B.10-68-37

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HYPERON BEAMS AT A 200-GeV ACCELERATOR

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July 13, 1968

The 200-GeV accelerator will offer the possibility to perform hyperon experiments which cannot be done with presently available equipment. Many hyperon decays have already been observed, but measurements of their decay properties are difficult. The experiments require large numbers of events not conveniently obtainable. To obtain a few hundred leptonic hyperon decays now consumes hundreds of hours of accelerator operation or requires millions of bubble-chamber pictures. Our knowledge of the strong interactions of hyperons is limited to observation of production processes or scattering lengths at low energy. Without hyperon beams precise hyperon cross-section measurements like those achievable with pions or kaons are impossible.

We shall describe some of the possibilities to study hyperon interactions with the 200-GeV accelerator. The list of the experiments that we propose is by no means exhaustive. The intent is to discuss some experiments possible within the framework of our present

knowledge of hyperons and to suggest further topics to be studied during the summer of 1968, with the goal to demonstrate how to implement a hyperon program at NAL. We shall choose examples of what appear to us to be some of the more difficult but yet interesting experiments.

To perform hyperon experiments, a number of the characteristics of the 200-GeV accelerator may be exploited. One of these is the availability of intense secondary beams to produce tertiary beams of hyperons. A Λ^0 scattering experiment which uses Λ^0's produced by a secondary neutron beam has already been discussed.[1] Another possibility is to transport a K^- beam to a target. We confine our attention to K^- yield for momenta less than 40 GeV, above which the K^- yield falls rapidly. The shortcomings of this type of facility may be appreciated by comparing it to a similar one at existing accelerators. We note that the K^- yields from 200-GeV protons are about the same as pion yields from 30-GeV protons. The implication is then that in tertiary beams the 200-GeV accelerator will produce ten times as many hyperons as the 30-GeV accelerator. Our judgment is that, except for special experiments, this added advantage is too small to be useful.

A more promising approach is to exploit the time dilation of high momentum and to produce the hyperons directly with 200-GeV protons.

Hyperon Fluxes from Proton Collisions

To estimate the hyperon fluxes from the collision of 200-GeV protons with a target we use the model of Hagedorn and Ranft.[2] The results

for the Σ^+ hyperon are available here at the Summer Study. The Σ^- flux is then assumed to be one half the Σ^+ flux.[3] For the purpose of discussion, the Ξ^- flux is assumed to be less than the Σ^- by a factor of ten, the Ω^- flux less than the Ξ^- by again a factor of ten. The assumption is that the particle production cross section is reduced by a factor of ten for each unit of strangeness difference between the incident and outgoing particles.[3] A better estimate will presumably be possible within the next few years when more data is available from Brookhaven for 30-GeV protons and Serpukov for 70-GeV protons.

Before discussing the beam design, we first consider the attenuation of the hyperon intensity by hyperon decay.[4] Figure 1 shows the number of hyperons which survive to a distance given by the abscissa of the graph. For the intensities shown, we choose a negative beam with a central momentum of 150 GeV/c, whose channel subtends a solid angle of 2.5 microsteradians with the target, and accepts a momentum spread of ± 1.5%. If experiments with Ω^- hyperons will be possible with several thousand Ω^- per pulse then the beam length should be about 20 m.

A Design for a Hyperon Beam

The requirements set forth for the hyperon beam are well within the technology of magnet design as it is presently developed. The only new requirement is the manufacture of a quadrupole with a 1 cm bore with the same precision as a quadrupole with a 20 cm bore. The fabrication of a 1 cm quadrupole presents no intrinsic difficulty. The ray

trace for a hyperon beam is shown in Fig. 2. The beam has a double focus at 10 m and a second double focus again at 20 m from the target where the momenta are recombined in both space and angle. Where there is no quadrupole field there is a dipole field of 20 kG which serves to deflect the hyperon beam away from the primary proton beam by 40 mrad. The hyperon beam then emerges from the shield wall 40 cm from the zero degree beam line. At the first focus the momentum dispersion is 1 mm per percent $\Delta p/p$.

Negative hyperons produced directly forward at 0 mrad to the incident beam direction are spatially separated from the proton beam by the 20 kG magnetic field. At a distance of 1.5 m from the target the separation is complete whereupon the proton beam stop and hyperon channel can commence. The target section is illustrated in Fig. 3.

To demonstrate that it is possible to construct the quadrupoles necessary for this beam, we have chosen two symmetric triplets as the focusing elements. The field lens at the first focus is of relatively modest strength. The two outside quadrupoles are each 0.7 m long, and the one in the center is 3 m long. The apertures are 1 cm and the field at the pole tip is 15 kG. A sketch of the cross section of the quadrupole is shown if Fig. 4. The current sheets are 5 mm by 24 cm and have a current density of about 1500 amp/cm^2. Similar coils are now in use in the septum magnet in the slow external beam at the Brookhaven AGS and can be designed to operate in high radiation areas. This design presents no new or difficult problems. A second attempt at the beam design might

employ quadrupole doublets instead of triplets. In this application the high fields potentially available from superconductors could be used to great advantage.

The quality of this beam is good. At the second focus the beam size is equal to the target size, presumably 1 mm; it has an angular divergence of ± 1.5 mrad in both planes. Momenta up to 150 GeV/c can be transported. At the 10 m focus the image size is again 1 mm $\times$ 1 mm which is a convenient size for good beam definition.

An Experiment to Study an Ω^- Decay Mode

Hyperon decays are easily studied at high energy because of the fortunate circumstance that the Q value for most decays is small. In the laboratory system the decay products move with nearly the same velocity that the hyperon had before decay. The average momentum of a decay product (from an unpolarized hyperon) is then proportional to its mass. The baryons retain a large fraction of the initial hyperon momentum and are emitted at small angles while the lighter lepton or boson has a lower momentum and is emitted at relatively large angles. This is illustrated in Figs. 5 and 6 in which transverse momentum is plotted against longitudinal momentum for the decay products of several hyperon decays. The curves for the three body decays should be interpreted as kinematic limits.

We shall outline an experiment which illustrates how a decay experiment might be done in the 150 GeV/c hyperon beam. The decay to

be described is

$$\Omega^- \rightarrow K^- + \Lambda^o.$$

The first point to notice from Figs. 5 and 6 is that the maximum K^- momentum is 67 GeV/c and that there are no other negative particles emitted from any decay at this momentum. For the detection of the decay mode and the measurement of the parameter, we shall analyze only those events with K^- momenta between 61 and 67 GeV/c. The corresponding Λ^o momenta are then 83 to 88 GeV/c. Both the K^- and the Λ^o are confined to emission angles less than 2 mrad from the beam direction.

The apparatus is sketched in Fig. 7. There is an Ω^- decay region which is 3 m long, or about one mean decay distance. There is a second decay region in which the Λ^o decays. Between the two decay regions is a bending magnet M_1 which is 1.5 m long and has a 20 kG field. M_1 deflects the charge particles away from the neutral Λ^o decay product. One meter from the magnet a 1 cm anticoincidence counter defines the neutral lambda decay region. By appropriately focusing the hyperon beam, it misses the anticoincidence counter and the neutral Λ^o beam is defined. It is important to determine that the K^- came from an Ω^- in or near the decay region and was not a π^- from Σ^- decay. The optical system shown reimages an undispersed image of the decay Ω^- region. Any particle in the image of the decay region was in the decay region

and has the momentum defined by the magnets and slits. It appears possible to accurately define the decay region, as would be needed for a measurement of a branching ratio, by selecting K^- from large angle decays. To be sure the negative particle is a K^-, a Cerenkov counter is at the end of the negative arm.

The detection of the Λ^o will not be discussed in detail. It is felt that the detection of a 70-BeV proton from the neutral beam is sufficient evidence that there was a Λ^o. The α parameter of the decay is measured from the proton momentum spectrum alone. The gamma parameter determination is not possible since it requires a polarized Ω^-.

The probability to detect an Ω^- which enters the decay region is estimated.

Probability of Ω^- to decay in decay region	2/3
Fraction of K^- in accepted momentum band	1/6
Probability of Λ^o decay after anticoincidence	1/2
Branching fraction of $\Lambda^o \rightarrow p + \pi^-$	2/3
$\Omega^- \rightarrow K^- \Lambda$ detection efficiency	0.04

On the basis of the flux estimates already discussed, 8000 Ω^- enter the decay region per pulse. The counting rate is

$$\sim 300 \times (\text{branching fraction of } \Omega^- \rightarrow K^- \Lambda^o)$$

counts per pulse. Even if the Ω^- flux is two orders of magnitude less than assumed, the experiment is still possible.

A Study of $\Sigma^- p$ Elastic Scattering and Some Other Two-Body Final States

These experiments utilize the Σ^- beam already described. It is possible to cover a wide range of momentum transfer $0.1 < t < 3.0$. For this large range of momentum transfer two experimental arrangements for elastic scattering of $\Sigma^- p \rightarrow \Sigma^- p$ are required. One of these is shown in Fig. 8 for the t range $1 < t < 3$ GeV/c^2.

In this experiment the measured kinematic quantities are the momentum and the angle of the recoil proton. The scattered Σ^- is identified from its decay products. Since the method of measuring the momentum of the proton depends on its magnitude this experiment is done in two parts. First for the range of $0.1 < t < 1.0$ GeV/c^2. The proton is slow so its energy and mass can be measured by range and time of flight. The second range covers $1 < t < 3$ GeV/c where $1 < p < 2.3$ GeV/c. In this case the momentum of the proton is magnetically analyzed with a wire chamber spectrometer. Σ's are detected by identifying a neutron and a π i.e. a V with a characteristic opening angle. Some characteristic kinematic properties of the Σp scattering process are shown in Table I. The incident Σ^- momentum and direction known from the properties of the beam, together with the measured proton quantities lead to a one constraint kinematic fit. The "event" trigger requires an incoming Σ^-, a recoil proton and a Σ^- decay. The primary beam will contain π^-, K^-, Σ^-, $\bar{p}$. The incoming Σ^- will therefore be identified with a threshold anticoincidence Cerenkov counter which vetos pions and

kaons. The Cerenkov counter is 30 m long and operates at a nitrogen pressure of 0.06 atmospheres. The inelastic background is eliminated by the kinematic conditions imposed by the two-body final state.

On the basis of

10^6 Σ^- per pulse

1 m target length

decay neutron detection efficiency = 1

scattered proton detection efficiency = 1/10 ($0.1 < t < 1$ GeV/c)

$d\sigma/dt = 100\ e^{-8t}$ = 1/40 ($1 < t < 3$ GeV/c)

our calculated event rates are

1800 events/pulse	$0.1 < t < 1$
0.5 events/pulse	$1 < t < 3$
0.1 events/pulse	$t \gtrsim 3$

The $\Sigma^- p \rightarrow \Lambda^o n$ and $\Sigma^- p \rightarrow \Sigma^o n$ can be done by surrounding the hydrogen target with a scintillator counter in anticoincidence with the triggering logic. In that case only the directions of the neutrons and the Σ^o or Λ^o will be measured and a two constraint kinematic fit can be obtained. The $\Sigma^o \rightarrow \Lambda\gamma$ events will be identified by a γ detector. The experimental arrangement to study these reactions will be similar to the Σp experiment but the proton detection apparatus will not be substituted by a neutron detector.

Conclusions

The intensities of hyperons at the 200-GeV accelerator will be large enough to study hyperon-proton scattering to momentum transfers

squared, $t = 3\ \mathrm{GeV}/c^2$, which is nearly as large as will be achievable with pions. In addition, the kinematic circumstances of two and three-body decays are favorable to measure the decay parameters (α, β, and γ) for some two-body pion-baryon modes and G_V/G_A for leptonic processes. There is a large class of hyperon decays, including $\Delta S = 2$ and $\Delta S = 3$ leptonic and nonleptonic decays, which have a high detection efficiency and a sufficiently unique signature that they can be studied in the presence of a high background and with a low counting rate. Table II shows some of the modes we have considered.

Further Related Hyperon Topics for the Summer 1968

1. Survey of hyperon fluxes.

2. Hyperon bubble chamber beam. At 20 m from the proton target the ratio of Σ^- to π^- is 1 : 15. Can an rf separated beam make any improvement on this and is it possible to separate Σ^+ from protons to make a Σ^+ beam of high purity?

3. Polarized proton and neutron beams from $\Sigma^\mp \rightarrow \binom{n}{p} + \pi^\mp$. Both longitudinal and transverse nucleon polarization are achievable.

4. Polarized Λ^o beam from $\Sigma^\pm \rightarrow e^\pm \Lambda^o \pi^o$ or $\Xi^- \rightarrow \Lambda^o \pi^-$.

REFERENCES

[1] T. Romanowski, NAL Summer Study Report C.1-68-19, 1968.

[2] Computation of fluxes with a computer program by Ranft. Results distributed by T. G. Walker at 1968 NAL Summer Study.

[3] We are grateful to M. Ross for suggesting how to make the estimate of the ratio of $\Sigma^+ : \Sigma^-$. From the decay of Y_o^* or Y_1^* the ratios of $\Sigma^+ : \Sigma^-$ are 1 and 2 respectively. On this basis our estimates are plausible. The estimate for Ω^- may be high by a factor of 100 on the basis of some models.

[4] Life times are from UCRL-8080. It should be noted that the uncertainty of the Ω^- lifetime measurement is about a factor of 2.

[5] A similar technique has been proposed to study Ω^- decay at the Brookhaven AGS. The proposal is by a group from Yale University.

Table I. Properties of the Σp Scattering Process.

t Range: $0.1 < t < 1\ \mathrm{GeV}/c^2$ $\qquad \sigma_T\,(0.1 < t < 1) = 4.5$ mb

$P_{Pmin} = 100$ MeV/c

$90^\circ < \theta p < 70^\circ$

$P_{pmax} = 1$ GeV/c

$p_{\Sigma max} = 150$ GeV/c

$0 < \theta_\Sigma < 0.3^\circ$

$p_{\Sigma min} = 149.7$ GeV/c

t Range: $1 < t < 3\ \mathrm{GeV}/c^2$ $\qquad \sigma_t\,(1 < t < 3) = 4.2 \times 10^{-3}$ mb

$P_{p_{min}} = 1$ GeV/c $48^\circ < \theta_p < 70^\circ$

$P_{p_{max}} = 2.3$ GeV/c

$P_{\Sigma_{max}} = 149$ GeV/c

$0.3^\circ < \theta_\Sigma < 0.8^\circ$

$P_{\Sigma_{min}} = 147.8$ GeV/c

Decay of 150 GeV/c Σ^-

$97 < P_{p1n} < 144.5$ GeV/c; $\theta_{p_{max}} = 0.09$

$5.5 < P_\pi < 53$ GeV/c; $\theta_\pi = 0.63^\circ$

$\theta_{p\pi} = 0.68^\circ$

Table II. Hyperon Decays.

Negative Particle Beam
$p = 150$ GeV/c
$\Delta p = 3$ GeV/c
$\Omega = 2$ μsterad
10^3 proton interactions/pulse

Particle	Mean Decay Length (m)	Number Per Pulse After 20 m	Decay modes and Branching Fraction	Remarks	Is the apparatus sketched suitable for this decay mode?
π^-	8470	2×10^8	$\mu\nu$ ~1.0		
K^-	1125	4×10^5	$\mu\nu$ $\pi\pi$ $\pi\pi\pi$ $\pi\ell\nu$		
Σ^-	6.20	1.2×10^7	$n\pi^-$	All decay parameters measured	Not γ parameter
			$n\pi\gamma$		Yes
			$n\mu\nu$ }	G_V/G_A known to ~50%	Yes-No
			$ne^-\mu$ }		Polarization
			$\Lambda^o e^-\nu$	Only a few events now. Can be accurately measured with Λ^o polarization.	Yes with Λ^o polarization
Ξ^-	5.20	$(1 \times 10^6?)$	$\Lambda^o\pi^-$	Decay parameters will be known to a few %	Not γ parameter
			$\Lambda e^-\nu$	} γ ray from Σ^o must be identified	} Yes with Λ^o polarization
			$\Lambda\mu^-\nu$		
			$\Sigma^o e^-\nu$		} Yes--poor polarization
			$\Sigma^o\mu^-\nu$		
			$ne^-\nu$	$\Delta S = 2$. Rate for part of the e^- spectrum only	Yes
			$n\pi^-$	No decay parameters	Yes
Ω^-	2.96±1.5	$(8 \times 10^3?)$	$\Lambda^o K^-$	α parameter only	Yes
			$\Xi^o\pi^-$		Yes
			$\Xi^-\pi^o$		?
				Other possibilities include $\Delta S = 1, 2, 3$ leptonic and non-leptonic decays many of which are feasible over the full or perhaps part of the spectrum of decay products	

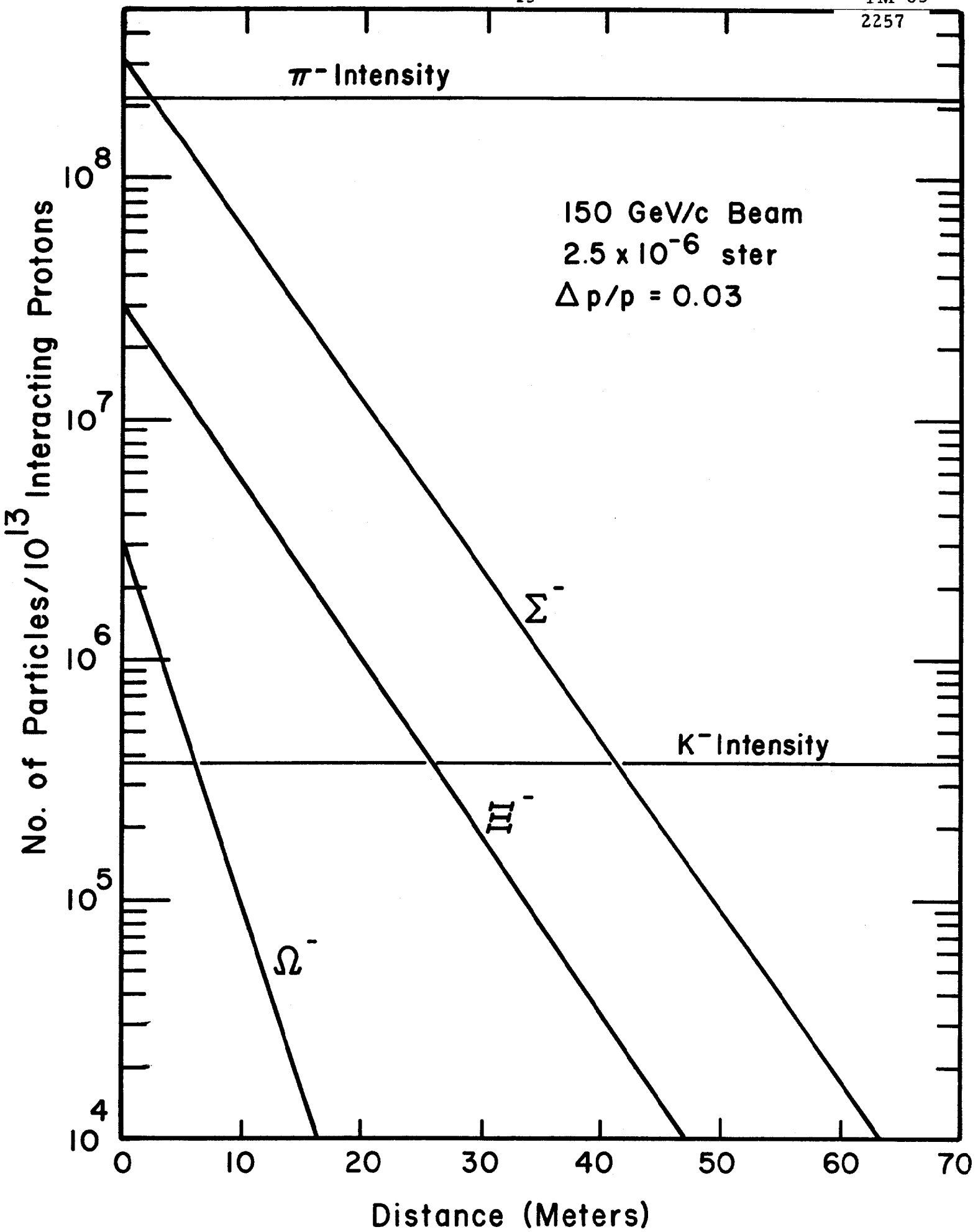

Fig. 1. Decay in intensity of a 150 GeV/c hyperon beam with distance;

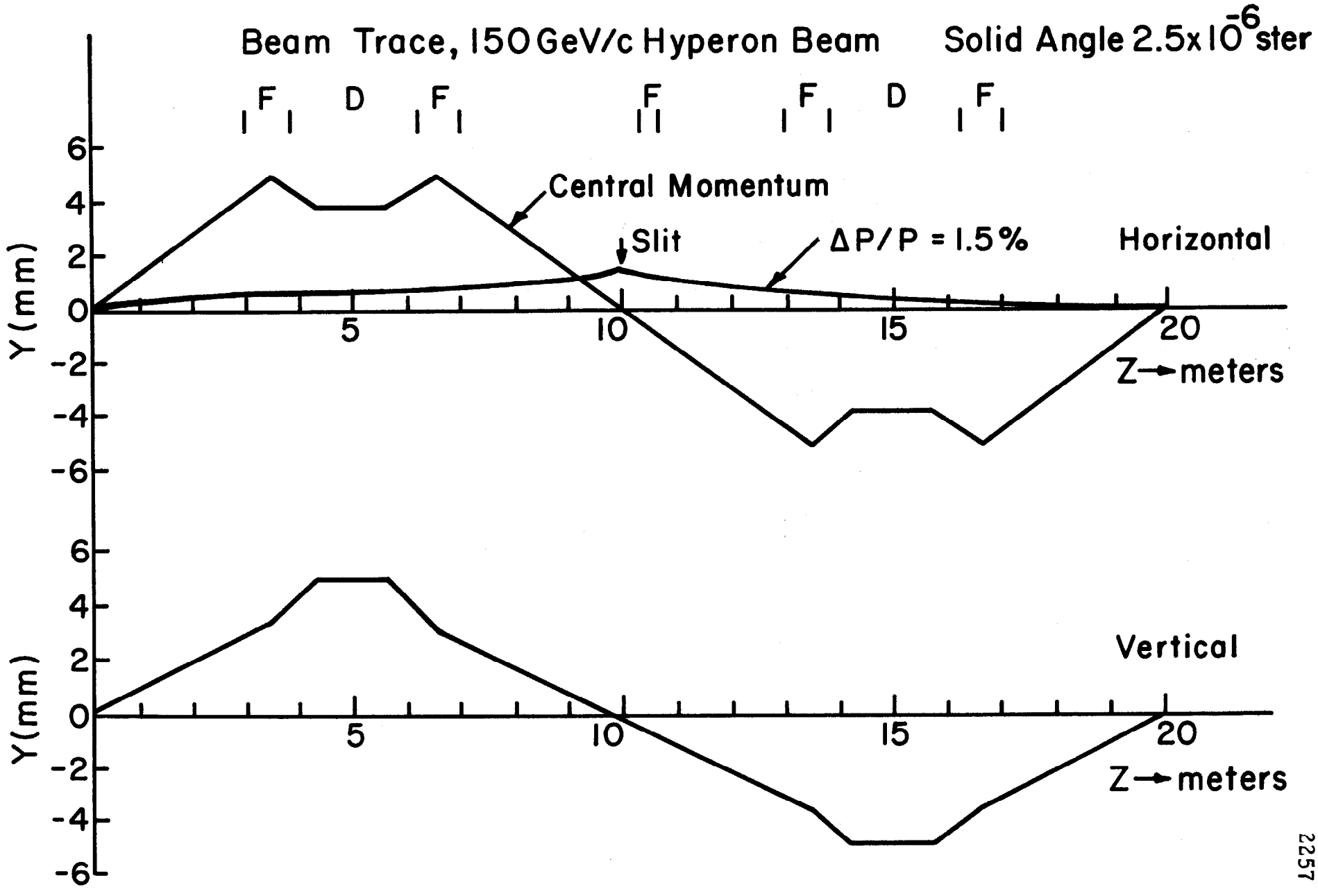

Fig. 2. Vertical and horizontal plot of a 150 GeV/c hyperon beam.

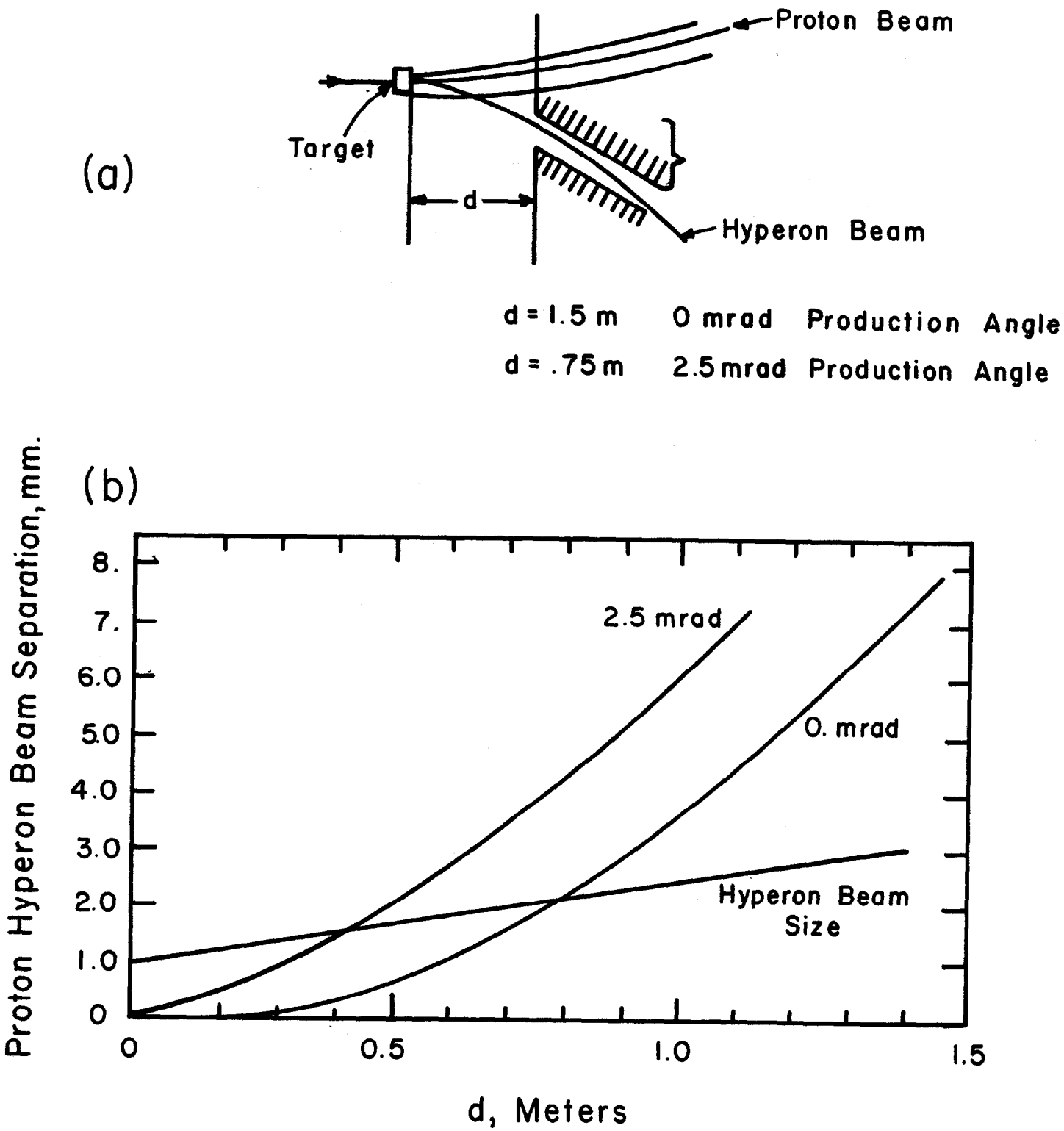

Fig. 3(a). Magnetic separation of a negative hyperon beam from the primary protons. (b) Geometrical separation achievable as a function of production angle.

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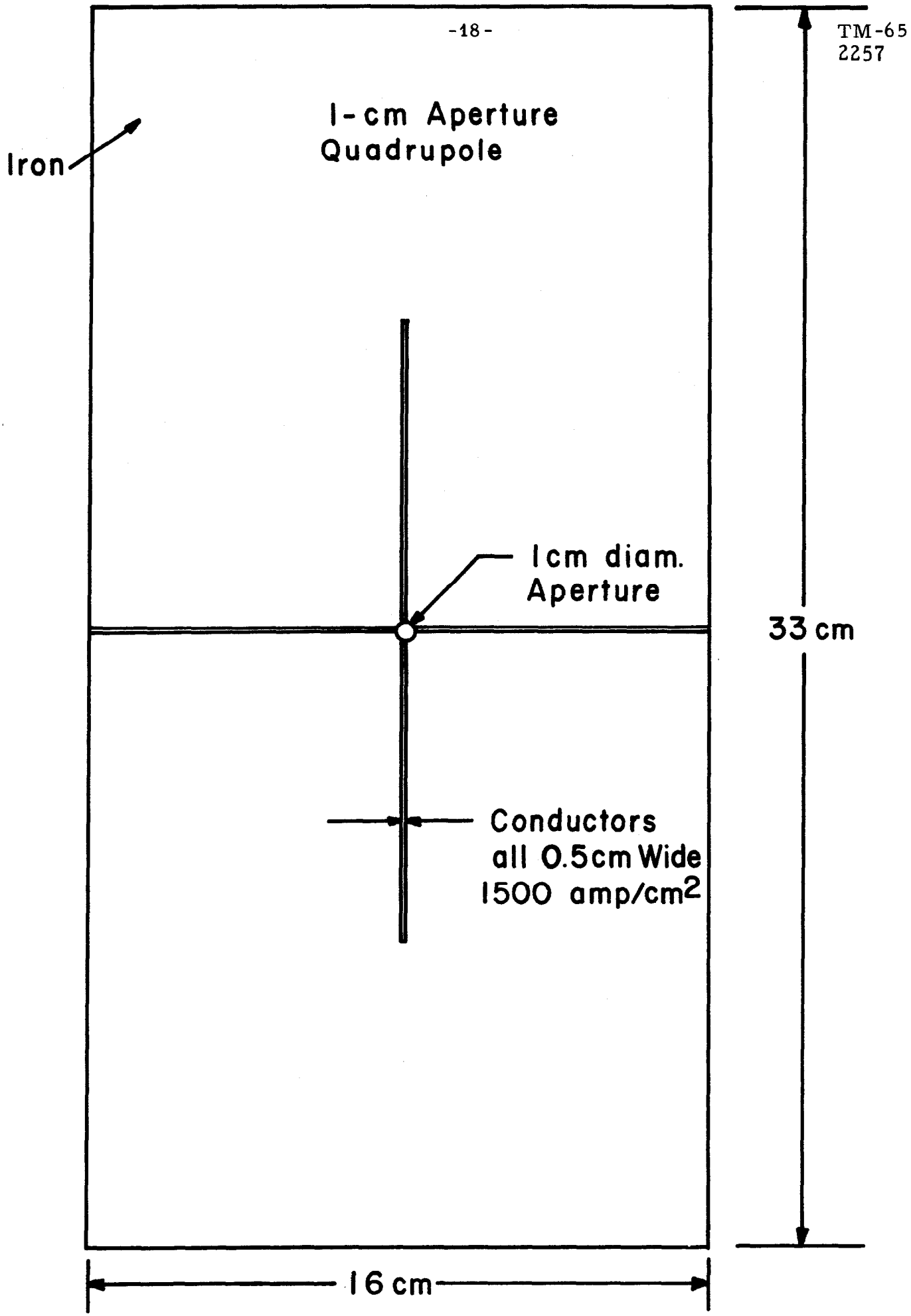

Fig. 4. Cross section of a 1-cm bore quadrupole.

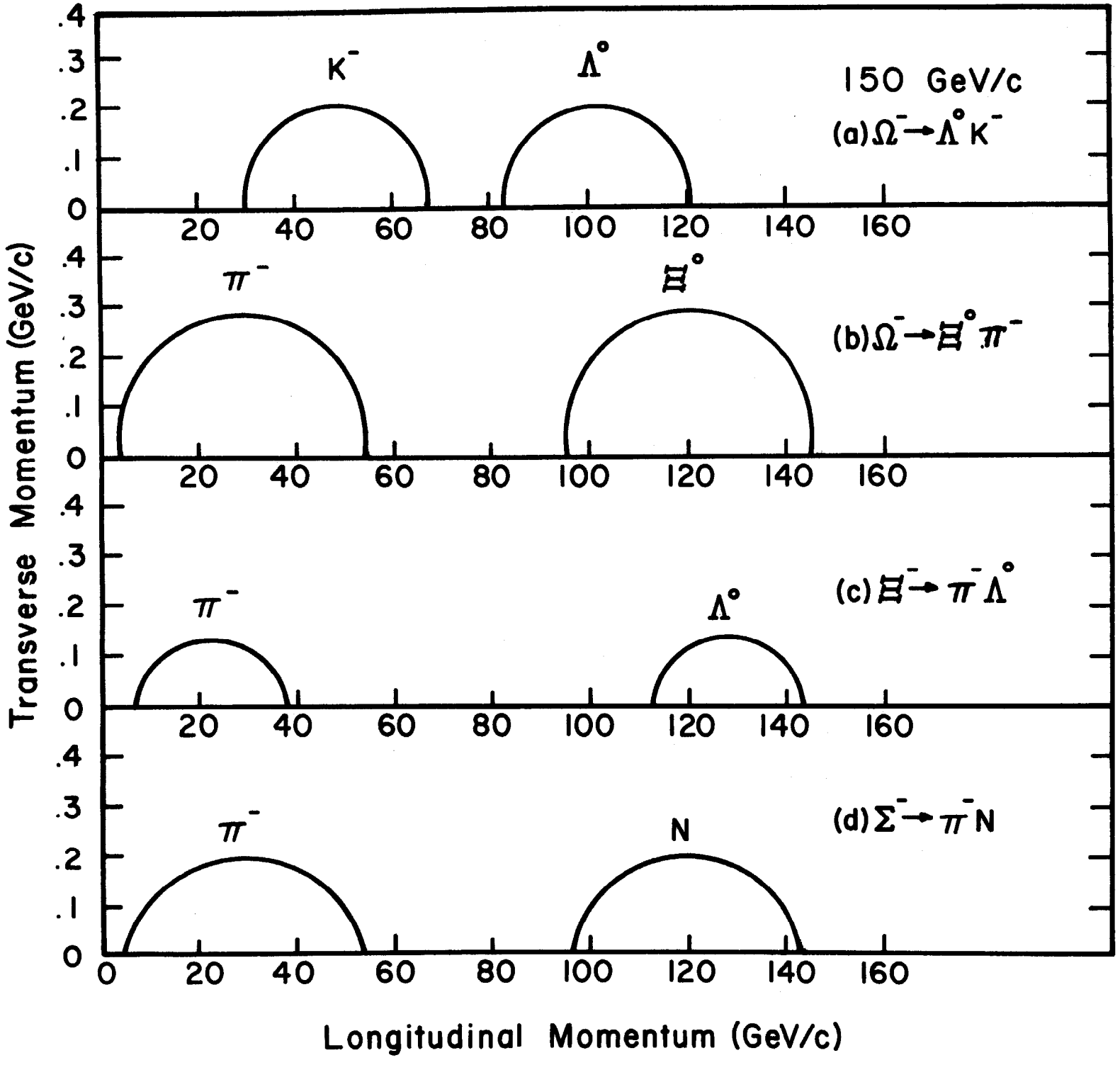

Fig. 5. Kinematic limits of momentum for the decay products of 150 GeV/c hyperons.

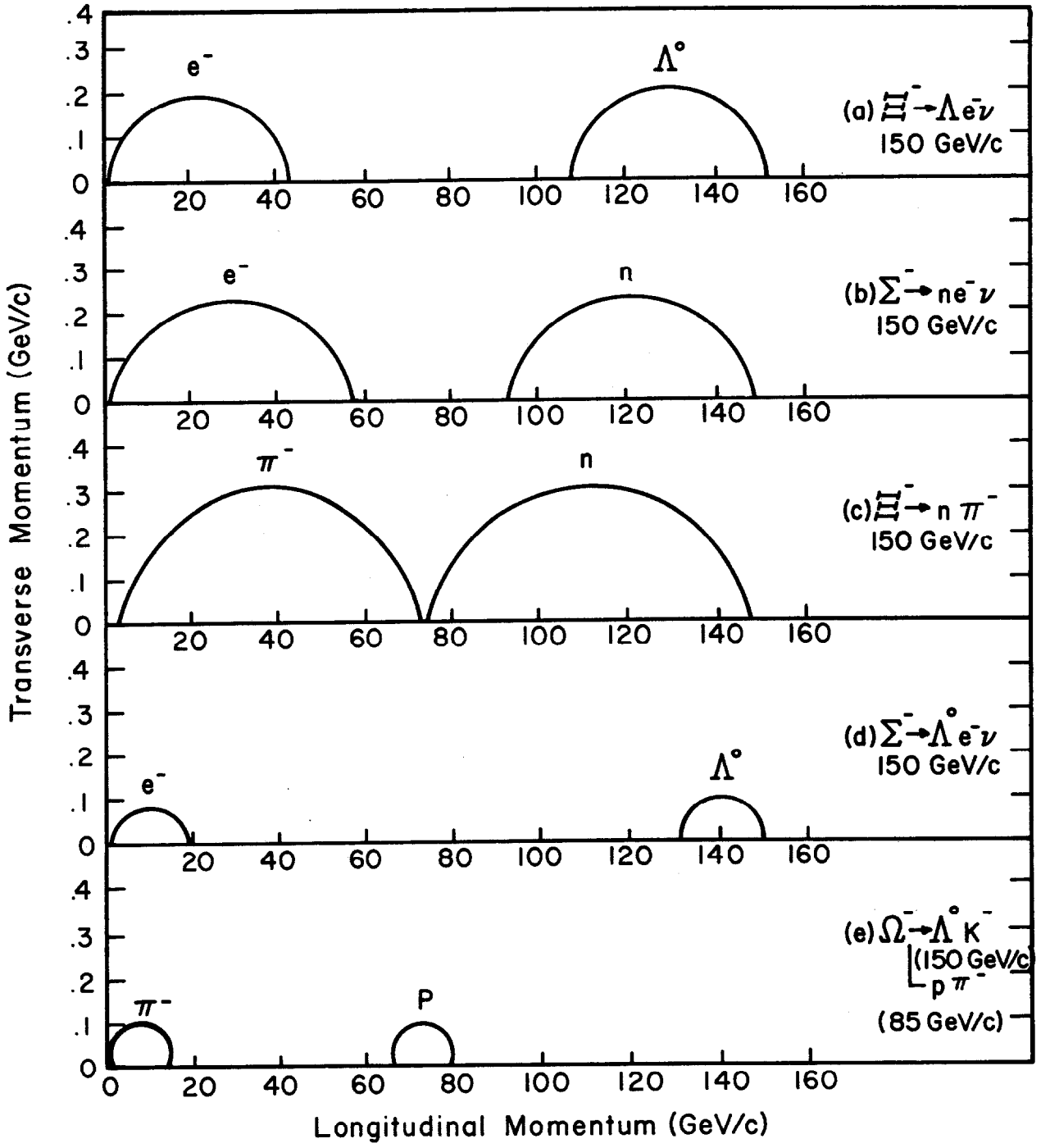

Fig. 6. Kinematic limits of momentum for decay products of 150 GeV/c hyperons, including leptonic and cascade decays.

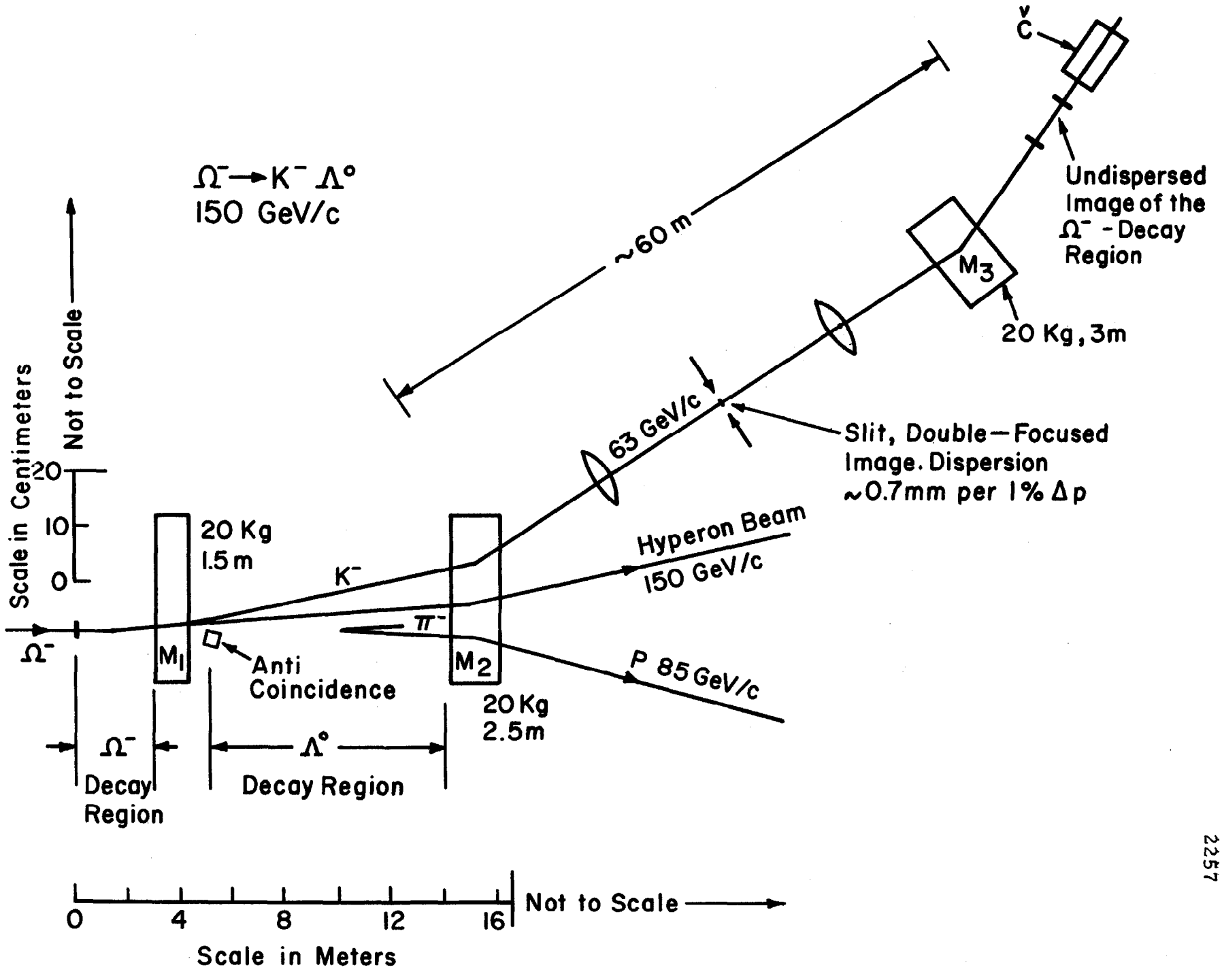

Fig. 7. Apparatus for study of Ω^- decay; it will measure the α parameter and rate of decay.

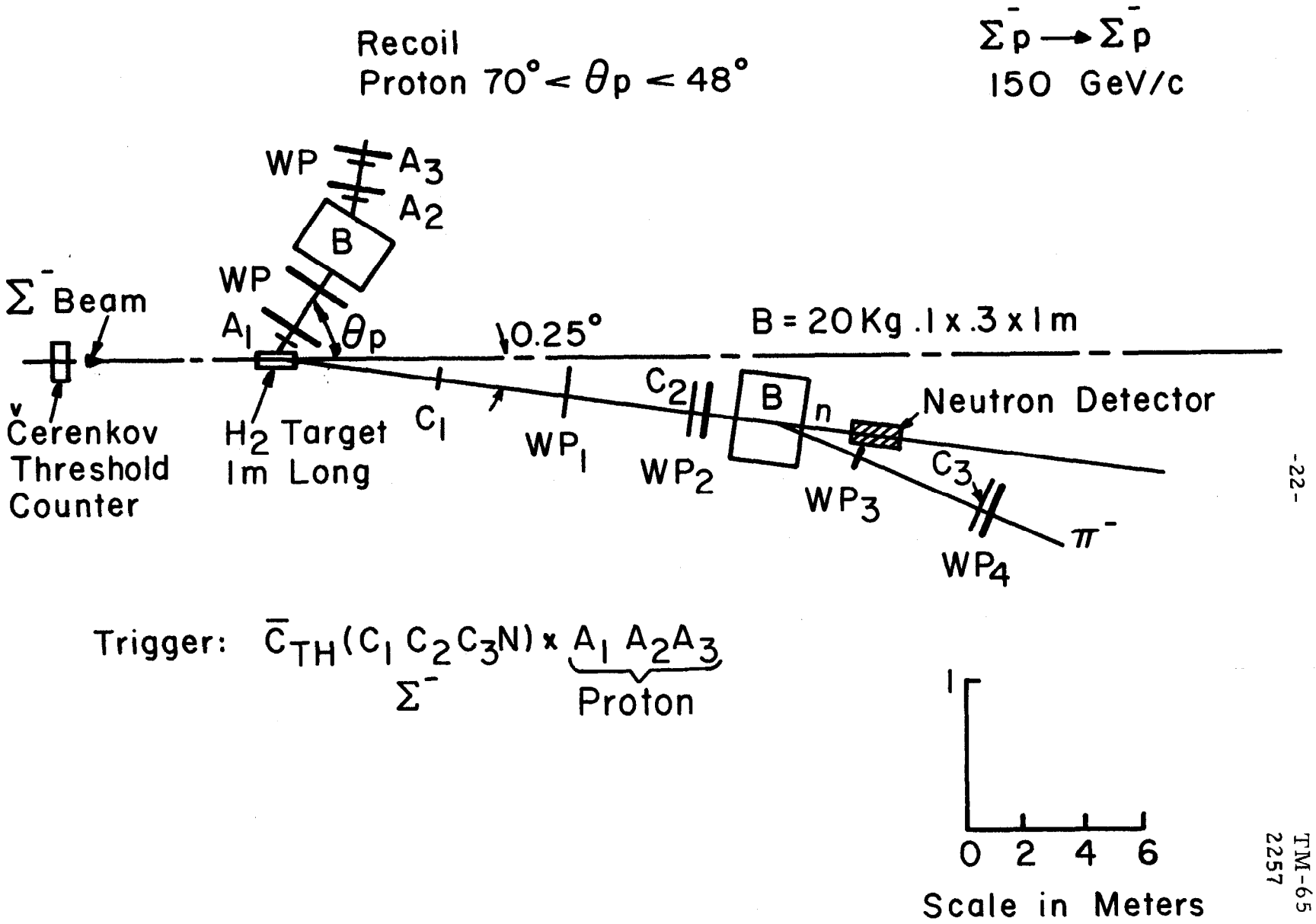

Fig. 8. Apparatus for measurement of elastic (and inelastic) Σ^--p scattering.