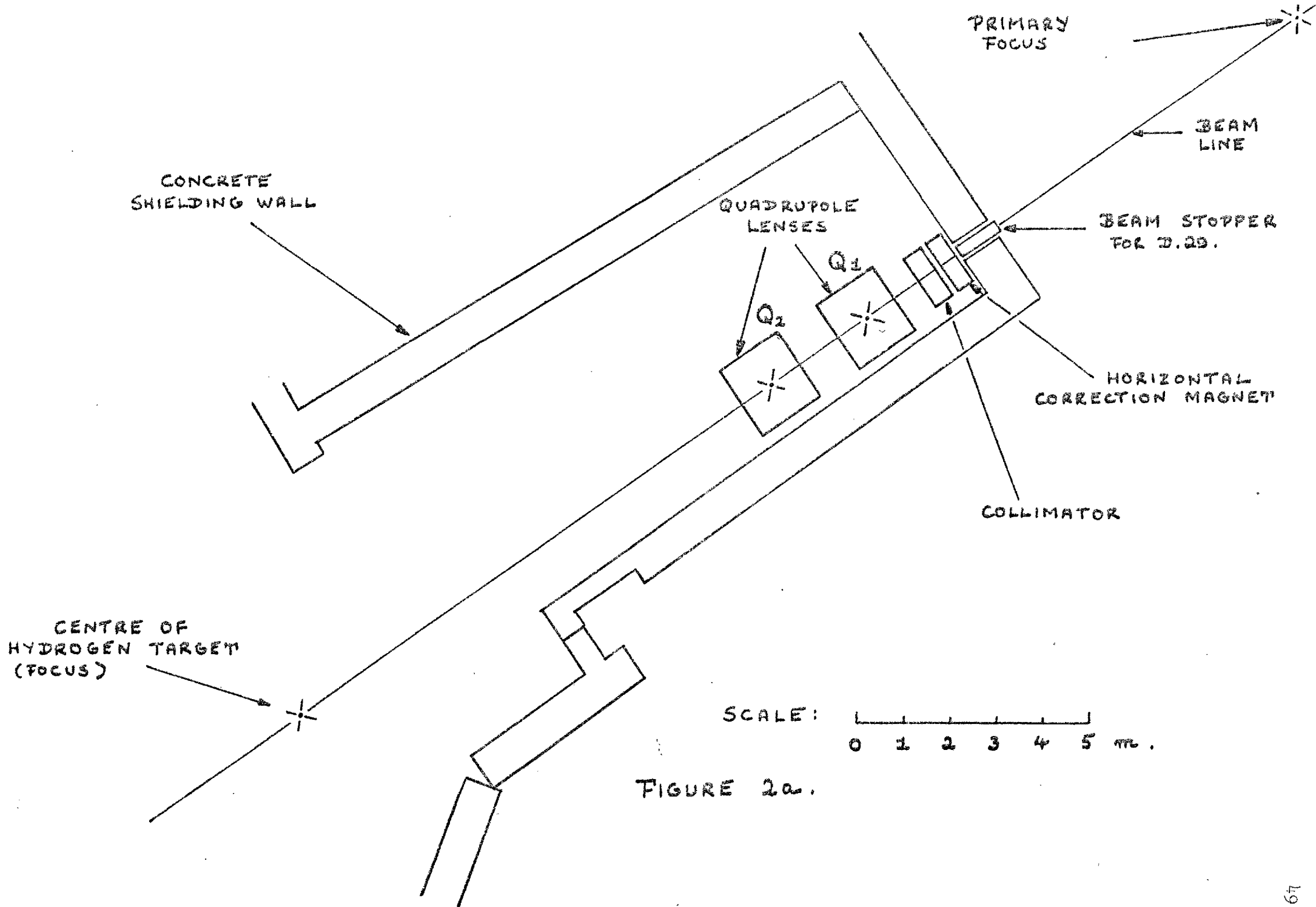


FIGURE 2a.

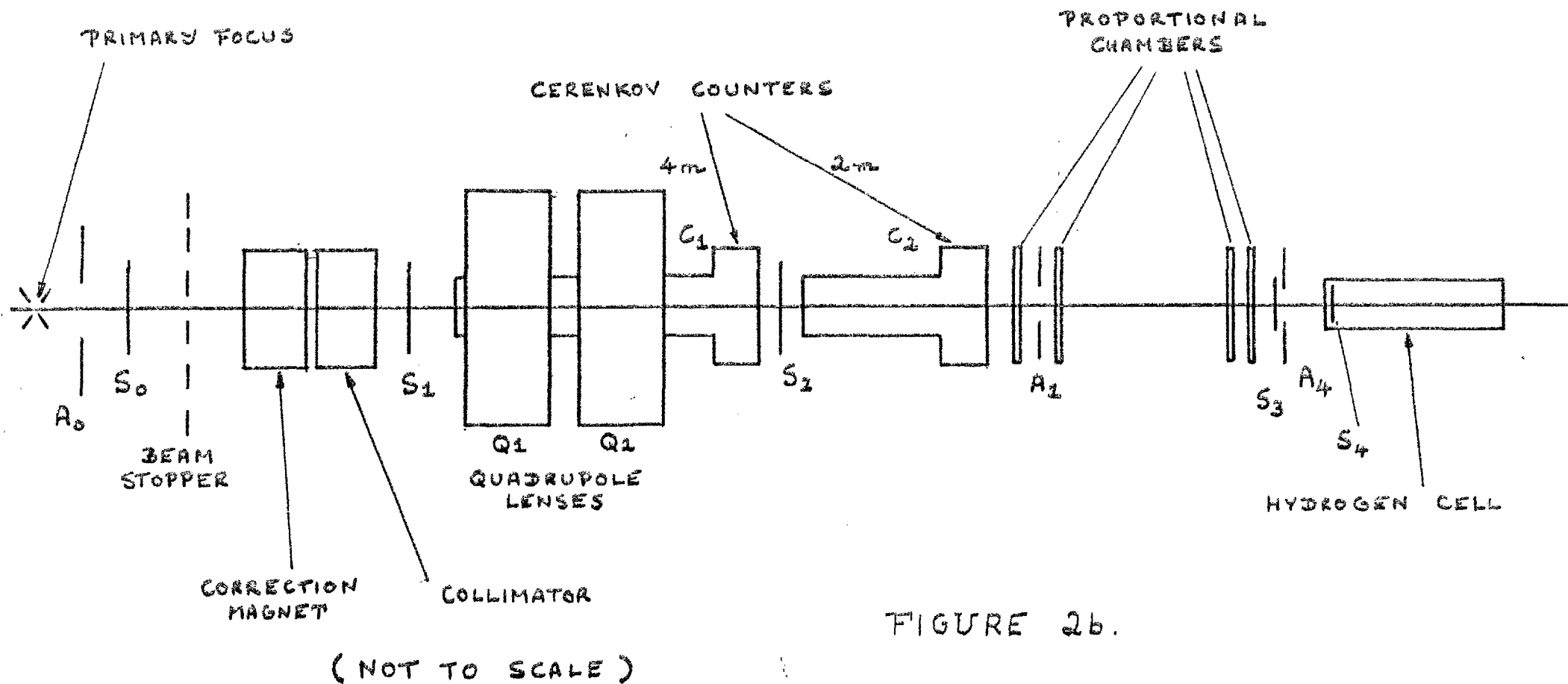


FIGURE 2b.

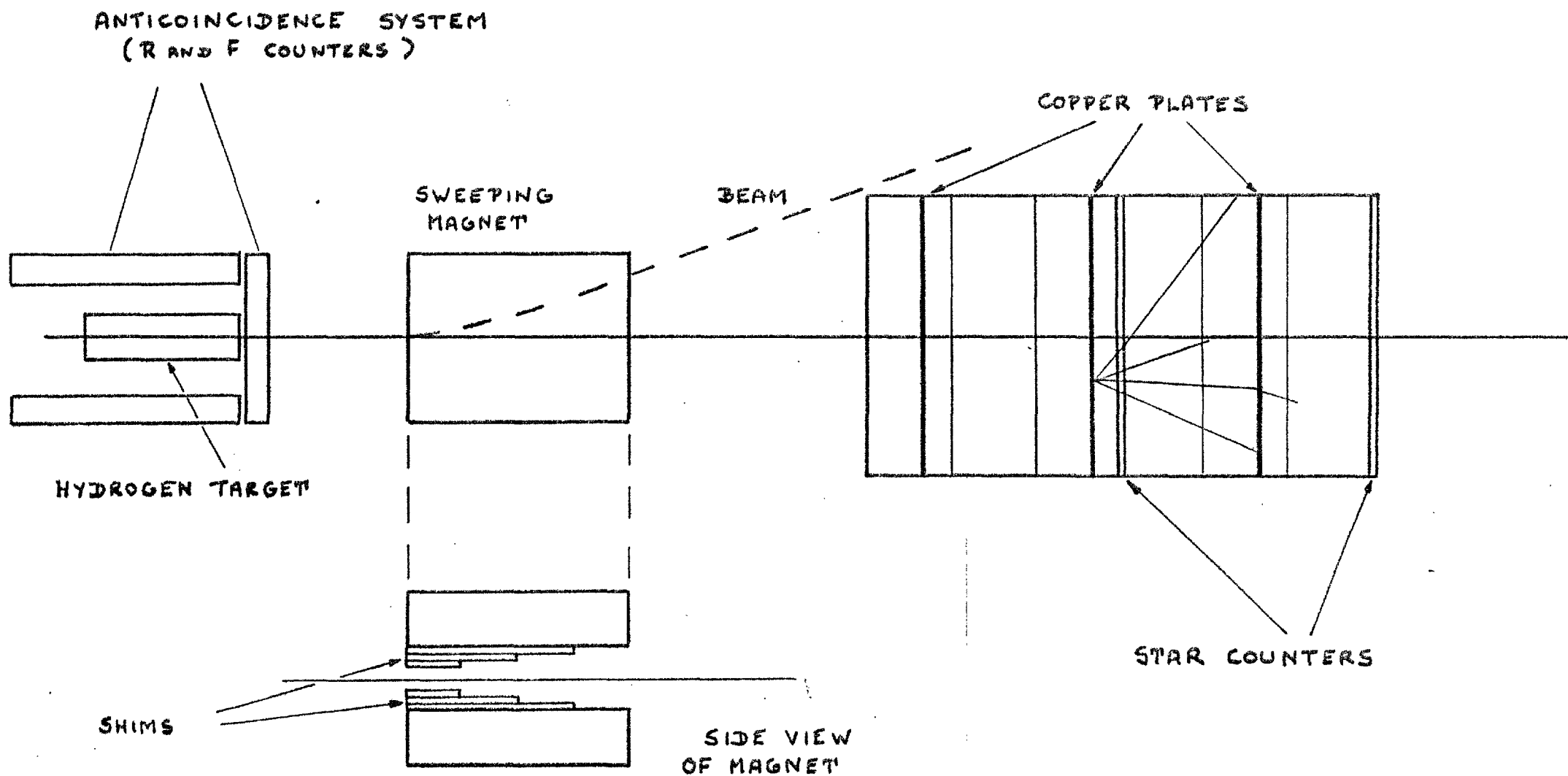
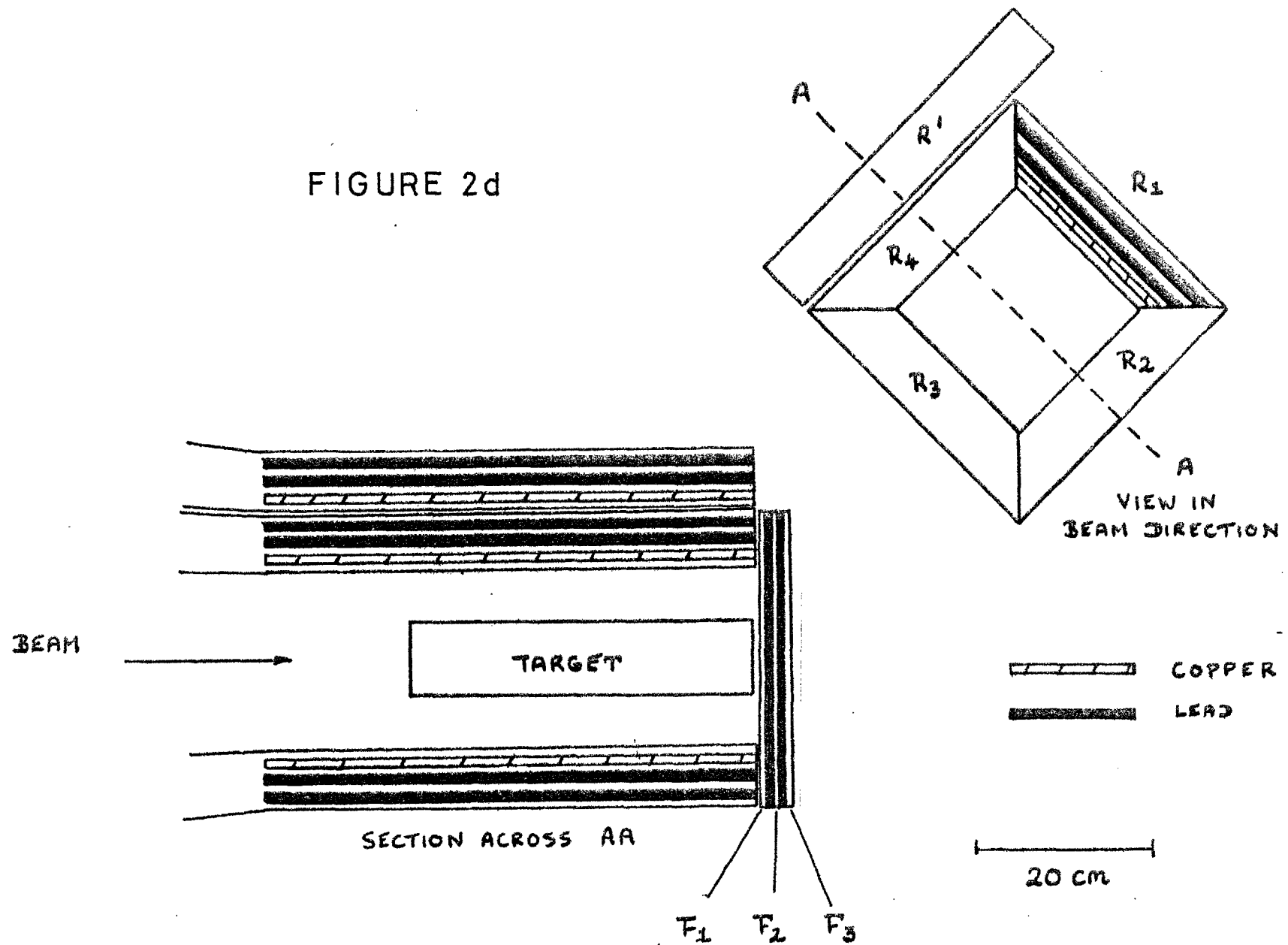


FIGURE 2c

FIGURE 2d



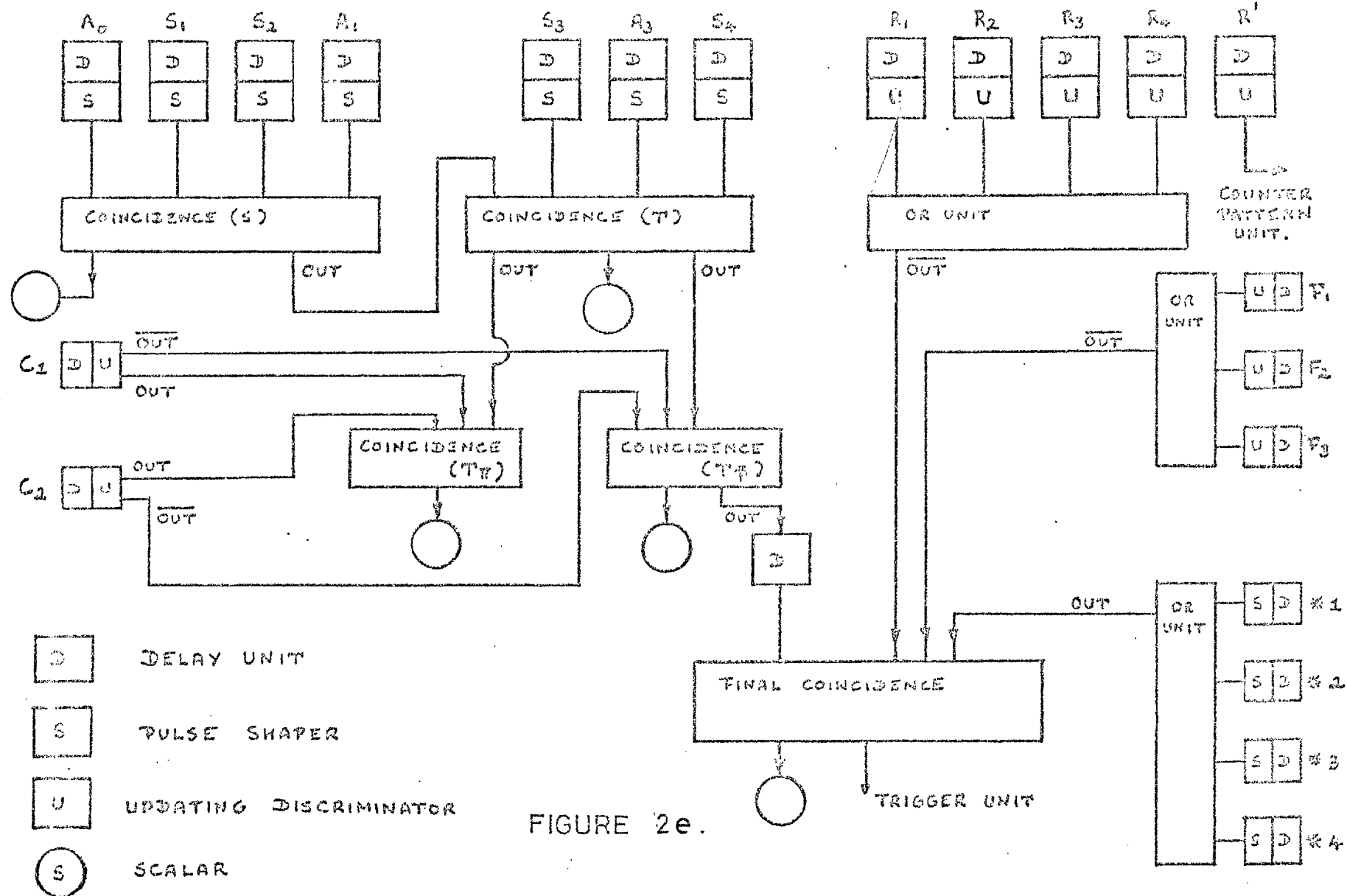


FIGURE 2e.

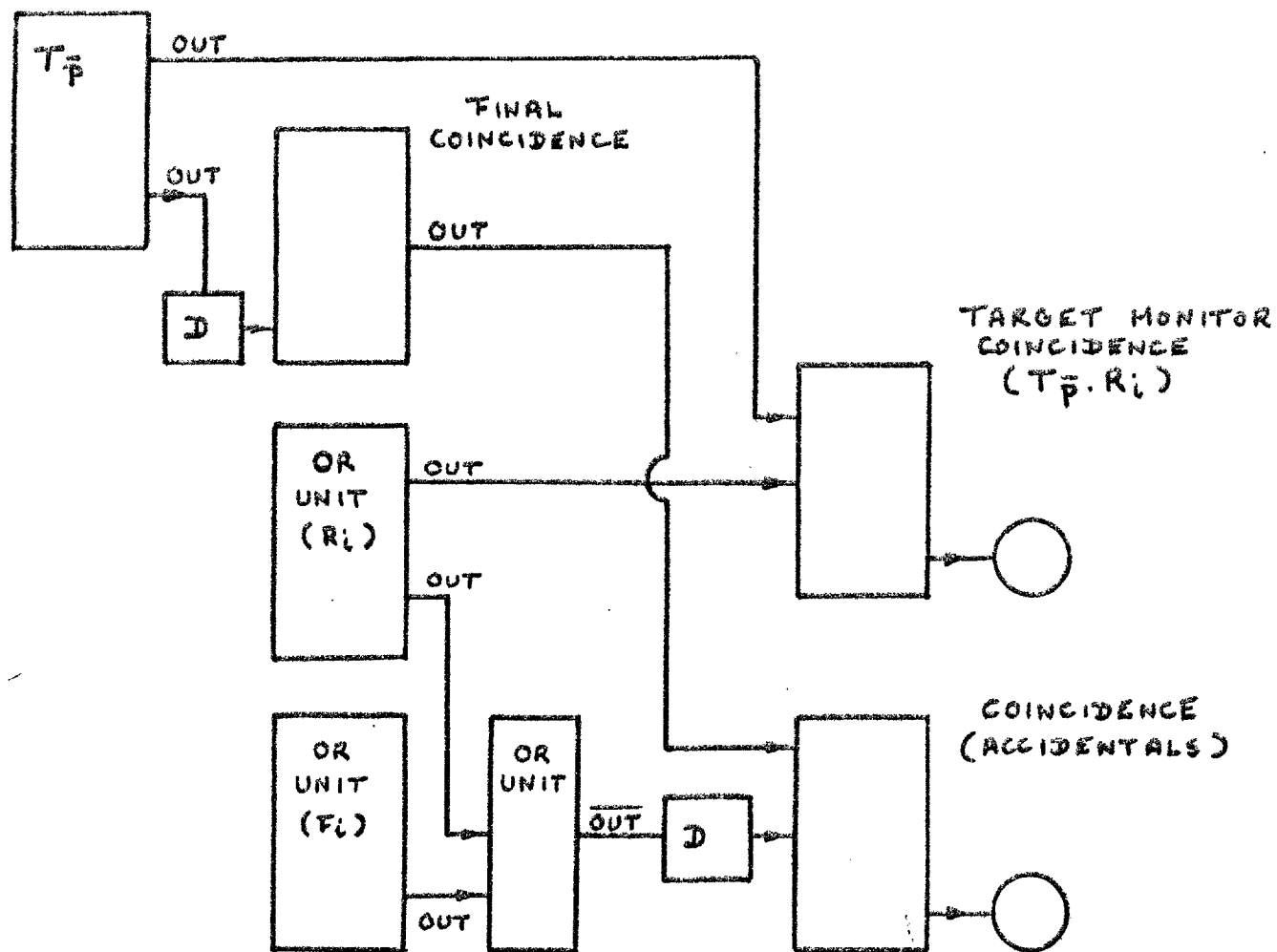


FIGURE 2f

MAGNET SPARK CHAMBER
SECTION ALONG BEAM DIRECTION

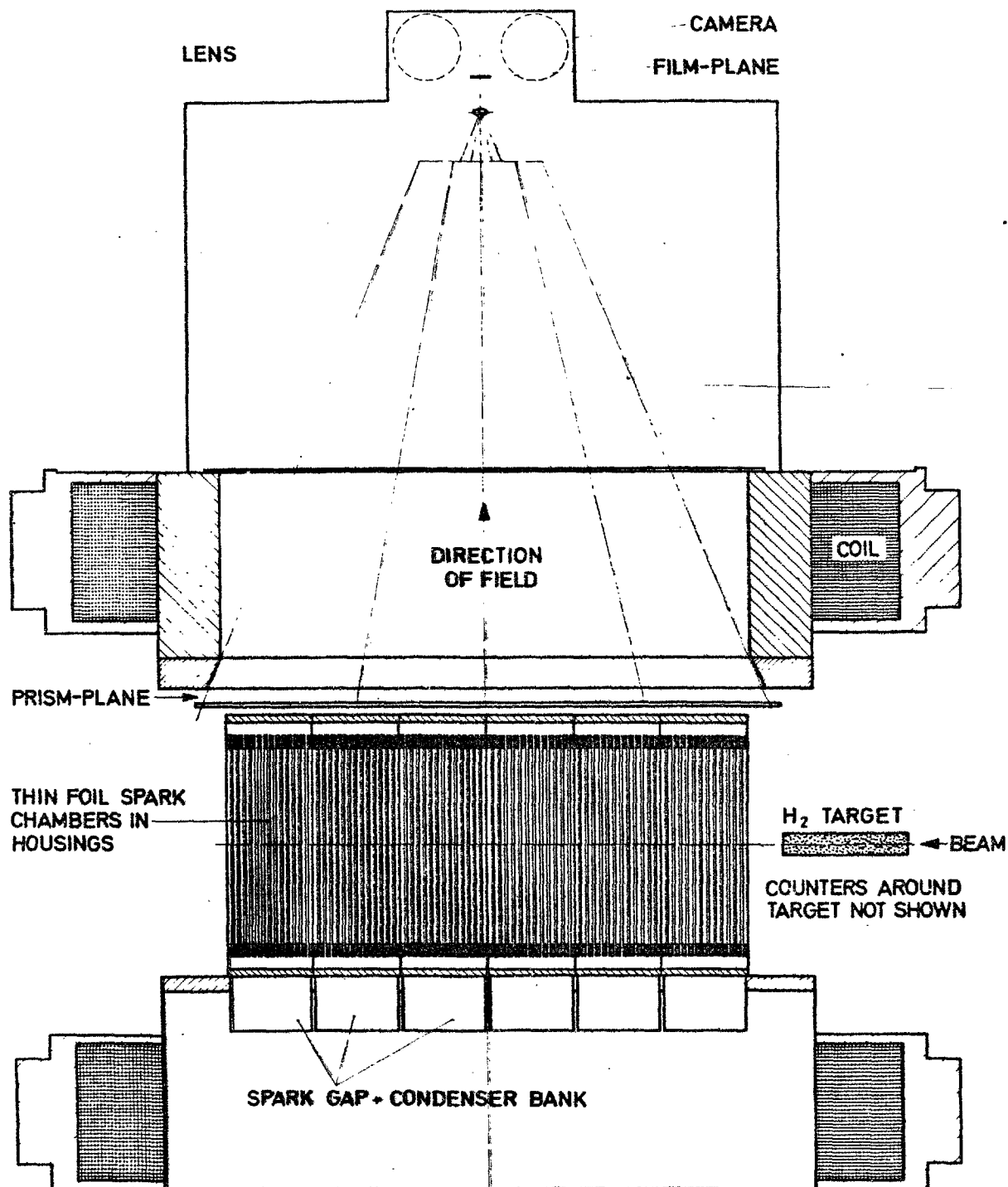


FIGURE 2g

MAGNET SPARK CHAMBER

SECTION ACROSS
BEAM DIRECTION

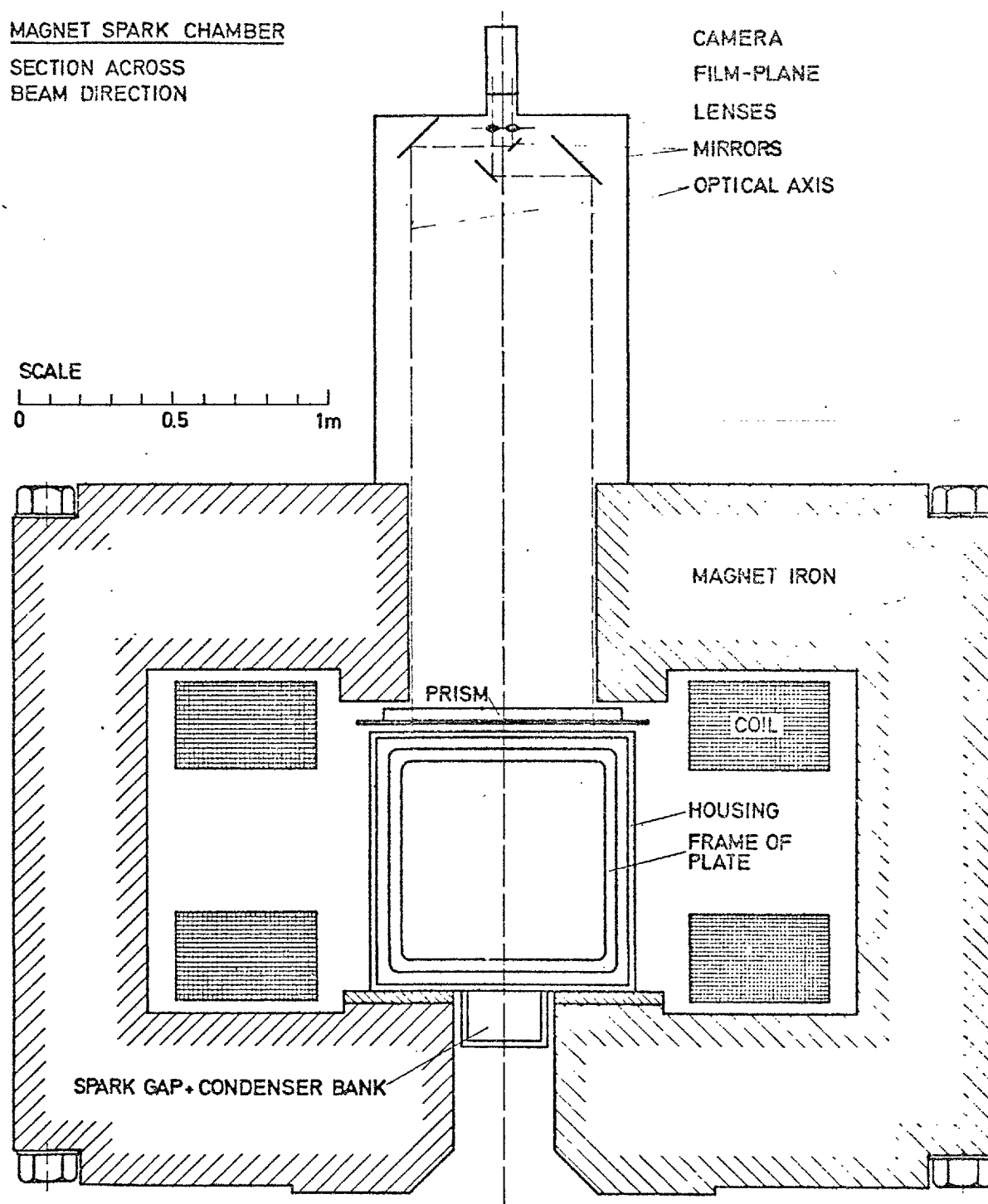
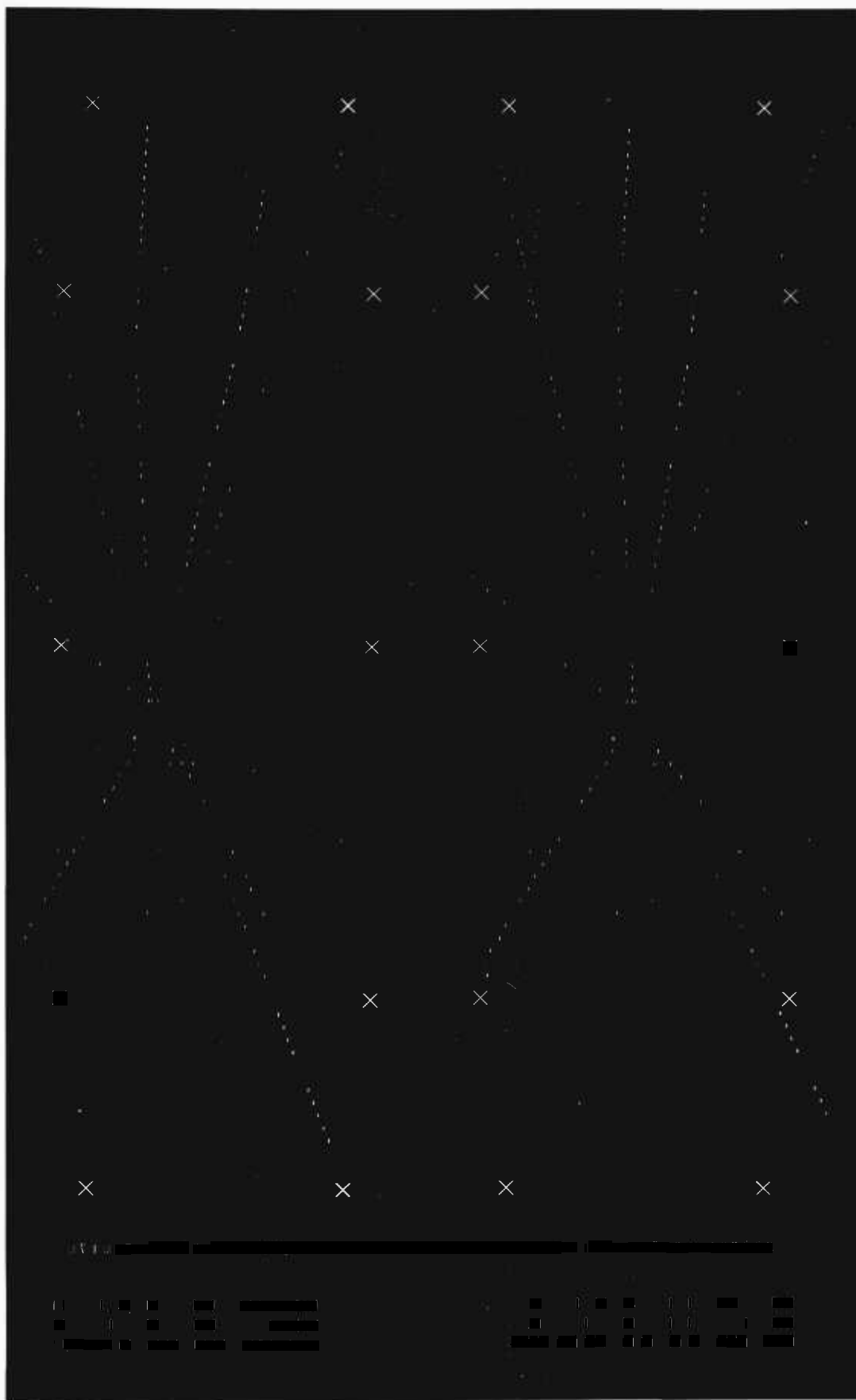
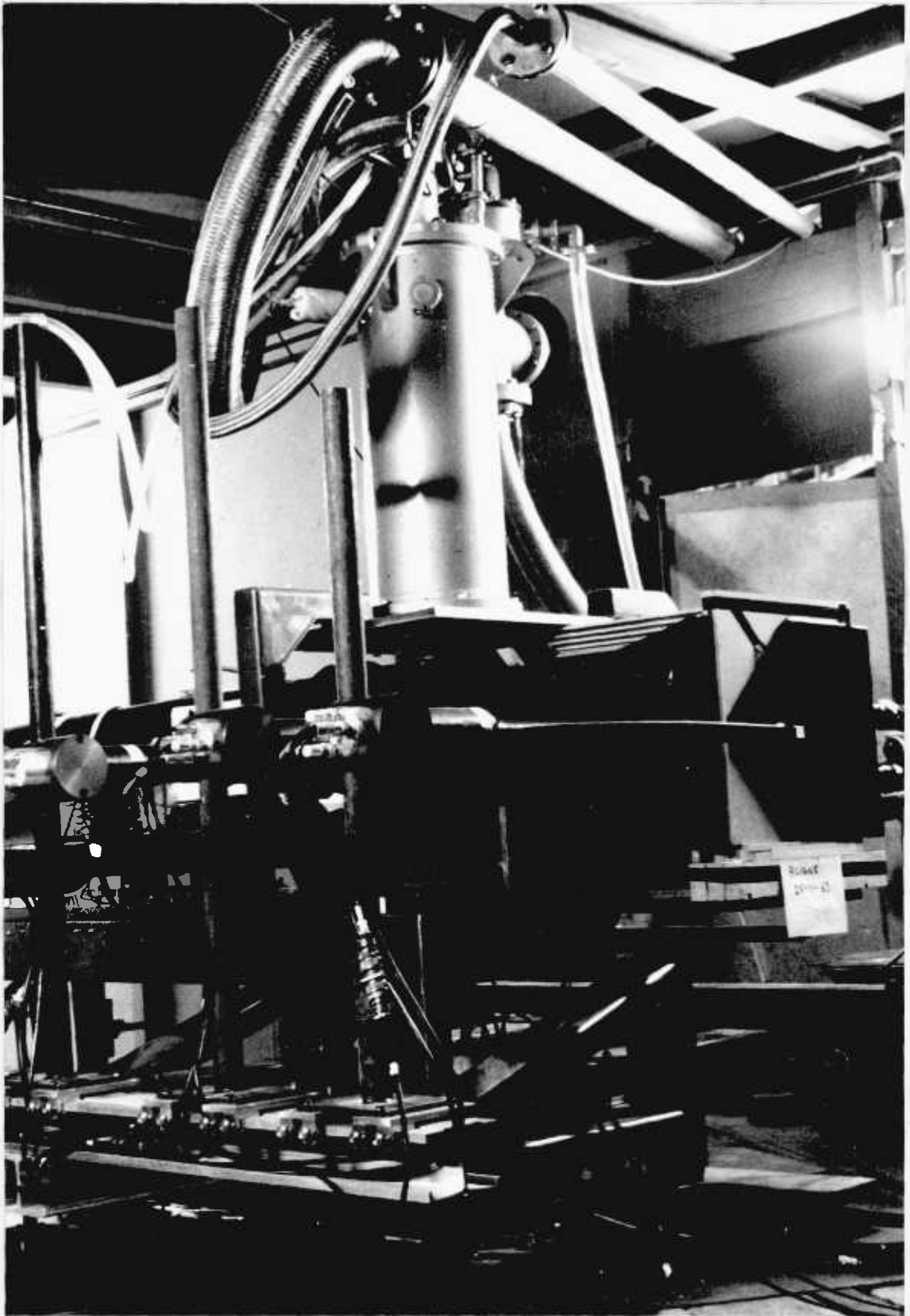


FIGURE 2h



PHOTOGRAPH 2i



PHOTOGRAPH 2j

C H A P T E R 3

BEAM MEASUREMENTS USING PROPORTIONAL CHAMBERS

3.1 Proportional Chambers

An important requirement in a high-precision experiment on the forward $\bar{p}p$ charge exchange process was to measure the trajectory of the incident antiproton so that the interaction point in the target was known as accurately as possible. It was therefore necessary to incorporate into the beam line a measuring system which, whilst having a good spatial resolution, had sufficient time resolution to allow it to function in a high-intensity beam. With a possible 250,000 particles in a 400 msec burst, the overall time resolution required was somewhat better than 1 μ sec whilst the interaction point in the target plane was needed to within a few millimetres. These requirements were satisfied by a system of multiwire proportional chambers which were both less expensive than an equivalent scintillation counter hodoscope and, being direct digital chambers, were ideally suited for coupling to an on-line computer for data collection.

The system of four chambers is shown in Figure 3a together with the position of the target and neighbouring scintillation counters.

The two upstream chambers, B_H and B_V , each consisted of 60 active wires whilst chambers A_H and A_V , situated at a position close to the beam focus, each had 20 active wires. The indices H and V, horizontal and vertical, refer to the orientation of the wires and thus chambers A_H and B_H measure trajectories in the vertical plane. Similarly, A_V and B_V measure the horizontal plane. The positioning of scintillation counters and other apparatus was arranged so that the level of scattering of the beam by material in the measurement region was kept to a minimum. The only counter present between the two planes of chambers was Al and, being in anticoincidence, contained a hole 10 cms in diameter through which the beam passed.

Each proportional chamber consisted of a plane of gold-plated molybdenum wires, each 30 microns in diameter and spaced 3 mm apart, set between two planes of stainless steel mesh. The distance between each mesh and the wire plane was 7.5 mm and each mesh was maintained at a constant negative potential of somewhat over 2000 volts. The outer walls of each chamber were made from 80 micron mylar and the last wire on each side was thicker than the others in order to avoid excessive field gradients on those wires. Each wire passed out of the chamber to an amplifier through a frame of araldite. A guard strip, held at earth potential, protected against electrical breakdown through this dielectric frame. The amplifiers, mounted two on a card, had an input impedance of 8,000 ohms, a voltage gain factor of 400, and an overall recovery time of 300 nsec. The time resolution of a chamber depended upon the

jitter of the signals but was typically 85 nsec; this compares with a few nanoseconds for a scintillation counter. The gas supplied to the chamber system was a mixture of argon with 5% propane. Fifteen per cent of the total gas mixture was passed through heptane which acted as a quenching agent and allowed operation of the chambers at considerably higher voltages than would otherwise have been possible. The use of high voltages increased the amplification that could be achieved and this in turn led to a higher efficiency of the chambers. Figure 3b shows schematically the main features of a chamber and photograph 3c shows one of the 60 wire units in position in the beam line. The amplifier cards can be clearly seen together with the cables used to transfer the output signals to the 'Pattern Units'. These units, consisting of a flip-flop for each wire, stored the information from the chambers and could be interrogated and reset by the Data Transfer system (Section 3.2). Provision was made in the pattern units for each input to be given a discrimination level set from a potentiometer on the front of the unit.

3.2 Data Acquisition System

The read-out system enabling data from the four proportional chamber planes to be sent to a computer connected on-line was designed and constructed at C.E.R.N. and a full description, including circuit diagrams can be found in reference⁽¹⁶⁾. The electronic modules were designed so that they could be used in a variety of configurations,

and Figure 3d shows schematically the arrangement used in this experiment. We shall now outline the operation of the system together with the sequence of events which led to the input of data into the computer.

Once the trigger requirements (Section 2.2) were satisfied, the Fast Coincidence Unit sent the final trigger signal to the Timer Unit and also a fast gate signal to each of the Pattern Units. On reception of the final trigger, the Timer Unit, responsible for sequencing the initial stages of the read-out operation, sent a busy signal to the Gate Control Unit which in turn gated the final coincidence so that events occurring in the period of the read-out would be ignored. The Timer Unit then allowed a fixed delay for the data to be written into the Pattern Units after which it sent out the Start Record Signal requesting transfer from the Data Transfer Unit. This unit, through which all data passed during read-out, was controlled by, and directly connected to the on-line computer and merely served to feed the computer with data at the required rate. The start record signal initiated a further busy signal to the Timer Unit and an event interrupt to the computer interface.

The interrupt was handled by the program in the on-line computer and for normal acceptance of the event, the execution of a parallel output, POT, instruction would initiate the transfer. This instruction contained the start address in computer memory where the words would be placed (A) together with the number of words to be transferred (N). A series of N pulses separated by 8 μ sec intervals

were output by the computer into the address increment line and, on reception of each pulse, the relevant pattern unit was addressed by the Channel Selector and the data were transferred. The data 'en route' to the computer passed via the Data Transfer unit where a parity generator added, if necessary, a bit, such that all transfers were effected under even parity. The data then passed into the computer where an interlace controller ensured that the incoming words were set in successive order, starting at address A and finishing at address $(A + N - 1)$.

A cessation of the pulses in the address increment line terminated the transfer and an automatic reset system lifted the busy signals so that further events could be accepted. An important point about the overall system was that the transfer was controlled by the on-line program, although parameters such as the cycle time, the time taken to transfer one 24-bit word, were determined by the hardware in the computer interface. On each data transfer, a total of 40 words were input to the computer, eight of these being from the proportional chamber pattern units and the remainder being either zero or information about the event from parameter units. In the latter category were included the event number, beam momentum and date, together with a word which indicated the scintillation counters that fired during the event.

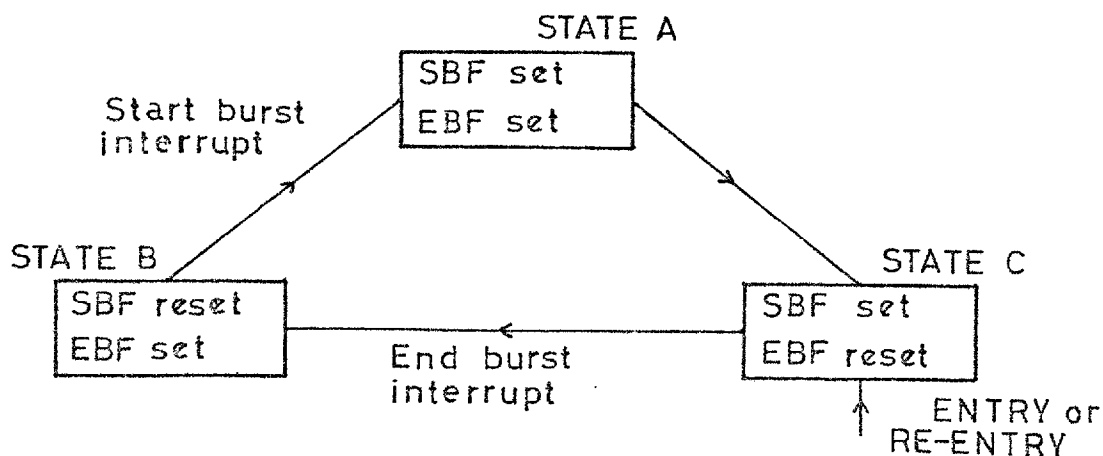
3.3 The On-Line Computer

The machine that was connected on-line to the experiment was an "SDS 920" (17) with a memory of 8192, 24-bit words and a cycle time of 8 μ s. Hardware facilities for floating point arithmetic were not provided in the machine and in view of the somewhat slow cycle time, lengthy calculations requiring floating point numbers had to be avoided. The input/output was provided by standard peripheral units, namely a typewriter, a paper tape reader and punch, and two 7-track magnetic tape units. A 16-level priority interrupt feature made the machine ideally applicable to an on-line role and communication with the experiment was via a C.E.R.N.-built interface. A data link of 24 lines connected the experimental electronics with the computer and a Tektronix Memoscope and control box were coupled to the SDS 920 interface so as to provide display facilities. All programs used on the machine were written in SYMBOL, the SDS 920 assembly code, and were initially punched on cards and copied to magnetic tape using an auxiliary machine. This method of input was used to make program editing considerably easier and quicker than using the typewriter. Source programs were then read from the magnetic tape by the "Symbol Assembler" and a relocatable binary version of the program was produced on paper tape; this tape was then used to load the program.

3.4 On-Line Computer Program

The basic tasks required of the program were to monitor the performance of the chamber system during the experiment and to record incoming data on magnetic tape. Monitoring facilities were provided by a series of histograms which were constantly updated from the data and could be displayed on the memoscope by means of a control box request. The raw data going to magnetic tape underwent a minor sorting process before being recorded and the contents of any tape record could be listed on the typewriter so as to provide a check on the data transfer system. The complete program occupied virtually all of the 920's 8K store, about 2,000 words being used by instructions and the remainder being taken by histogram bins and display buffers.

On entering the program, various constants and buffers were initialized by a 'set-up' routine and after enabling the interrupts, control passed to a wait loop routine where the machine would idle, awaiting the arrival of an interrupt signal. The interrupt cycle can be represented as shown below.



Two flags -- SBF, the start burst flag and EBF, the end burst flag -- were used in the program to describe the four possible states in which the system could find itself; three of these states are shown on the previous page and the fourth, when both flags were reset, corresponded to the abnormal state and was only used on entry or re-entry into the running cycle. The 'set-up' routine ensured that the normal cycle was entered in "state C" and the subsequent arrival of an end burst interrupt caused state B to be entered. A start burst interrupt, signifying the arrival of a P.S. beam burst, set the start burst flag and caused the input buffer to be reset so as to prepare for the incoming events. Once this buffer was initialized, the end burst flag was reset and state "C" entered. This state was the only condition in which events were accepted by the program and an event interrupt in this period caused the data for one event to be transferred to the input buffer. The subsequent arrival of an end burst interrupt terminated the event acceptance period and the events which had accumulated in the buffer were recorded on magnetic tape. In all, five interrupts were used in the program and they are listed below in their order of decreasing priority.

End Burst Interrupt.

Error Interrupt.

Start Burst Interrupt.

Event Interrupt.

Control Box (Display) Interrupt.

The error interrupt was initiated by a failure in the data transfer unit (Section 3.2) and caused an error message to be typed and the

computer to halt.

As the data for events arrived in the machine, they were stacked awaiting analysis in a buffer and a pointer-word was used to indicate the current position of the analysis. On each wait loop cycle, the contents of the first unprocessed word in the buffer were inspected and, if data required analysis, control passed out of the wait loop to the histogram updating routines. Information was extracted event by event and each plane was assigned a "plane state" which indicated the multiplicity of triggered wires in that plane. The following histograms were constructed:

- a) Histograms of triggered wires for each proportional chamber plane; two such sets of histograms were accumulated simultaneously according to different "plane state" conditions.
- b) Histograms showing the multiplicity of triggered wires in each chamber.
- c) Angles histograms giving distributions in the dip and azimuth angles.

Any of the above histograms could be reset or displayed on the memoscope by means of a request from the control box. This latter device consisted of a panel of 24 switches together with a button to provide an interrupt to the computer. On receiving the request for a display, the program would read the contents of the switches, decode the information and display or reset the relevant histogram.

Figure 3e shows some typical histogram displays taken from photographs of the memoscope screen.

3.5 Role Performed By Proportional Chamber System and On-Line Computer.

During the setting-up period of the experiment and particularly when focussing the beam, the 920 display was constantly used to show the effects of current changes in the quadrupole lenses; this allowed a more elegant way of beam tuning and alignment than the usual method of placing photographic plates to record the position of the beam. Once the beam element currents had been finally adjusted, the available displays provided a constant check on the consistency of beam conditions throughout the data taking period. Also during the running period, the behaviour of the proportional chambers themselves was monitored from the various memoscope displays, allowing one to check for dead chamber wires, faults in amplifiers or power supplies, and for general chamber inefficiencies due to an incorrect gas mixture being supplied.

Besides the display facilities supplied by the S.D.S. 920, the computer offered some important advantages in terms of data transfer over, for example, an incremental tape unit where the data are buffered and written directly onto magnetic tape. Hardware in the data transfer unit (Section 3.2) generated a parity bit for each word and subsequent checking of the parity of any word

referenced by the 920 processor provided a reliable monitor on the quality of the transferred data. Provision in the on-line software allowed the contents of the output tape records to be inspected by printing them on the typewriter. Also, a running record of the data taking conditions was provided by the typewriter. This form of on-line feedback ensured a consistency in the experimental conditions and that a dependable record for each event was written on magnetic tape.

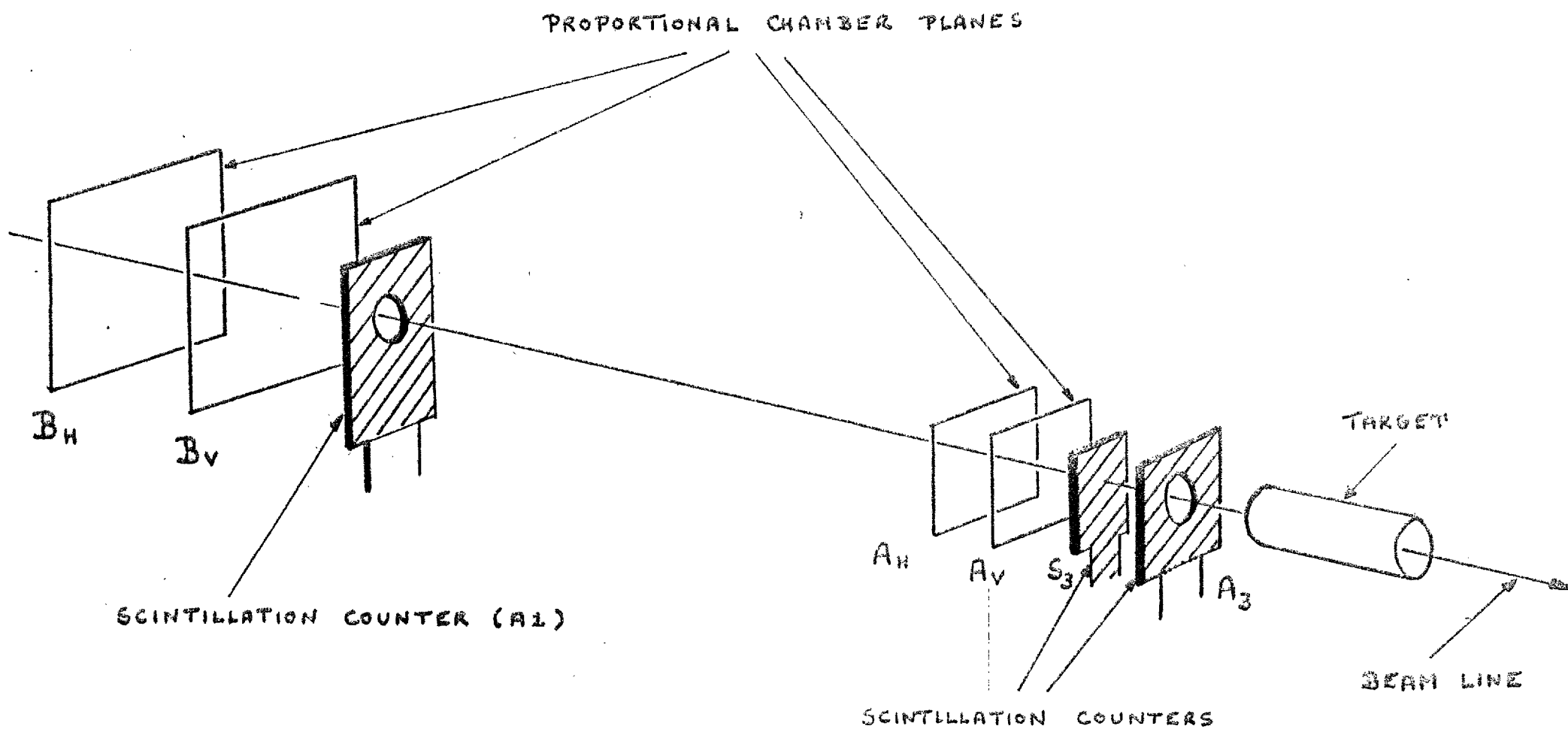


FIGURE 3A

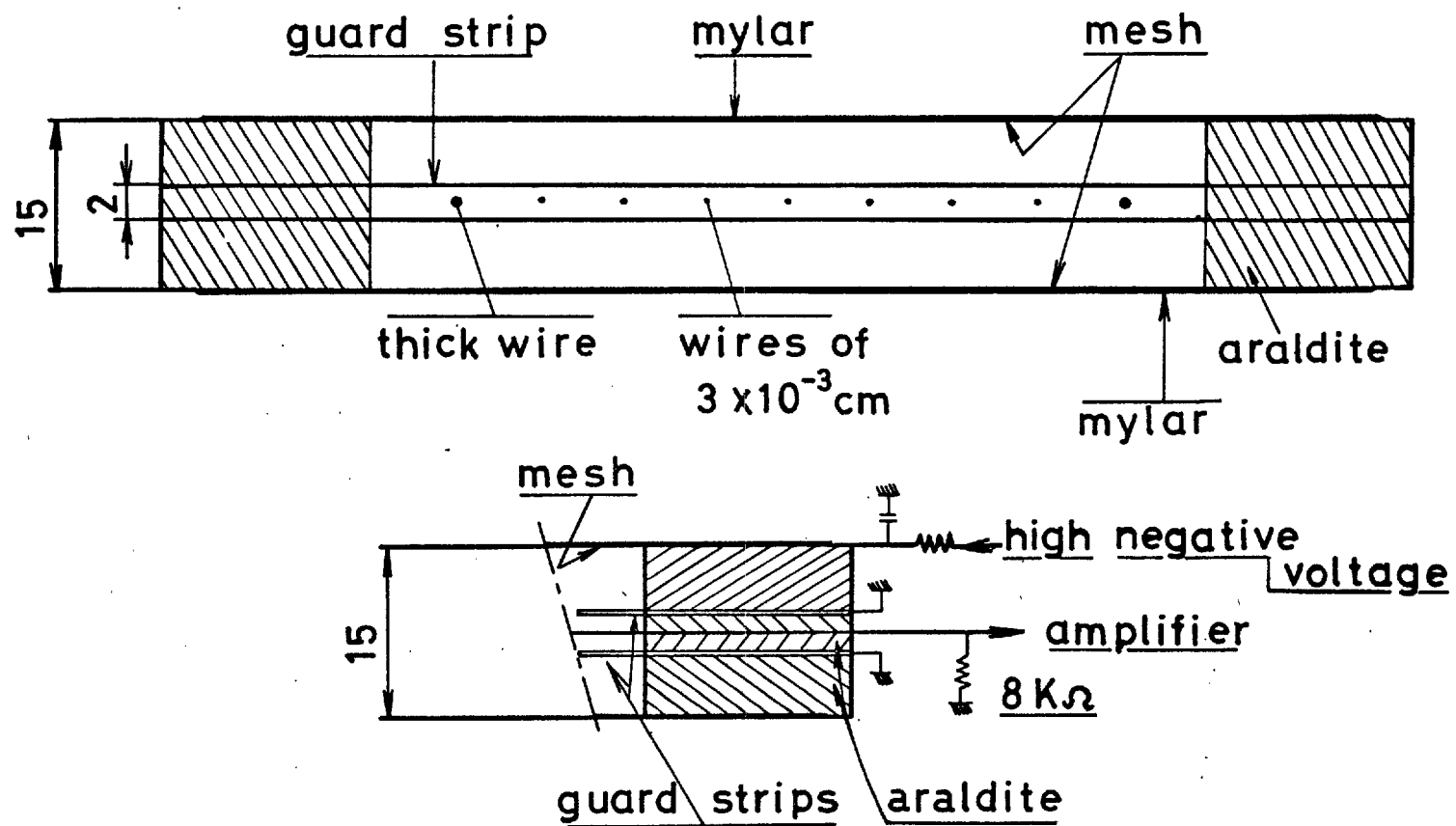


FIGURE 3B

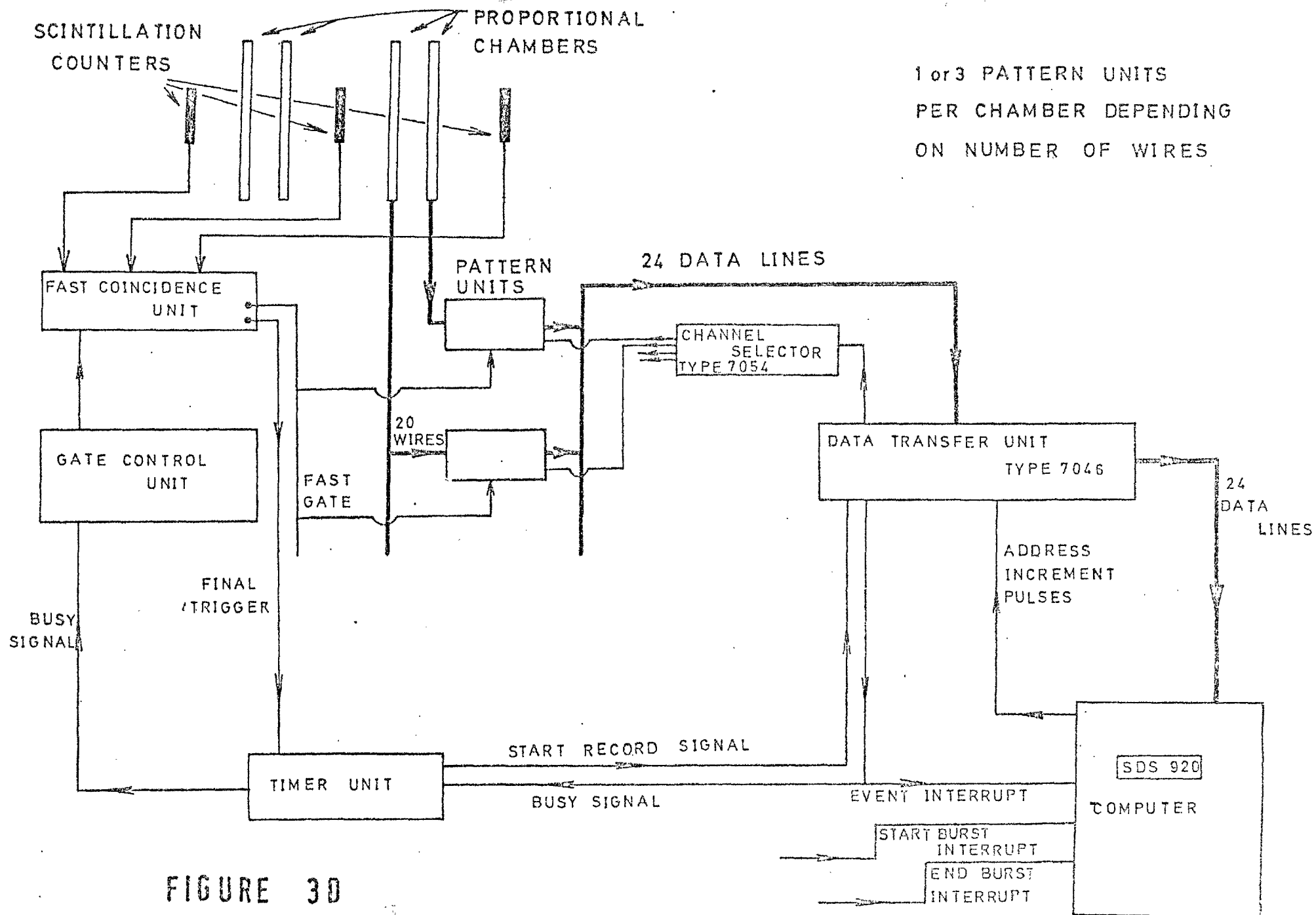
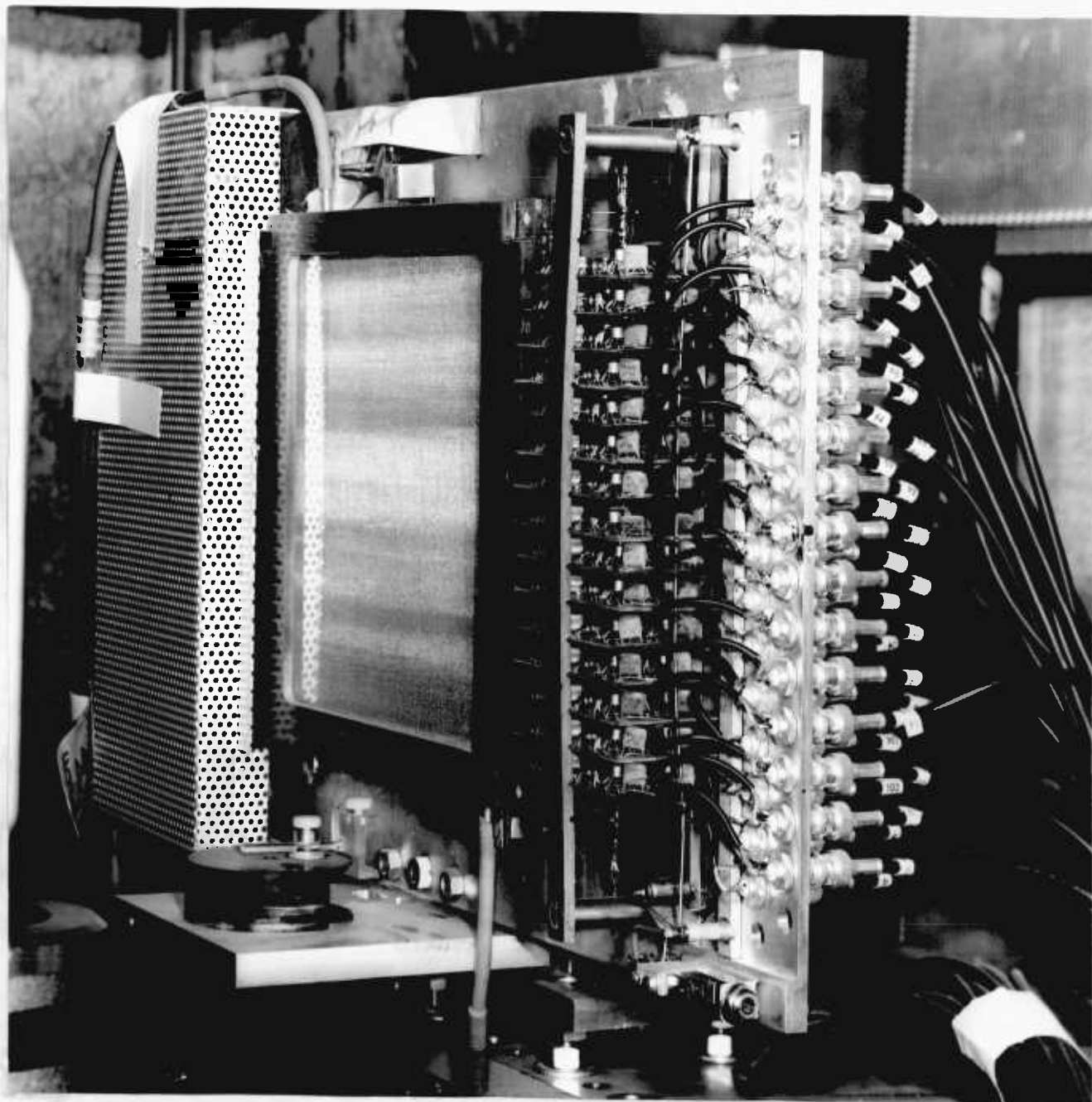
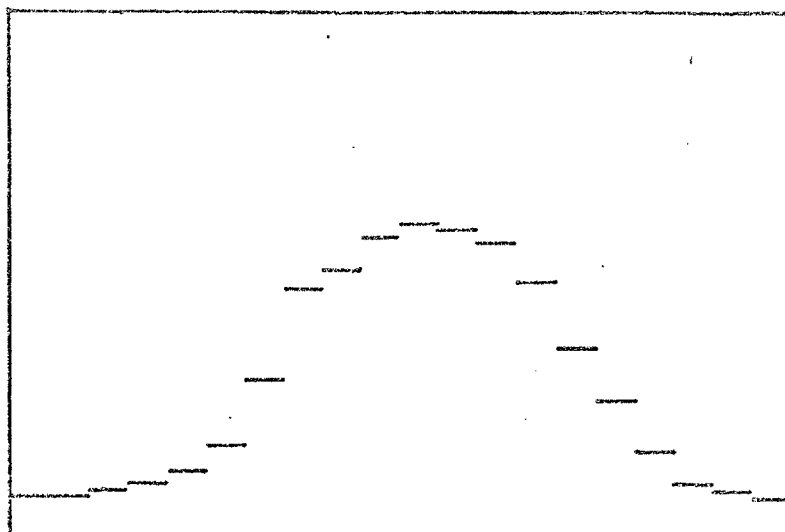


FIGURE 30

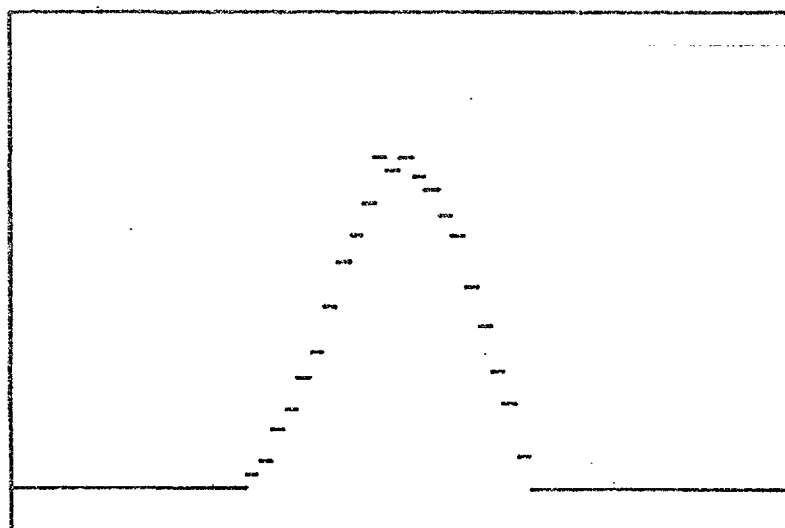


PHOTOGRAPH 3c

20 WIRE
PLANE



60 WIRE
PLANE



4 FOLD
HISTOGRAM

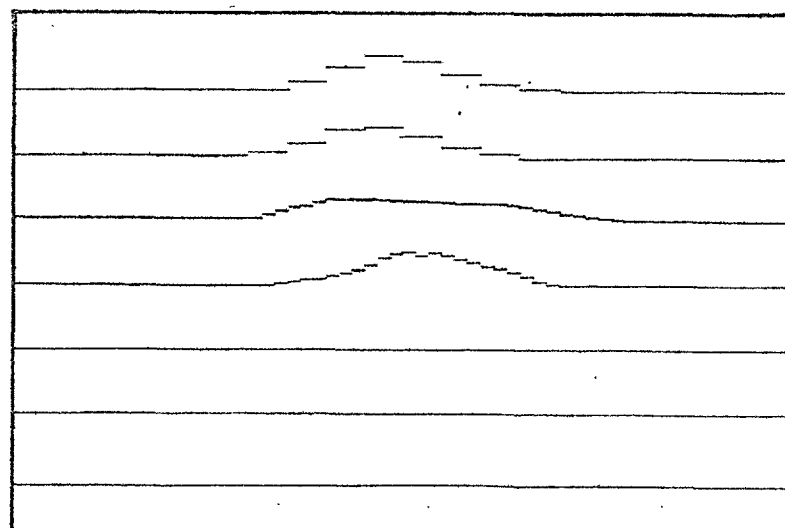


FIGURE 3E

C H A P T E R 4

DATA ANALYSIS

In this chapter, we shall outline the processes which were responsible for extracting the information contained in the photographs, processing it, and writing a summary of the data on magnetic tape; this output tape was known as a Data Summary Tape or D.S.T. The diagram overleaf shows the flow of the data during analysis, together with the various programs which were used in the chain.

4.1 Scanning

As no kinematical fits were applied for the identification of the antineutron, the scanning and, in particular, the choice of event types were extremely important in this experiment. Furthermore, the estimates of the total cross-sections came directly from the scanning information. Following "pre-scanning" of a sample of film, a set of criteria were drawn up which were to be used in event selection and classification; a summary of the scanning criteria used is given at the end of this chapter. For each photograph,

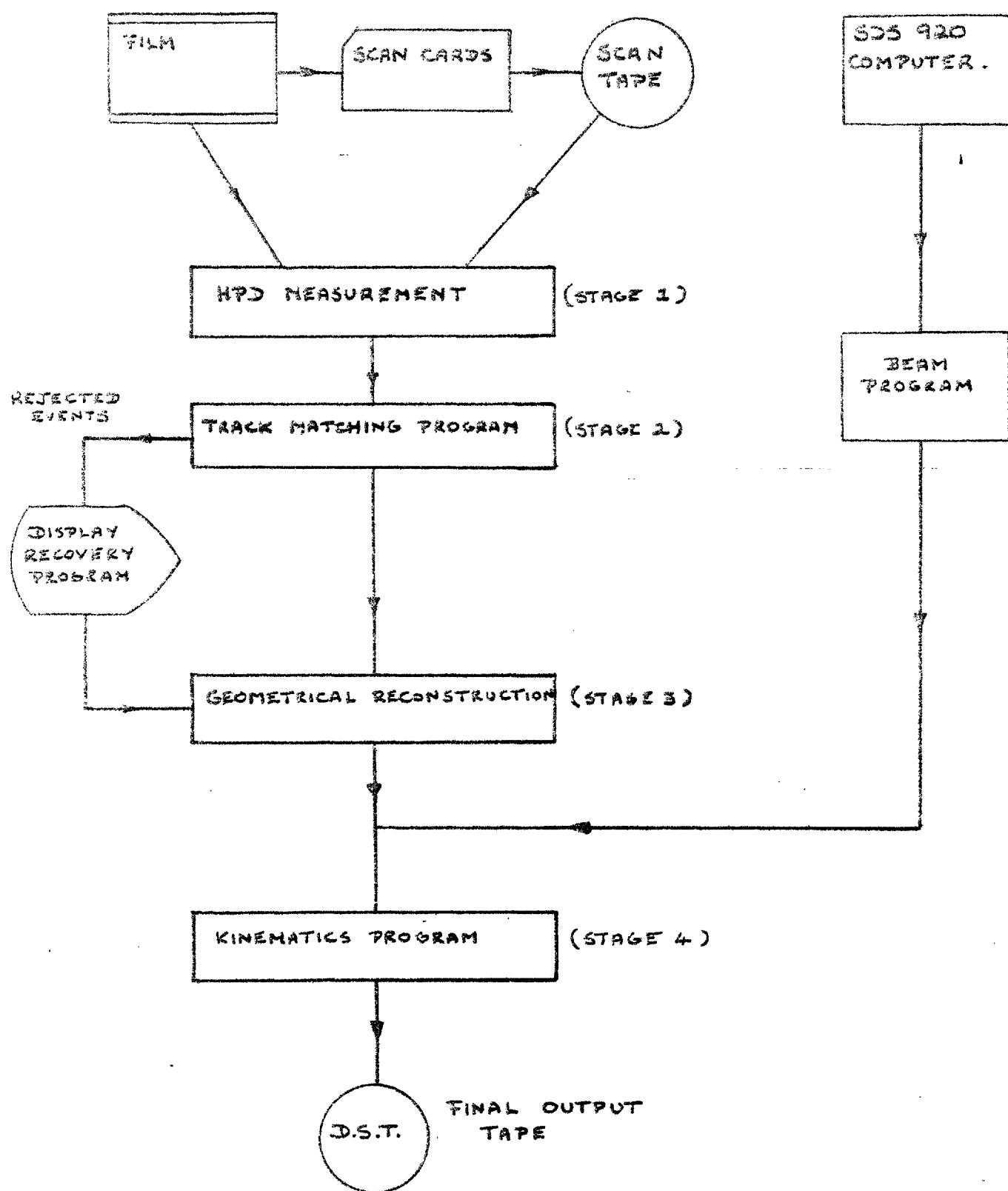


FIGURE 4A

DATA ANALYSIS

where an event was identified, a scan card was produced giving the type and position of the antineutron star, as well as ancillary information such as experiment and event numbers. The scan cards were later used to produce a scan tape where one record corresponded to an event. In view of the comparatively small number of photographs produced ($\sim 80,000$), it proved possible to scan all the film twice, thus enabling one to make an accurate estimate of the scanning efficiency.

In order to provide some sort of check on identification of stars, the opening angle of the cone containing the charged secondaries was plotted for the $\bar{n}$ events. A similar process was also performed for the antiproton stars used for calibration and, in both cases, the mean opening angle was $\sim 50^\circ$. A similar exercise performed for γ rays gave an opening angle of $\sim 15^\circ$.

4.2 H.P.D. Measurement and Track Matching.

The digitising of the film was made using a "flying spot" device (18) (C.E.R.N. H.P.D.I), connected on-line to a CDC 6600 computer. The Flying Spot Digitiser operates by using a pencil light beam which is split and used to scan simultaneously both the film and a precision grating. Signals from a photomultiplier tube placed behind the grating are fed into a counter whose contents represent the distance of the spot from the start of the scan. The resolution was determined by the separation of the grating signals and the latter, known as an H.P.D. count, corresponded to about 2.5 microns. A second photo-

multiplier situated behind the film gave a signal each time a spark (or other dark point) was encountered by the spot and, by noting the contents of the counter at that instant, the coordinate of the spark could be found. Facilities in the device allowed for a variety of scan modes, although the normal mode was in a raster pattern, back and forth across the film. Whilst undergoing a scan, the film was held in place on a "stage" and the whole device controlled by the monitoring program. The frames requiring measurement were found from the scan tape by the Stage I monitoring program which subsequently found and identified the fiducial marks, decoded the data box information and gave a coordinate for the centre of each spark found. A spark required at least three digitisings in a chamber gap and, in this way, dust and background marks on the film were filtered out and not recorded on the output. The data for an event were then written on magnetic tape. The units used at this stage of the analysis were H.P.D. counts, where one count corresponded to about 2.5 microns.

The H.P.D. output tape was then used as input to the track matching (Stage 2) program. After initialising variables, the Stage 2 program looked for the first fiducial and, if this was not present in the data, it deduced the position from the 2nd and 3rd fiducials. Control then passed to the track following routines where sparks were associated into tracks, this being performed in each view separately. The track following process was performed backwards beginning at the last gap. A track was initialised whenever a set

of four sparks was found and the distance between any two consecutive sparks was not greater than two gaps.

Curves were then fitted to the initialised tracks and these predicted values used to add other sparks to the track. On reaching the first gap, track continuity checks were applied and any tracks, apart from beam tracks, which could not be associated with the vertex given in the scan data, were rejected. Once the track following procedure had been completed in each view, the final process, in which the tracks in the two views were paired together (Track Matching), was performed. For all possible track pairs, four tests were applied.

- a) A comparison of the curvatures of the tracks in each view.
- b) The correspondence of missing sparks in each view.
- c) Length of track test.
- d) Reality test; the matched pair was reconstructed approximately in three dimensions and the vertical (Z) coordinates checked to be within the chamber limits.

The data for the event were then recorded on an output result tape. In the case where events had insufficient fiducials, too few tracks in one view, or ambiguous track-matching, the event was rejected and an error code set giving the reason for reject. For such events, a reject tape was provided on which was recorded the raw input data (spark information) for the event. This allowed one to examine the reject events for possible biases and to recover a fraction of them by means of an interactive recovery program.

The overall efficiency (before recovery) of the Stage 2 program proved to be about 80%.

4.3 Interactive Recovery Program

The recovery program was specially written for this experiment and operated on a CDC 3200 machine coupled to an interactive display. The basic purpose was to study the sort of events that were rejected and, where possible, use the intervention of the operator to recover the event. Figure 4B shows the sequence of operation which we shall now describe.

a) Both views are displayed showing the position of the copper plate and the event type. The operator then uses the light pen to select the first view which is then displayed showing the copper plate containing the star together with the adjacent chamber regions.

b) The operator looks for tracks and, using the light pen, selects two sparks in each track. The program fits a line through the sparks and extrapolates to the copper plate. A maximum of 12 lines per view can be initialised in this way.

c) The program takes the lines found as above and searches for further sparks which can be incorporated in the tracks. This is performed in a parallel manner for each gap, assigning a spark to the nearest track. By this method one helps to avoid the misplacing of sparks in the region of the apex where the tracks are very close

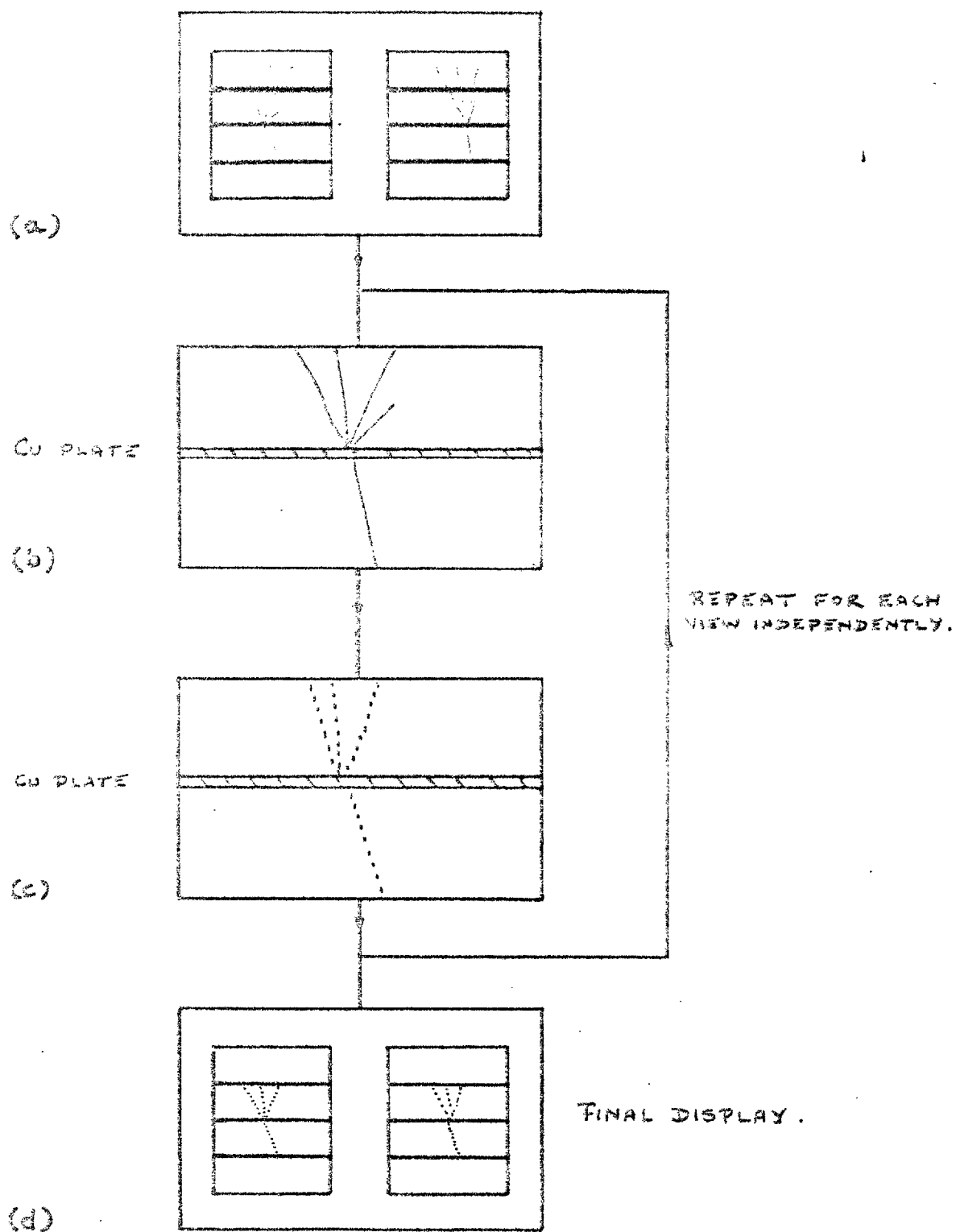


FIGURE 4B STAGES IN DISPLAY RECOVERY PROGRAM

together. The program then finds the apex and any tracks not originating from this point are rejected.

d). After completing operations (b) and (c) for each view, the final stage is to perform a 'track match' similar to that in "Stage 2"; the final match being displayed in both views.

Facilities in the program allowed one to find additional sparks and tracks, resolve track-match ambiguities and correct errors in the scanning information. An output tape of recovered events was written in the same format as the Stage 2 result tape.

Table 4g at the end of this chapter shows that about 90% of rejects were recovered by this program and the remaining 10% fell into the following categories:

- 1) Operator drop before the track-match operation.
- 2) Error in scanning.
- 3) Less than two matched tracks.
- 4) Less than two tracks in one view.
- 5) Two apices in one view.

Categories (2) and (3) accounted for most of the failures.

4.4 Geometrical Reconstruction.

The topology of the 'star' events was such that it was decided to write a special geometry program rather than modify the existing "THRESH"⁽¹⁹⁾ program which contained many features not required by this experiment. The basic capability of the program was to use the paired tracks given by Stage 2 to reconstruct the position of the vertex. In the interest of high precision, the vertex determination was performed in three dimensions where the tracks were straight lines. The coordinate system used for the real space coordinates in the program is shown in Figure 4C. The system is right-handed, with the origin at the centre of the fiducial plane of the spark chambers. The X coordinate is in the theoretical beam direction and the Y coordinate perpendicular to this, in the fiducial plane. We shall give now a brief outline of the program's operation:

(a) The data for an event were read from the input tape and, following fiducial checks, the transformation coefficients were calculated. These are given below and relate HPD coordinates to X and Y coordinates in the fiducial plane.

$$\begin{bmatrix} X_{sp} \\ Y_{sp} \end{bmatrix} = \begin{bmatrix} CX(1) & CX(2) & CX(3) \\ CY(1) & CY(2) & CY(3) \end{bmatrix} \begin{bmatrix} 1 \\ X_{LC} \\ Y_{LC} \end{bmatrix}$$

Fiducial Plane

H.P.D. least counts

The coefficients were calculated using the HPD measured positions of the fiducials and the known real space positions and they corrected for linear film stretching in X and Y and rotations in the XY plane. Once the transformation matrix was known, it was used to convert

the track points to real coordinates in the fiducial plane.

(b) Corrections for the optical distortions were applied to the fiducial plane points in each view separately and a selection of corresponding points was made. Corresponding points were those where the spark existed in both views. The distortions, introduced by imperfections in the optical system, required a correction of typically 0.25 mm. Where a point was present in one view only, a quadratic fit to the relevant track was used to estimate the position of the missing point. Light rays through the optical system were reconstructed for each pair of corresponding points and the line equations solved exactly to give the Y and Z coordinates of the spark in real space. Figure 4D shows a light ray in the XZ plane together with one of the prisms and the various glass plates. To obtain the X coordinate of the spark, the approximate X values in the fiducial plane were used to determine the chamber gap number and the known real space position of the gap used as the coordinate. It was necessary to use this method of finding the X values, since the distance between the centres of two adjacent gaps was a function of Y when viewed in the fiducial plane. At the same time, a correction for electric drift (Figure 4E) was made by alternately adding and subtracting 1 mm to the X values. The three-dimensional points for each track were finally fitted with a straight line, smoothing being applied to the fits where necessary.

(c) The position of the vertex was determined by considering a search region in X extending 3 cm on each side of the relevant copper

OPTICAL CHAMBER COORDINATE SYSTEM

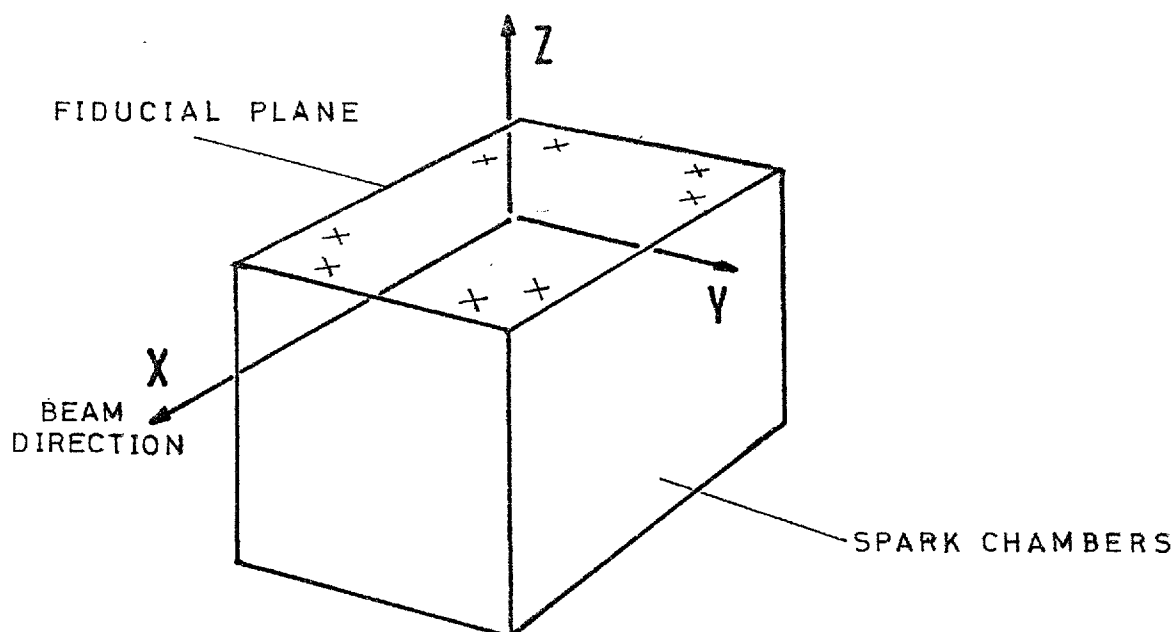


FIGURE 4C

LIGHT RAY RECONSTRUCTION

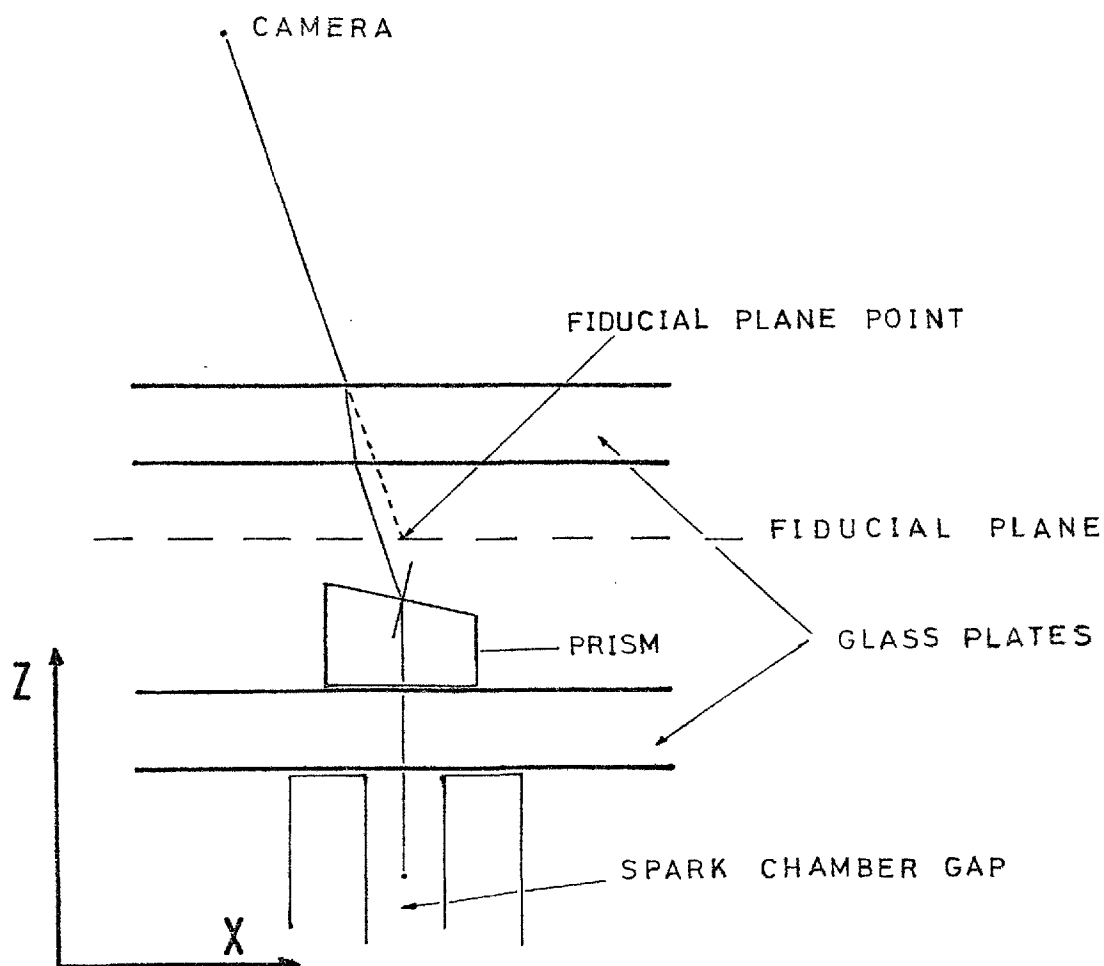
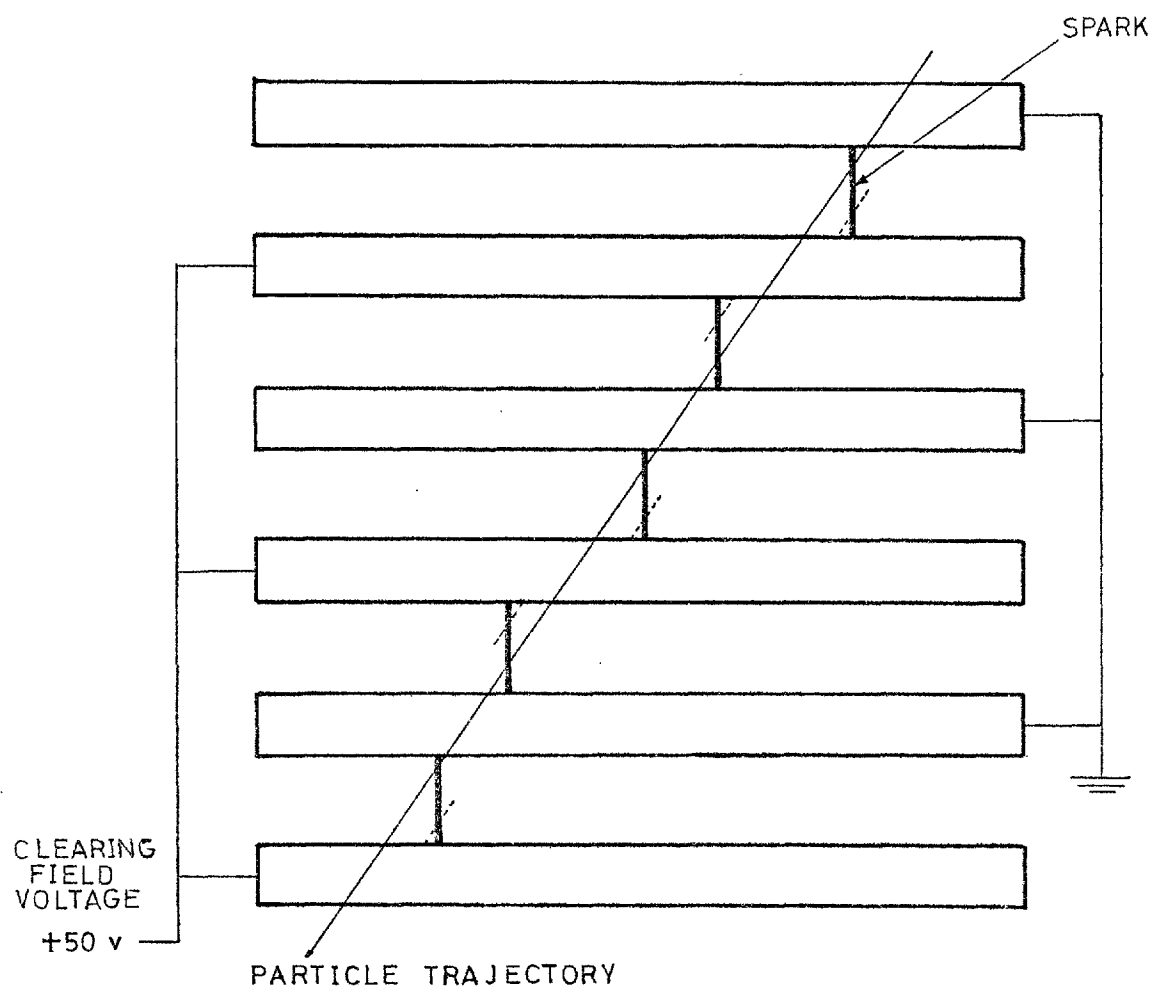


FIGURE 4D

ELECTRIC DRIFT

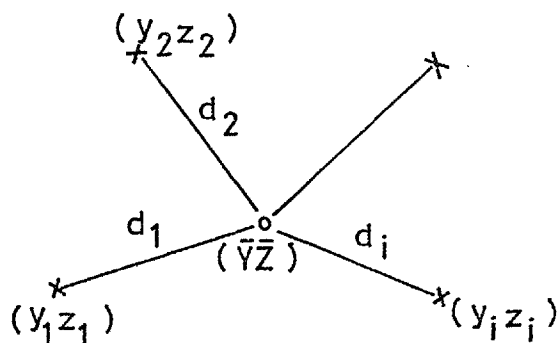


----- IONISATION AFTER TIME t

t = TIME DELAY BETWEEN PASSAGE OF PARTICLE
AND APPLICATION OF H.T. PULSE

FIGURE 4E

plate. The intersection points of the tracks in the YZ plane at the start of the search area were found, and the centre of the set of points found by least squares.



$$\bar{Y} = \frac{\sum_{i=1}^m w_i y_i}{\sum_{i=1}^m w_i}$$

where $w_i = 1/\sigma_i^2$, the weight of the i^{th} track in the xy plane

The weight for each track was calculated from the R.M.S. deviation of the data about the fitted line.

Similar relations to those above apply in the xz plane.

The uncertainty in the position of the point $(\bar{Y}, \bar{Z})$ is given by:

$$D = \left[\frac{\sum_{i=1}^m w_i (y_i - \bar{Y})^2}{m(m-1) \sum_{i=1}^m w_i} + \frac{\sum_{i=1}^m w_i (z_i - \bar{Z})^2}{m(m-1) \sum_{i=1}^m w_i} \right]^{1/2}$$

This process was repeated for a complete set of closely spaced planes throughout the search region and the minimum value of D found. The (X,Y,Z) coordinates corresponding to this minima were taken as the antineutron interaction point and the value of D used as a measure of the size of the vertex. In cases

where the vertex size exceeded 5mm, the track with the least weight was rejected and the vertex search repeated. A maximum of two tracks could be rejected in this way. For about 92% of events, a vertex was successfully found. The distribution of the vertex size, D , is shown in Figure 4f. The remaining 8% of events which failed the "Stage 3" program were categorized into the three classes given below:

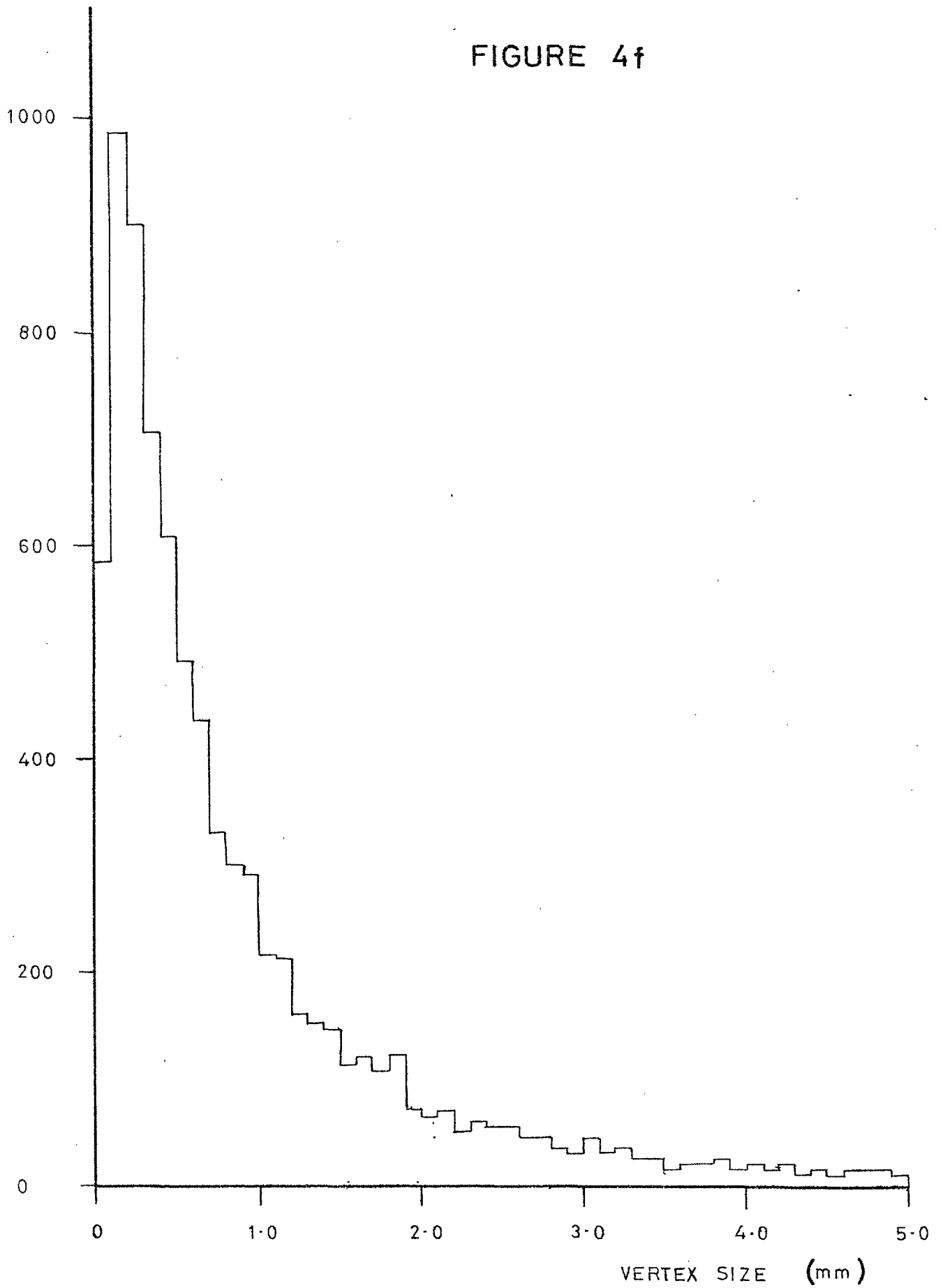
- a) The vertex was too large even after the rejection of two tracks.
- b) Less than two tracks were available for vertex reconstruction.
- c) Any other cases.

The rejects of class (a) accounted for $\sim 1.6\%$ and class (b) for $\sim 6.4\%$. Table 4h gives the total number of photographs taken at each energy and table 4i gives the number of events passing each stage of the analysis.

4.5 Beam Data and Kinematics

The beam information from the proportional wire chambers was recorded on magnetic tape by the S.D.S. 920 computer. This tape was subsequently passed through a program which unpacked the S.D.S. records and, from the known positions of the chambers, determined the trajectory of the incident antiproton. The positions of the proportional chambers were obtained from measurements taken with a theodolite and were known to a precision of about 1 mm. The analysis program demanded one and only one

FIGURE 4f



triggered wire in each plane to give a unique track and, with no chamber redundancy, the overall efficiency of the system was limited to about 45%. For events where a unique trajectory was found, an output record was written on magnetic tape which gave the Y and Z coordinates at the target together with the dip and azimuth angles.

The final stage of the analysis ("Stage 4") involved merging the geometrical reconstruction output with the beam data in order to calculate the scattering angle (θ) and momentum transfer, t . Where no "Charpak" information existed for a particular event, the mean beam parameters, as given by the "Charpak" chambers, were used in the calculation of the scattering angle. The momentum transfer, t , was calculated using the relation $t = -p^2 \theta^2$, this approximation being correct to $< 0.1\%$ for $\theta < 100$ mrad. The output from the program took the form of the 'Data Summary Tape' where one event corresponded to one logical record. This data record contained all the scan information, the geometrical reconstruction data, the beam data and the final values of θ and t . All such ancillary data was included so that various checks and tests could be applied in forming the final distributions -- these tests were performed using the statistical analysis program, SUMX.⁽²⁰⁾

D I S P L A Y W O R K				
	# E V E N T S			
	1st meas. 8/3 - 30/4		2nd meas. 1/5 - 29/5	
	analysed	recovered	analysed	recovered
	5 GeV/c 7.76 GeV/c	973 4 139	939 3 872	4 139 3 991
		5 112 4 811	4 139 3 991	
5 GeV/c BT 7.76 GeV/c BT	654 386	385 226		
	1 040	611		

TABLE 4g

SUMMARY OF DATA							
MOMENTUM (GeV/c)	Category*)	# PICTURES					
		Normal Run		BT		Calibration	
		taken	scanned	taken	scanned	taken	scanned
5	1	1 573	1 561	550	474		
	3	7 377	7 377	300	300	2 310	2 305
		8 950	8 938	850	774	2 310	2 305
	2	118	118				
	4	100	100				
		218	218				
7.76	5	20 261	20 257	1 289	1 289	1 346	1 346
	7	31 385	31 352	2 912	2 640	1 540	1 540
		51 646	51 609	4 201	3 929	2 886	2 886
	6	599	599				
	8	300	300				
		899	899				

*) Category:

Target Full

Target Empty

1

2

3

4

5

6

7

← sweeping magnet →

8

TABLE 4h

DIFFERENT STAGES OF THE ANALYSIS OF EXP. 20

Category	# EVENTS											
	Type 1→6		Type 1→4+6	Type 1→6						Type 1→4 + 6 (2)		
	Total	Considered (1)		Measured	ST 2		ST 3		DST ⁽²⁾	CHARPACK inf.	Final SUMX	Final Plot
					in	out	in	out				
1 3	418	418	392	415		275						
	3 864	3 428	3 203	3 845		3 008	2 985	2 652	2 896	2 173	2 078	2 028
2 4	4 282	3 846	3 595	4 260		3 283	2 985	2 652	2 896	2 173	2 078	2 028
	29	29	23	29		18						
	48	48	44	48		36						
5 7	77	77	67	77		54						
	9 347	8 227	7 253	9 277	9 113	7 171	7 012	6 139	7 722	3 685	2 960	2 671
	9 715	8 876	8 610	9 690	9 645	7 597	7 579	6 970	8 741	3 446	2 324	2 158
6 8	19 062	17 103	15 863	18 967	18 758	14 768	14 591	13 109	16 463	7 131	5 284	4 829
	255	142	127	255	251	186	185	158				
	105	69	69	105	104	83	81	69				
	360	211	196	360	355	269	266	227				

TABLE 4i

(1) Events of rolls without experimental bias

(2) As (1) & recovered events included

SCANNING CRITERIA

Definitions:

- Star - A neutral interaction in a copper plate.
 At least 3 prongs emerging from a common apex.
- Prong - A track of at least 4 visible sparks.
- Secondary
Interaction - A neutral interaction of less than 3 prongs.

Event type

Description

- | | |
|---|---|
| 1 | One and only one star present in the fiducial volume of the chambers. All prongs are straight and there are no background tracks. |
| 2 | One star present subject to:
a) Prongs may have slight scatters.
b) There may be an uncorrelated track present. |
| 3 | One star present, together with a secondary interaction downstream from the star. |
| 4 | More than one star present subject to:
a) The stars must be within the fiducial volume in both views.
b) The stars must not be in the same plate. |
| 5 | A star present in which a backward prong simulates a beam track. This prong must be straight and emerge from the front of the spark chambers. |
| 6 | Other events where the following conditions may apply:
a) A secondary interaction occurs in the same plate, or a plate upstream, to that containing the star.
b) The prongs of the star do not define a clear apex. |

EXPERIMENTAL RESULTS

5.1 Instrumental Resolution

The prime aim of this experiment was to study the form of the differential cross-section in the small momentum transfer region -- $0 < |t| < 0.02 \text{ (GEV/C)}^2$. With the aim in mind therefore, it was necessary to measure the laboratory scattering angle to a precision which allowed binning considerably finer than the above $|t|$ interval.

Assuming all particles in the reaction have the same mass, the momentum transfer, t , is given by

$$t = -2p^2 (1 - \cos \theta)$$

Furthermore, in the range of values of θ considered in this experiment, we can approximate this to

$$t(p, \theta) \approx -p^2 \theta^2$$

Expanding this expression up to second order terms:

$$\begin{aligned} t(p + \Delta p, \theta + \Delta \theta) - t(p, \theta) &= \Delta t \\ &= \left\{ \frac{\partial t}{\partial p} \right\} \Delta p + \left\{ \frac{\partial t}{\partial \theta} \right\} \Delta \theta + \frac{1}{2} \left[\left\{ \frac{\partial^2 t}{\partial p^2} \right\} \Delta p^2 + 2\Delta p \Delta \theta \left\{ \frac{\partial^2 t}{\partial p \partial \theta} \right\} \right. \\ &\quad \left. + \left\{ \frac{\partial^2 t}{\partial \theta^2} \right\} \Delta \theta^2 \right] \end{aligned}$$

Inserting the differentials:

$$\Delta t = \{2p\theta^2\Delta p + 2p^2\theta\Delta\theta\} + \frac{1}{2}\{2\theta^2(\Delta p)^2 + 8p\theta\Delta p\Delta\theta + 2p^2(\Delta\theta)^2\}$$

Neglecting terms involving Δp , since $\frac{\Delta p}{p} \ll \frac{\Delta\theta}{\theta}$ we find:

$$\Delta t = 2p^2\theta\Delta\theta + p^2(\Delta\theta)^2$$

This expression was used to estimate the binning that was used in the plots of the differential cross-section versus t . The value of $\Delta\theta$ was estimated by considering the following contributory sources:

a) Incident beam trajectory.

The measurement of the antiproton beam was limited by the spacing of the proportional chamber wires and by the precision with which the beam coordinate system and the optical chamber system could be aligned. The alignment of the two reference systems was effected by reconstructing beam tracks in both frames and by comparing the track parameters at a reference plane in the spark chambers.

b) Antineutron Vertex.

The uncertainty in $\Delta\theta$ arising from the size of the reconstructed antineutron vertex was estimated from the plot shown in Figure 4f. The magnitude of the contribution varied slightly for each of the copper plates, but was typically 0.2 mrad and thus gave rise to only a small part of the overall $\Delta\theta$.

c) Finite length of the hydrogen target.

For all events, the antiproton interaction point was taken to be in the YZ plane situated at the middle of the hydrogen target.

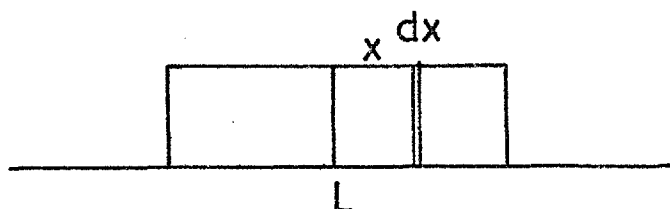
This assumption gives rise to a contribution to $\Delta\theta$ which was estimated as follows:

For scattering angle, θ ,

$$\Delta\theta \approx \theta \frac{\Delta L}{d}$$

where d = target centre - copper plate distance and

ΔL is the standard deviation of a rectangular distribution of width L



$$(\Delta L)^2 = \frac{1}{L} \int_{-L/2}^{+L/2} x^2 dx = \frac{L^2}{12}$$

$$\Delta L = L/\sqrt{12}$$

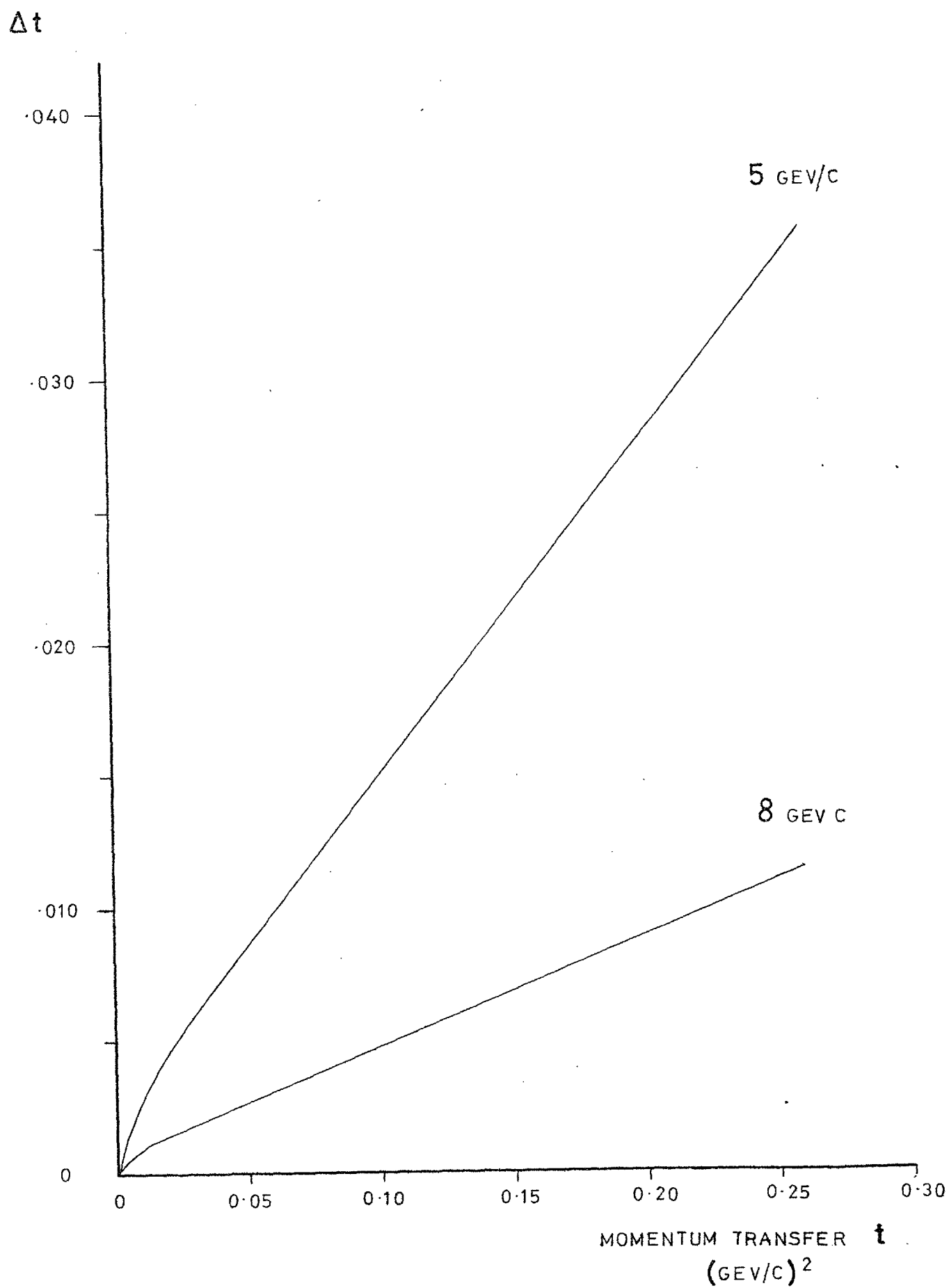
$$\Delta\theta \approx \frac{\theta L}{d \sqrt{12}}$$

This component of $\Delta\theta$ is a function of θ whereas (a) and (b) are independent of scattering angle.

In Figure 5a, the uncertainty in the momentum transfer, Δt , is plotted as a function of t for the 2 momenta concerned. In Table 5b, the various components contributing to $\Delta\theta$ are given for each set of data taken.

The momenta given in Table 5b are the nominal beam momentum in the case of the 5.0 GEV/C data, whereas at 7.76 GEV/C, a measurement performed by another experimental team operating in the same beam line was taken to be the value.

FIGURE 5a



ANGULAR RESOLUTION

	5.0 GEV/C	7.76 GEV/C	
		Without Sweeping Magnet	With Sweeping Magnet
$\Delta\theta$ COMPONENTS (mrad)			
$\bar{P}$ Trajectory Measurement	2.26	0.79	0.51
$\bar{N}$ Vertex size	0.60	0.24	0.15
Length of Target	0.06.0	0.03.0	0.02.0

TABLE 5b

5.2 Cross-Section Normalisation

The normalisation of the differential cross-section data and, consequently, the integrated cross-section values were estimated from the measurements of the incident antiproton flux and the corresponding number of ($\bar{n}n$) final states produced.

In general, we have:

$$\sigma_{\text{CEX}} = \frac{\text{Number of } (\bar{n}n) \text{ states produced}}{(\text{Incident flux of antiprotons}) \times (\text{No. of protons per unit area in target})}$$

The liquid hydrogen target used in the experiment was 41.0 cm in length and, taking the density of liquid hydrogen as 0.07 gm/cc, we find the number of target protons per unit area to be 1.765×10^{24} .

The antiproton flux was taken from the readings of the scalars made at the end of each roll of data and consistency checks were made when estimating the overall values used for normalisation.

The number of ($\bar{n}n$) states produced was related to the number of antineutron 'stars' seen in the copper plates by means of detection efficiency factors. These factors arise since only a fraction of the ($\bar{n}n$) final states give rise to antineutron 'stars'

$$\text{No. of } (\bar{n}n) \text{ produced} = \frac{\text{No. of 'stars'}}{E_1 E_2 E_3 \dots E_n}$$

where $E_1 \dots E_n$ represent the various correction factors which must be applied. These factors can be conveniently divided into two

categories, those independent of t and those dependent upon t .

We shall now consider the former category in more detail:

(a) Scanning Efficiency.

During the scanning of the film, genuine antineutron 'stars' can be overlooked and this gives rise to a loss of events. It is reasonable to assume that this loss is independent of momentum transfer and the correction factor was estimated by scanning all the data in two independent runs and comparing the number of events found in each case. The figures found are given in Table 5c and the overall scanning efficiency proved to be very high -- about 97%.

(b) Trigger Electronics Losses.

In normal circumstances, charge exchange events, giving rise to a neutral final state, give no signal in the veto counters around the target. However, uncorrelated beam particles and the presence of noise pulses in the photomultiplier tubes can give rise to signals in the anticoincidence system which kill the event. These losses, known as the "accidentals", reduced the effective antiproton flux. During data taking, the effect was monitored by delaying the veto counters by ~ 100 msec and recombining with the final trigger (Figure 2f). The "accidental" rate was scaled and recorded at the end of each roll of film.

(c) $\bar{p}$ and $\bar{n}$ absorption in the Hydrogen Target.

Absorption of antiprotons and antineutrons in the liquid

hydrogen contained in the target constituted a loss of events. The effect was estimated using values of the $\bar{p}p$ total cross-section and the correction factors are given in Table 5c.

(d) Detection Efficiency of the Copper Plates.

The efficiency of the copper plates for converting an antineutron into an antineutron 'star' was obtained using antiproton interactions. The calibration data were scanned with the same criteria as those used in the normal data and it was assumed that the total inelastic cross-sections of $\bar{p}$ and $\bar{n}$ on copper nuclei were equal. 'Stars' resulting from neutron interactions (from the backward peak of $\bar{p}p - \bar{n}n$) could not be distinguished in the scanning but this was not considered a serious source of background since double baryon exchange would be involved. Moreover, the slow antineutron associated with this process would annihilate in the target or veto counters suppressing such triggers with high efficiency.

(e) Antineutron absorption in the Veto counters.

The calibration data were also used to give a correction for $\bar{n}$ absorption in both the lead plates of the 'F' counters and in the scintillator of the 'F' counters. The values of the correction obtained are given in Table 5c.

CORRECTION FACTORS INDEPENDENT OF t

	5.0 GEV/C.	7.76 GEV/C.	
		Without Sweeping Magnet.	With Sweeping Magnet
LOSSES IN TRIGGER ELECTRONICS	0.97 ± 0.01	0.95 ± 0.01	0.93 ± 0.01
SCANNING EFFICIENCY	0.983 ± 0.01	0.967 ± 0.01	0.961 ± 0.01
DETECTION EFFICIENCY OF ONE 2 cm COPPER PLATE	0.124 ± 0.006	0.115 ± 0.006	0.115 ± 0.006
π ABSORPTION IN LEAD PLATES OF VETO COUNTER	0.929 ± 0.007	0.885 ± 0.011	0.885 ± 0.011
π ABSORPTION IN SCINTILLATOR OF VETO COUNTER	0.966 ± 0.006	0.972 ± 0.008	0.972 ± 0.008
π AND $\bar{\pi}$ ABSORPTION IN HYDROGEN TARGET	0.88 ± 0.01	0.90 ± 0.01	0.90 ± 0.01
EVENTS PRODUCED ON EMPTY TARGET	0.10 ± 0.02	0.12 ± 0.02	0.15 ± 0.03

TABLE 5C

5.3 "t" Dependent Corrections.

Two correction factors, dependent upon the momentum transfer, were applied to the data.

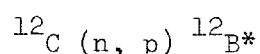
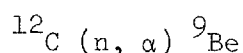
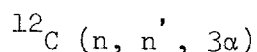
(a) Anticoincidence Correction.

The reaction $\bar{p}p - \bar{n}n$ produces a forward-going high momentum antineutron, together with a slow neutron, emerging at about 85° to the beam direction. The neutron passes through the veto counter assembly (Figure 2d) and, as a result of interactions in the counter, a fraction of genuine events are killed. The probability for detection depends strongly upon the neutron energy and hence the correction is a function of momentum transfer.

The "R" counters consisted of four layers of 1 cm thick scintillator interspersed with lead and copper plates and, in view of the wide range of possible reactions, it was necessary to make reasonable assumptions at the different neutron energies. The neutron detection efficiency curve that was used to correct the data is shown as curve A in Figure 5e. For neutron energies of 10 Mev and less, the only consideration was the detection of the neutron by means of neutron-proton scattering on the hydrogen in the scintillator. At these energies, the cross-section for such a process is large -- typically 1 barn. However, at the extreme low-energy limit, there was a cut-off introduced both by neutron absorption in the target and by the voltage settings on the veto counter photomultipliers. The setting of the anode voltages was made using a ^{60}Co source giving

a threshold of ~ 1.1 Mev for electrons corresponding to 3 - 3.5 Mev for protons.

At neutron energies of 10 Mev and above, interactions on the carbon nuclei ceased to be insignificant, the three important channels being:



The effect of neutron interactions in the copper and lead plates was difficult to estimate in view of the wide range of possible reactions. However, at low neutron energies, the plates were assumed to have a purely absorptive role since any charged secondaries would have an extremely small range in the copper and lead. Elastic scattering of neutrons on the heavy nuclei was not considered important since, being strongly forward peaked, it changed little the neutron energy.

The results of Weigand (21) and Kurz (22) (Figure 5d) were used to give the detection efficiency in the four layers of scintillator and a correction was applied to allow for the slightly different threshold in the Weigand experiment. The effect of the Pb and Cu plates was estimated by allowing simulated neutrons to interact according to the total reaction cross-sections (23) and assuming that where a neutron interacted, all secondaries were absorbed.

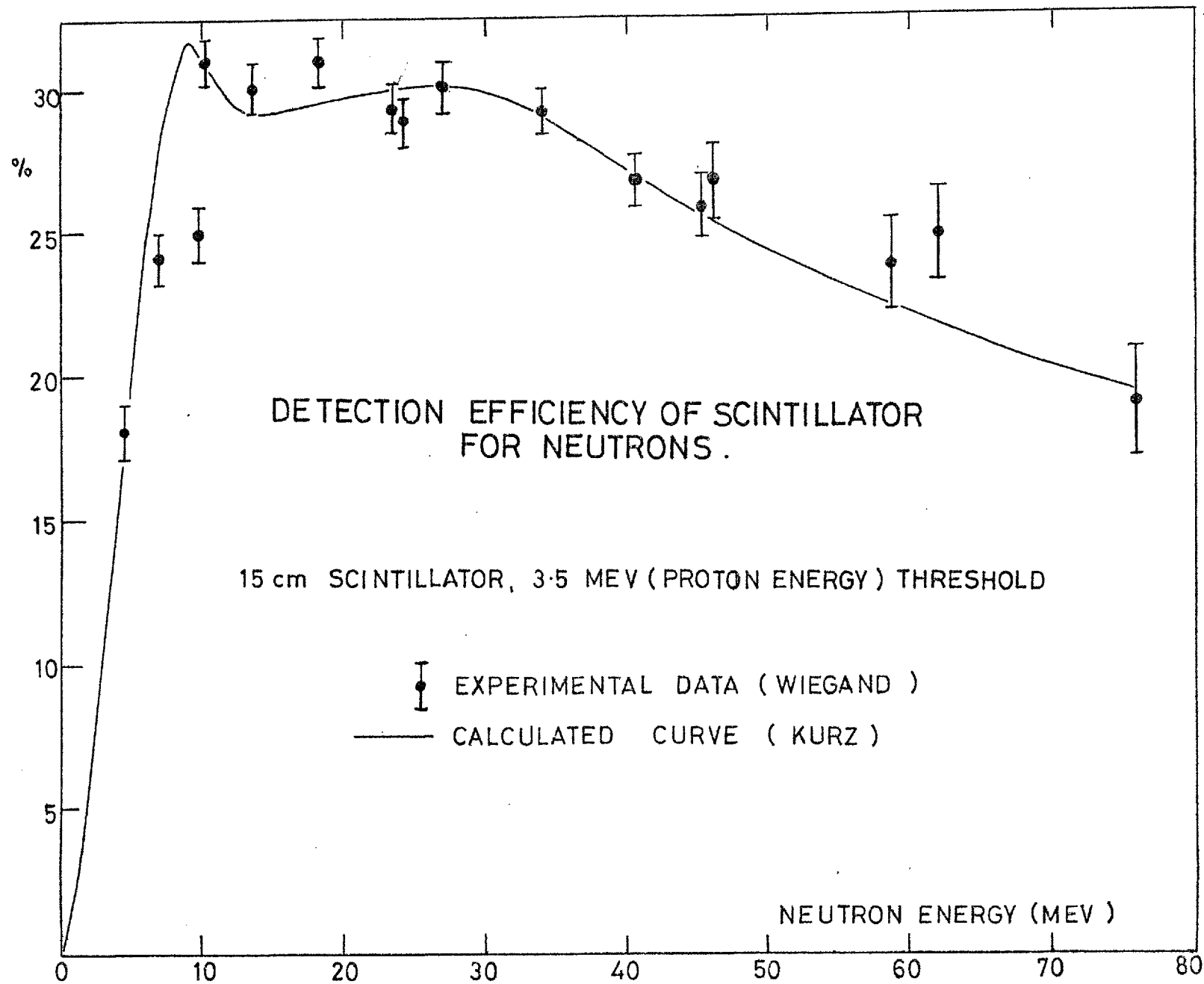
In order to provide a check on the validity of the above assumptions in the $[t]$ interval considered, a 2nd curve, B, (Figure 5è) was calculated which represented the high energy limit. The detection efficiency of the scintillator was the same as that used for curve A, but the Cu and Pb plates were no longer taken as being purely absorptive. It was assumed that the only type of process which gave rise to neutron detection was a "knock-on" where a proton with a high energy was ejected from the nucleus. The cross-section for such a process was taken as

$$\sigma = \frac{Z}{A} A^{2/3} \sigma_{np} \quad \text{where } \sigma_{np} = \text{np scattering cross-section.}$$

At low energies (less than ~ 40 Mev), the above expression exceeds the total reaction cross-section and therefore, in this region, the total reaction cross-section was used to estimate neutron detection. The approximation implied by the above formula is only valid for heavy nuclei at energies greater than ~ 200 Mev. However, it does give us some limit to the detection efficiency which is asymptotically correct at high neutron energies.

The error in the correction that was applied to the data was introduced mainly by the uncertainty in the veto counter thresholds, and was estimated to affect the data by less than 5%.

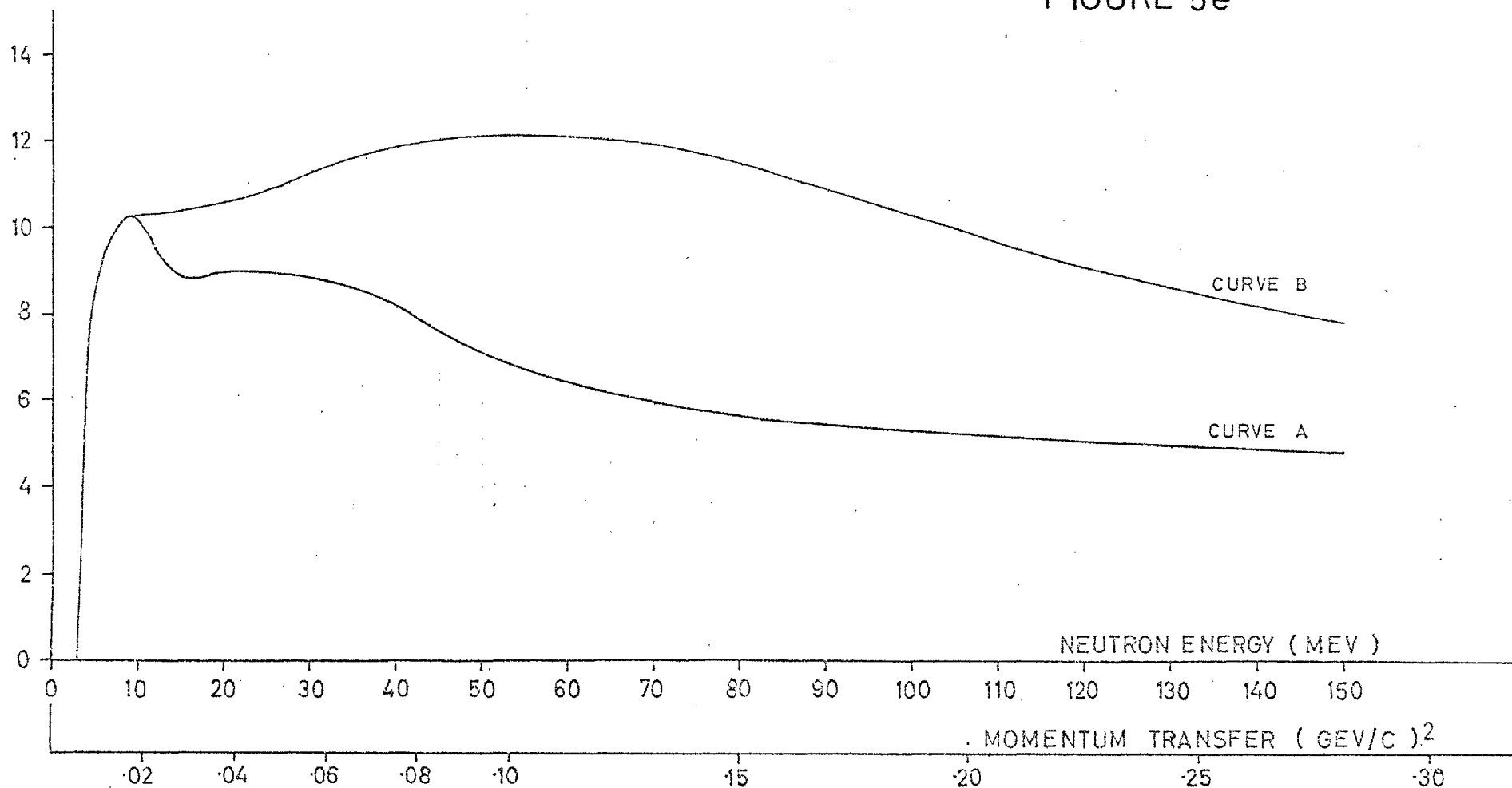
FIGURE 5d



DETECTION
EFFICIENCY (%)

NEUTRON DETECTION EFFICIENCY FOR 'R' COUNTER

FIGURE 5e



(b) Angular Acceptance.

The size of the copper plates positioned in the spark chambers, together with the presence of the sweeping magnet, gave rise to a limited angular acceptance for the apparatus and a correction was incorporated into the 't' distributions. The method employed was to use the data for each event to calculate a "weight" which represented the inverse of the detection probability.

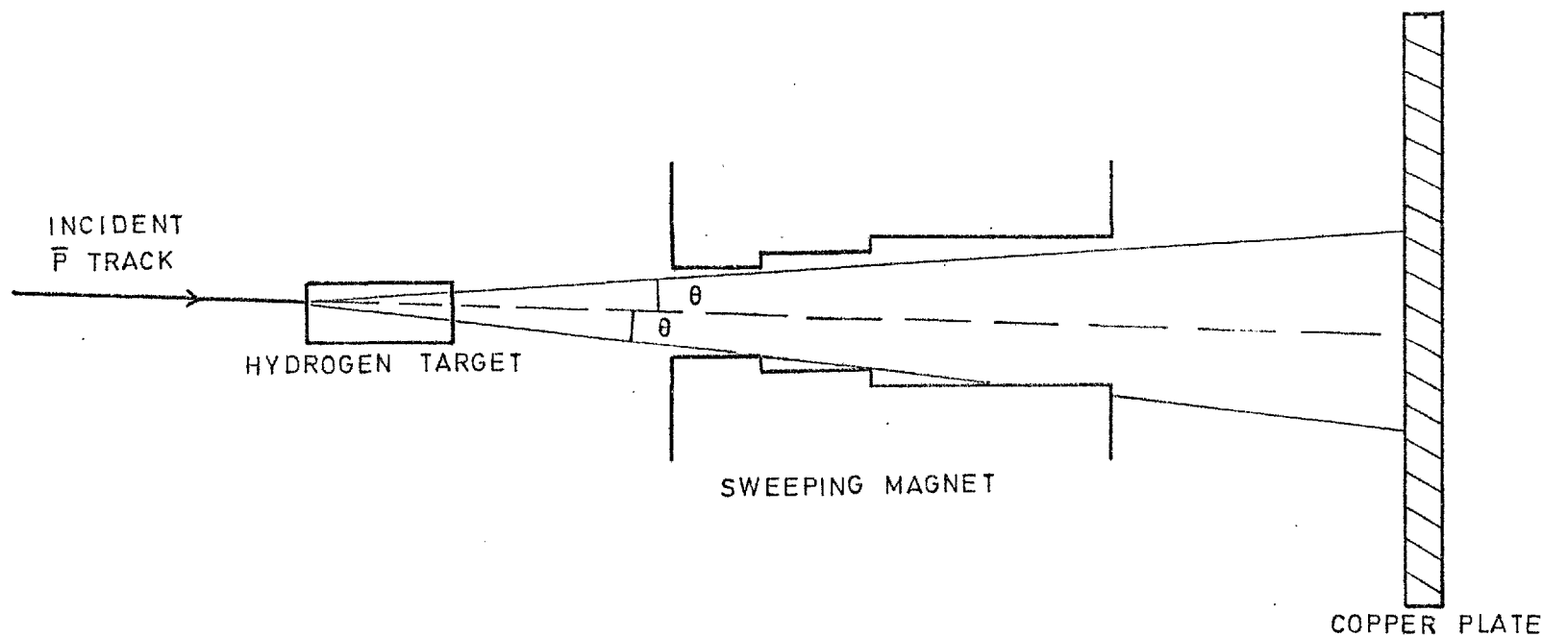
For each event, the antiproton track, as given by the proportional chambers, was projected as far as the copper plate containing the antineutron star (Figure 5f). A cone around this track was then generated corresponding to θ , the scattering angle for the event. Cuts, imposed by the iron of the sweeping magnet, were also projected on to the copper plate and the intersections of these cuts with the scattering circle were used to give the probability for detection of the event. Referring to the example in Figure 5f, the weight of the event is given by:

$$\text{Weight} = \left[\frac{1}{1 - \frac{\phi}{2\pi}} \right]$$

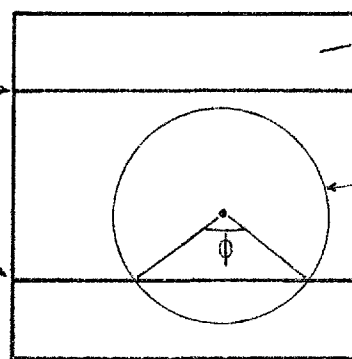
At larger scattering angles, the edges of the copper plate began to cut the circle and this also was included in calculating the weight factor.

The extent of the weighting varied with the different experimental runs, but was most pronounced for the 7.76 GEV/C with the sweeping magnet present. Here, event weights exceeded 1.0 at $|t|$ values greater than $0.01 (\text{GEV}/C)^2$, Figure 5g. In the case of the 5 GEV/C

GEOMETRICAL ACCEPTANCE



INNERMOST CUTS IMPOSED BY
MAGNET PROJECTED TO COPPER
PLATE.



COPPER PLATE

CIRCLE CORRESPONDING
TO SCATTERING ANGLE, θ .

END VIEW

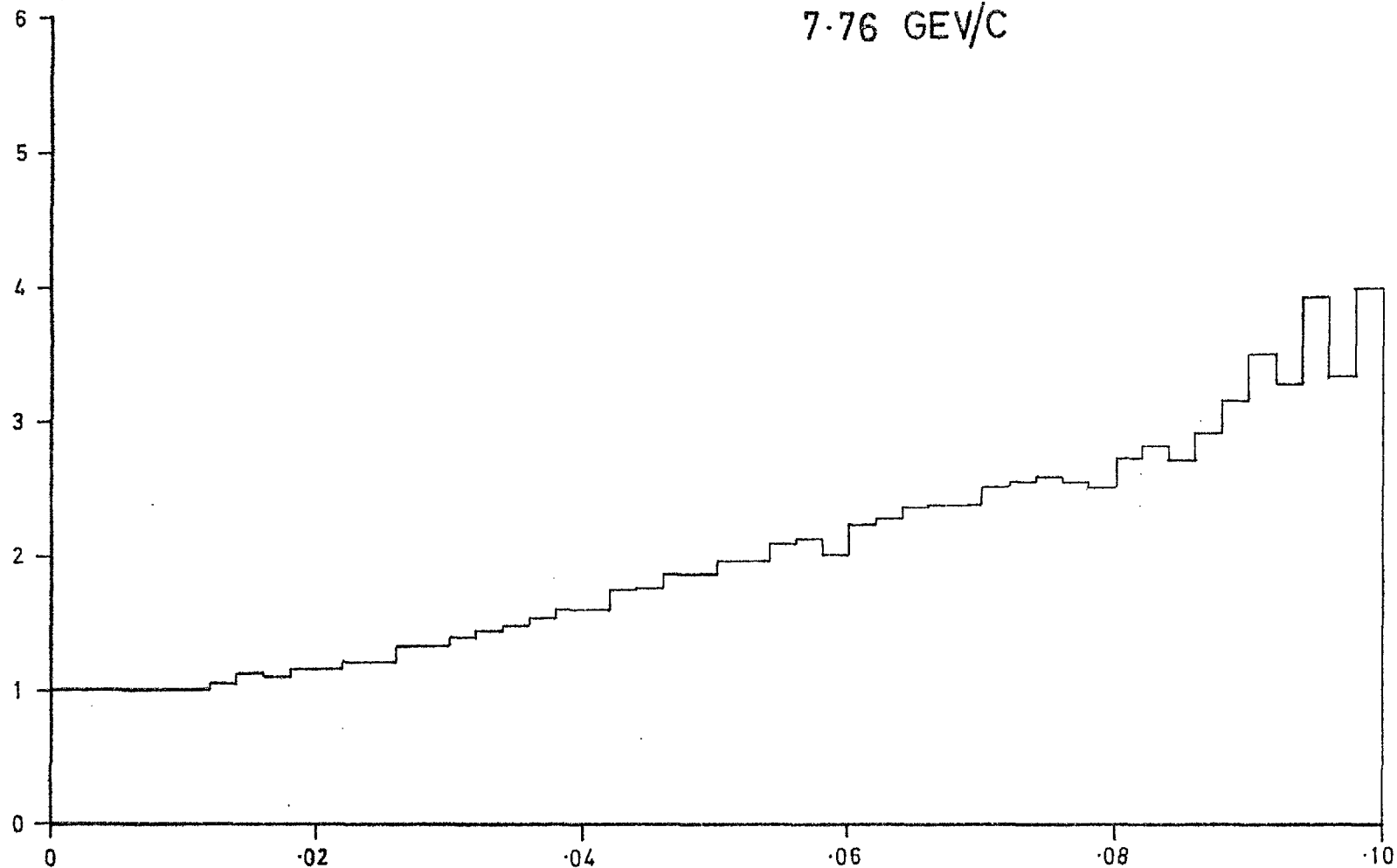
FIGURE 5f

FIGURE 5g

EVENT WEIGHTS AS A FUNCTION OF t

7.76 GEV/C

WEIGHT, $W(t)$



t , MOMENTUM TRANSFER
(GEV/C)²

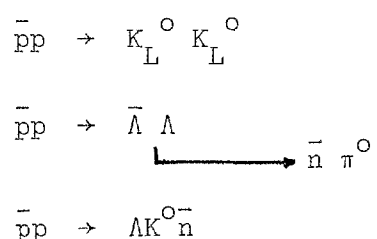
data where no sweeping magnet was used, the size of the copper plates did not limit the angular acceptance in the 't' range considered and all events in this distribution had a weight equal to unity.

5.4 Background Contamination

The two main types of background in this experiment were non-hydrogen events, produced by interactions in the walls of the target cell and contamination from other channels in which a neutral final state was produced. The first type was estimated from a number of rolls of data recorded with the target cell emptied of liquid hydrogen. Non-hydrogen events gave rise to a correction of about 12% (Table 5c).

The second form of background contamination involving other reaction channels fell into two principal categories:

a) Process where, either directly or by a subsequent neutral decay, a long-lived neutral particle was produced which was then detected by a nuclear interaction in the spark chambers. Examples of such processes are



Although no detailed data existed for such channels, rough cross-sections were known and the correction to the charge exchange normalisation was about 3% (Table 5h).

b) Processes in which charge exchange was accompanied by π^0 production.

$$\bar{p}p \rightarrow \bar{n}n + m\pi^0 \quad (m \geq 1)$$

Most events of the above type were vetoed by π^0 conversion in the 'F' counters which had an efficiency of about 97% (3).

The remaining correction factor amounted to about 2% (Table 5h and Reference (3)).

Background Channel	Correction Factor
$\bar{p}p \rightarrow \bar{\Lambda}\Lambda \rightarrow n\pi^0$	0.5%
$\bar{p}p \rightarrow K_L^0 K_L^0$	1.2%
$\bar{p}p \rightarrow \Lambda K^0 \bar{n}$	1.2%
$\bar{p}p \rightarrow \bar{n}n + m\pi^0$	2.0%

Table 5h

5.5 Event Selection

Table 4i summarizes the analysis of the photographs as far as the final differential cross-section distributions. The overall efficiency of the analysis programs was about 90% at both 5.0 and 7.76 GEV/C with most of the remaining 10% being rejected in the geometrical reconstruction stage as the "star" had too few tracks to give a unique vertex.

In selecting events from the Data Summary Tape (D.S.T.) for the final distributions, any rolls of data recorded with abnormal experimental conditions were rejected. Also rejected were events which either originated from outside the target cell or whose "star" lay outside the theoretical positions of the copper plates. Furthermore, in the interest of high resolution, only those events with proportional chamber information were accepted in the final plots. The efficiency of the proportional chambers, for a unique antiproton track, was 64% at 5.0 GEV/C and 44% at 7.76 GEV/C. The events without beam information showed approximately the same angular distribution and their exclusion was not considered to introduce any serious biases.

A further selection was made on the "type" of events used for the angular distribution. Events found in scanning were classified in the six "types" as listed in Chapter 4. An event was classed as "type 5" if one of the prongs in the star was produced in a backward direction and emerged from the front of the spark chambers. Such an event would be indistinguishable from a beam track inter-

action. The data taken at 7.76 GEV/C without sweeping magnet contained about 12% of events classified as Type 5 and the angular distribution of these events alone showed a very strong forward structure compared with the distribution given by the other event types. However, in the 7.76 GEV/C data with the sweeping magnet, Type 5 events contributed only 3% of the total and their distribution was consistent with that obtained from the other event types. This indicated that most of the Type 5 events in the run without sweeping magnet were background resulting from beam interactions. Such background can arise from the following sources:

- a) A charge exchange occurs and the $\bar{n}$ is not converted to a 'star' in the copper plate. However, in the resolving-time of the S^* counters, a beam particle interacts in a copper plate firing the S^* counters.
- b) The antineutron from charge exchange gives less than three prongs in a copper plate and, in the memory time of the spark chambers, a beam particle produces a 'star'.

The 5.0 GEV/C data (no sweeping magnet) showed a similar behaviour to the data at 7.76 GEV/C without sweeping magnet with about 12% of events as Type 5. In view of this background, it was decided to exclude all Type 5 events from the differential cross section distributions at both 5.0 and 7.76 GEV/C. For the normalisation estimates, the figure of 3% Type 5 events, obtained in the sweeping magnet run, was used in the other data categories.

5.6 Differential Cross-Sections.

The differential cross-section data at 5.0 GEV/C and 7.76 GEV/C are presented in Table 5i and plotted in Figures 5j and 5k. Also shown for comparison in Figure 5k are the data ⁽²⁾ for pn-np at 8 GEV/C due to Engler et al. The error bars indicated on the plots are statistical only.

The data at 7.76 GEV/C were a superposition of two sets of data; those taken with the sweeping magnet and those taken without. The angular distributions of the two sets was essentially the same except for a difference in normalisation which is considered below. It was useful to make the two separate runs at 7.76 GEV/C for two reasons:

- a) In the sweeping magnet run, the $|t| = 0$ region did not correspond to the beam direction and thus events in this region must be produced by a neutral interaction.
- b) The run without sweeping magnet provided a check on the extent of $\bar{n}$ scattering from the iron of the sweeping magnet pole pieces.

After all corrections had been applied, the two sets of 7.76 GEV/C data showed a systematic difference in normalisation of about 13%, the run with the sweeping magnet giving the higher cross-section. In trying to understand this difference, various checks were made on the two sets of data. The efficiency of the S^{*} counters was checked

and found to be the same in the two runs. Also checked, from the experimental logbook, was the consistency of the voltage settings of the veto counters since widely differing thresholds in the two runs would produce a normalisation difference. Another possible cause of the discrepancy that was considered was the re-scattering of antineutrons, from the iron of the sweeping magnet, into the acceptance zone of the spark chambers. Such scattering would be largely diffractive elastic scattering and would have a highly forward peaked distribution. In this way, only the edges of the pole pieces could give rise to any background and the effect would be confined to the larger $|t|$ region. Variations in the analysis of the data were not reasonable causes for the normalisation difference since the analysis efficiency was consistently high in both runs. Moreover, the "display recovered events" showed similar distributions to the other events.

A hydrogen target only partly full or systematic miscounting of the antiproton rate throughout a whole run could both introduce normalisation inconsistencies. However, it was not possible to check these effects at the analysis stage. It was therefore decided to combine the data in the following way. The integrated cross-sections in the range $0 < |t| \leq 0.06$ were computed and the weighted mean value found. From these values, correcting factors were computed which were then applied to the individual data points of the two data sets. Finally, to obtain the values used in the differential cross-section, the weighted means of the corrected data points were found. The final normalisation error was estimated to be $\sim 8\%$ at 5.0 GEV/C and 12%

at 7.76 GEV/C.

The differential cross-sections show a smooth exponential behaviour over the measured t range and at 7.76 GEV/C, a small peak is seen at $|t| < 0.01 \text{ (GEV/C)}^2$. The 5.0 GEV/C data, although having a slightly poorer resolution, exhibit a structure consistent with that of the 7.76 GEV/C data. Earlier data ⁽³⁾ show that the smooth exponential behaviour continues out to $|t| \approx 1 \text{ (GEV/C)}^2$ and that the distribution, outside the very forward region, can be very well fitted by a parametrisation of the form Ae^{-bt} . The same parametrisation has been used on the present data to compute the integrated cross-sections. The results are presented below and are plotted in figure 51 together with other ⁽²⁴⁾ $\bar{p}p - \bar{n}n$ total cross-section measurements.

BEAM MOMENTUM (GEV/C)	t REGION (GEV/C) ²	SLOPE (GEV/C) ⁻²	CROSS-SECTION μb
5.0	0.06 - 0.6	4.51 ± 0.16	504 ± 36
7.76	0.03 - 0.3	4.07 ± 0.26	380 ± 42

MOMENTUM = 5.0 GEV/C			MOMENTUM = 7.76 GEV/C		
$ t $	Δt	$d\sigma/dt$	$ t $	Δt	$d\sigma/dt$
0.002	± 0.002	2624 ± 404	0.001	± 0.001	1990 ± 157
0.006		1904 ± 340	0.003		1587 ± 141
0.010		1716 ± 315	0.005		1334 ± 129
0.014		2094 ± 344	0.007		1366 ± 130
0.018		2436 ± 371	0.009		1306 ± 124
0.022		2141 ± 350	0.011		1404 ± 125
0.026		2131 ± 350	0.013		1340 ± 126
0.030		2070 ± 344	0.015		1324 ± 127
0.036	± 0.004	1764 ± 224	0.017		1195 ± 122
0.044		1793 ± 226	0.019		1311 ± 127
0.052		1877 ± 231	0.022	± 0.002	1269 ± 90
0.064	± 0.008	1549 ± 149	0.026		1176 ± 90
0.080		1536 ± 149	0.030		1506 ± 102
0.096		1552 ± 150	0.034		1180 ± 93
0.112		1355 ± 140	0.038		1519 ± 108
0.132	± 0.012	1387 ± 117	0.042		1258 ± 100
0.156		1183 ± 108	0.046		1136 ± 97
0.180		937 ± 97	0.050		1229 ± 103
0.204		980 ± 99	0.054		1159 ± 102
0.232	± 0.016	871 ± 97	0.058		1108 ± 98
0.264		685 ± 86	0.065	± 0.005	1241 ± 74
0.300	± 0.020	664 ± 72	0.075		1212 ± 77
0.340		454 ± 63	0.085		1082 ± 79
0.380		316 ± 52	0.095		1126 ± 84
0.428	± 0.028	357 ± 64	0.105		984 ± 80
0.488	± 0.032	221 ± 47	0.115		950 ± 87
0.556	± 0.036	172 ± 39	0.125		948 ± 88
			0.135		896 ± 88
			0.145		890 ± 84
			0.155		914 ± 92
			0.165		718 ± 90
			0.175		690 ± 90
			0.190	± 0.010	694 ± 65
			0.210		711 ± 85
			0.230		659 ± 86
			0.250		539 ± 84
			0.270		503 ± 87
			0.290		433 ± 89

$d\sigma/dt$ in MICROBARN/(GEV/C)²

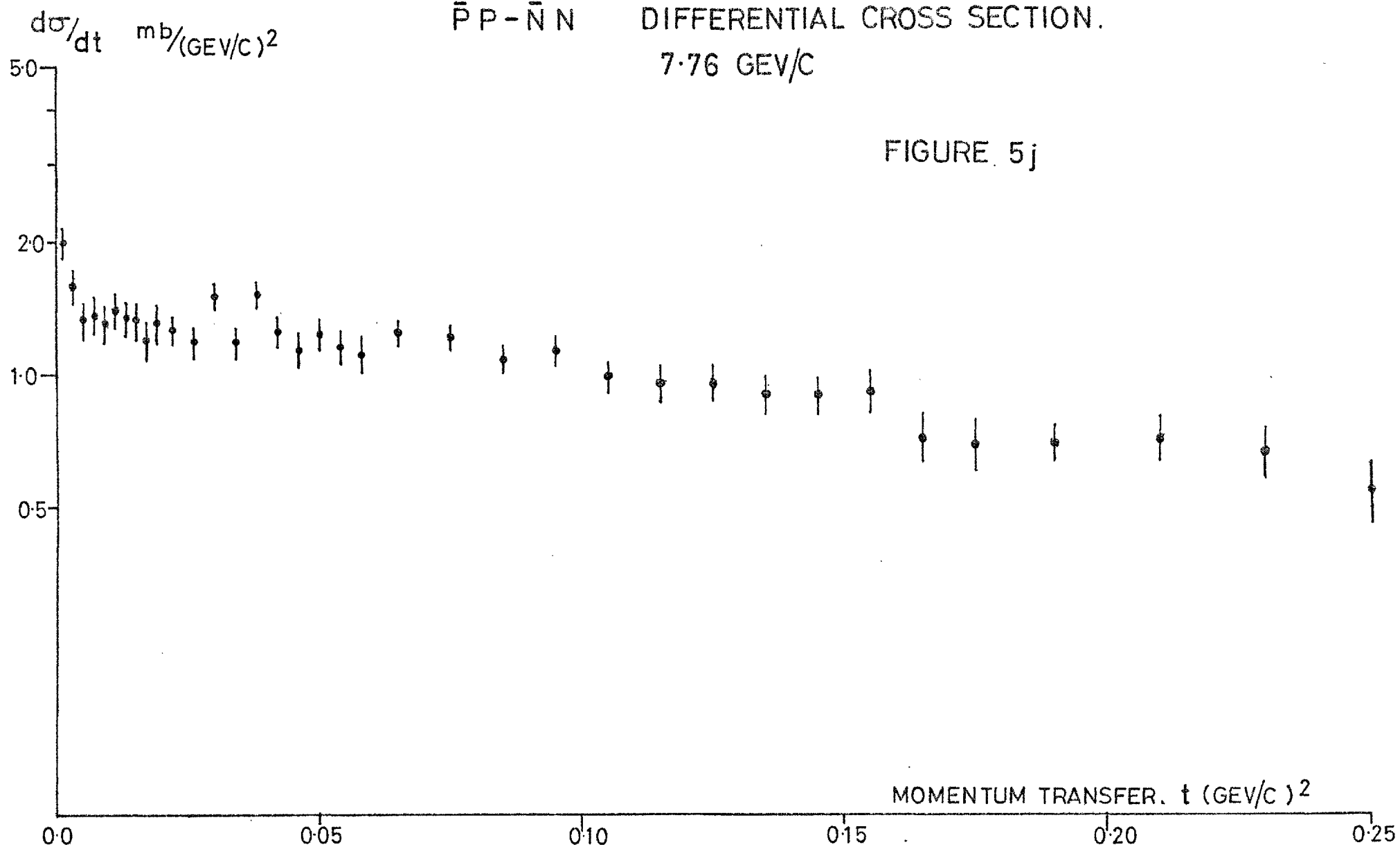
TABLE 5i

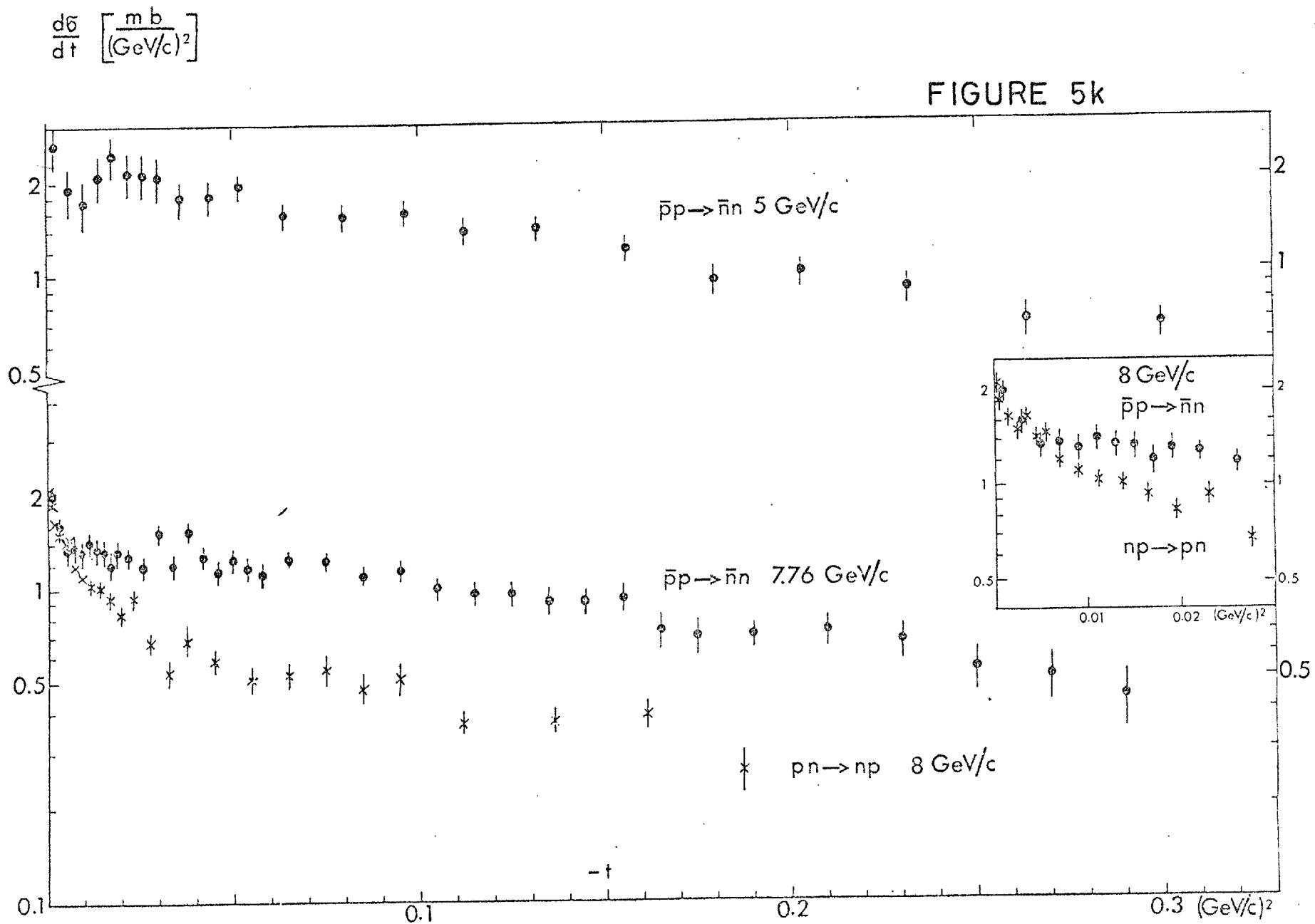
$\bar{P}P - \bar{N}N$

DIFFERENTIAL CROSS SECTION.

7.76 GEV/C

FIGURE 5j





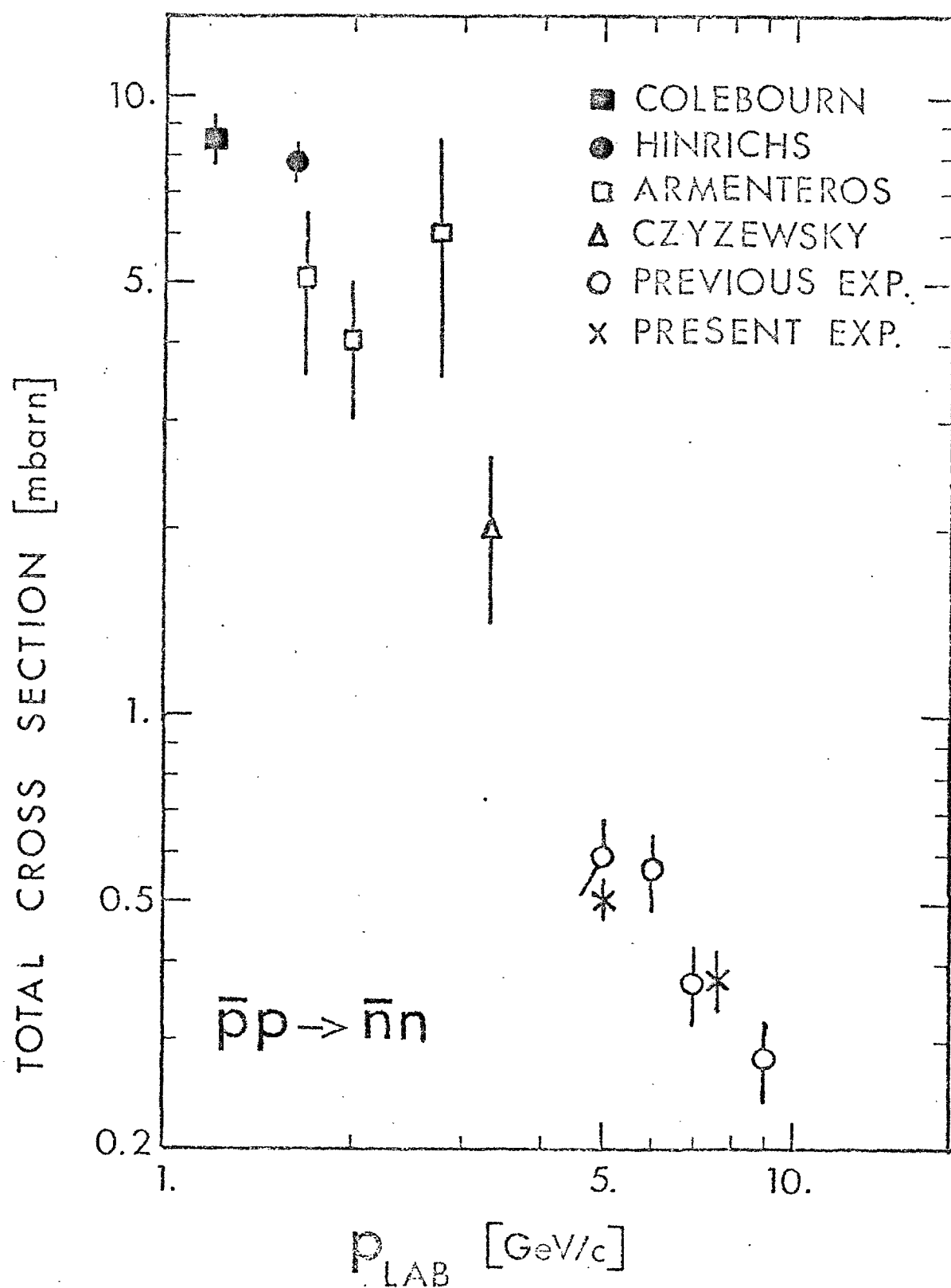


FIGURE 51

C H A P T E R 6

DISCUSSION

6.1 An Empirical Fit to the Data at 7.76 GEV/C

Following the ideas of the absorption models for pion exchange, (Section 1.6 and references 25,26) the data at 7.76 GEV/C were fitted to the following relation:

$$\frac{d\sigma}{dt} = \frac{\pi}{2m_p^2 P_L^2} \left\{ \frac{g^2}{4\pi} \right\}^2 \left[\left| C e^{\beta t} - \frac{t}{t - \mu^2} e^{\gamma(t - \mu^2)} \right|^2 + \left| \frac{t}{t - \mu^2} e^{\gamma(t - \mu^2)} \right|^2 + \left| B e^{\delta t} \right|^2 \right]$$

μ = Pion mass

m_p = Proton mass

P_L = Laboratory beam momentum.

$g^2/4\pi$ = 14.6, the πNN coupling constant.

The terms $\left| \frac{t}{t - \mu^2} e^{\gamma(t - \mu^2)} \right|$ represent the Reggeized helicity amplitudes for the pion pole. The pion amplitude corresponding to zero net helicity flip between initial and final state interferes with an absorption correction parametrised by $C e^{\beta t}$. The third term in the fitted expression, $B e^{\delta t}$, represents a non-interfering background contributed by all other possible exchanges.

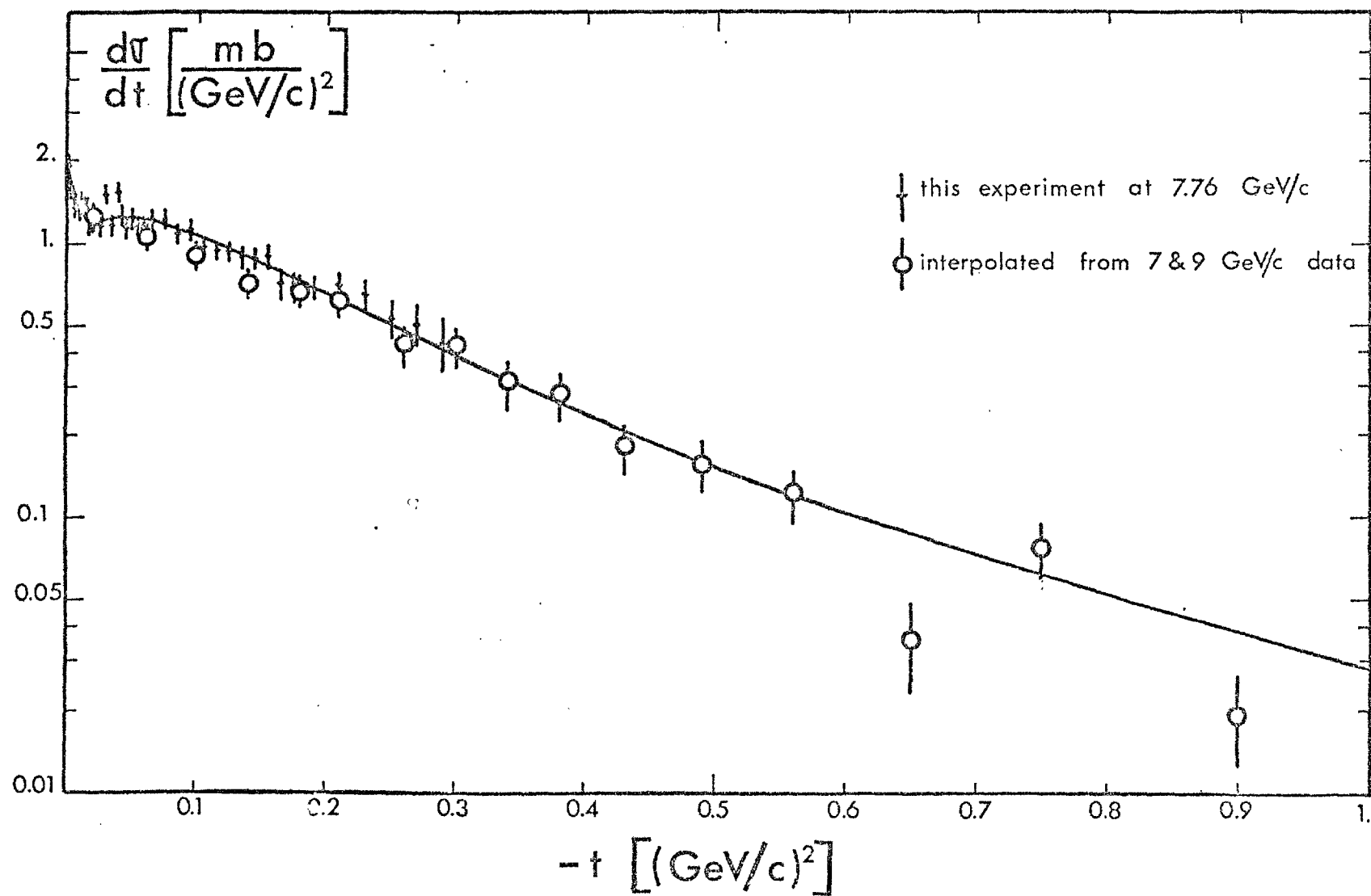


FIGURE 6a

The fit obtained with the above parametrisation is shown in Figure 6 a . Also shown on Figure 6 a are data points from an earlier measurement ⁽³⁾ of the $\bar{p} p - \bar{n} n$ differential cross-section. The points are interpolations made at 8.0 GEV/C from data at 7.0 GEV/C and 9.0 GEV/C. The fit is good in the $|t|$ range of the 7.76 GEV/C data ($\chi^2 = 31$ for 35 degrees of freedom) and the interpolated data points show that the good agreement continues out to higher $|t|$ values. The values of the parameters obtained in the fit were:

$$C = 0.81 \quad \text{and} \quad B = 0.46$$

$$\text{with} \quad \beta = 1.8 \text{ (GEV/C)}^{-2}$$

$$\gamma = 3.3 \text{ (GEV/C)}^{-2}$$

$$\delta = 3.3 \text{ (GEV/C)}^{-2}$$

The contribution to the cross-section from non-pionic exchanges (represented by the term $Be^{\delta t}$) was found to have roughly the same magnitude as the pion contribution. This applied for the whole $|t|$ region outside the forward spike. In the forward direction, the data indicated that the non-pionic contribution was non-vanishing since parametrisations of the form $-tBe^{\delta t}$ or $\sqrt{-t}Be^{\delta t}$ were unsatisfactory. This is in contrast to what has been obtained in a similar parametrisation of n - p charge exchange where the non-interfering background term was found to be <1% of the pion contribution ⁽²⁷⁾

The absorption correction, $Ce^{\beta t}$ interferes with the pion amplitude and modifies very strongly the form of the contribution from the lowest partial waves. The fit indicates that these waves have

approximately the same magnitude but opposite sign to those of an unabsorbed pion. This requirement, whereby the low partial waves are not merely reduced in magnitude but are changed in sign, is known as "over-absorption" and appears difficult to interpret in terms of the absorption model ideas, as outlined in Section 1.6.

The values of the slope parameters (β , γ and δ) do not exceed typical elastic scattering values and, in particular, β is about $\frac{1}{4}$ of the slope in $\bar{p}$ p elastic scattering. This contrasts with p-n charge exchange scattering where, in a similar fit ⁽²⁷⁾, the parameter in the absorption correction term was about twice the elastic value. This reflects the more gentle fall-off of the differential cross-section in the case of antiproton charge exchange.

6.2 Other Pion Exchange Reactions.

The strongly absorptive pion required in $\bar{p}$ p charge exchange is also important in other processes where π exchange contributes. In ρ production, $\pi^- p \rightarrow \rho^0 n$, the pion contributes to both $n = 0$ and $n = 1$ amplitudes where n corresponds to the net helicity flip between initial and final states. In the case of the $n = 1$ amplitude, the Regge pole prescription gives a satisfactory behaviour and the amplitude as required by angular momentum conservation, falls to zero at $t = 0$. However, the $n = 0$ amplitude

from the π exchange also falls to zero at $t = 0$ and in order to explain the data, it is necessary to introduce absorptive corrections into this amplitude. A crude approximation involving the complete removal of the 's' wave alone in the $n = 0$ amplitude drastically changes the behaviour and no longer produces an overall amplitude falling to zero in the forward direction.

Similar ideas apply to the role of the pion in photoproduction ($\gamma p \rightarrow \pi^+ n$) where the forward peak in the differential cross-section is generated by absorption of the low ℓ waves in the $n = 0$ amplitude.

A C K N O W L E D G E M E N T S

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