PROBLEMS OF EXPERIMENTATION WITH COLLIDING PROTON BEAMS

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I. General Considerations

The experiments that have been suggested as suitable for colliding proton beams can be classified into two basic classes. In the first class one is interested particularly in processes involving small angles with the incident proton beam. Either there are very few particles in the final state or one is not interested in details of the final state. The experimental equipment is for the most part disposed close to the two colliding beams, well downstream from the interaction region. Experiments of this class include:

1. Elastic p-p scattering.
2. Quasi-elastic p-p scattering and peripheral collisions.
3. Total p-p interaction cross sections.

In the second class of experiment a much more detailed study is needed of individual particles emitted from the interaction and observation cannot be restricted to small angles with the incident beam. The detection devices will surround the whole experimental region. Experiments of this class include the following:

4. Study of the details of high energy p-p interactions, particularly of collisions involving high momentum transfer.
5. Identification of unstable isobars produced in p-p collisions.
6. Study of the extent to which strangeness conservation is obeyed at very high energies.

7. Investigation of possible production of vector bosons in p-p collisions.

Considerable attention has been paid already to arrangements suitable for the first class of experiment.[1] Experiments of the second class have also been discussed to some extent but in less detail. In this report we concentrate attention, therefore, on this class of experiment. In particular we consider experiment (4) of the above list. The discussion is of relevance also to the other experiments of this class, however, since it concerns the background against which the processes sought in these experiments would have to be observed.

One general conclusion emerges from this study. This is the great importance of ensuring that at a time when parameters for storage rings are being worked out, much thought should be given to the way experiments will be carried out using them. With intersecting-beam experiments the storage rings form an integral part of the actual experimental apparatus in a far more real sense than is the case with conventional accelerators.

For example, it is essential that the straight sections near the intersecting regions should be made of adequate length to permit the identification of the particles produced in the interactions. This may necessitate substantially larger rings than would otherwise have been designed, or alternatively a reduction in the number of intersections. Provision should be made for breaking the ring near intersecting regions and interchanging experimental setups. The storage rings should be designed so that it is an easy matter to dispose adequate magnetic fields, both transverse

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1. See, for example, report by B. de Raad, CERN Internal Report AR/Int. SG/62-12. Also K.M. Terwilliger, p. 238 of this volume.

and longitudinal, around parts of the intersecting regions to facilitate particle identification.

II. Momentum and Angular Distributions of the Secondary Particles Produced in p-p Collisions

Since many of the experiments envisaged with colliding beams involve the identification of secondary particles, it is of interest to consider how these particles are distributed in momentum and angle. Considerable uncertainty exists about these distributions. Much of this uncertainty will, of course, be cleared up in the first few minutes of operation of the colliding-beam apparatus. In the meantime, one has to rely on the meager evidence available from cosmic-ray studies.

The distributions usually assumed are based on a formula given by G. Cocconi, L.J. Koester and D.H. Perkins.[2] This formula is based on the following assumptions suggested by cosmic-ray evidence:

(1) The multiplicity, n_s (including neutrals) is given by

$$n_s = 2.5\, U_c^{1/2}$$

where U_c is the total energy (in Gev) in the C system.

(2) The distribution $n(P_T)dP_T$ of the transverse momentum P_T of the secondaries and of the nucleons after interaction is independent of the primary energy, the nature of the secondary particles and of their longitudinal momentum and is given by

$$n(P_T)dP_T = 36\, P_T\, e^{-6\, P_T}\, dP_T$$

where P_T is expressed in Gev/c.

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2. G. Cocconi, L.J. Koester and D.H. Perkins, Berkeley High-Energy Physics Study, Summer 1961, p. 167 (Lawrence Radiation Laboratory Report TID-4500).

(3) The longitudinal distribution $n(P_L)dP_L$ of the momentum P_L of the mesons and baryons created in the collision is given by

$$n(P_L)dP_L = B\ e^{-2B|P_L|}dP_L$$

where $B = 3.3\ U_c^{-\frac{1}{2}}$, ($P_L$ in Gev/c).

(4) The longitudinal distribution $n(P_L^N)dP_L^N$ of the momentum P_L^N of the nucleons after interaction is given by

$$n(P_L^N)dP_L^N = C\ e^{-C|P_0^N - P_L^N|}\ dP_L^N$$

with $C = (4/U_c)$, (P_L^N in Gev/c),

where P_0^N is the initial momentum of the nucleons in the C system.

The form of variation of the constant B in (3) implies that the inelasticity of the collisions is independent of U_c. The value of C in (4) is obtained on the assumption that the inelasticity is equal to 0.5.

P_L in (3) cannot exceed P_0, the largest possible momentum for the particular secondaries in the C system.

It is clear that these assumptions can give only a rough approximation to the actual distribution in momentum and angle of the secondary particles produced in p-p interactions. The actual multiplicity for a given U_c varies between wide limits. This is not taken into account. Recent measurements of the average inelasticity at high energies suggest that it is considerably smaller than the value of 0.5 assumed, (R. Levi Setti, private communication) and it too will vary greatly between different interactions for a given U_c.

Cocconi, Koester and Perkins give figures based on the above assumptions for the angle and momentum distributions of secondary particles in the laboratory system for collisions between high-energy protons and stationary protons. These figures agree reasonably well with distributions obtained for 30-Gev protons on a stationary target, and it seems possible that at higher energies also where they have not been tested they may give results that are of the right order of magnitude. In any case it is difficult to obtain a better prediction of these distributions.

Figs. 1 to 4* show curves based on these assumptions for the energy and angular distributions in the laboratory system of secondary particles produced by the interaction of colliding beams of protons of energy 25 Gev. From these figures it is seen that most of the secondary particles produced have a momentum of the order of 1 Gev/c or less. This is a region in which considerable experience has already been obtained in particle identification. Further, although the secondary particles are peaked forward, the angles concerned are not so small as is sometimes assumed and indeed more than 40% of the secondaries are emitted at an angle greater than 30 degrees with the incident proton direction.

On the other hand the primary nucleons, after interaction, are distributed over a range of small angles to the incident direction. This angle appears to remain small even in many cases where the inelasticity is high. The assumptions outlined above imply that the transverse momentum distribution of the scattered baryons is the same as for the

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* I am indebted to Mr. K. Jellett for calculating these distributions.

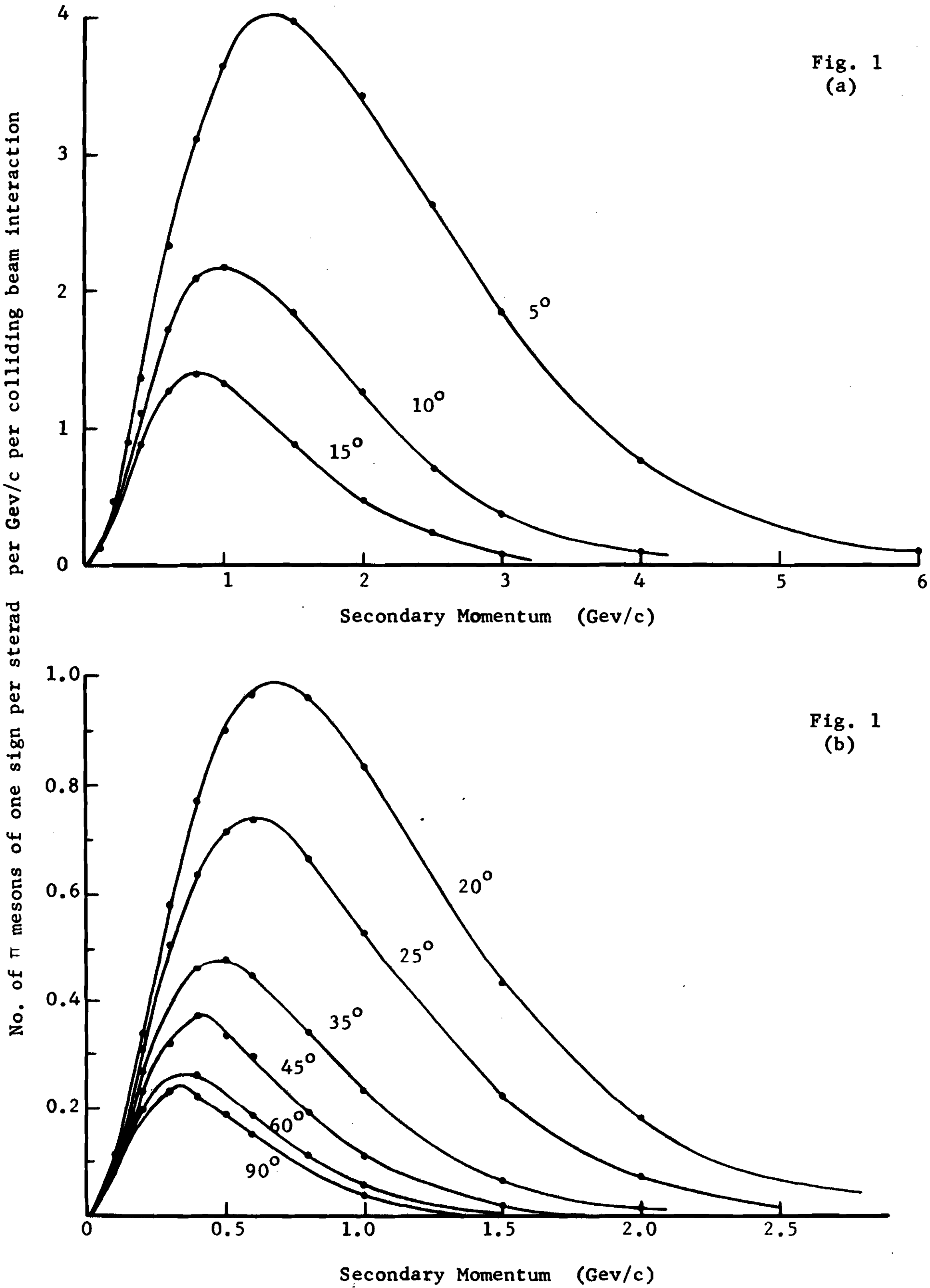

Fig. 1 - Intensity of secondaries emitted per unit solid angle per unit momentum range at different angles, θ, to the incident beam.

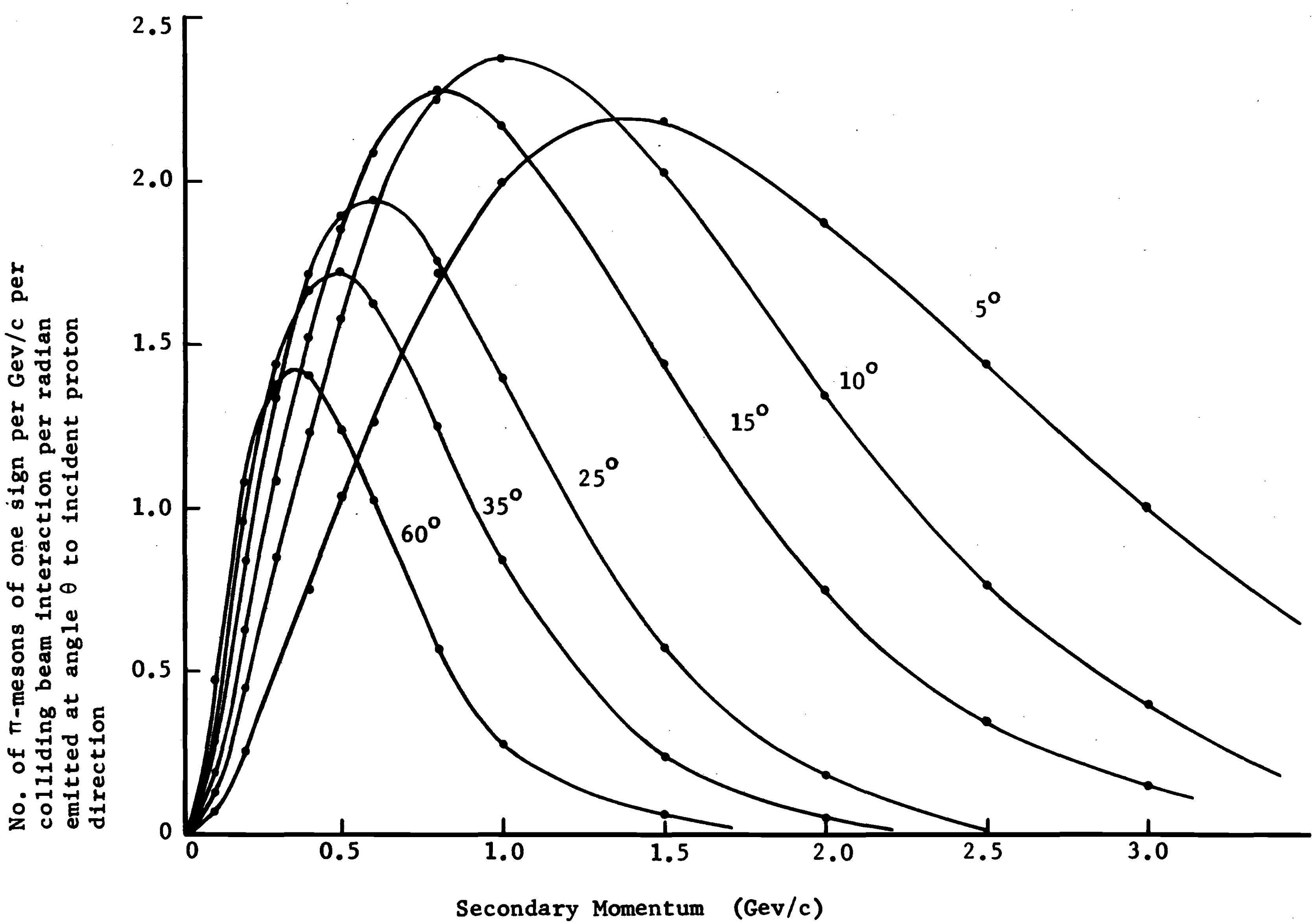

Fig. 2 - Total number of secondaries emitted per unit momentum range per radian at different angles, θ, to the incident beam (i.e., these curves are obtained from those of Fig. 1 by multiplying by 2π sin θ).

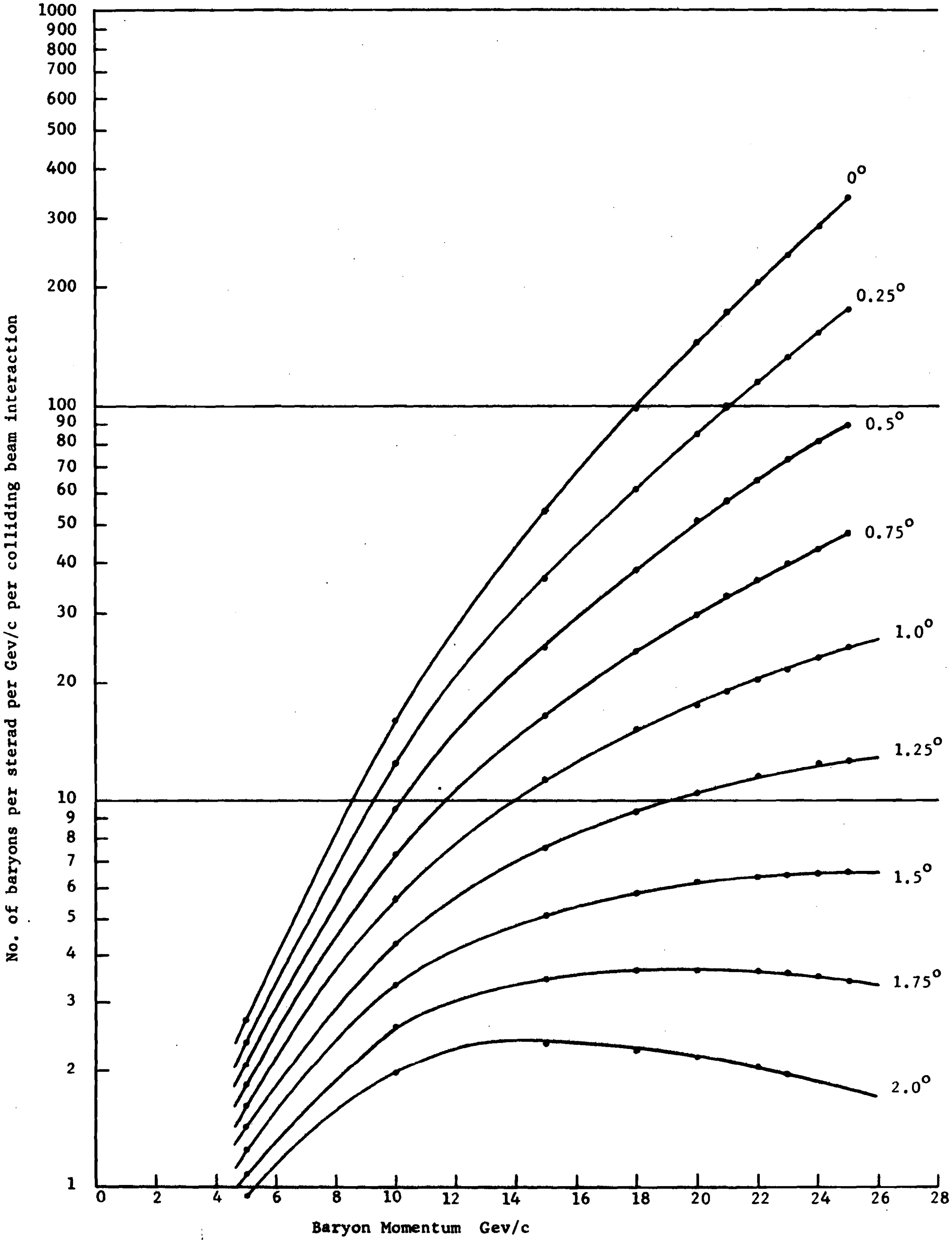

Fig. 3 - Intensity of scattered primary baryons per unit solid angle per unit momentum range at different angles, θ, to the incident beam, assuming their transverse momentum distribution is the same as that of the secondaries.

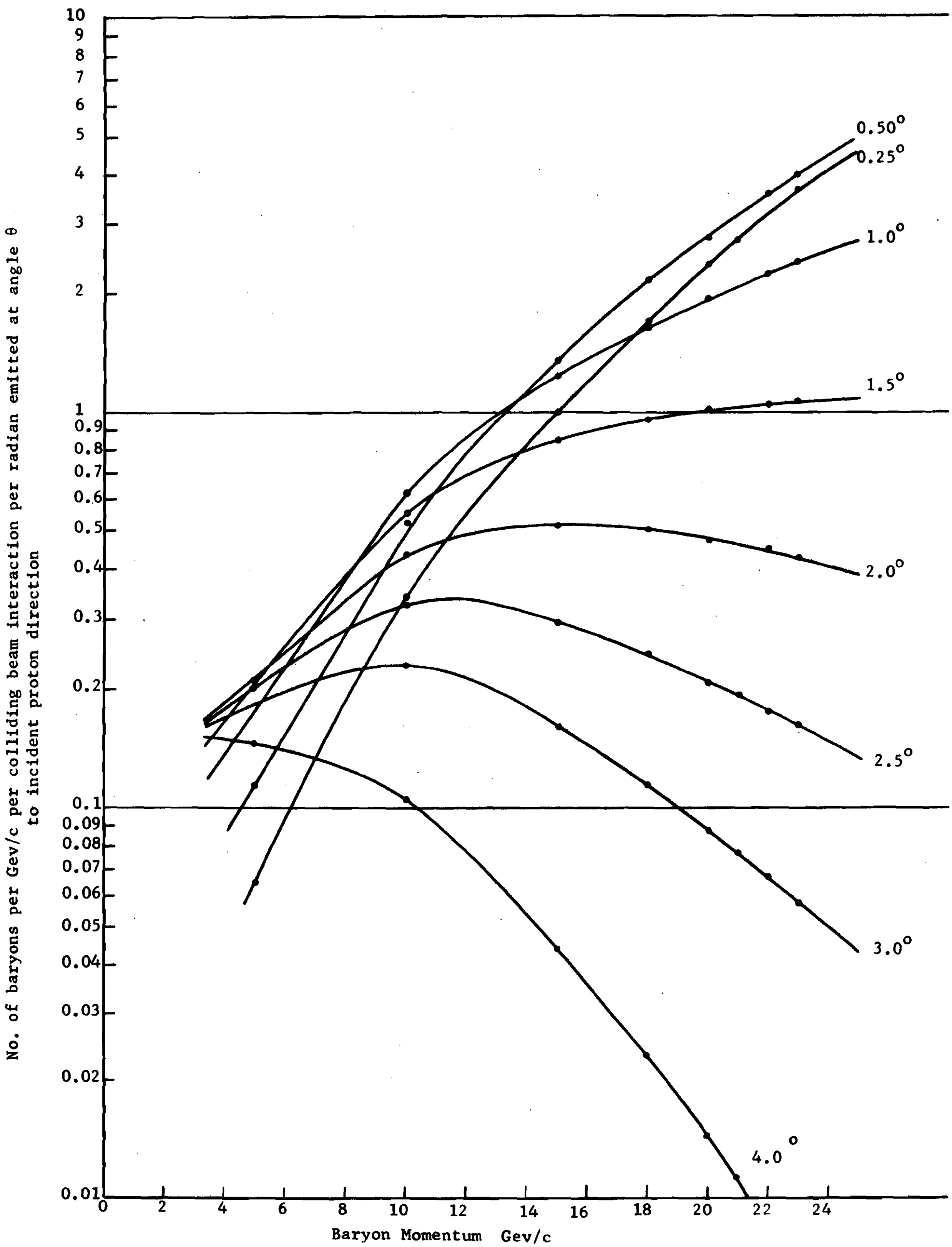

Fig. 4 - Total number of scattered primary baryons per unit momentum range per radian at different angles, θ, to the incident beam, assuming their transverse momentum distribution is the same as that of the secondaries (i.e., these curves are obtained from those of Fig. 3 by multiplying by $2\pi \sin \theta$).

secondary particles emitted. Since at these energies each nucleon will, on the average, emit 8 or 9 particles it seems very surprising that they should be emitted in such a way as to generate the same nucleon transverse momentum distribution as that of the secondary particles individually. If the transverse momentum were normally distributed it might be expected that the average transverse momentum would be $(n_s/2)^{\frac{1}{2}}P_T$. Figs. 5 and 6 are plotted on the assumption that transverse momentum of the scattered baryons is distributed as in (2) but with a mean value three times as great as that for the secondary particles emitted. The resulting angular distribution is still markedly peaked forward, but less so than in Figs. 3 and 4.

III. Study of the Details of High-Energy p-p Interactions

In spite of a great deal of effort using cosmic radiation during the past 20 years the knowledge of details of p-p interactions is still very meager. Cosmic-ray investigations in this field suffer from uncertainty in the nature of the incident particle and of its momentum, uncertainty of the importance of secondary effects and even of the effective mass of the target particle. They suffer also from the very slow rate of accumulation of data. At the present time we have almost no experimental knowledge of the elastic-scattering cross section for energies above 30 Gev, nor of its variation with energy. The total cross section is known to remain of the same order of magnitude over a large range of energy but its actual value at a given energy is known only to an accuracy of about 50%. Measurements of the mean multiplicity and mean inelasticity and their variation with energy are subject to large errors and very little is known about how

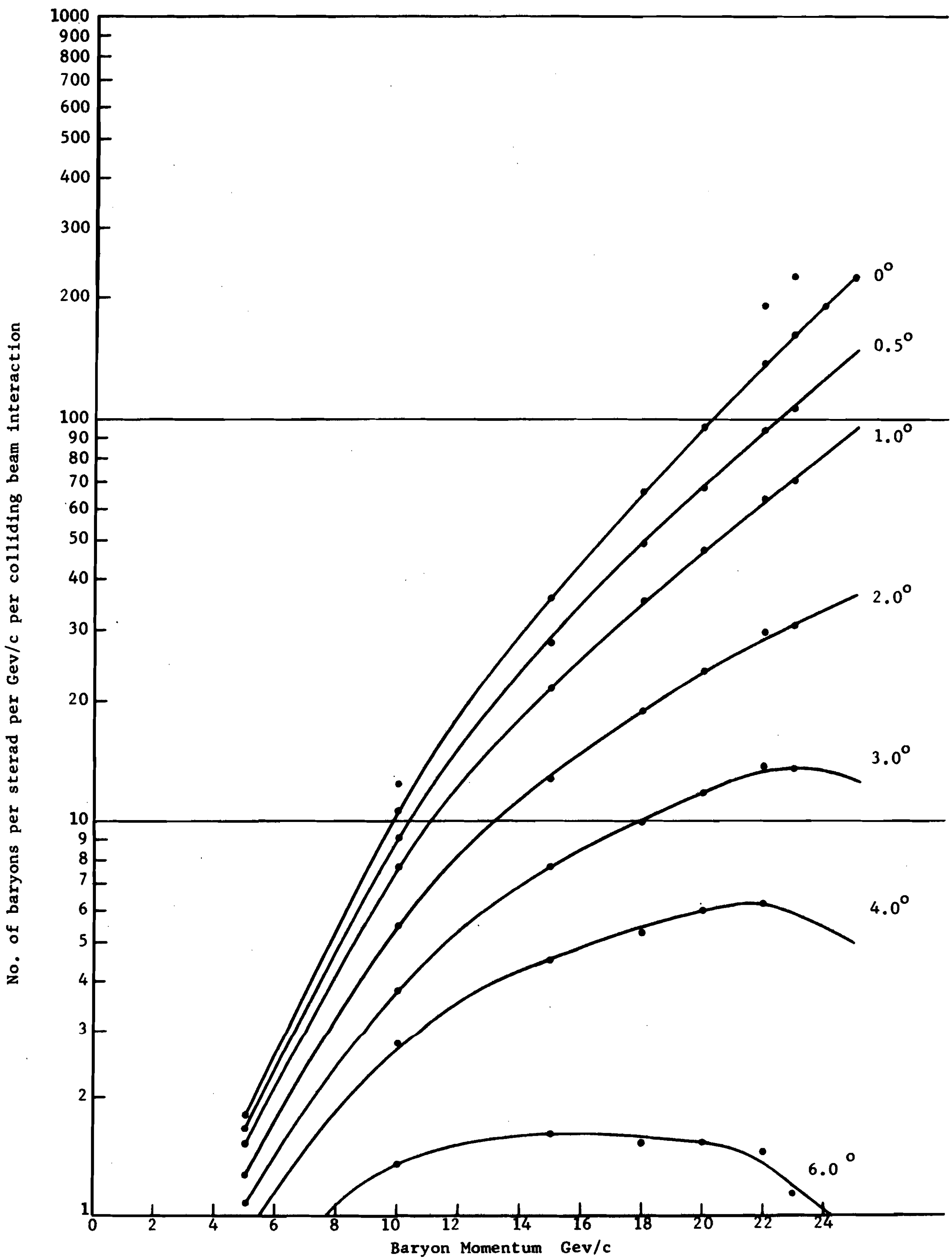

Fig. 5 - As for Fig. 3 but with the mean transverse momentum greater by factor of 3.

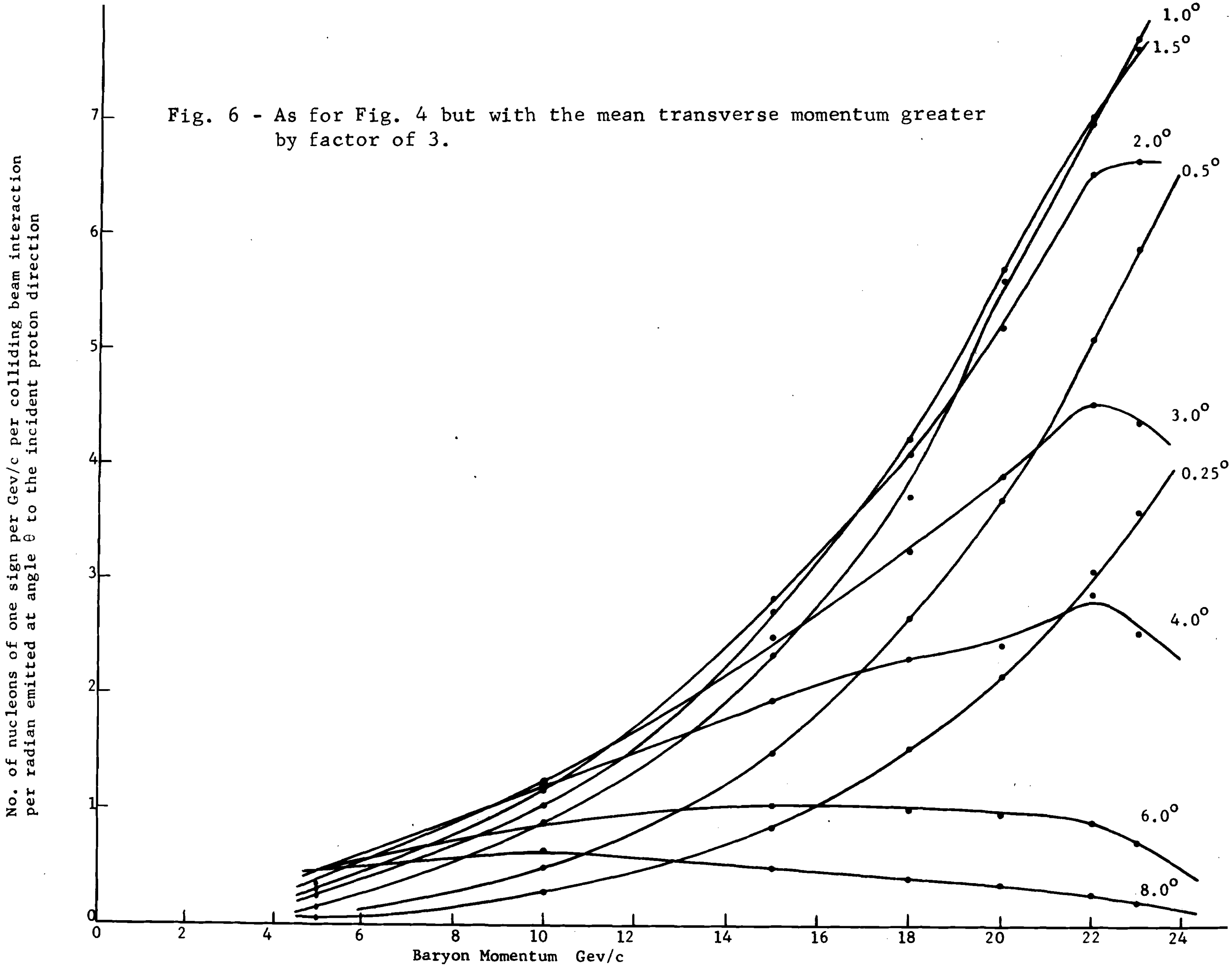

Fig. 6 - As for Fig. 4 but with the mean transverse momentum greater by factor of 3.

these quantities are distributed about the mean values at a given energy. Present experimental data is not sufficient to give detailed information about the angular and momentum distribution of the secondary particles in the C system, of the possible role of mesonic "fireballs" or of excited baryons in the interactions. If such entities exist and play an important role in high-energy interactions their study could possibly reveal the existence of new types of matter of great fundamental significance.

Data on all details of these processes will be provided at a tremendous rate in colliding-beam experiments. The expected number of beam-beam interactions with a pair of colliding beams associated with the CERN PS is of the order of 10^5 per second. If the details of these processes are to be studied and especially if new processes or unknown particles involved are to be identified, it will be necessary to be able to measure the momentum and direction of emission of a large proportion of the charged and neutral particles emitted. In this section we examine the extent to which such a complete analysis is possible. We discuss first the various measurement techniques.

IV. Experimental Techniques for Particle Measurement and Identification

1. Momentum measurements

These involve the use of a magnetic field. The field required may have different geometries -- either longitudinal in the direction of the proton beams, or vertical and transverse to the beam direction. In either case the assumption is made that sufficiently strong magnetic fields can be established in the space surrounding the colliding-beam regions without upsetting the stability of the stored proton beams themselves. Preliminary studies made at CERN and elsewhere[3] suggest that this is indeed possible.

To carry out the momentum measurements one could envisage an arrangement of single-gap spark chambers of 2 m radius surrounding the colliding-beam region as shown in Fig. 7. These are spaced 50 cm apart. Further chambers could be added to increase the accuracy with which the trajectory can be defined, but the estimates given here are based on the assumption that the radius of curvature is determined from three measurements in chambers 50 cm apart and that the position of a spark can be located to an accuracy of 0.5 mm.

TABLE I

Momentum Gev/c	Angle of emission relative to primary beam	Sagitta (mm)	
		Longitudinal field	Transverse field
24	1°	0.1	6.25
24	5°	0.5	6.25
2	5°	6.5	75
	15°	19.5	75
	30°	50	75
0.5	15°	76	300

Table I gives the sagittae for particles of various momenta emitted in different directions relative to the primary beam for a magnetic field of 16,000 gauss applied longitudinally or transverse to the primary beam. In the transverse case the Table refers to particles emitted in the plane perpendicular to the direction of the field.

3. See contributions by L.W. Jones, B. de Raad and L. Resegotti, CERN Internal Report AR/Int. SG/62-11.

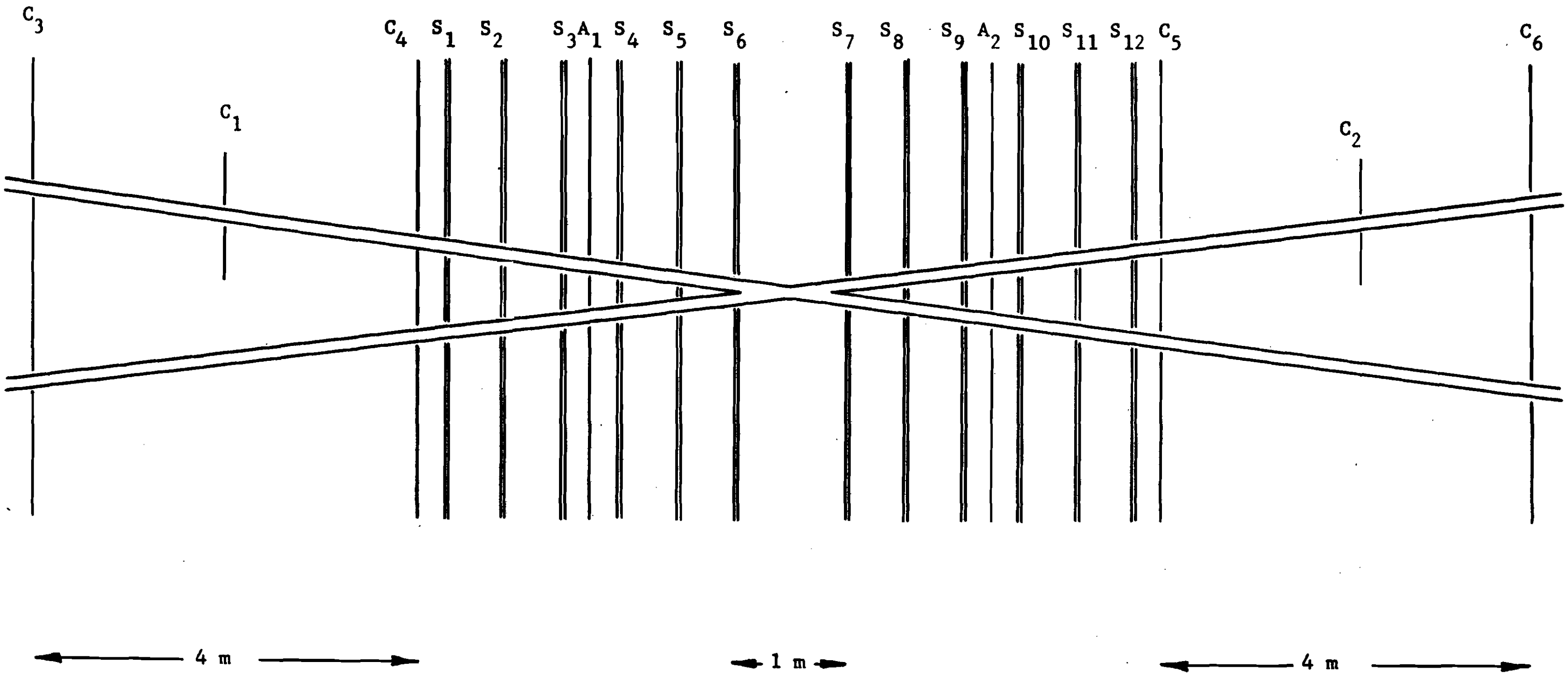

Fig. 7 - Illustrating a possible arrangement for particle identification using momentum loss and time-of-flight methods.

C_1, C_2, C_3, and C_4 are counter arrangements for time-of-flight measurements. Each would consist of a large number of individual counters.

S_1 - S_{12} are one gap spark chambers. These chambers are supposed to be in a magnetic field.

A_1, A_2 are plates of material for degrading the momentum of the secondary particles.

We conclude that the momenta of almost all the secondary particles could be determined to within better than a few percent using either field geometry. Indeed, a much lower magnetic field ($\sim$ 6000 gauss) would suffice for this purpose. For the scattered-beam particles, however, meaningful momentum measurements could be made only in the case of the transverse-field configuration. Even for transverse field it is doubtful whether the accuracy is good enough for the scattered-beam particles to be of much assistance in the interpretation.

It should be noted further that, supposing the interaction to occur at the center of a 5-cm-diameter vacuum chamber, a particle emitted at 1° to the beam would emerge 1.4-meters downstream from the interaction and would miss the first three spark chambers in Fig. 7. Momentum measurements based on the first three chambers would only be available for particles emitted at angles greater than 6 degrees. This excludes almost all the scattered primary nucleons. To obtain momentum measurements on these the magnetic field (longitudinal or transverse) would have to be extended for at least three meters along the beam in either direction, thus increasing still further the formidable problem of providing the magnetic field over such a large volume.

2. Particle identification

Many of the secondary particles have momenta such that they can be identified using rate of energy loss or direct-velocity measurement techniques. We discuss now the proportion of particles that are likely to be identified by these methods.

a. Rate of energy loss

The arrangement shown in Fig. 7 would enable measurements to be made on the momenta of the secondaries after they have passed through a degrader in the form of a disc of suitable material. A disadvantage of this method is that it involves the extension of the magnetic field along the beam. The choice of the dimensions and material of the disc is governed by the consideration that it should be thick enough to give an appreciable momentum loss, but not so thick that straggling will affect the discrimination between different kinds of particle. The thickness should be small compared with the interaction length so that sufficient strongly-interacting particles will emerge. Further, the disc could serve as a powerful means of detecting photons from π^o decay so that it should be several radiation-lengths thick. These last two considerations suggest the use of a very heavy material. For example, a sheet of uranium 1-cm thick has a thickness of 3.4 radiation lengths so that the chance of conversion of a photon passing through it is 96.5%. At the same time it represents a thickness of 0.11 interaction lengths. The energy loss at minimum ionization of such a sheet is 20.8 Mev and the straggling is less than 20% of the momentum loss over most of the range of particle momenta concerned.

Assuming that position measurements can be made with the spark chamber to an accuracy of 0.5 mm, estimates have been made of the range of momenta and emission angles over which (1) protons can be distinguished from π's and K's, and (2) all three particles, π's, K's and protons can be distinguished. These estimates have been made for both longitudinal and transverse magnetic field geometries.

Such estimates have been made for the following different arrangements of spark chamber separation, h, degrader thickness, t, and magnetic field H.

I	h = 50 cm	t = 1.0 cm U	H = 6,000 gauss
II	50 cm	1.0 cm U	15,000 gauss
III	50 cm	0.5 cm U	6,000 gauss
IV	100 cm	1.0 cm U	6,000 gauss

The curves of Fig. 2 showing the spectra of secondaries have then been used to estimate the fraction of secondary particles that could be identified for momentum loss for different emission angles up to 35° with the incident proton direction. (This is the limiting angle that can be studied in the arrangement of Fig. 7.) The results are shown in Table II.

TABLE II

Fraction of secondary particles that can be identified by momentum loss.

	p - (πK) separation				p - π - K separation			
Case	I	II	III	IV	I	II	III	IV
Emission angle θ								
(a) Longitudinal magnetic field								
5°	.082	.135	.055	.16	.020	.05	.014	.07
15°	.30	.37	.23	.44	.160	.225	.13	.275
25°	.50	.64	.46	.715	.350	.44	.305	.49
35°	.61	.73	.58	.79	.47	.55	.42	.60
(b) Transverse magnetic field								
5°	.135	.25	.12	.29	.105	.12	.09	.14
15°	.28	.43	.26	.50	.215	.27	.19	.29
25°	.51	.67	.49	.73	.37	.46	.34	.52
35°	.65	.80	.63	.82	.54	.62	.52	.67

b. Time-of-flight measurement

Many of the secondary particles have momenta in a region where identification is possible using time-of-flight measurements. In Fig. 7, C_1, C_2, C_3 and C_4 represent sheets of scintillator which could be used for such measurements. To enable such measurements to be made on many secondary particles emitted in the same interaction it would of course be necessary to divide each scintillator into a number of independent counters, each with its own light-pipe and photomultiplier. For example, if each sheet were divided into 50 such sections, so adjusted that there is equal probability of a secondary particle passing through each section and if, typically, seven secondary particles from a certain interaction passed through each scintillation sheet, the chance that no individual counter would have more than one particle passing through it would be 0.64.

For a flight path of 4 meters, Fig. 8 shows the flight time in nanoseconds of protons, K's and π's of different momenta. It appears feasible to achieve a time resolution of about 2 nanoseconds in measurements of this kind, so that it should be possible to resolve p's and K's of momentum 1.4 Gev/c and π's and K's of momentum 800 Mev/c.

For the secondaries emitted at an angle less than 35° with the beam direction, it is interesting to compare the fraction that would be identified using the time-of-flight and momentum-loss methods. This comparison is made in Table III. In making the estimate for the time-of-flight method it is assumed that each scintillator sheet is divided into 50 individual counters so that the efficiency of detection of 0.64 is assumed.

Fig. 8 - Time of flight over a 4-meter path for particles of various kinds and momenta.

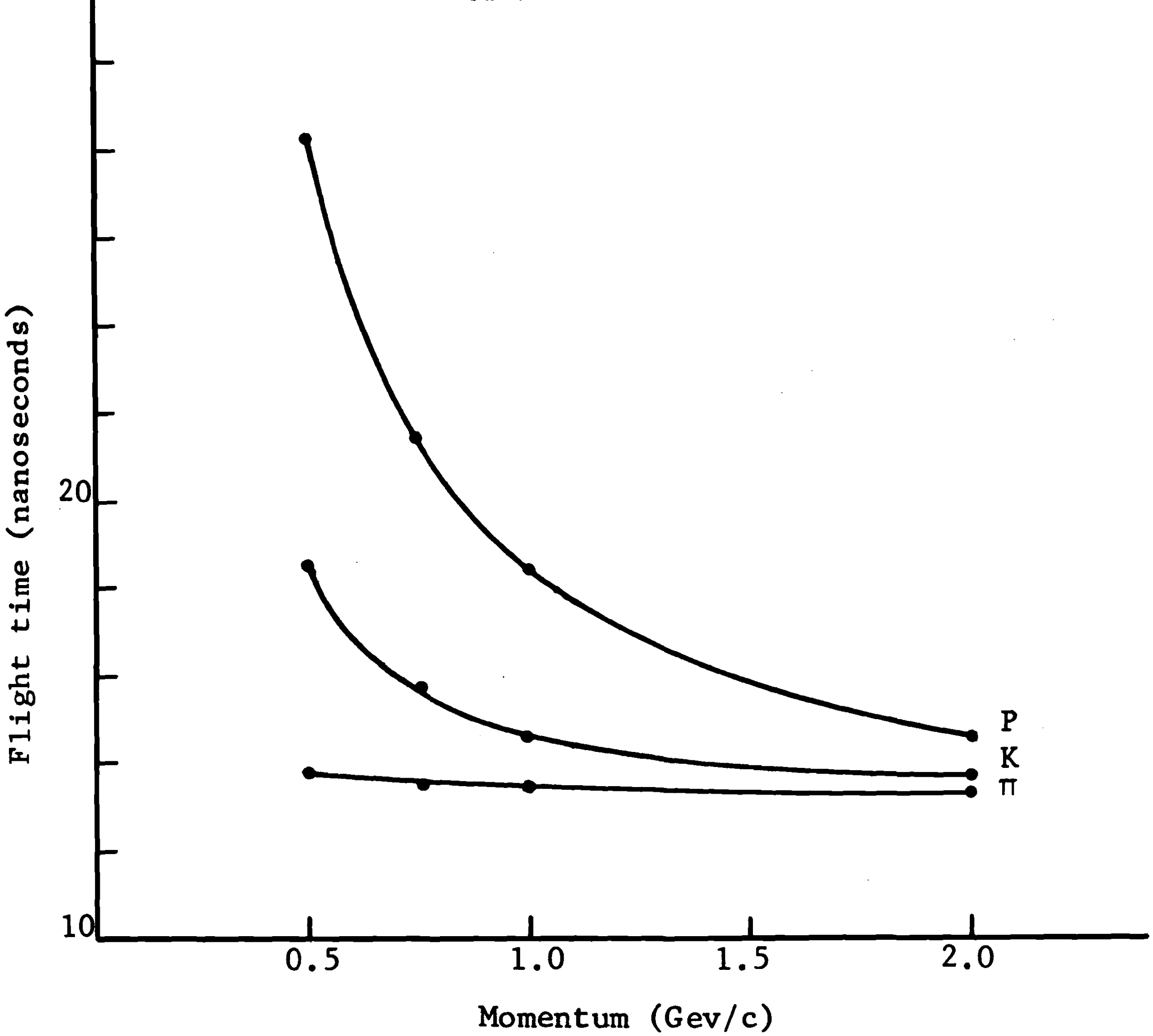

TABLE III

Fraction of secondary particles emitted at angles 0-35° that can be identified

	p - (πK) separation	p - π - K separation
Longitudinal magnetic field		
Case I	0.32	0.22
II	0.36	0.23
III	0.27	0.17
IV	0.46	0.31
Transverse magnetic field		
Case I	0.34	0.25
II	0.43	0.27
III	0.31	0.22
IV	0.53	0.34
Time-of-flight measurement	0.45	0.23

Efficiencies of complete identification for the time-of-flight and momentum-loss (case I) methods are seen to be remarkably similar. Both are capable of improvement by introducing greater complication: the momentum-loss method by introducing larger separation between spark chambers (case IV) which involves increasing the length of the magnetic field; the time-of-flight method by increasing the flight path or by increasing the number of individual scintillation counters in each sheet.

By the time a detecting device will be needed it appears probable that techniques greatly superior to those discussed above will be available. In prospect,* for example, are wire plane hodoscope arrays with high spatial resolution, high efficiency and speed, and capable of being constructed with large dimensions. If such a device were developed it is probable that complex final-state interactions could be analyzed with high efficiency and up to very high incident energies.

A time-of-flight method can also be applied to particles emitted at angles greater than 35^o by surrounding the magnetic-field region with two concentric arrays of scintillators, allowing a 4-meter flight path between them. From Fig. 2 it is seen that the momenta of secondary particles emitted at such large angles are comparatively small. This means that it may be possible to identify up to 90% of those emitted at these angles. Altogether, then, it appears that it should be possible to determine the identity of approximately 60% of all secondary particles emitted using the time-of-flight method in association with magnetic-stiffness measurements.

c. Cerenkov detectors

To identify the remainder of the secondary particles emitted at angles less than 35^o and with momenta above 800 Mev/c it seems attractive to try to use Cerenkov detectors. At 800 Mev/c the velocities, β, of protons,

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*I am indebted to Dr. G.B. Collins for drawing my attention to this possibility.

K mesons and π mesons are respectively 0.65, 0.85, 0.98. At 1.4 Gev/c the corresponding velocities are 0.83, 0.94, 0.995.

The condition for the emission of Cerenkov radiation is $\beta n > 1$, where n is the refractive index of the medium of the Cerenkov detector. Protons are distinguishable from K mesons at momenta up to 1400 Mev/c by the time-of-flight method described above. A Cerenkov detector containing a medium of refractive index 1.06 would enable π's and K's to be distinguished at momenta above 800 Mev/c and protons and π mesons at momenta of above 1.4 Gev/c. For such a medium the variation of Cerenkov angle, θ, given by $\cos\theta = \frac{1}{\beta n}$, is given in Table IV.

TABLE IV

β	θ
.94	0
.95	8.2°
.96	11.5°
.98	16.5°
1.00	20.4°

To obtain a refractive index of 1.06 a gas at very high pressure would need to be used. For example, CO_2 at a pressure of 150 atmospheres would be suitable. The number of emitted photons is proportional to $\ell\theta^2$, where ℓ is the length of path of the particle in the detector. According to L.C.L. Yuan,[4] a Cerenkov detector of length 107 cm emits sufficient light at a Cerenkov angle of 5°. It appears, therefore, that a length of 50 cm will be required in this case.

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4. L.C.L. Yuan, "Cerenkov Counter and Cerenkov Chamber", Experimental Program Requirements for a 300 to 1000-Bev Accelerator and Design Study for a 300 to 1000-Bev Accelerator, p. 85, BNL 772, August 1961 (revised December 1962).

Cerenkov detectors recording a number of particles of different velocities and moving simultaneously through the detector with a range of incidence angles have not yet been developed, although suggestions for such devices ("Cerenkov chambers") have been made. The Cerenkov light would need to be focused on a screen consisting of a mosaic of light-sensitive elements of some kind. If with such a device a resolution of 2° could be obtained it would be useful for distinguishing K mesons of velocity $\beta = 0.99$ ($p = 3.5$ Gev/c) from π mesons of the same momentum. Protons of this momentum have $\beta = 0.965$. If such a Cerenkov chamber were developed it would be possible, therefore, by combining it with momentum and time-of-flight measurements to identify between 80 and 90% of all secondary particles.

One might also consider the possibility of measuring the velocity of the scattered nucleons with momenta up to 25 Gev/c by following the above detector by a similar larger one operating at a lower pressure. A 10% estimate of momentum could be obtained if β could be determined with an accuracy of 10^{-4}.

The velocity resolution of a Cerenkov counter is given by

$$\Delta\beta = \beta^2 n \sin\theta \, \Delta\theta \,, \quad \text{where } \Delta\theta \text{ is the angular resolution.}$$

By putting $\theta = 2^{\circ}$, $\Delta\theta = 3$ millirads this resolution might be approached (see reference 4). A detector length of 7 meters would be needed, however, in order to give sufficient light. Further, at 25 Gev/c a 10% momentum determination is perhaps not very useful.

One concludes, therefore, that the prospect of determining the momenta of the scattered nucleons after colliding-beam interactions does not appear very promising.

d. Detection of photons

As pointed out already, the inclusion of uranium plates 4-radiation-lengths thick in the detection arrangement should make it possible to detect photons with 96.5% efficiency. If a cylinder of a similar thickness and 2-meters radius were placed around the colliding region, together with a cylindrical spark chamber, it should be possible to detect photons from π^o decays in 93% of all cases. If some estimate could be made of photon energies from studies of the showers produced it would be possible to determine the direction and momentum of the π^o meson producing them from the kinematics of the π^o decay which gives rise to the following relations:

$$\gamma \beta m_o \sin \theta_2 = E_1 \sin (\theta_1 + \theta_2)$$
$$\gamma \beta m_o \sin \theta_1 = E_2 \sin (\theta_1 + \theta_2)$$
$$\gamma m_o = E_1 + E_2$$

where γ, β, m_o refer to the π^o meson, E_1, E_2 the energies of the two quanta produced in its decay and θ_1, θ_2 their directions relative to the line of flight of the π^o. Knowing the positions at which the photons produce showers it should be possible to estimate $(\theta_1 + \theta_2)$. If, then, E_1 and E_2 could be estimated it should be possible to solve these equations for γ, θ_1, θ_2.

Unfortunately the estimates of photon energy that could be obtained in this way are likely to be very rough. The estimates could be improved by dividing the converter into a number of sheets and using these as the plates of a spark chamber. In this way details of the development of the photon-electron cascade could be studied. An investigation of the accuracy of photon energy estimate that could be obtained in this way would be worth studying. In the meantime, however, one can assume only that the position of the photons could be obtained by such a device.

e. Detection of strange particles

B. de Raad (see reference 1) has discussed the possibility of detecting strange particles produced in colliding-beam interactions. The nonaccessibility of the interaction region is a serious disadvantage of colliding beams from the point of view of the observation of short-lived particles. For example, he estimates the fraction of ν, Λ^o, Σ^-, Σ^+ and Ξ^- particles that emerge from the vacuum chamber to be 0.26, 0.31, 0.17, 0.16 and 0.06 respectively. ν and Λ particles decaying via the charged mode can be identified from measurements of the invariant mass of their secondary products. This will not in general be possible for the charged-particle decays in which a neutral particle is usually emitted.

V. Interactions Involving Large Momentum Transfers

Collisions of this kind should be characterized by the appearance of one or more particles having a large transverse momentum. Such cases could be selected if a longitudinal-magnetic-field geometry is used. For example, in a longitudinal field of 6000 gauss, a particle of transverse momentum 3 Gev/c would have a radius of curvature of 7 meters. If, therefore, the field extends over a radius of 2 meters, when the particle leaves the field region it will be moving at an angle of 13.5^o with the radius. The two concentric cylinders of scintillators needed for time-of-flight measurements could then be used to select any events in which at least one particle moves in a direction making an angle less than this with the radial direction. To avoid ambiguities it may be necessary to add a third intermediate cylinder of detectors. Using the formula (2) above for the transverse momentum distribution the proportion of secondaries with transverse momentum greater than 3 Gev/c is

$$19\ e^{-18\ P_o} = 3 \times 10^{-7} .$$

Or, supposing an average of 17 secondary particles per interaction, about one interaction in 2×10^5 would have such a high transverse momentum. Although there is no experimental justification for assuming the validity of this expression out to such large momentum transfers this calculation does suggest that the events selected in this way would be rare, corresponding to a cross section of the order of 10^{-31} cm^2.

VI. Conclusions

1. A magnetic field of at least 6000 gauss is required around the interaction region over a radius of 2 meters. From the point of view of momentum measurements of the secondaries produced the transverse field would permit measurements of higher accuracy for high momentum particles at small angles. The number of such particles is small and the advantage is not decisive. The transverse magnetic field would also permit momentum determination of about 10% accuracy on the scattered nucleons. It is doubtful, however, whether such an accuracy is of much value since the momentum of most of these will be distributed over a narrow spread of about 5%.

On the other hand a longitudinal magnetic field would permit selection of events of high momentum transfer by a relatively straightforward method.

This seems such a great advantage that we suggest the longitudinal field geometry should be adopted.

2. Cylindrical arrays of scintillation counters will need to be placed around the magnetic field to enable time-of-flight measurements of the secondaries emitted at angles greater than 35^{o} to the beam direction. Identification of secondaries emitted at smaller angles could be obtained either using momentum-loss or time-of-flight measurements, with comparable efficiency of detection. The use of momentum loss for the identification, however, would require the extension of the large magnetic field for an additional axial distance of 4 meters. It seems preferable, therefore, to use time of flight for this purpose. This means that the length over which it will be necessary to establish the longitudinal magnetic field of 6000 gauss and radius 2 meters will be about 3 meters. Many hundreds of individual scintillation counters, each with their own photomultiplier, will, however, be required. Alternatively, it may be possible to develop arrays of spark counters so small as to provide a high resolution.

3. The identification of the high momentum secondaries moving at small angles with the clashing beams could be accomplished by studying the emission of Cerenkov light, provided a large Cerenkov chamber of radius 2 meters and length 0.5 meters filled with CO_2 gas at a pressure of 150 atmospheres could be developed. The problem is a very difficult one because several particles will pass through the chamber following each event and these will be moving over a considerable angular range. The Cerenkov chambers could be placed in the space over which the flight of the particles is being timed.

4. A high efficiency for the detection of gamma rays could be obtained by employing a cylinder and discs of heavy material such as uranium, four-radiation-lengths thick, completely surrounding the magnetic-field region. These discs could be built of thinner discs forming the plates of spark chambers. If from a study of the development of such showers estimates of photon energy could be obtained it might be possible to reconstruct the directions and momenta of the π^0's produced.

5. Detection of charged unstable particles which decay before emerging from the vacuum chamber would be difficult or impossible so that only about 20% of charged strange particles are likely to be detected. Neutral strange particles decaying by the charged mode should be detected without too much difficulty however.

6. No detailed consideration has been given to the question of how the magnetic field is to be obtained. In view of the fact that no space has been left for vast amounts of metal around the colliding region it may be that a cryogenic magnet will be needed to produce the required field.

Fig. 9 gives a schematic impression of the type of experimental setup envisaged in order to obtain the maximum amount of detail about the colliding-beam interaction. No indication is given of how the longitudinal magnetic field of at least 6000 gauss is to be produced in the central region of diameter 4 meters and length 3 meters. Time-of-flight and magnetic-field measurements of momentum are envisaged for identification of secondaries emitted at angles greater than 5° to either beam direction. Cerenkov-radiation and magnetic-field measurements are envisaged for secondaries emitted at smaller angles. A set of three detecting cylinders

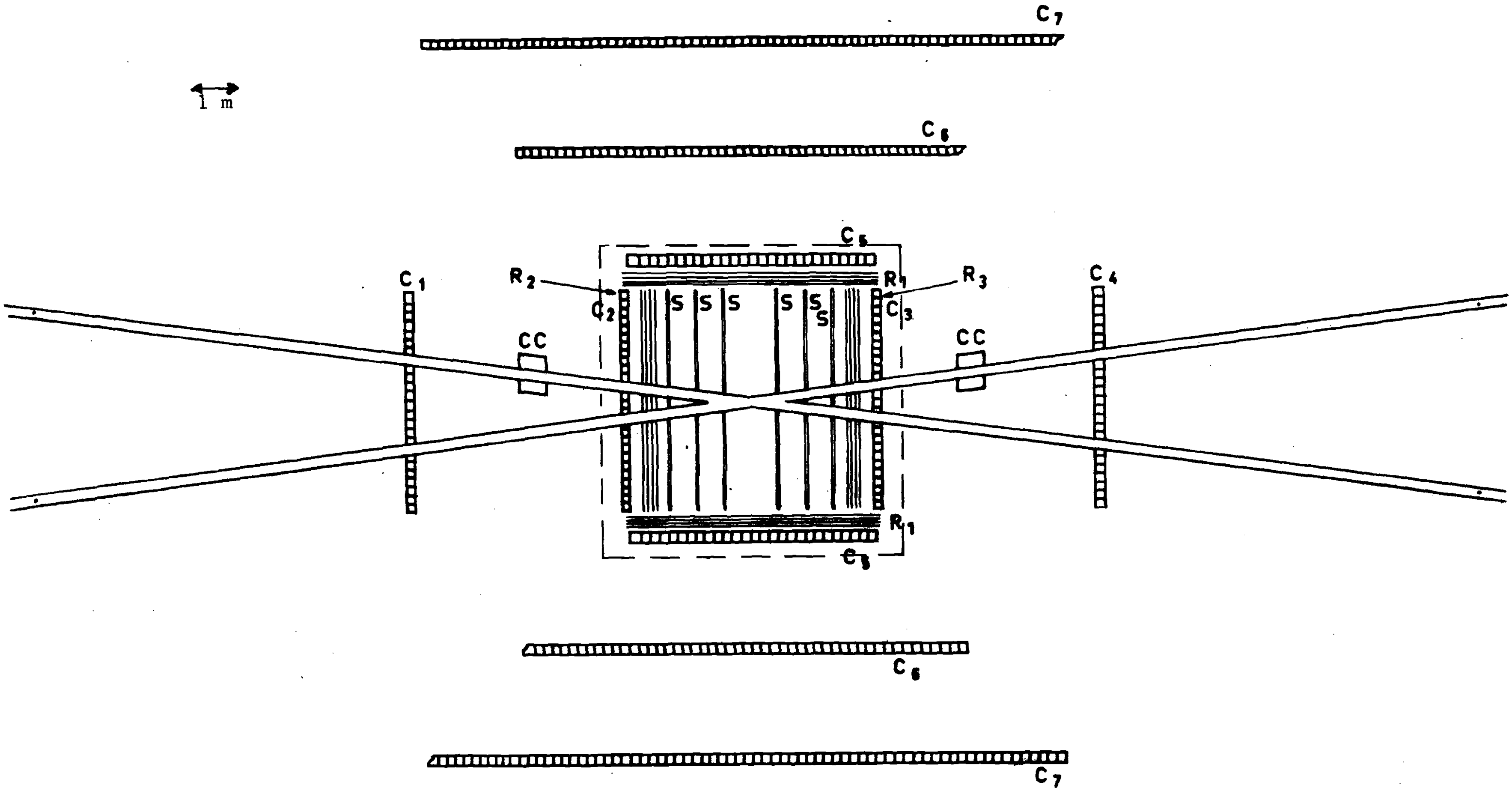

Fig. 9 - Arrangement envisaged as most suitable for secondary particle momentum measurement and identification. C_1, C_2, C_3, C_4 are disc-shaped arrays of counters for time-of-flight measurements. C_5, C_6, C_7 are cylindrical arrays of counters for time-of-flight measurements and for identification of particles with high transverse momentum. S are six spark chambers for momentum measurement. R_1 cylindrical spark chamber with electrodes of heavy material for observing cascades produced by photons. R_1, R_2 are flat spark chambers with electrodes of heavy material for detecting photons. CC are Cerenkov chambers suitable for measurement of particles of velocity $\beta > 0.94$. The longitudinal magnetic field (< 6000 gauss) is supposed to be established within the region drawn in with dashed lines.

surrounding the interaction region is envisaged to enable the separation of events in which particles of large transverse momentum are produced. Neutral particles are detected by the photon-electron cascades produced in spark chambers placed around the interaction region and built of plates of a material of high Z.

In addition to the above it is very clear that a group of competent physicists must be associated with the planning of the machine parameters at a very early stage to ensure that these are influenced decisively by the problems of adapting the storage rings to a useful program of experimentation. Such a group should, in addition, be responsible for carrying out a research program aimed at developing methods of particle identification using storage rings. This program should include the following topics:

(1) Development of high-resolution detection arrays capable of supplying information directly to the store of a large computer. This is required for time-of-flight measurements.

(2) Development of Cerenkov chambers suitable for measuring the velocity of particles with $\beta > 0.94$.

(3) Study of the use of spark chambers containing plates of heavy material to estimate the energy of photons from π^0 decays.

(4) Study of methods of triggering an event of large momentum transfer.

(5) Study of means of producing a large magnetic field around the interaction region using coils of a form consistent with the requirements of particle identification, and study of the effects of this on the beam optics of the storage rings.