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HYPERON BEAMS AT THE 200-GEV WESTON ACCELERATOR AND POSSIBLE EXPERIMENTS WITH THESE BEAMS

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Introduction

Hyperons can be produced in nucleon-nucleon collisions $N + N \rightarrow Y + K + N$, pion-nucleon collisions $\pi + N \rightarrow Y + K$, kaon-nucleon collisions $K + N \rightarrow Y + N$, and finally beams of hyperons can be obtained from the decay of other hyperons $Y \rightarrow Y' + \pi$. The production of hyperons by pions results from the peripheral collisions, and therefore, the spectra of hyperons will be relatively "soft." The hyperons produced by kaons probably come from baryon exchange, and the hyperon spectrum should be somewhat "harder" as compared with the pion-produced hyperons. The intensity of these hyperon beams will be limited by the available kaon-beam intensities. Several designs of charged and neutral hyperon beams were proposed in the past. Longo[1] suggested that a Λ^o beam can be obtained from roughly momentum-analyzed Ξ^- beams. He estimated that beams with 1.5×10^5 Λ^o at 90 GeV/c and $\Delta p/p$ of 40% can be obtained from 10^{13} 200 GeV/c protons per pulse incident on a production target. In that beam the predicted $n : \bar{n} : \Lambda$ ratio is 100 : 15 : 1. Garbutt et al.[2] considered a labeled beam of Λ^o produced from Ξ^o decay ($K^- + p \rightarrow \Xi^o + K^o$, where K^o is detected at the production target). Their conclusion was that a beam of Λ's produced in this manner is of low intensity and cannot be used in any practical way. V. Cook[3] considered a beam produced with separated K^- beam ($K^- + p \rightarrow \Xi^- + K^+$). In that beam, Ξ^-'s were selected by detecting K^+. This method also suffers from a low intensity of Ξ^-. He also discussed a beam of Ξ^- in the range of 50-100 GeV/c selected from a negative beam of particles. The expected rate of Ξ^- in such a beam is $5\ \Xi^-/10^7$ beam particles.

In this note two methods of producing high-flux hyperon beams are considered.

(i) Hyperon beams are produced with neutrons in the so-called 2.5-mrad neutral beam which is proposed for the Target 1 Station in the EPB.[4]

(ii) Hyperon beams are produced with the primary EPB beam in a separate target area. This method is most desirable. However within the present concept of Target 1 Area the space requirements for a charged hyperon beam are not compatible with proposed π and ν beams which are produced near 0°. Detailed considerations in designing hyperon beams show that a special target area should be provided for these beams. In order to learn about these design problems a 150 GeV/c Σ^- beam was discussed in some detail elsewhere.[5]

In thinking about hyperon beams a few general remarks should be made. The combination of masses and mean lives imply that mean decay lengths for several pairs of hyperons are approximately the same and these pairs are $\Xi^0\ \Lambda^0$, $\Xi^-\ \Sigma^-$, and $\Omega^-\Sigma^+$ (Figs. 1 and 2).

The lengths of hyperon beams should be kept short, say 20 m. A 20 m length for a 100 GeV/c Λ^{o} beam corresponds to a decay-loss factor of ~ 18. Also, the hyperon beams should be designed at 5 mrad production angle where the ratio of neutron/neutral hyperons and protons to charged hyperons is the lowest. Hagedorn and Ranft[6] computed production of particles with 200 GeV/c protons on protons and other targets using several production models. The yields of Σ's, Λ's, $K^{\pm}$, p and $\pi^{\pm}$ as computed according to the thermodynamical model are shown in Figs. 5-12 of Report B. 5-68-24.

It is evident that if the predictions of Hagedorn and Ranft become a reality, the 200 GeV/c Weston Accelerator will be a unique source of intense hyperon beams.

In an attempt to learn about the problems which one may encounter in working with hyperon beams, the following experiments were designed: scattering of Λ and Σ on protons, and search for the violation of $\Delta S = -\Delta Q$ rule via beta decay of $\Sigma^{\pm}$. These feasibility studies also helped to decide what experimental facilities, like special magnets, Cerenkov counters, computers, etc. should be provided by NAL. Many problems were uncovered in the course of, so to speak, "zeroth order" designs of these experiments and in a relatively short time, it was not possible to supply answers to all of them. Therefore, these designs should not be considered by any means final.

<u>Elastic Scattering of 100 GeV/c Lambdas on Protons</u>

This experiment was designed to operate in the 2.4 mrad neutral beam proposed in the EPB Target Area 1. The characteristics of the neutron beam are $\Delta\Omega = 10^{-7}\pi e$, i.e. the divergence of the beam is 0.3 mrads. The neutron spectrum and intensities are as predicted by Hagedorn and Ranft for the protons, i.e. the neutron spectrum at 2.5 mrads production angle should be peaked at ~ 160 GeV/c with $\Delta p/p = 0.8$. Taking 10^{13} interacting protons at a production target in the EPB, a flux of 2×10^9 neutrons per pulse impinges on a 4 cm × 4 cm × 20 cm beryllium target which is placed in a sweeping magnet. See Fig. 3. The predicted flux of lambdas within a 5 mrad cone per 2×10^9 neutrons per pulse and with $\Delta p/p = 1/2$ for the Λ beam is 5×10^5 Λ's.

The expected total number of neutrons per Λ in that beam as a function of the production angle is shown in Fig. 4, and it is also evident that the lowest ratio of neutrons per Λ is obtained at 5 mrads production. Charged particles are swept up and down by a horizontal sweeping field, to keep the charged particles flux on the left and right side of the beam at a minimum.

In the design of this experiment, an attempt was made to assure that the recoil protons with the lowest possible momenta can be measured, since the diffraction cross section for Λp scattering is strongly peaked forward, and the detectable momentum range for the recoil protons is $P_p = 200\text{-}700$ MeV/c or $0.32 < t < 0.5$ $(\text{GeV/c})^2$. Recoil protons are

Table I. Some Kinematic Characteristics of 100 GeV/c Λ's and K's.

	P_t (MeV/c)
$\Lambda\pi p$	100
$\Lambda\beta$	163
$\Lambda\mu$	131
$K\pi\pi$	206
Ke_3	229
$K\mu_3$	216
$P\Lambda$ 100 GeV/c $\Lambda \rightarrow \pi p$	6.4 GeV/c $< P\pi <$ 24.4 GeV/c 75.6 GeV/c $< Pp <$ 93.5 GeV/c $\theta_{max}(p\pi) = 0.5°$
PK 100 GeV/c $K \rightarrow \pi\pi$	8 GeV/c $< P\pi <$ 92 GeV/c $\theta_{\pi\pi} = 0.5°$

within the angular range in the laboratory of 90° - 73°. The momentum of scattered Λ is in the range of $99 < P_\Lambda < 100$ GeV/c and the scattering angle is 0-0.7°. Some kinematic characteristics of Λ and K decays are summarized in Table I.

In this experiment the lambda beam is incident on a 1-m long cylindrical hydrogen target 18 cm in diameter with a cylindrical hole 10 cm in diameter. Such a target design allows for the neutron beam to pass through the target without interacting. Similarly, the spark chambers will also have a hole for that beam. This arrangement gives the n/Λ ratio in the angular range of interest of 20/1. Forward-going lambdas are detected by an arrangement of hodoscopes, wire chambers and a magnet as indicated in Fig. 4. The direction of the recoil proton is detected by an arrangement of wire chambers and the energy of that proton by range. Also, time of flight of the recoil protons is measured and therefore the identity of the proton is determined. In the elastic Λ scattering the incident beam of Λ's has a wide momentum spread but its direction is known to within 10 mrad and therefore the final state of $\Lambda p \rightarrow \Lambda p$ is completely determined. The experiment then provides two constraints fit for the Λp scattering. Because of the stringent kinematic criteria for this reaction, it may be possible to measure only the angle of the recoil proton and still be able to identify the elastic scattering. This question can only be answered after backgrounds in this experiment are known. In fact, the estimates show that it is sufficient to measure the energy and angle of the recoil proton only to within 5% and the momentum of the Λ and its angle to 3% in order to identify the Λp elastic process. The event trigger will be $\overline{AC_{1..4}}$ $H_{1..4}$ (2 only) $C_{1..4}\overline{AC_5}$. (See Fig. 4). The event rate in this experiment was calculated by assuming that the $d\sigma/dt = 100\,e^{-8t}$. The flux of Λ's at the hydrogen target is 2.5×10^4 Λ's per pulse/10^{13} interacting protons and the combined Λ and p detection efficiency is 15%. With these assumptions, we obtain about $2\Lambda p$ elastic events per pulse; in 100 hours therefore we would be able to collect about 50 K events taking 50% for the operating efficiency.

The backgrounds in this experiment are Λp inelastic scattering and K^0p scattering. These types of events can be ruled out on the basis of kinematics. The event $\Lambda + p \rightarrow \Sigma^0 + p$ will also be eliminated by γ detection in anticoincidence; the gamma ray corresponding to a high momentum and forward Λ is emitted at about 10° angle with respect to the incident Λ direction.

The experiment discussed above can be modified to detect cross section in the region of high momentum transfer. Furthermore by adding carbon plates around the target region the polarization of the recoil proton can be analyzed. In the event when more Λ flux is provided, a gaseous hydrogen target can be used which would allow for detection of lower momenta of recoil protons.

The flux of Λ's in the beam can be measured by detecting Λ's in the forward direction with the empty target. It may be added that with the beam of Λ's described above, we also have a K^o beam with approximately 2×10^5 K_s/burst in the primary neutron beam.

Experiment on $\Delta S = \Delta Q$ Rule with a Beam of Charged Σ's

The question of the validity of the $\Delta S = \Delta Q$ rule has received wide attention in the past. The knowledge of the degree of violation of that rule has a direct bearing on the interpretation of the K^o decays and on the CP violation in some theoretical models. Experiments designed to put limits on the violations of that rule were made by studying the K_{e_4} decays and K^o leptonic decays.

In this experiment we propose to search for the forbidden leptonic decay of Σ^+ by $\Delta S = -\Delta Q$. The present limits are

$$\frac{\Gamma(\Sigma^+ \to \ell^+ n\nu)}{\Gamma(\Sigma^- \to \ell^- n\nu)} = 0.04 \pm {}^{0.04}_{0.02}$$

i.e. the present upper limit on $\Sigma^+ \beta$-decay is $\sim 5 \times 10^{-5}$. It may be worthwhile to lower that limit by two orders of magnitude.

The $\Sigma^- \rightarrow n\beta\nu$ rate is 1.2×10^{-3} and $\Sigma^- \rightarrow n\mu\nu$ is 0.6×10^{-3}. The kinematic characteristics of the Σ decays are as follows:

		Rate
$\Sigma^- \rightarrow n + \beta + \nu$	$P_T = 230$ MeV/c	1.2×10^{-3}
$\Sigma^- \rightarrow n + \mu + \nu$	$P_T = 210$ MeV/c	0.6×10^{-3}
$\Sigma^- \rightarrow n + \pi$	$P_T = 193$ MeV/c	~ 100%

A two-body decay of 100 GeV/c Σ has a maximum opening angle of 1° in the laboratory and the range of the neutron and pion momenta are

$$64 < P_N < 96 \text{ GeV/c}, \qquad 3 < P_\pi < 35 \text{ GeV/c}.$$

We propose to make a parallel 100 GeV/c Σ beam 2 mm in diameter with the momentum bite of 1%. In the experiment the incoming Σ are identified with a threshold Cerenkov counter and are allowed to decay in a vacuum box (Fig. 5). We will detect the electron and muon and measure their momenta only in the kinematic region which does not overlap with the π^- from the two-body decay; also neutrons from Σ decay will be detected. Since the direction of the Σ is well known, the extrapolated electron trajectory to the incident beam gives the decay point of Σ. The detected neutron now gives the opening angle for the Σ decay and since the momentum of the Σ beam and the π^- are known, a two-body decay can be kinematically identified (3c fit). In order to keep down the trigger rate on the two-body decay a guard counter covering the kinematic region for π^- is used as an anti. Electrons and muons are identified by a shower counter and a coincidence counter placed after a suitable amount of absorber. Any Σ-decay event which has more than one charge particle originating from the decay volume will be rejected by a suitable arrangement of counters. In addition information on the spectrum of leptons from the Σ^- decays will be obtained in this experiment.

We provide a hole in the detection apparatus and sweep the beam away from the gamma and neutron detectors.

Backgrounds in the Experiment and Rates

In this experiment we are trying to detect a branching ratio of $\sim 10^{-7}$. Clearly the success of that search will depend on the identification of the desired event and the understanding of backgrounds. In considering that problem a list of known decay modes of Σ's should be studied since decay particles from some of these decays may simulate a $\Sigma\beta$ event. See Table II.

In the search for the $\Sigma^+\beta$ mode the $\beta\pi^0$ decay can be a source of Dalitz pairs. In this case the protons go forward in the beam and since the signature for the event requires one positive charged particle a pair will be rejected, $n\pi^+$ mode has a π^+ which is vetoed, and the decay is two body, $n\pi^+\gamma$ has no electron. $\Lambda \rightarrow (n\pi^0)e\nu$ will have more than one shower. Similar arguments can be used in discussing backgrounds in the Σ^- decay. Decay of other beam particles like K, π do not contribute to the backgrounds.

Table II.

Σ^+ (100 GeV/c)			
Mode	Decay Fraction	P_T MeV/c	Rejection
$p\pi^o$	53%	189	Kinematic and shower counter $66 < p_p < 96$ GeV/c $\theta_{p_{max}} \overset{p}{=} 0.13^o$ $3.5 < p_{\pi^o} < 37$ GeV/c $\theta_{\pi_m} = 0.85^o$ Need factor of 10^7
$n\pi^+$	47%	185	$64 < P_n < 96$ GeV/c $\theta_{n_{max}} \overset{n}{=} 0.13^o$ $4 < P_{\pi^+} < 35$ $\theta_{n_{max}} = 0.9^o$ Need factor of 10^7
$p\gamma$	2×10^{-3}	225	$86 < P_p < 99$ $\theta_{p_{max}} = 0.045$ $0 < P_\gamma < 12.5$ $\theta_\gamma = 12.5^o$ Need a factor of 10^4
$\Lambda e^+ \nu$ ↳ $n\pi^o$	10^{-5}	72	$80 < P_\Lambda < 99$ $\theta_{P_\Lambda} = 0.04^o$ $6 < P_{\pi^o} < 24$ $\theta_{P_\pi} = 0.5^o$
$n\mu^+\nu$ $ne^+\nu$	10^{-4}	202 224	Need a factor of 10^2 Want to detect!
Σ^- (100 GeV/c)			
$n\pi^-$	1.00	193	Need factor of 10^{-5}
$ne\nu$	1.2×10^{-3}	230	Need factor of 10^2
$n\mu\nu$	0.6×10^{-3}	210	
$\Lambda e\nu$	0.6×10^{-4}	79	
$n\pi^-\gamma$	10^{-3}	193	

Taking a beam of 10^5 Σ's and the detection efficiency of neutrons to be 1 and that for β's ~ 5% we need 10^4 pulses or 10 hours of the accelerator time to obtain the 10^{-7} sensitivity in the search for $\Sigma^+ \to n\beta\nu$ decay.

Conclusion

We considered only a few experiments with hyperons and demonstrated their feasibility. Clearly there are many more!

The 200 GeV/c accelerator will be a unique source of high flux, high-momentum hyperons and practical hyperon beams can be designed and constructed. In my opinion it is important to provide a hyperon beam in the first round of experiments.

The investigation of these few experiments with hyperons showed that equipment listed below would be necessary to perform them.

1. Sweeping Magnet

   Gap: Width 0.2 m

   Height 0.5 m

   Length 3.0 m

   B = 20 kG

2. C Magnets

   Gap: Width 0.5 m

   Height 0.3 m

   Length 1.0 m

   B = 20 kG

3. Spectrometer Magnet

   Gap: Width 1 m

   Height 0.3 m

   Length 3.0 m

   B = 20 kG

4. A small computer on line: 16-K memory, magnetic tapes and disk, scope display and a plotter.

REFERENCES

[1] M. T. Longo, Lawrence Radiation Laboratory UCRL-16830, Vol. I, 1966, p. 58.

[2] D. Garbutt et al., CERN/ECFA 67/16, Vol. II, p. 31.

[3] V. Cook, Lawrence Radiation Laboratory UCRL-16830, Vol. III, 1966, p. 133.

[4] D. H. White, A Proposal for a Unilateral Target Station Number I, NAL Summer Study Report B. 7-68-16, 1968.

[5] D. Berley, J. Lach, A. Maschke, and T. Romanowski, Hyperon Beams at a 200-GeV Accelerator, NAL Summer Study Report B. 10-68-37, 1968.

[6] J. Ranft, MPS/Int. MU/EL 67-8, CERN.

FIGURE CAPTIONS

Fig. 1. Decay length vs momentum for strange particles.

Fig. 2. Survival of hyperons from point of origin to point of decay.

Fig. 3. Experiment on elastic lambda-proton scattering. Lambdas, produced by neutrons in a target, are scattered in a liquid hydrogen target, projecting a slow proton sideways, and then decaying.

Fig. 4(a). Relative numbers of hyperons and neutrons from a neutron beam, as a function of angle.

Fig. 4(b). Ratio of hyperons to neutrons at 100 GeV/c, as a function of production angle.

Fig. 5. Experiment to search for the leptonic decay of Σ^+ hyperons.

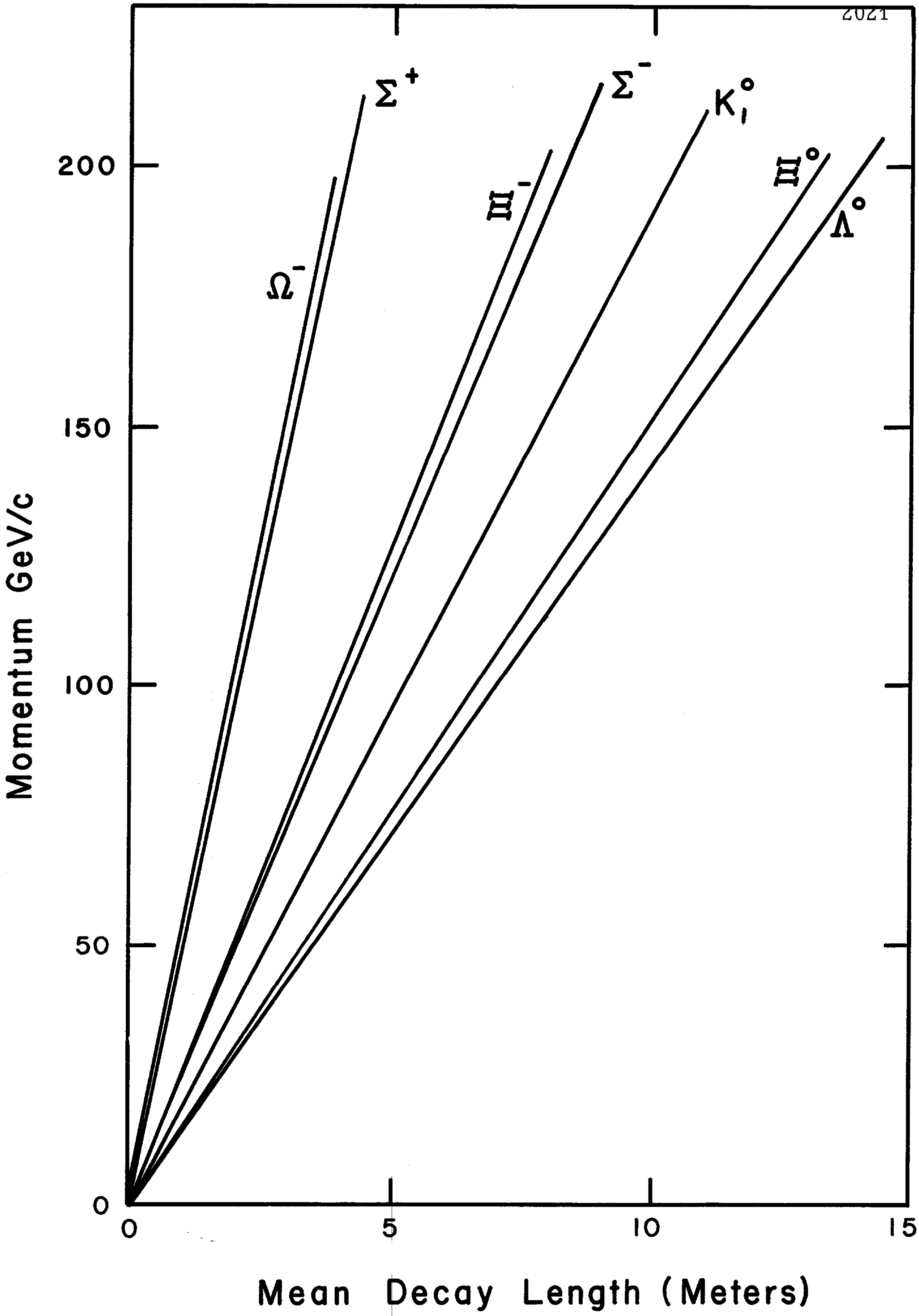

Momentum GeV/c
Mean Decay Length (Meters)
0
50
100
150
200
0
5
10
15
Ω^-
Σ^+
Ξ^-
Σ^-
K_1°
Ξ°
Λ°

Fig. 1

TM-78
2021

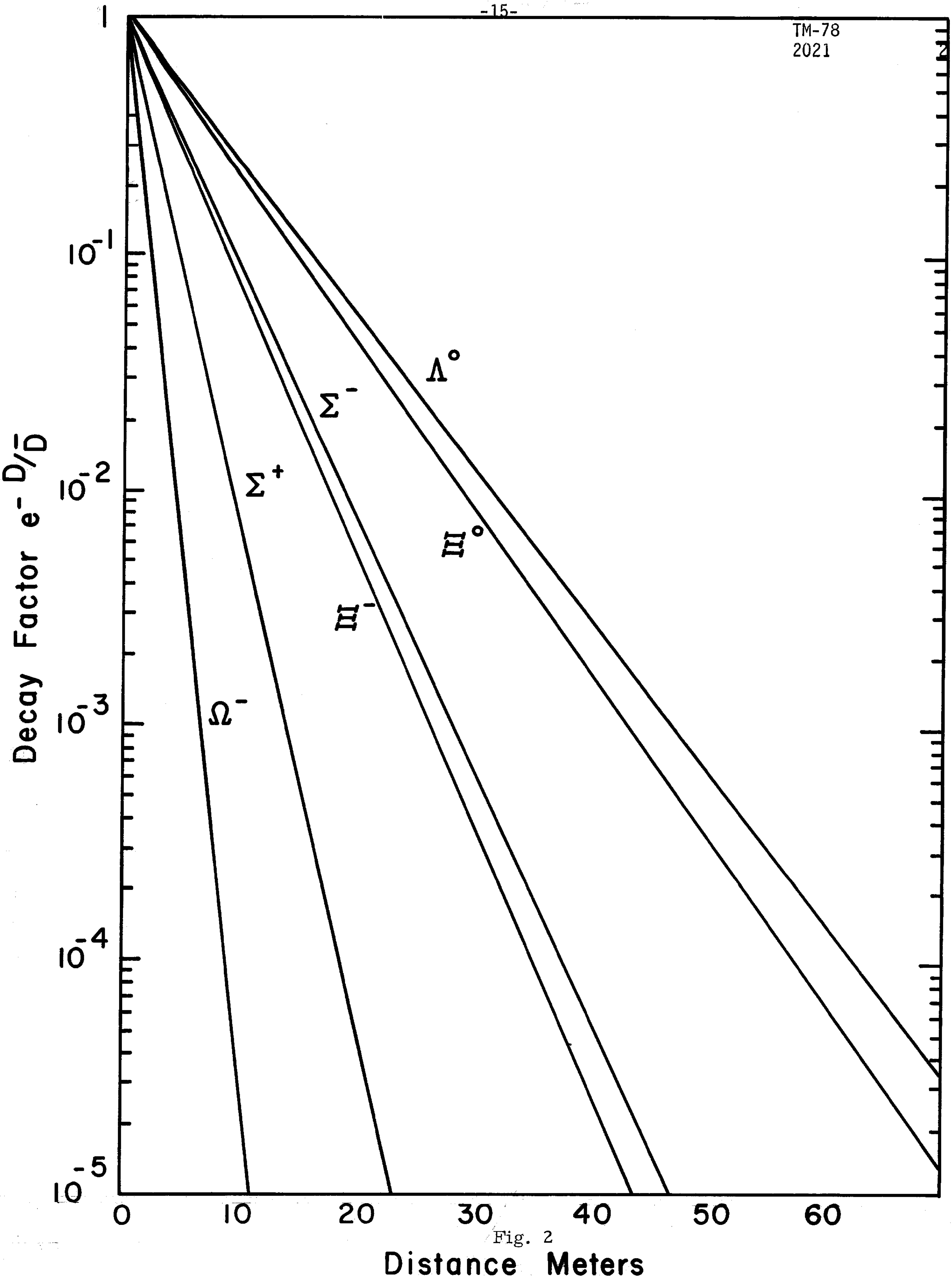
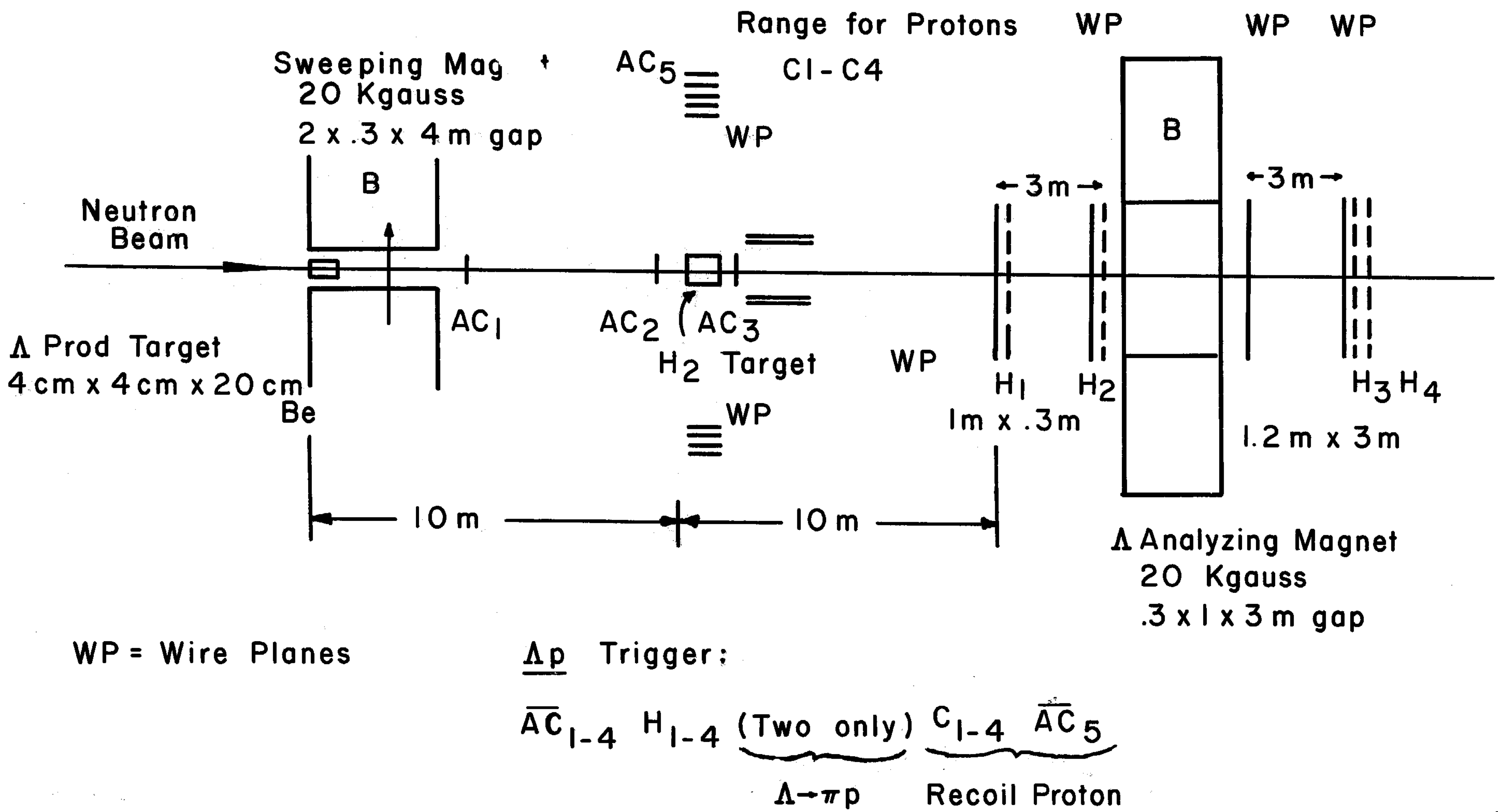


Fig. 2



Range for Protons
WP
WP
WP
Sweeping Mag
20 Kgauss
2 x .3 x 4 m gap
AC5
C1-C4
WP
B
B
Neutron
Beam
←3m→
←3m→
AC1
AC2
AC3
Λ Prod Target
4 cm x 4 cm x 20 cm
Be
H2 Target
WP
H1
H2
H3 H4
WP
1m x .3m
1.2 m x 3 m
10 m
10 m
Λ Analyzing Magnet
20 Kgauss
.3 x 1 x 3 m gap
WP = Wire Planes
Λp Trigger:
$\overline{AC}_{1-4}$ H_{1-4} (Two only) C_{1-4} $\overline{AC}_5$
Λ→πp
Recoil Proton

Fig. 3

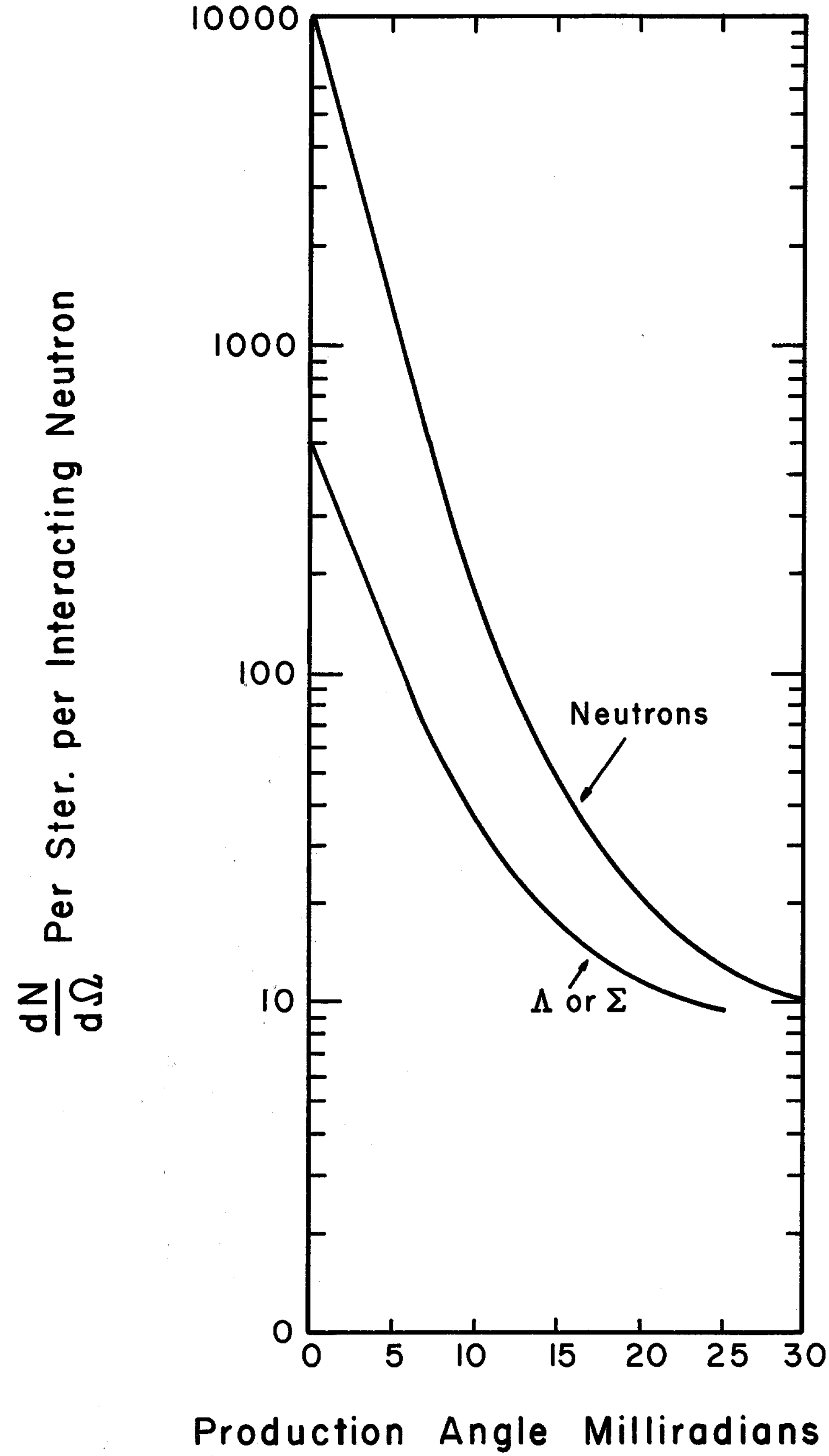

10000
1000
100
10
0
0
5
10
15
20
25
30
Neutrons
Λ or Σ
$\frac{dN}{d\Omega}$ Per Ster. per Interacting Neutron
Production Angle Milliradians

Fig. 4(a)

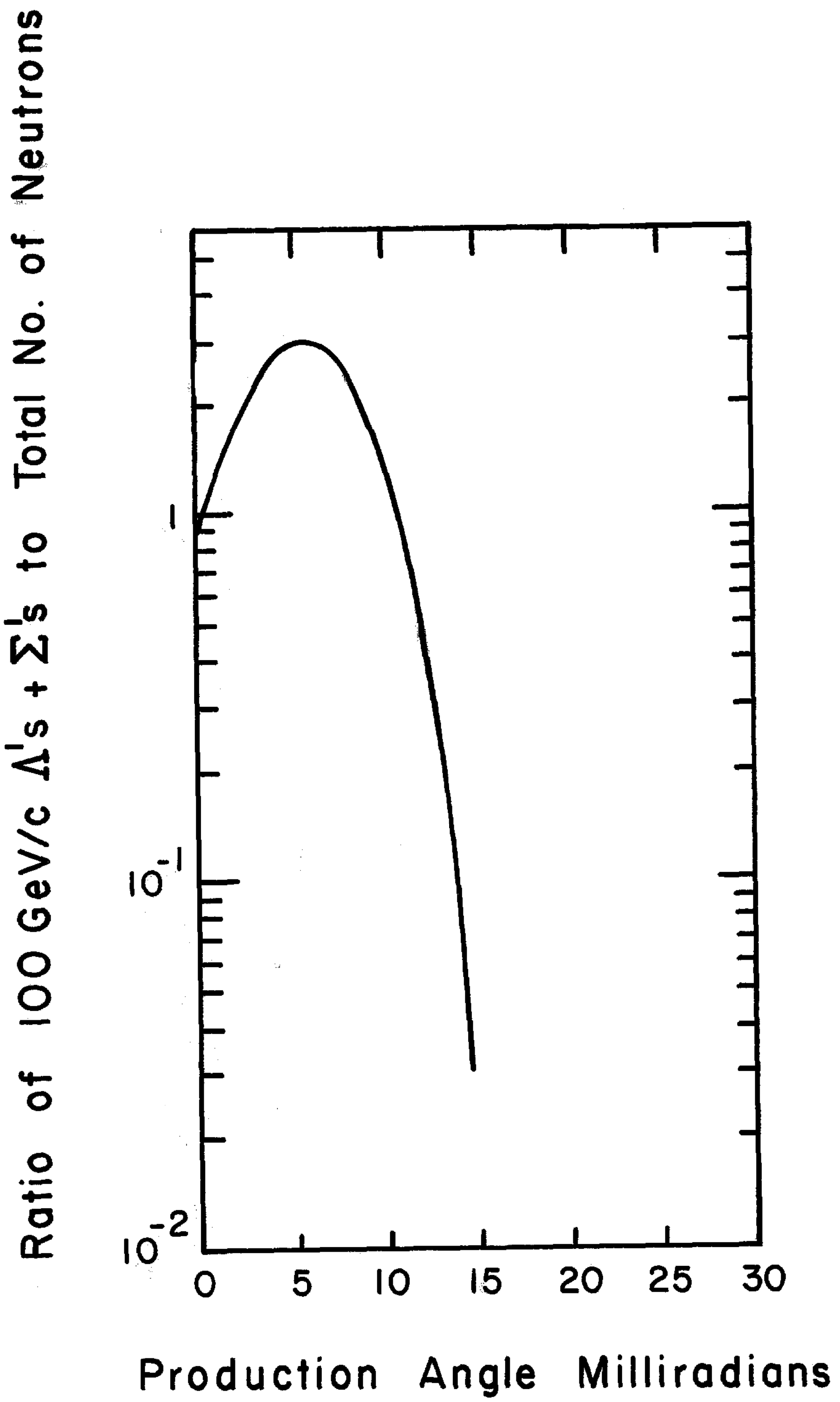
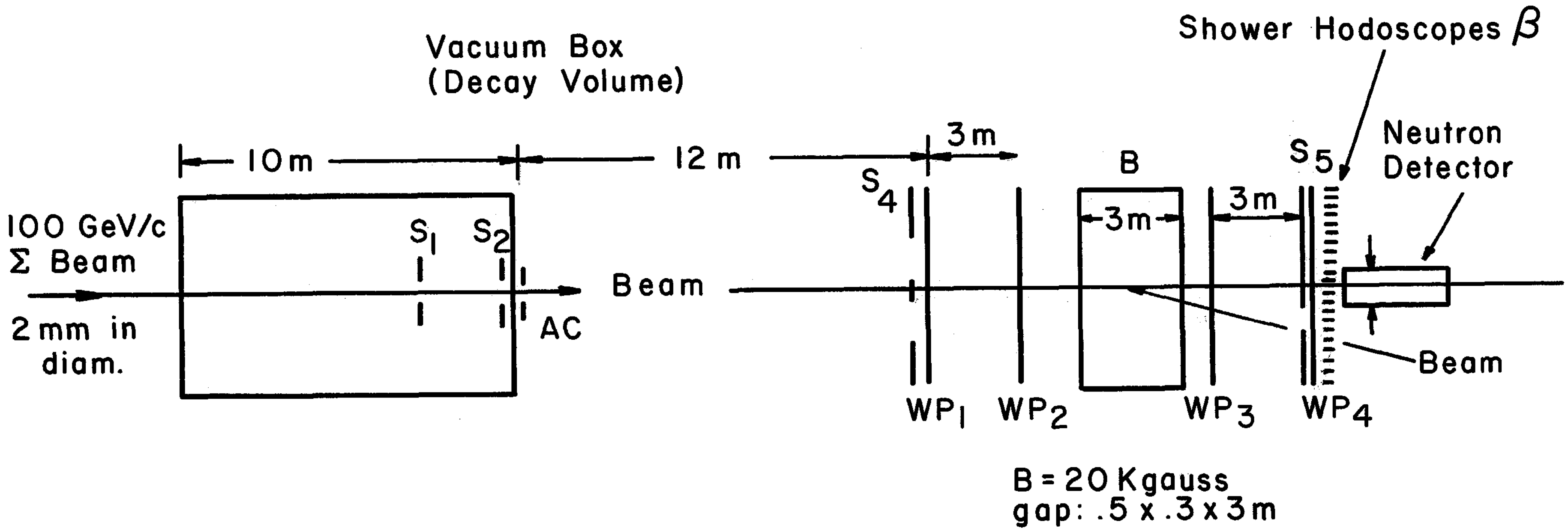

Ratio of 100 GeV/c Λ's + Σ's to Total No. of Neutrons
1
10-1
10-2
0
5
10
15
20
25
30
Production Angle Milliradians

Fig. 4(b)



Trigger: (Only one in $S_1 S_2 S_3 S_4 S_5$) $\beta n \cdot \overline{AC}$

Fig. 5