FNAL PROPOSAL No. 485

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A PROPOSAL TO INVESTIGATE EXOTIC REGGEON EXCHANGE IN THE INCLUSIVE PRODUCTION OF CHARGED HYPERONS

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THE INCLUSIVE PRODUCTION OF CHARGED HYPERONS

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Summary

We propose to measure the inclusive production of the charged hyperons Σ^- and Ξ^- in the reaction $p + \text{nucleon} \rightarrow (\Sigma^-, \text{ or } \Xi^-) + M_x$ as a function of the variables s, t, and M_x^2. An analysis of the data using triple Regge theory will measure the trajectory, $\alpha(t)$, of the exchanged Reggeon for t values $-5 \text{ GeV}^2 \leq t \leq 0 \text{ GeV}^2$. The exchange is exotic, characterized as a doubly-charged meson with S = +1 and +2 for Σ^- and Ξ^- production, respectively. A measurement of $\alpha(0)$ and $\alpha'(0)$ consistent with triple Regge results for non-exotic exchanges lends support for the existence of exotics, and will yield definite experimental predictions of the possible masses and spins of exotic mesons to be searched for as s-channel resonances. The polarization of the charged hyperons will also be measured.

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I. Introduction

We propose an experiment to study the composition and some aspects of the production dynamics of a charged hyperon beam at Fermilab using the triple Regge theory of inclusive processes as a guide to determine what constitutes an interesting set of measurements. The emphasis is on a simple approach towards achieving a first look at the Σ^- and Ξ^- components of such a beam, and reflects the experience of several of the authors in a recently completed set of experiments in the charged hyperon beam at the AGS.[1)] Our apparatus would utilize existing Fermilab magnets for both the hyperon beam channel and the particle detection spectrometer. The knowledge of the beam that can be achieved with a simple first experiment will be very useful in designing future experiments involving elaborate instrumentation for studying rare decays of hyperons: *semi-leptonic decays* ($\Xi^- \rightarrow \Lambda e^- \nu$), *rare decays involving* $\Delta S = 2$ ($\Xi^- \rightarrow n\pi^-$), or strangeness-changing neutral currents ($\Xi^- \rightarrow \Sigma^- \nu\bar{\nu}$).

II. Physics Justification

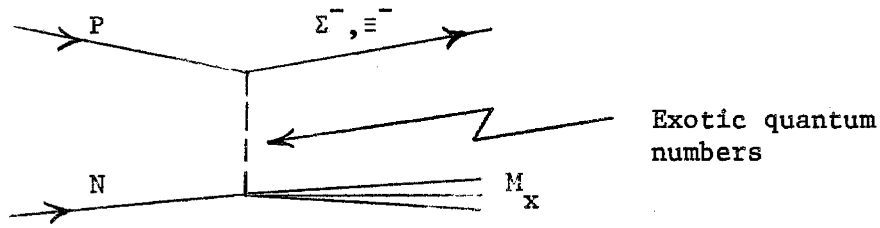
The physics interest in this proposal involves a study of the following reactions:

$$(1) \quad p + \text{nucleon} \rightarrow \Sigma^- + M_x, \qquad \text{and}$$

$$(2) \quad p + \text{nucleon} \rightarrow \Xi^- + M_x$$

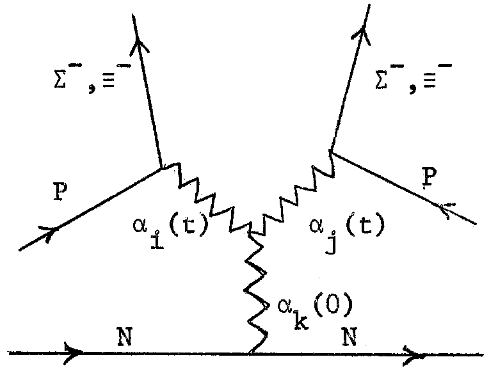
where M_x is the missing mass in these reactions. Reactions (1) and (2) are to be studied over a range of hyperon production angles ranging from 0 to 7.5 mrad., and hyperon momenta between 200 GeV/c and 400 GeV/c. The range of t covered is $-5\ \text{GeV}^2 \leq t \leq 0\ \text{GeV}^2$. In addition, the polarization of hyperons produced at angles other than 0° can be determined.

Recent work in the neutral hyperon beam at Fermilab involving a study of the reaction p + nucleon → $\Lambda^\circ + M_x$ has revealed that Λ° production is consistent with a mechanism mediated by Reggeized K^* exchange.[2)] Single Reggeon exchange is also indicated for the K_s^o and $\overline{\Lambda}^\circ$ inclusive production data. In the case of $\overline{\Lambda}^\circ$ production this is a striking result because here single Reggeon exchange must be exotic. Whether or not Σ^- and Ξ^- production also proceed by single Reggeon exchange is of interest because a production process of the sort



would require that the exchanged Reggeon be an exotic meson, i.e., it would carry quantum numbers which cannot be constructed by a quark, anti-quark pair. One reason for a quick look at the negative hyperon yields is that the exotic character of their production may well result in a suppression of the yield below the estimates made using lower energy cross-sections and scaling to higher energies.

To apply the triple Regge theory to the inclusive production of Σ^- and Ξ^- studied as a function of s,t, and M_x^2; it is necessary to compare the measured invariant cross sections s $d^2\sigma/dtdM_x^2$ with a form determined from the triple Regge diagram shown below.



The form of the cross section corresponding to this diagram is given by[3)]

$$s \frac{d^2\sigma}{dt dM_x^2} = \frac{1}{s} \sum_{ijk} G_{ijk}(t) \left(\frac{\nu}{s}\right)^{-\alpha_i(t)-\alpha_j(t)} (\nu)^{\alpha_k(0)} \qquad (3)$$

where G_{ijk} is the triple Regge term, and $\nu = M_x^2 - t - M_{nucleon}^2$. If this process is governed by single-Reggeon exchange, then $\alpha_i(t) = \alpha_j(t)$ are the trajectories of exotic mesons with charge +2 and strangeness +1 and +2 for Σ^- and Ξ^- production respectively. If $\alpha_k(0)$ is the Pomeron, which is expected to dominate, then $\alpha_k(0) = 1$. Therefore, equation (3) becomes

$$s \frac{d^2\sigma}{dt dM_x^2} = G(t) \left(\frac{\nu}{s}\right)^{1-2\alpha(t)} \qquad (4)$$

The purpose of the experiment is to measure the quantity $\alpha(t)$ as a function of t for fixed s. If the exchange of the exotic quantum numbers is due to a single, exotic meson, then $\alpha(t)$ might have a slope of $\sim 1\ \mathrm{GeV}^{-2}$. If the exchange involves two particles, then a simple argument predicts that $\alpha(t)$ will have a slope of about $\frac{1}{2}\ \mathrm{GeV}^{-2}$. It is not clear that this argument, which is made for two body reactions, can be extended to triple Regge theory, but in any case, it is clear that the slope of the effective trajectory is sensitive to the exchange mechanism. Therefore, an experimental determination of this trajectory is important. If the measured slope of $\alpha(t)$ is indeed equal to $\sim 1\ \mathrm{GeV}^{-2}$, then this lends some credence to the prediction (within the errors involved in extrapolating $\alpha(t)$ to positive values of t) of the masses of exotic mesons corresponding to various spin assignments which might be seen as s-channel resonances.

A second feature of the experiment which we propose is to measure the polarization of the Σ^- and Ξ^- as a function of hyperon production angle. Polarization has been observed in the Fermilab neutral hyperon beam. If the Ξ^- particles are observed to be polarized, one would then consider designing an experiment to measure the magnetic moment of the Ξ^-. We are proposing an essentially symmetric detection apparatus (the calometer would have to be moved during the experiment) for detecting hyperons, and this design feature together with the capability of reversing the $\vec{B}$ field of the spectrometer magnet will provide a method for determining systematic effects in a polarization measurement. Given the known values for the α parameters for the Σ^- and Ξ^- decays (- 0.07 and - 0.39, respectively), a sample of 10,000 Σ^- and Ξ^- decays would enable us to measure P_{Ξ^-} to a statistical accuracy of ± 0.04 and P_{Σ^-} to an accuracy of ± 0.2.

Some speculation

In our attempt to present a conservative set of goals, we cite the following physics as perhaps feasible with the proposed apparatus.

The reaction p + nucleon $\rightarrow \Omega^- + M_x$ with the subsequent decay $\Omega^- \rightarrow \Xi^- + \pi^\circ$ would be recognized by observing a Ξ^- which is non-colinear with the beam particle (Ω^-) and whose momentum is substantially lower than the channel momentum. Assuming the parent particle for the decay reaction to be an Ω^-, the calculated missing mass for the decay reaction should equal the mass of the π°. This reaction may not be observable because the Ω^- production rate may be too low when compared with background reaction rates which can simulate the event (see section VII).

The hyperon channel $\vec{B}$ field could be reversed to transport a positive hyperon beam (Σ^+) to the detector area. An inclusive study of Σ^+ production is interesting because the reaction proceeds by non-exotic exchange, (Q = 0, S = +1, n = 0) and would provide an interesting comparison with Σ^- production. The problem here is that the proton beam dump location in the hyperon channel would be situated farther downstream in the channel, thereby increasing the background levels at the detectors. We feel that a Σ^+ study is possible at production angles of about ± 7.5 milliradians but difficult at production angles close to 0°. (See section IV)

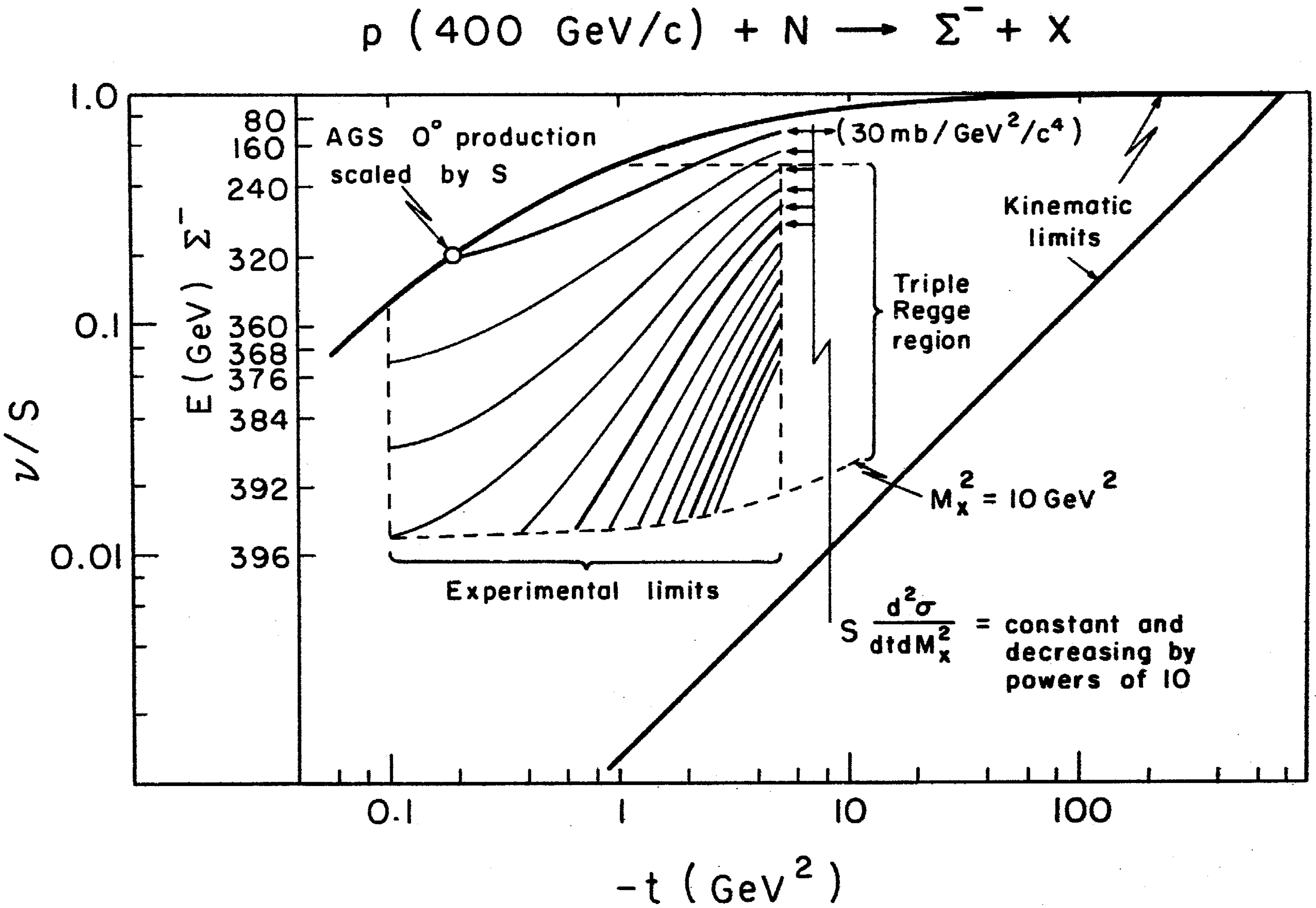
III. Triple Regge Theory and the Kinematics of Hyperon Production

The equation

$$s \frac{d^2\sigma}{dt\,dM_x^2} = G(t) \left(\frac{\nu}{s}\right)^{1-2\alpha(t)} \qquad (4)$$

can be expected to describe the data in a region of small $|t|$ for large M_x^2 and $\frac{\nu}{s} << 1$, which we have taken to be $M_x^2 > 10$ GeV^2/c^4, and $\frac{\nu}{s} < 0.5$. In estimating expected rates we have assumed G(t) = constant, and $\alpha(t) = \alpha(0) + \alpha'(0)t$ with $\alpha(0) = -0.7$ for Σ^- production, $\alpha(0) = -2.0$ for Ξ^- production, and $\alpha'(0) = 1$ GeV^{-2} for both Σ^- and Ξ^- production. These choices are based on the Σ^- and Ξ^- production data from the AGS (29.4 GeV/c protons on Be)[4] and CERN (24 GeV/c protons on W),[5] Chew-Frautschi plots of meson and baryon mass systematics which indicate $\alpha'(0) \sim 1$ GeV^{-2}, and recent FNAL data on Λ°, K_s^o, and $\bar{\Lambda}^\circ$ inclusive production which support the applicability of triple Regge theory with single-particle exchange.

The allowed kinematic region of Σ^- production (Ξ^- production is similar) is shown in Fig. 1 for 400 GeV/c incident protons. The interior dashed curve shows the area of proposed experimental investigation, and the contour lines are lines of constant $s \frac{d^2\sigma}{dt\,dM_x^2}$ decreasing by powers of ten, the topmost line having the value 30 mb/GeV^2/c^4 as determined from the AGS zero degree Σ^- production spectrum.[4]



p (400 GeV/c) + N ⟶ Σ⁻ + X
ν/S
1.0
0.1
0.01
E (GeV) Σ⁻
80
160
240
320
360
368
376
384
392
396
AGS 0° production scaled by S
(30 mb/GeV²/c⁴)
Triple Regge region
Kinematic limits
M²x = 10 GeV²
Experimental limits
S d²σ/dtdM²x = constant and decreasing by powers of 10
0.1
1
10
100
-t (GeV²)

Figure 1.

(485)

The Σ^- production cross section at 29.4 GeV/c scaled by s to 400 GeV/c is shown in Fig. 1 as a circled point. In Fig. 2 is shown a plot of $\frac{\nu}{s}$ versus the Σ^- laboratory production angle for contours of fixed t and constant $s \frac{d^2\sigma}{dtdM_x^2}$. The intersection of the contours of fixed t and constants $s \frac{d^2\sigma}{dtdM_x^2}$ represent a matrix of points at which measurements of the invariant cross sections yield data from which the trajectory $\alpha(t)$ of equation (4) may be determined.

Specifically, measurements of $s \frac{d^2\sigma}{dtdM_x^2}$ at the contour intersections along a line of fixed t should (according to triple Regge theory) fall at equal spacings on a straight line when plotted as $\log (s \frac{d^2\sigma}{dtdM_x^2})$ versus $\log (\frac{\nu}{s})$. The slope of this line is $\alpha(t)$ for that t value. The matrix of possible data points covers a range of laboratory angles between 0 and 7.5 mrad., and laboratory momenta between 200 GeV/c and 400 GeV/c. Accurate measurements of $\alpha(t)$ can be obtained by measuring the production cross section over three or more orders of magnitude at fixed t.

Further Speculation

If the triple Regge term, G(t), is roughly the same for Σ^- and Ω^- inclusive production, then the Σ^-/Ω^- production ratio at fixed t is equal to $(\nu/s)^X$ where $X = -2(\alpha(t)_{\Sigma^- \text{ production}} - \alpha(t)_{\Omega^- \text{production}})$. Writing $\alpha(t) = \alpha(0) + \alpha'(0)t$, and assuming $\alpha'(0)_{\Sigma^-} = \alpha'(0)_{\Omega^-} \sim 1 \text{ GeV}^{-2}$; we have

$$(5) \qquad \frac{\Sigma^-}{\Omega^-} = (\frac{\nu}{s})^{-2(\alpha(0)_{\Sigma^-} - \alpha(0)_{\Omega^-})} .$$

$\alpha(0)_{\Sigma^-}$ is ~ -0.7 from above and $\alpha(0)_{\Omega^-}$ is expected to be considerably more negative leading to a large negative value for X. At small values of ν/s this

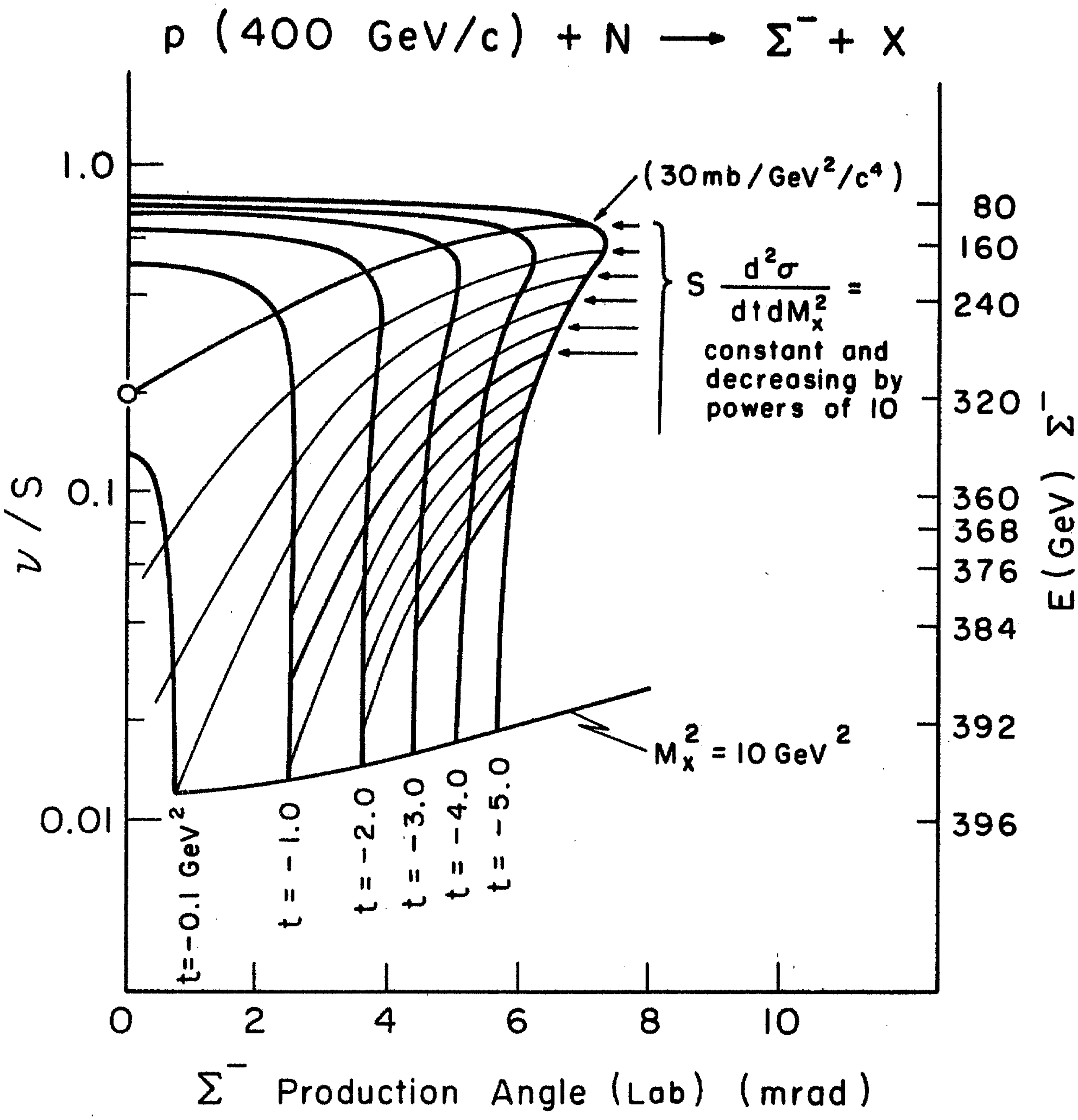

p (400 GeV/c) + N ⟶ Σ⁻ + X
1.0
0.1
0.01
ν / S
(30 mb / GeV²/c⁴)
S d²σ / dt dM²ₓ =
constant and
decreasing by
powers of 10
80
160
240
320
360
368
376
384
392
396
E (GeV) Σ⁻
M²ₓ = 10 GeV²
t=−0.1 GeV²
t = −1.0
t = −2.0
t = −3.0
t = −4.0
t = −5.0
0
2
4
6
8
10
Σ⁻ Production Angle (Lab) (mrad)

Figure 2.

gives a very large (unfavorable) Σ^-/Ω^- ratio, but for large ν/s, i.e. $\nu/s \to 1$, the ratio will approach unity. It is, of course, an open question whether or not the triple Regge theory will fail well before this favorable region is reached, but the ratio of $\Lambda^\circ/\bar{\Lambda}^\circ$ production in the FNAL neutral hyperon beam[2)] lends considerable support to this speculation. ($\Lambda^\circ/\bar{\Lambda}^\circ \sim 6.7$ at $\nu/s = 0.83$ and ~ 720 at $\nu/s = 0.42$ independent of t.)

IV. Hyperon Beam

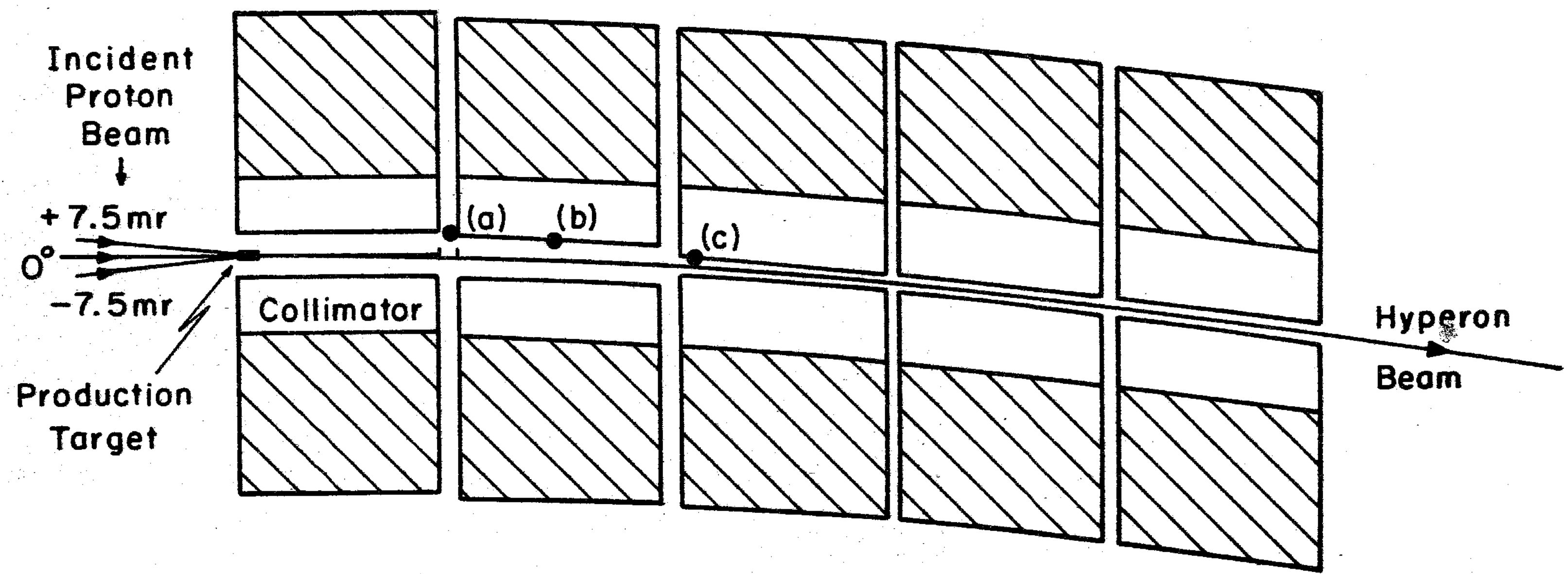
The hyperon beam channel consists of five Fermilab 5 - 1.5 - 120 EPB magnets containing collimating material along the entire length of the channel as well as tungsten at those locations where the proton beam is expected to be dumped. Figure 3 is a plan view of the beam and is designed to transport 400 GeV/c negative particles to the experimental area. The final three magnets contain narrow collimation which defines a beam spot 2 cm. wide by 2 cm. high. There is no Cerenkov counter in the beam to tag hyperons or to separate hyperons from the larger π^- component in the beam. This beam is essentially a scaled-up version of the AGS charged hyperon beam. Since the charged pion multiplicities which are responsible for the background muons at the detection apparatus vary as log s and s varies as the proton beam energy, the length of magnetic shielding downstream of the proton beam dump position must be a factor of 3 greater than the comparable distance in the AGS beam. Having satisfied this requirement by the use of 5 standard EPB dipoles, we arrive at the following beam characteristics for the negative beam.

$$p_{max} = 400 \text{ GeV/c}$$

$$\text{Total Bend} = 18 \text{ milliradians}$$

$$\Delta\Omega = 1.35 \times 10^{-6} \text{ steradians}$$

$$\Delta p/p = 5\%$$



(a) Position of proton beam dump for − 7.5 mr hyperon production angle.

(b) Position of dump for 0° production angle.

(c) Position of dump for + 7.5 mr production angle.

All magnets are 5 − 1.5 − 120 EPB dipoles.

1 m

10 cm

Figure 3.

(485) 7A

Shown in Figure 3 are the approximate locations in the channel where the proton beam is to be dumped. These locations correspond to - 7.5, 0 and + 7.5 mrad. The collimator should be lined with an effective stopping material such as hevimet to provide rapid absorption of pions produced in the dump before they can decay into muons.

Further speculation

If the polarity of the channel $\vec{B}$ field were reversed to produce a Σ^+ beam, the beam dump location for a Σ^+ production angle of - 7.5 mrad. would lie between positions (a) and (b). For a production angle of + 7.5 mrad. the dump location would be approximately opposite the point (a) in the channel. For production angles between 0° and + 5 mrad., the proton beam could traverse the entire channel, emerging at the downstream end at full intensity and this would represent an unacceptable situation.

V. Experimental Apparatus

The experimental apparatus beginning with the downstream aperture of the hyperon channel is shown in Fig. 4. A cluster of high resolution proportional wire chambers (PWC's) is located at the end of the beam channel to tag the incident hyperon trajectories. This is followed by a 10 m decay region. Two BM109's instrumented with PWC's provides information on the decay angles and momenta of the charged decay products. The final element in the apparatus is a hadron calorimeter of ∿ 3 interaction lengths to detect the final neutron or proton from the hyperon decay.

The apparatus trigger is designed to detect the following decays:

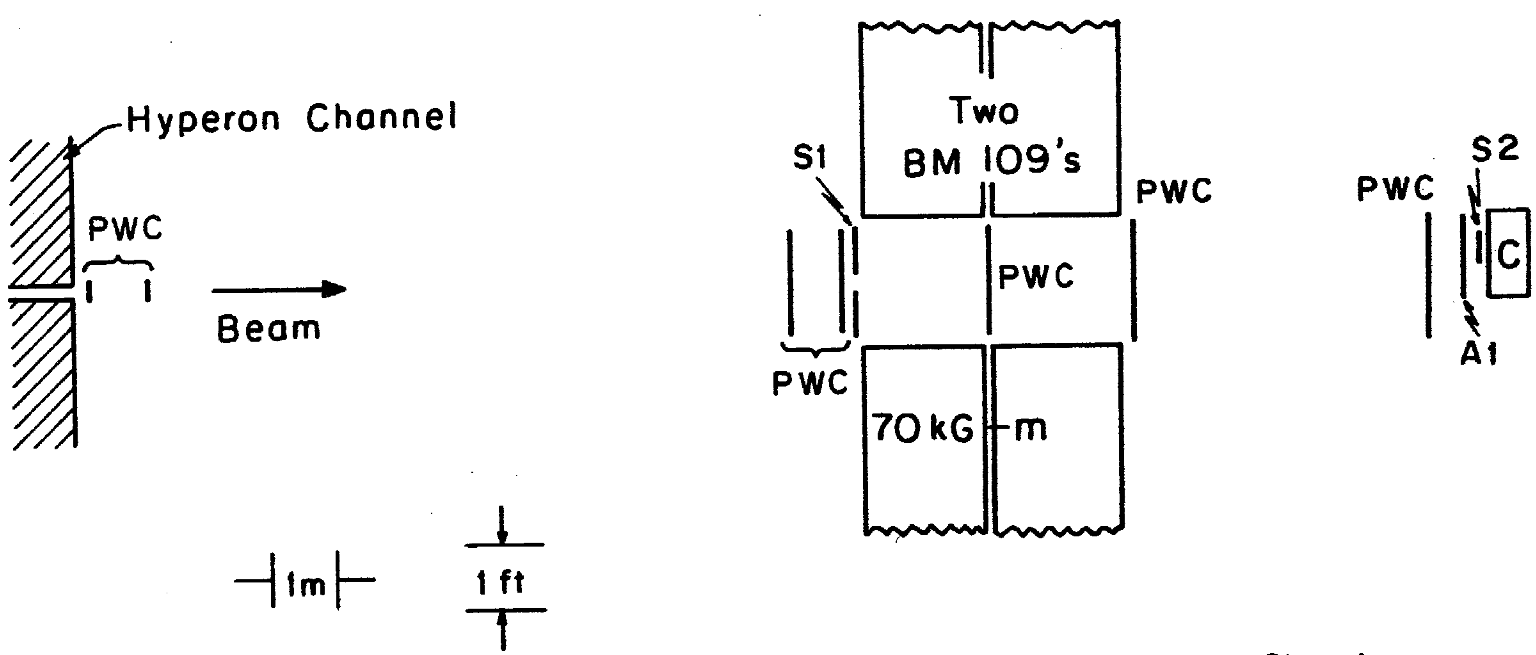
(6) $$\Sigma^- \rightarrow \pi^- + n$$

(7) $$\Xi^- \rightarrow \pi^- + \Lambda^\circ, \quad \Lambda^\circ \rightarrow \pi^- + p$$

(485) 8A

Schematic of Proposed Apparatus

(Plan View)



PWC = Proportional Wire Chamber

A1, S1, S2 = Scintillation Counters

C = Calorimeter

Figure 4.

A thin scintillator (S1) with a hole to accommodate the beam and the forward going baryon will be located in front of the magnet to detect the π^- from Σ^- and Ξ^- decays. An anti-coincidence counter (A1) in front of the calorimeter plus the signal from the calorimeter (C) will give a positive identification for the neutron from Σ^- decay. The proton from either Ξ^- (or Ω^-) will also register in the calorimeter and will be further identified by a scintillator (S2) appropriately placed in front of it. The beam will be counted by the initial set of PWC's (B). If necessary, a further strengthening of the trigger can be accomplished by incorporating the information from the PWC's before and after the BM109 is into the trigger. The final trigger will be an "OR" of the Σ^- and Ξ^- triggers:

(8) Σ^- trigger = $B \cdot S1 \cdot \overline{A1} \cdot C$

(9) Ξ^- trigger = $B \cdot S1 \cdot S2 \cdot C$

Because of the relative preponderance of Σ^- to Ξ^- it is expected that some prescaling of the Σ^- trigger and event buffering may be necessary in order to accommodate the full Ξ^- flux. The PWC's are well suited to this mode of data taking and to the high event rate which can be expected.

VI. Rates and Running Time

Based on the suppositions of triple Regge theory as discussed in section III, and the measured rates at lower energy we can calculate the hyperon flux at the exit of the beam channel. A representative set of rates is shown in Table I. For the momentum range from 200 GeV/c to 400 GeV/c between 10% and 30% of the hyperons produced within the momentum bite and solid angle of the channel survive their passage through the channel's 17m length.

Estimates of the π^- component of the beam have been made, and the hyperon yields shown in Table I can be achieved with a total beam intensity (including π^-) that does not exceed 10^6 particles/10^{10} incident protons. At the lower values of $\frac{\nu}{s}$ the π^- component drops along with the hyperon component.

Table I

Numbers of Σ^- and Ξ^- at the exit of the hyperon channel for 10^{10} protons onto a 10 cm Be target.

$t = -0.1\ GeV^2$		
$\frac{\nu}{s}$	Σ^-	Ξ^-
.070	$2.6x10^4$	26
.029	$3.0x10^3$	0.75
.012	$3.1x10^2$	$3.1x10^{-3}$

$t = -2.0\ GeV^2$		
$\frac{\nu}{s}$	Σ^-	Ξ^-
0.48	$3.1x10^4$	$4.7x10^3$
0.34	$8.0x10^3$	$5.0x10^2$
0.24	$1.3x10^3$	32
0.165	$1.8x10^2$	1.6
0.115	22	0.12

$t = -5.0\ GeV^2$		
$\frac{\nu}{s}$	Σ^-	Ξ^-
0.48	$3.1x10^2$	47
0.40	55	5.1
0.33	0.84	$4.8x10^{-2}$
0.27	0.11	$3.7x10^{-3}$
0.23	$1.4x10^{-2}$	$3.1x10^{-4}$

The fraction of hyperons which decay in the 10 m drift region after the channel, and are detected, is shown in Table II.

Table II

Fraction of hyperons which both decay and are detected by the spectrometer.

p(GeV/c)	Σ^-	Ξ^-
200	0.74	0.29
400	0.49	0.13

We would require approximately 500 hours of beam time to do the experiment. It would be our intention to take the bulk of the data at an incident beam energy of 400 GeV using an intensity of between 10^{10} and 10^{11} protons/pulse. Because of the triple Regge prediction that the cross sections scale as s, we would like to do some running at 200 and 300 GeV using a "front porch" mode of accelerator operation.

VII. Background

A goal of this experiment is to construct a set of apparatus which presents a minimum of mass to the hyperon beam. We anticipate that the ratio π^-/Σ^- in the Fermilab beam will be no greater than about 10:1. Our reason for rejecting the inclusion of a beam Cerenkov counter into the proposed Fermilab beam (such as is present in the AGS beam for separation of pions and hyperons) is that threshold counters must by their nature be very long (100 meters), and sophistocated differential counters are expensive and not required for the type of physics that we propose.

In the proposed experiment we are triggering on hyperon decay topologies. The background will consist mainly of beam pions interacting in material upstream of the spectrometer magnet, a claim that can be supported by our AGS experience. In the AGS beam our background triggers for Ξ^- were entirely consistent with the pion flux interacting with 2 cm of lucite associated with scintillation counters and plastic Cerenkov counter mirrors.

VIII. Requirements of Fermilab

We have designed the experiment around existing laboratory magnets. We request that the laboratory supply two BM109's, five EPB magnets, standard fast electronics, and the necessary shielding for the channel. The experimenters plan to construct the remainder of the apparatus. The arrangements for steering the primary beam onto the production target at a variable angle would also need to be worked out.

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FIGURE CAPTIONS

Fig. 1. The allowed kinematic region as a function of ν/s, and t for the reaction p + nucleon $\rightarrow \Sigma^- + M_x$. The interior dashed curve is the area of proposed experimental investigation. The contour lines are lines of constant invariant cross section $(s\frac{d^2\sigma}{dt\ dM_x^2})$ decreasing in powers of 10. The circled point is the inclusive cross section scaled from the lower energy AGS data.[4)]

Fig. 2. ν/s versus the Σ^- laboratory production angle (θ) in the reaction p + nucleon $\rightarrow \Sigma^- + M_x$ for contours of fixed t and constant invariant cross sections $(s\frac{d^2\sigma}{dt\ dM_x^2})$. The cross section contours are decreasing in powers of 10, and the circled point is the inclusive cross section from the lower energy AGS data.[4)]

Fig. 3. The proposed negative hyperon channel for 400 GeV incident protons. Black dots indicate the points where the primary beam is dumped for production angles of −7.5, 0, +7.5 mrad. The total bend is 18 mrad.

Fig. 4. A schematic of the proposed experimental apparatus for the detection of Σ^- and Ξ^- hyperons.

ADDENDUM TO PROPOSAL 485
(Inclusive Production of Negative Hyperons)

We have developed a specific arrangement for the magnetic channel and other apparatus which will fit between the two arms of the E-288 spectrometer in the existing proton central facilities. The placement of the major components of the experiment is shown in Fig. 1.

A variable hyperon production angle between +7.5 mrad and -7.5 mrad is achieved through the use of two magnets. First, the primary proton beam is deflected by $\leq$0.83 mrad by a horizontal steering magnet, ST 504, upstream of the normal target enclosure. Secondly, it is bent back onto the hyperon production target by the B1 dipole immediately upstream of this target.

The details of the magnetic channel represented by the two B1 dipoles downstream of the production target are shown in Fig. 2. This arrangement is essentially equivalent in bending power and overall length to the five EPB magnets shown in Fig. 3 of the original proposal (one B1 is approximately equal to 2.5 EPB's). It has the advantage that it allows the beam to be dumped at a fixed longitudinal distance along the channel and outside the magnets. We believe that this will give more uniform backgrounds over the various channel momenta and production angles required for the experiment.

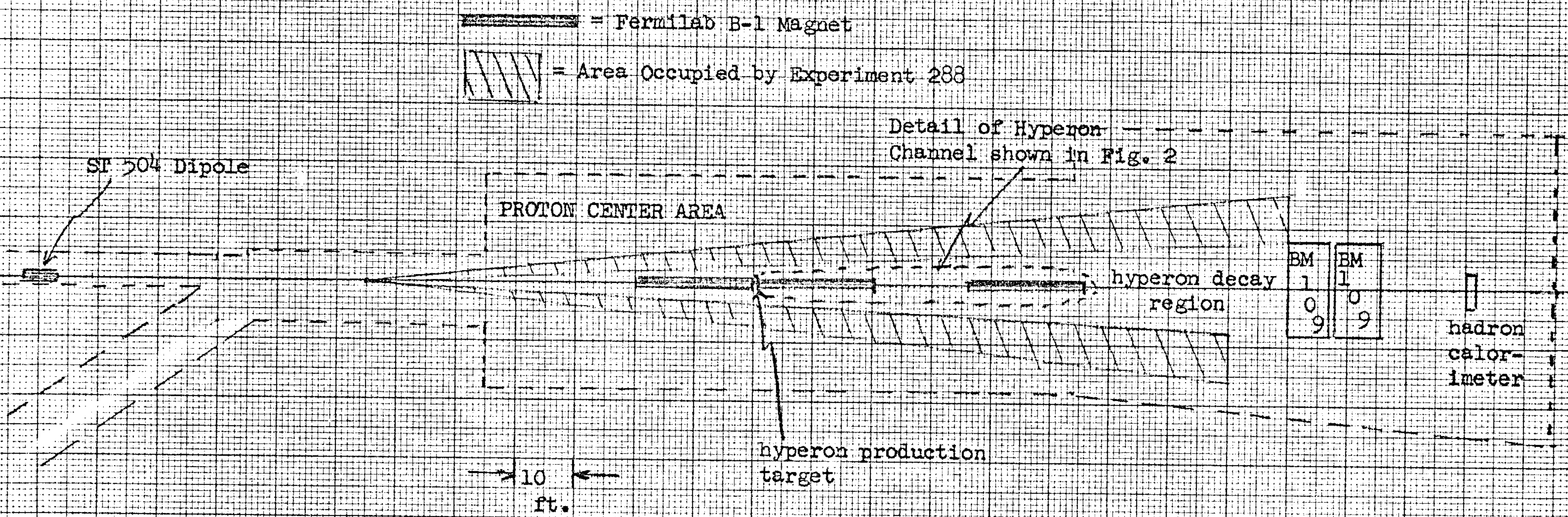

Fig. 1. Approximate Plan View of Hyperon Spectrometer System Using Fermilab B-1 Magnets

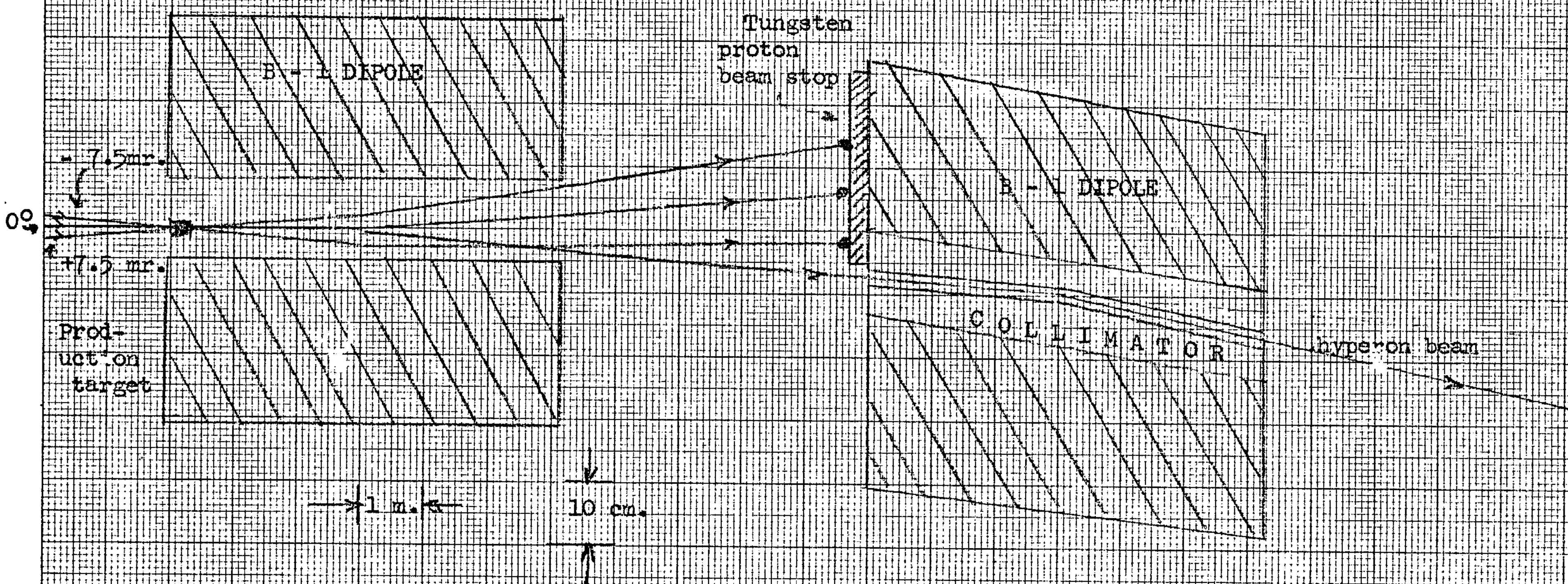

Fig. 2. Detail of Hyperon Channel

The total angle of bend of the hyperon channel relative to the 0° proton direction is 16.6 milliradians.