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TRANSVERSE SHIELDING FOR THE 300 GeV
PROTON SYNCHROTRON AND THE TRANSFER TUNNEL
UP TO THE WEST AREA TARGET STATION

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ABSTRACT

This report gives an estimation of the shielding required for the 300 GeV proton synchrotron ring tunnel and for the transfer tunnel from the main ring to the West Experimental area. We have based our estimates on the parameters of the 300 GeV accelerator and its foreseen implantation as given in the report 'Alternative ways of realizing the CERN 300 GeV programme' JBA/pd dated 6.4.1970¹⁾.

Solution B has meanwhile been slightly modified and presented to the Council as Document CERN/943²⁾. We further discuss some of the implications with respect to shielding for eventual higher energies.

I. DOSE RATE LIMITS AND DESIRABLE RADIATION LEVELS
OUTSIDE THE ACCELERATOR SHIELD

The two countries, France and Switzerland, on whose territories the accelerator is to be built, have similar regulations and laws for radiation protection. In both countries the radiation dose for the population at large is 5 rem/30 years. The individual members of the population may receive dose rates up to 0.5 rem/year. From experience we know that the exploitation period of a large and costly high-energy accelerator will be at least about 10 to 20 years. The large project now under discussion will probably have a longer period of utilization; it is therefore safe to use for the shielding estimates, a yearly average dose of 170 mrem for the population at large which is a factor of 3 lower than the dose rate for individual members of the population.

Last year a discussion was initiated by J.W. Gofman and A.R. Tamplin³⁾ on the permissible levels for the population at large; the authors advocated a dose rate ten times lower than the one presently accepted by the US Atomic Energy Commission which is based on the Recommendations of the ICRP⁴⁾. If this philosophy were accepted the yearly average dose would be only 15 mrem/y for the population at large, and 50 mrem/y for the individual members of the public.

We shall use here for our estimations radiation levels recommended by the ICRP which are also accepted by France⁵⁾ and Switzerland⁶⁾ as well as by all the other CERN Member States. Where appropriate, we shall consider the implications raised by a ten-times lower dose rate level. The yearly average of 170 mrem might be divided by the number of operational hours, estimated to be 6000 per year, resulting in a dose rate limit of 25 μ rem/h. Compared to this, the natural background at the CERN site is about 90 to 120 mrem/y or about 10-14 μ rem/h. We shall give first an estimation of the required shielding for the main ring. We might expect a future development of the 300 GeV proton synchrotron up to 800 GeV energy, therefore the necessary shielding for the main ring tunnel should be evaluated with this possibility of energy increase in mind.

It is proposed to locate the machine in a tunnel bored in the molasse rock at a depth of about 30 m below ground level. For the countryside above it there will be almost no disturbance and planning should be made such that the present utilization of the area can be maintained. The first part of our report is based on the assumption that at all locations above the ring tunnel there is a layer of at least 20 m of earth and rock. In this way we make provisions for ditches and trenches across the site and for the foundations of the buildings, etc.. For this shielding thickness we have estimated the dose rate on the surface for the different types of particles of the radiation field.

The second part of the report discusses the shielding required for the transfer tunnel to the West Experimental Area, for a maximum proton energy of 300 GeV. The 300-GeV transfer tunnel opens on the transfer tunnel of the CERN PS to the West area (TT4 - TT5). From the shielding estimations we can give limits for energy and intensity to be dealt with in this area. We would then consider modifications of the existing shielding arrangements in order to allow for operation of a beam of 300 GeV energy and 10^{13} proton/sec intensity.

II. SHIELDING OF THE MAIN RING OF THE 300 GeV PROTON ACCELERATOR

Three sources of radiation at the surface of the shield are considered:

- (1) The hadron radiation, mainly neutrons penetrating into the earth and rock shield on top of the main ring,
- (2) The muons originating from decay of those pions produced as first generation of secondaries by protons interacting in small items like targets, vacuum chambers, etc... These muons penetrate into the shield under small angles with the primary proton beam ('target muons'),
- (3) The muons which are decay products of pions produced in a large nucleon meson cascade developing in a large mass of material like

magnets, large beam stoppers, tunnel walls, etc... These pions are the product of many generations of 'secondaries' and may escape under large angles with the proton beam ('cascade muons').

(A) Estimation of hadron shielding by Monte-Carlo cascade calculations

Shielding requirements for proton synchrotrons and external proton beam lines can be estimated by considering the hadronic cascade in matter, which represents in transverse direction the most penetrating component of the radiation field. The spatial development of hadron cascade depends on the distribution of matter around the source point, where the primary protons interact. If the proton beam interacts in a massive block of material (end-stop) the cascade develops within a relatively small region in space. If the proton beam hits a small target in an otherwise empty beam tunnel, the cascade develops only in the tunnel walls. The secondary particles emitted at small angles from the target hit the tunnel wall over an extended region and the hadron cascade becomes rather diluted geometrically. The shielding necessary for a fixed number of interacting protons depends therefore strongly on the geometrical arrangement.

The hadronic cascade and the resulting shielding requirements were considered in the past for some simple geometrical layouts. The massive end-stop was treated in Ref. 7 and 18, Ref. 7 giving tables with shielding dimensions. Ref. 7 deals also with the shielding necessary for a linear line source in otherwise compact matter. These data were also obtained from the end-stop calculations.

The cascade resulting from protons interacting in medium-sized objects, such as beam stoppers or synchrotron magnets in an empty tunnel, was considered in Ref. 9 and 13.

Here we describe the hadron cascade in still another situation, a small target within an empty tunnel. We assume that a certain fraction of the beam interacts at this one spot.

Figures 1 to 4 give the longitudinal and transverse star and flux densities in the tunnel walls which were obtained in a Monte Carlo calculation using the programme MAGTRA²⁰⁾. We consider primary protons of $p_0 = 20$ and 300 GeV/c and a tunnel of radius $R = 1$ m with a length of $l = 100$ m. At $p_0 = 20$ GeV/c about 90% of the primary proton energy is deposited in the 100 m of tunnel wall considered but at $p_0 = 300$ GeV/c this fraction is only 22%. The reasons are the small production angles at the higher energy where many of the secondaries do not reach the wall within the first 100 m.

According to figures 1 to 4 about equal amounts of transverse shielding are required for 20 and 300 GeV/c protons. This feature is explained by the different production angles. The following table gives the transverse shielding necessary to attenuate the particle fluxes in the wall down to fluxes of 1 particle/cm² for losses of 10^9 to 10^{12} protons on a target in the centre of the tunnel. At larger depths we have here the same transverse attenuation lengths as in Ref.7.

No. of interacting protons		10^9	10^{10}	10^{11}	10^{12}
p_0 (GeV/c)	Material	g/cm ²	g/cm ²	g/cm ²	g/cm ²
20	Fe	1080	1380	1680	1980
20	earth	845	1085	1325	1565
300	Fe	1050	1350	1650	1950
300	earth	840	1080	1320	1560

As expected, these shielding thicknesses are less than those obtained for a simple beam end-stop (Ref. 7).

The amount of shielding necessary should always be estimated from the results calculated under geometrical assumptions which represent best the actual situation. For beam tunnels with magnets etc... we believe

that the shield estimates given here would be too optimistic and it is certainly wiser to design the shield according to the requirements for a linear line source or for a partially filled tunnel. The results given here should only be applied in the case of a nearly empty tunnel.

(B) Dose rate on the surface above the main ring due to hadrons

The shielding calculations performed at CERN (MPS/Int MU-EP 67-1, 17.1.67)⁷⁾ for transverse shielding of the 300 GeV ring tunnel assume that the flux density of 0.43 neutrons/cm² sec corresponds to a dose rate of 1 mrem/h (see remark by R. Thomas, MPS/Int. MU-EP 67-1, Add.1)⁷⁾. However, experience has shown that the flux density of all hadrons above 20 MeV energy, which corresponds to 1 mrem/h, is about 3 to 4⁸⁾. In the calculations of Ranft a low energy cut off of about 100 MeV was used for all particles. Taking the spectrum of particles outside the shielding tunnel into account⁹⁾ (K. Goebel and J. Ranft, CERN 70-16, 1970) we arrive at the following general conversion factor:

- 1 hadron/cm² sec (Monte Carlo calcul.) = 1 mrem/h
- 1 hadron/cm² sec (measured ¹¹C) = 0.3 mrem/h.

It has been assumed (ECFA-1967)¹⁰⁾ earlier that about 20% of the particles are lost inside the ring enclosure. NAL¹¹⁾ based their estimations on a few percent of beam losses in the main ring; their estimations were backed up by the better control of beam losses during ejection recently obtained at CERN and Brookhaven. To give a conservative figure of the dose rate we shall assume that 10% of the circulating beam of 10¹³ proton/sec (300 GeV) will be lost permanently over a 100-meter sector in the main ring.

The density of the shielding material is assumed to be 1.8 g/cm³, which is a safe estimate, since part of the shielding will be molasse rock (2.2 to 2.4 density) and alluvial compact gravel having a density very close to 2.

It was found from calculations that the required shielding thickness for the tunnel for a distributed loss and a flux density of

5 particle/cm² sec was 1740 g/cm². According to the same calculations 240 g/cm² are required to reduce the flux density by a factor of 10. With a total shielding thickness of 2450 g/cm² (or 14 m of earth of 1.8 density), the flux density would be below 0.005 n/cm² sec, corresponding to a dose rate of less than 5 μ rem/h.

From the same calculations the transverse shielding for beam losses occurring in a large block of material (backstop) is also obtained. For full beam loss of 10¹³ particle/sec the transverse shielding required to have less than 5 μ rem/h dose rate would correspond to 3000 g/cm² of concrete. This corresponds to 17 m of earth of 1.8 density. The corresponding figures for a beam loss of 10¹² particles interacting in a large block of material would be 2800 g/cm².

These Monte Carlo calculations can be compared with the experimental results at 20 GeV beam energy. In the CERN-LRL-RHEL-Shielding Experiment (UCRL-17941)¹²⁾ it was found that the maximum flux density of hadrons (\geq 20 MeV, ¹¹C) for 10¹² particles interacting in a target was about 1000 particle/cm² sec above 700 g/cm² of earth shielding. To arrive at a flux density of a factor 200 lower we have to add about 600 g/cm² to this value. The total shielding required would then be about 1300 g/cm² for 10¹² particle/sec at 20 GeV. The calculations give 1550 g/cm² for a distributed loss (over 100 m).

The corresponding figure for the lateral dimension of an end stop would be 1900 g/cm² of earth. Compared with the measurements, both the distributed loss and the end-stop calculations give overestimated values for the required shielding, because of the different geometries in the calculations and experiments. Consequently, another Monte Carlo programme was applied¹³⁾ to take into account the geometry of the PS ring tunnel and PS magnet. This programme (KASTRA) was used to compare with two experiments:

- (a) the CERN-LRL-RHEL-Shielding Experiment,
- (b) the CERN beam stopper experiment.

In the first experiment a 100 μ Be-target was irradiated by protons of 25.6 GeV energy at standard target position No. 32 inside the PS.

In the second experiment, a 3-meter long and 30 cm diameter steel beam stopper was irradiated by 20 GeV proton beam in the fast-ejected proton beam e_4 . Table 1 gives the calculated and measured values. They are within a factor of 2 to 3 the same. It was therefore felt that the M.C.C. could predict also the shielding at higher energies, as the agreement with measurements at lower energies was within the expected limits. Particle production in high energy interactions has been measured up to proton energies of 70 GeV/c. The transverse momentum dependence is nearly independent of primary proton energy. The secondary particle fluxes are well described by the thermodynamical model^{14,15}). The assumptions about particle production used in the Monte Carlo calculations agree well with the thermodynamical model predictions. Therefore we expect the 300 GeV Monte Carlo results to predict reliably the flux densities outside the shield. The estimates made in this section are summarized in Table 2. From this table we see that the transversal shielding thickness for local loss of 10^{12} protons (300 GeV) and for flux density of 5 part/cm² sec at the surface, scales as follows:

- a) 2100 g/cm² for loss in a large mass of material,
- b) 1750 " for local loss in a small tunnel (R : 80 cm) (beam stopper),
- c) 1600 " for target loss in a large tunnel (R \geq 200 cm) (synchrotron tunnel),
- d) 1740 " for the beam loss distributed linearly over 100 m,
- e) 1430 " for loss on a target in an empty tunnel (R = 100 m).

The difference between a) and b) corresponds to an attenuation factor of 20, the difference between b) and c) to an attenuation factor of 4; we obtain 2.0 m and 0.8 m for the difference in thickness of earth layer between the different calculations. To reduce the radiation to 5 μ rem/h or less on top of the 300 GeV tunnel, 2500 g/cm² for the tunnel calculations and 2800 g/cm² for the massive end stop would be required. The last figure corresponds to 15.5 m thickness earth layer.

For full beam loss of 10^{13} protons/sec of 300 GeV the maximum transverse shielding obtained from the calculations for the massive end stop would correspond to 17 m of earth. For this extreme case

the dose rate on top of the ring would still be, according to our estimations, below 5 $\mu\text{rem/h}$. For scaling up to full beam loss at 800 GeV, an additional attenuation factor of 3 would be required at most, which is the ratio of the proton energies. Very probably the additional attenuation factor will be proportional to $\sqrt{E_1/E_2}$ ⁽¹⁷⁾. It follows that about 18 m of earth are sufficient to shield off the radiation created by full beam loss of 10^{13} protons/sec at 800 GeV, to reduce the dose rate to less than 5 $\mu\text{rem/h}$. We can conclude that 20 m of earth and rock shielding on top of the main ring are more than sufficient to shield against hadrons. With the present technique it will be difficult to measure the radiation on top of the ring even when a full beam loss occurs underneath, since the dose rate expected would be less than 10% of the natural background.

(C) The dose rate on the surface above the main ring due to muons

It is generally assumed that muons do not contribute to the dose measured at the shielding surface under large angles with the beam. In fact, the contribution of all electromagnetic interactions to the radiation field outside the shielding enclosure is presently for the PS between 5 and 20% of the total dose ⁸⁾. The dose due to muons is not measured separately, but it is assumed that, under large angles with the beam direction, it constitutes only a very small fraction of the electromagnetic contribution. In order to get a feeling for the magnitude of the muon dose outside the main ring shielding, we have estimated the muon flux density at different locations with respect to assumed loss points. We have considered separately the 'target muons' (1) and the 'cascade muons' (2).

(1) In a target bombarded with 300 GeV protons, pions are produced with angular and energy distributions which can be estimated from the thermodynamic model (Ranft and Hagedorn) ¹⁵⁾. These pions have a chance to decay into muons inside the tunnel. Table 3 gives the $\frac{d^2N}{dE d\Omega}$ for pions produced by 300 GeV protons in a Cu-target (see fig. 5).

With the data from table 3 we arrive at the following estimates of muon flux density on top of the ring shielding assuming that we have a layer of at least 20 m of rock and earth:

emission angle (mradian)	100	200	300
penetration length L (m)	200(150)	100(75)	70(55)
penetration length (g/cm ²) (fig. 6)	$3.6 \cdot 10^4$	$1.8 \cdot 10^4$	$1.3 \cdot 10^4$
minimum μ energy E_{th} (GeV)	90(68)	43(30)	28(21)
number of π with $E \cong E_{th}$ (π /str.)	$<10^{-13}$	$<10^{-13}$	$<10^{-18}$
decay probability	0.8%	0.8%	0.7%
dist. to surface squared L^2	$2 \cdot 10^8$	$0.5 \cdot 10^8$	$0.3 \cdot 10^8$
μ flux density for 10^{12} p/sec interacting	$<10^{-10}$	$<10^{-10}$	$<10^{-12}$

The values given in brackets for the penetration length were arrived at by considering the multiple scattering of muons penetrating into the earth shield. We assume a lateral deviation of muons of ≤ 5 m. If this value is taken into account, the real penetration length in the rock up to the surface would be about 0.7 to 0.8 of the geometrically calculated length. To be conservative in our estimations, we have considered this shorter length for the flux density calculations even though only a small fraction of the muons are scattered out. We can therefore conclude that the muons originating from pion decay which are produced in the target, do not contribute to the dose rate on the surface.

(2) We now consider the case of protons hitting a large mass of material, such as magnets, beam stopper or the tunnel walls. In this case a nucleon meson cascade will develop and pions will escape from these elements under large angles with the primary proton beam. These pions may in turn decay in their flight through the tunnel and the muons produced will penetrate into the earth and rock shielding under much larger angles with the primary proton beam than the 'target muons'. As shown in the M.C.C. of a meson nucleon cascade ¹⁸⁾ muons are also produced by decay inside the massive elements. We shall therefore estimate these two

contributions from muons by assuming that the 300 GeV beam hits a steel cylinder of 40 cm diameter and 3 m length. The Monte-Carlo programme 'TRANSK' has been modified to give energy-angular distribution for muons and pions at the outer layer of the steel cylinder. As we are interested in the angular and energy distributions of pions and muons coming out of the steel cylinder, we have considered a cylindrical layer having a thickness of 1/5th of the radius. For small angles the statistics of the results are sufficient up to about 10 GeV, for angles up to 30° the statistics are sufficient up to only 5 GeV (see fig. 7). We could only estimate upper limits for the number of pions and muons in a certain energy and angular range. Assuming a shielding of 20 m, the penetration length of muons emitted under about 30° is about 40 m. From fig. 6 we see that we need at least a muon energy of 15 GeV to reach the surface. Pions above 15 GeV are of the order of 10^{-5} /incoming protons. To obtain a flux density on the surface of the cylinder we have to divide this value by the effective surface of the cylinder. We know from the pion-star distribution on the outer layer of the cylinder (fig. 8) that the pion-produced stars have a high density over about one meter area in longitudinal direction whereas upstream and downstream from this high density region, the star densities are one or two orders of magnitude lower. We therefore assume that the effective surface is about 10^4 cm^2 . The flux density of pions above 15 GeV emitted under about 30° would then be 10^{-9} pions/cm² protons. The ratio of the distance from the surface of the steel cylinder to the surface on top of the main ring shield is about 1 to 100. With 10^{13} particles lost per second and 1% decay probability we arrive at 0.010 muons/cm² sec flux density which corresponds to roughly a dose rate of 1 $\mu\text{rem/h}$. Estimations for different angles give similar results. Muon flux densities on the surface of the steel cylinder are two orders of magnitude lower than the pion fluxes.

From this estimate we see that the expected dose rate on top of the ring is of the order of a few $\mu\text{rem/h}$, which is higher than the expected contribution from hadrons. Our estimates are, however, based on the assumption that all protons interact with large items in the ring tunnel and we have used very conservative figures for the energy distribution of pions and their decay probability so we can expect that dose rates for the muons will also remain below the limits that can be measured with the present instrumentation.

III. SHIELDING REQUIREMENTS FOR THE TRANSFER BEAM FROM THE 300 GeV MAIN RING TO THE WEST AREA

In the preceding section we calculated the flux densities and dose rates expected on the surface above the main ring. We could assume a minimum shielding layer of earth and rock of 20 m thickness as the ring tunnel will be bored at a depth of roughly 30 m. For this type of calculations we could therefore make the most conservative assumptions about the particles spectra and angular distribution. We further have shown that even with a full beam loss of 10^{13} particles/sec in one point, the dose rate on the surface will be so low that it will be difficult to measure.

However, when discussing the shielding requirements for the transfer tunnel to the experimental area we have to consider the tunnels that have been already built for the ISR, and the transfer tunnel that will come to the surface inside the present CERN fences but close to Route Nationale 84. According to the tentative layout the transfer tunnel will pass at 10 m underneath Route Nationale 84 and will join the existing ISR transfer tunnels at a distance of 20 m only from RN 84. The present shielding arrangements around TT3, TT4 and TT5 can be modified to some extent at a reasonable cost, and we must allow for the necessary space between transfer tunnel and CERN fences for the CERN Route Nord, which is essential for the operation and safety of the West area.

As in the preceding section we shall look into the shielding requirements for hadrons and muons separately. For average beam losses the dose rate on the CERN fences at Route Nationale 84 should not exceed 25 μ rem/h, so on top of the shielding surface we may allow for dose rates of about 50 μ rem/h at places close to RN 84 and about 100 μ rem/h further downstream. In the transfer tunnel we shall assume for the shielding estimations an average beam loss of the order of 1% per 100 m. Occasionally, high losses during running in and other operations may occur so the radiations have to be monitored and controlled in order to keep the average doses below the above figures. We propose to install monitors inside the beam tunnel and outside along the CERN fences.

(A) Hadron shielding for the transfer tunnel

In table 2 of the preceding section the values for the transverse shielding for 10^{11} particles lost and for dose rates of 50 $\mu\text{rem/h}$ on the surface of shield are given. For the 300 GeV proton beam the transverse shielding required would be about 1700 g/cm^2 , for beam losses of the order of 10^{10} particles (1% of the total beam) the shielding needed would be 1450 g/cm^2 . According to the present plans of the junction chamber between transfer tunnel 3 and transfer tunnel 4 (where the transfer tunnel from the 300 GeV proton synchrotron will end) the shielding will be 950 g/cm^2 . Further downstream the shielding above transfer tunnel 4 varies between 6 and 7 m (1100 g/cm^2 to 1250 g/cm^2). The additional shielding required, according to our estimates, for this transfer tunnel would be between 300 and 500 g/cm^2 , or about 1.7 to 2.8 m of earth have to be added to complement the present shielding. The tunnel structure will support up to 15 ton/m^2 , so on top of the tunnel reinforcement of shielding will be possible at low cost. On the North side, however, the retaining wall parallel to the North Route has to be built higher up and some additional shielding must be put between the road and the retaining wall, where the present shielding is less than 1500 g/cm^2 . The old shielding estimations were based on a lower average intensity (10^{13} prot/sec were foreseen only for the neutrino experiment or else, an average of 10^{12} prot/sec) and on 20 GeV proton energy. Taking these two parameters into account, the new attenuation factor for 300 GeV (10^{13} part./sec) will be 60 to 70 times higher for the transverse shielding. This corresponds to 450 to 500 g/cm^2 additional shielding which is in agreement with our above estimates. The required hadron shielding, as estimated previously, is in agreement also with the calculations of K. O'Brien who has used a completely different approach to estimate the shielding for the 200 to 500 GeV proton synchrotron at Batavia. We shall assume, for the following section, that at least 1500 g/cm^2 or 8.5 m of earth of transverse shielding are available around the transfer tunnel.

(B) Shielding requirements for the transfer tunnel with respect to muons

As in the case of the main accelerator ring we consider the 'target muons' and the 'cascade muons' separately.

1. Muons from the decay of secondary pions can possibly reach the CERN fences along Route Nationale 84, if they are emitted under angles $> 9^\circ$ with beam direction. Seen under this angle the earth shielding around the transfer tunnel is at least 40 m thick permitting only muons of 17 GeV to penetrate the shield. We have chosen a number of proton loss points and calculated the muon fluxes at the CERN fences under the most unfavourable conditions.

Loss point	Angle ($^\circ$)	Earth thikn. m	Min. μ ener. GeV	π /ster. above min μ ener.	D^2 cm^2	Decay prob-ability	Prot. loss p/sec	Φ at fences $\text{part}/\text{cm}^2 \text{sec}$	Dose rate $\mu\text{rem}/\text{h}$
E	17	> 100	40	$< 10^{-18}$	$1.6 \cdot 10^8$	0.02	10^{13}	$< 10^{-15}$	-
C+60m	9	40	17	$1.3 \cdot 10^{-6}$	$4 \cdot 10^8$	0.03	10^{13}	10^{-3}	0.1
C+60m	16	32	13	10^{-9}	10^8	0.02	10^{13}	$2 \cdot 10^{-6}$	0.0002

As expected, the dose rates due to 'target muons' are small compared with the hadron component dose rates estimated to be 20 $\mu\text{rem}/\text{h}$.

At very small angles, however, we have muons accompanying the proton beam. Where it moves upwards, muons following the protons but travelling outside the magnetic field of the bending magnets or bending upwards, will penetrate into the top shielding layer and will reach the surface above transfer tunnel 4. We estimate the muon densities using the following parameters:

- earth layer to penetrate : 30 m
- decay probability : 6%
- minimum energy required : 12 GeV
- π /ster. : $5 \cdot 10^3$
- D^2 : 10^8 .

For a loss of 10^{10} protons we have about $5 \cdot 10^3$ muons/ cm^2 sec, above transfer tunnel 4. This muon beam is directed upwards under an angle of 15° and goes above the ISR South fences at a distance of ~ 500 m. At this place the dose rate will be ~ 20 mrem/h.

2. Cascade muons

As in the case of the main ring we estimate the pions produced in a large item such as magnets, etc... and coming out under a certain angle (see fig. 9) and above a given minimum energy (see fig. 10), using the Monte-Carlo calculations with the programme 'TRANSK'. We can estimate the pion fluxes from the pion flux density in the outer layer of the steel cylinder, or from the number of pions in the outer layer of the cylinder having a certain angle and a given energy.

The following table gives estimations for some beam loss points and pions produced under large angles:

Loss point	Angle (°)	Earth thic kn. m	Min. μ ener. GeV	π /ster. above min. μ ener.	D^2 cm^2	Decay prob- ability	Prot. loss p/sec	Φ at fences part/ cm^2 sec	Dose rate μ rem/h
E+10 m	30	60	25	$1 \cdot 10^{-7}$	$4 \cdot 10^7$	1%	10^{10}	$3 \cdot 10^{-7}$	< 0.1
E+110m	60	34	14	$2 \cdot 10^{-6}$	$1.3 \cdot 10^7$	1%	"	$1.5 \cdot 10^{-5}$	< 0.1
D+20 m	60	26	10	$1 \cdot 10^{-5}$	10^7	1.5%	"	$1.5 \cdot 10^{-4}$	< 0.1
B ₅	43	26	10	$1 \cdot 10^{-5}$	10^7	1.5%	"	$1.5 \cdot 10^{-4}$	< 0.1
	25	45	19	$3 \cdot 10^{-7}$	$3 \cdot 10^7$	1%	"	10^{-5}	< 0.1
C	31	30	12	$6 \cdot 10^{-6}$	10^7	1.7%	"	$1 \cdot 10^{-4}$	< 0.1
C+160m	46	28	11	$7 \cdot 10^{-6}$	10^7	1.2%	"	$8.5 \cdot 10^{-5}$	< 0.1
B	73	9	3	$3 \cdot 10^{-4}$	10^7	3%	"	$9 \cdot 10^{-3}$	~ 1.0
	41	12	4.5	$1 \cdot 10^{-4}$	$2.2 \cdot 10^7$	3%	"	$1.4 \cdot 10^{-3}$	< 1.0
	32	16	6.0	$3 \cdot 10^{-5}$	$4 \cdot 10^7$	3%	"	$1 \cdot 10^{-4}$	< 1.0

There are also muons coming out of the steel block which are produced from pions decaying inside the iron. However, these muon fluxes are (above 3 GeV) more than two orders of magnitude smaller than the pion fluxes and will therefore not contribute to the dose on the shielding surface. The dose rate given above for the muons is much below 25 μ rem/h, the value tolerated at the CERN fences.

IV. CONCLUSIONS

The minimum shielding of 20 m of earth and rock above the main proton synchrotron ring is sufficient to allow operation of the accelerator up to 800 GeV energy with an intensity of 10^{13} protons/sec.

The dose rate expected on the surface is only a small fraction of the natural background. The present activity in the areas can, from the radiation protection standpoint, be continued without any restrictions. This statement would be true even if in the future the permissible dose rate in the neighbourhood of nuclear installation were lowered by a factor of 10.

The transverse shielding of the beam transfer tunnel from the 300 GeV accelerator to the West area has to be 1700 g/cm^2 for 10^{11} protons lost per 100 m, and 1450 g/cm^2 for 1% of beam loss for a dose rate of less than $25 \text{ } \mu\text{rem/h}$ at the CERN North fences.

At some locations the presently foreseen shielding for the junction chamber between transfer tunnel 3 and transfer tunnel 4 and the transfer tunnels, is not sufficient for operation with 10^{13} particles of 300 GeV energy. However, this statement is based on the assumption that 1% of the protons are lost inside these transfer tunnels. K. O'Brien has assumed for the NAL accelerator beam losses about 40 times lower for the 500 GeV proton synchrotron than our assumptions for the transfer line. Less additional shielding of the transfer tunnel would be required if a control of the beam losses is guaranteed down to such low levels ($3 \cdot 10^4 \text{ p/cm sec}$).

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Table 1

Position	Shielding	Calculated part/cm ² sec 10 ¹² pr.	Measured part/cm ² sec 10 ¹² pr.
33/100/33*	earth 200 g/cm ²	1·10 ⁴	2.0·10 ⁴ (+)
34	" 200 "	6·10 ³	8·10 ³
33	" 700 "	0.6·10 ²	1.3·10 ²
34	" 700 "	0.2·10 ²	0.5·10 ²
32**	concr. 770 "	1·10 ³	2.6·10 ³ (++)
33	" 770 "	2·10 ²	4·10 ³
37	" 580 "	1.30·10 ⁴	0.7·10 ⁴
39	" 770 "	1·10 ³	1.0·10 ³

*) J. Ranft, 67-5; (+) measured values divided by 3.6 to allow for different energy cutt-off in the measurements and calculations.

The preliminary experimental data quoted in this report were not properly normalized.

**) K. Goebel and (++) flux values obtained from the neutron spectrum
J. Ranft, CERN \geq 100 MeV.
70-16;

Table 2

Transversal shielding estimations based on calculations
and extrapolation of measurements

Reference	Dose rate at shield. surface mrem/h	Flux at shield. surface p/cm ² sec	Earth or concr. shielding g/cm ²		Atten. length used g/cm ²	
			20 GeV	300 GeV	20 GeV	300 GeV
Distributed loss:						
10 ¹² part/100m sec ^{a)}	{ 5 0.005	5 (MC)	1560	1740	} 109	} 116
10 ¹¹ part/100m sec ^{b)}		0.005 (MC)	2300	2550		
10 ¹² prot/sec lost in end stop ^{a)}	{ 5 0.005	5 (MC)	1920	2110		
10 ¹¹ prot/sec lost in end stop ^{b)}		0.005 (MC)	2670	2910		
10 ¹² prot/sec lost in beam stopper in small tunnel ^{b)}	{ 5 0.005	15 (¹¹ C)	1500	1700	} 110	} 116
10 ¹¹ prot/sec lost in small tunnel ^{b)}		0.005 (¹¹ C)	2250	2500		
10 ¹² prot/sec lost in target, large tunnel (50% efficiency) ^{c)}	{ 5 0.005	15 (¹¹ C)	1300	1500		
10 ¹¹ prot/sec lost in target, large tunnel ^{c)}		0.005 (¹¹ C)	2100	2350		
10 ¹¹ prot/sec 100 m ^{d)}	0.05	0.15 (¹¹ C)	1550	1750		
10 ¹² prot/sec con- centrated loss in a small target in empty tunnel (MAGTRA)	{ 5 0.005	5 (MC)	1400*	1720*	105	
		0.005 (MC)	2150	2150	105	105

*) Values for 10 and 200 GeV, respectively

a) J. Ranft, MU/EP-67-1 (ref. 7)

b) K. Goebel and J. Ranft, CERN-70-16 (ref. 9)

c) CERN-LRL-RHEL-UCRL-17941 (ref. 12)

d) K. O'Brien, HASL-199 (ref. 16)

Table 3

Pion spectra for angles of 7° , 10° and 15° for pions
produced by 300 GeV protons in copper

GeV/c	part/GeV, str. 7°	part/GeV, str. 10°	part/GeV, str. 15°
1	1.99	1.55	1.06
3	1.96	$5.72 \cdot 10^{-1}$	$1.45 \cdot 10^{-1}$
6	$2.73 \cdot 10^{-1}$	$3.66 \cdot 10^{-2}$	$1.66 \cdot 10^{-3}$
9	$1.10 \cdot 10^{-1}$	$1.54 \cdot 10^{-3}$	$1.00 \cdot 10^{-5}$
12	$4.03 \cdot 10^{-3}$	$5.26 \cdot 10^{-5}$	$3.83 \cdot 10^{-8}$
15	$3.87 \cdot 10^{-4}$	$1.61 \cdot 10^{-6}$	$8.94 \cdot 10^{-11}$
18	$3.43 \cdot 10^{-5}$	$4.65 \cdot 10^{-8}$	$1.21 \cdot 10^{-13}$
21	$2.89 \cdot 10^{-6}$	$1.23 \cdot 10^{-9}$	-
24	$2.35 \cdot 10^{-7}$	$3.29 \cdot 10^{-11}$	-

FIGURE CAPTIONS

- Fig. 1 Longitudinal star or track densities on the inner surface ($r = 1$ m) of the tunnel wall. One proton of $p_0 = 20$ GeV/c interacts on a target at $z = 2$ m in the centre of the tunnel.
- Fig. 2 Transverse star or track densities in the Fe shield of a tunnel at z position near to the longitudinal maximum of the densities.
- Fig. 3 Longitudinal star or track densities on the inner surface ($r = 1$ m) of the tunnel wall. One proton of $p_0 = 300$ GeV/c interacts on a target at $z = 2$ m in the centre of the tunnel.
- Fig. 4 Transverse star or track densities in the Fe shield of a tunnel at a z position near to the longitudinal maximum of the densities.
- Fig. 5 Pion energy spectrum at 100 mrad for pions produced by 300 GeV protons in a Cu-target.
- Fig. 6 μ -energy-range relation from D. Keefe's report UCID 10018¹⁹).
- Fig. 7 Pion energy spectrum for 0° and 30° from TRANSK energy-angular distribution above 15 GeV extrapolated (pure statistics).
- Fig. 8 π -star distribution in a steel cylinder at the axis and at 20 cm radius.
- Fig. 9 π -angular distribution at a radius of 40 cm in steel (TRANSK).
- Fig. 10 π -energy distribution at a radius of 32 cm in steel (TRANSK).

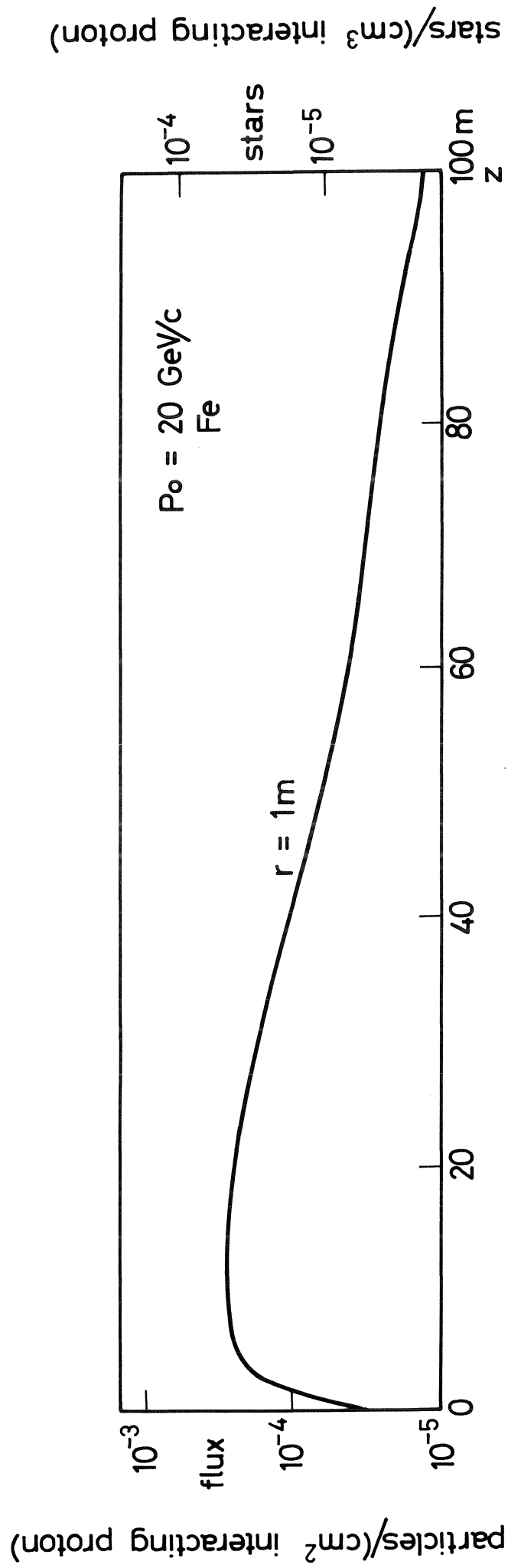


Fig. 1

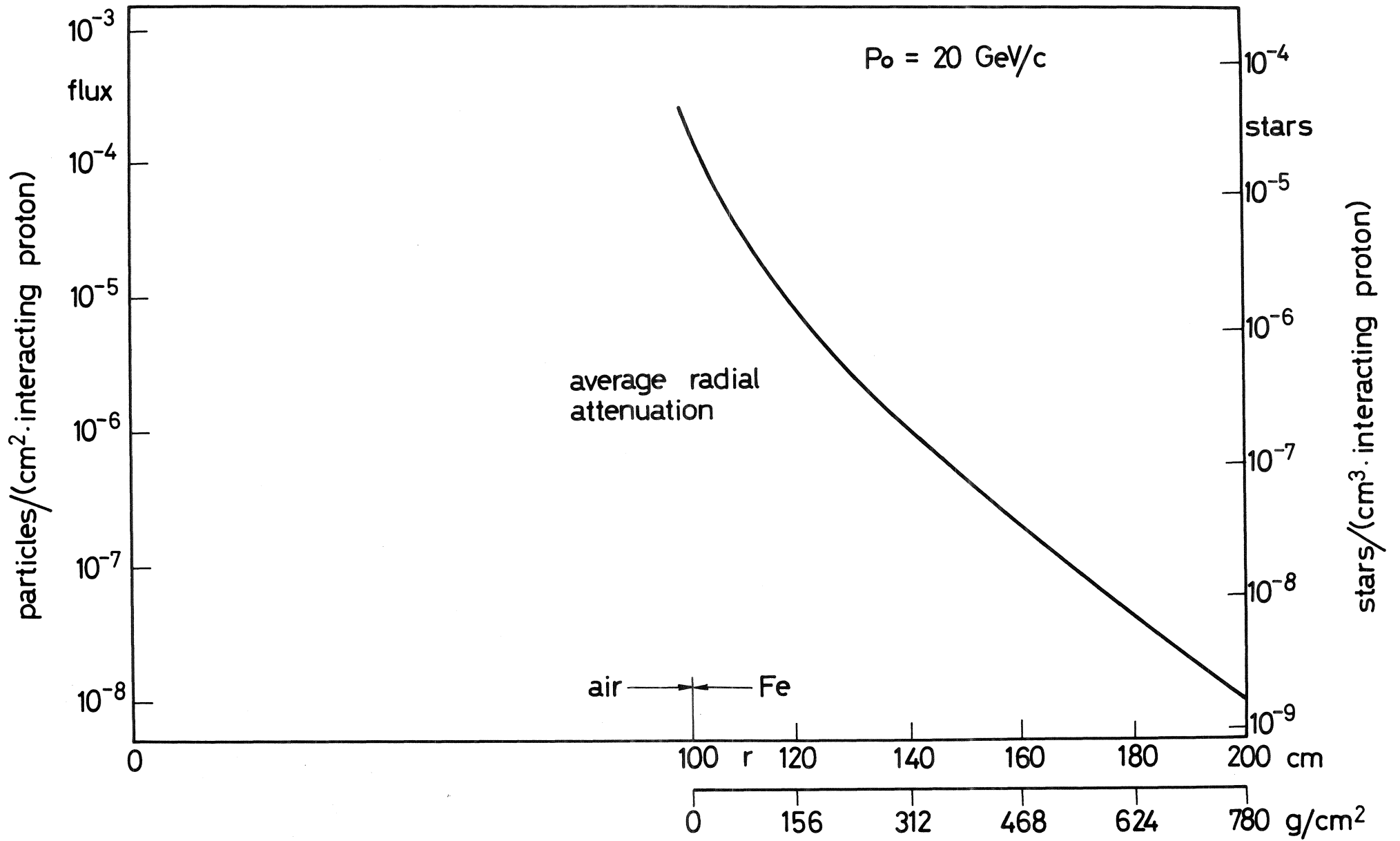
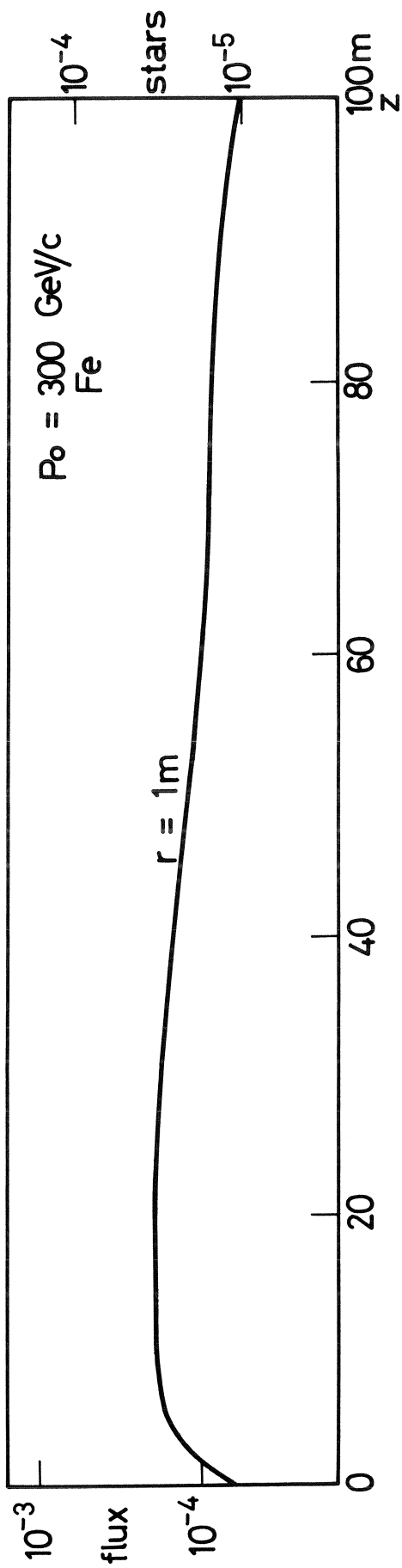


Fig. 2

particles/(cm²·interacting proton)



stars/(cm³·interacting proton)

Fig. 3

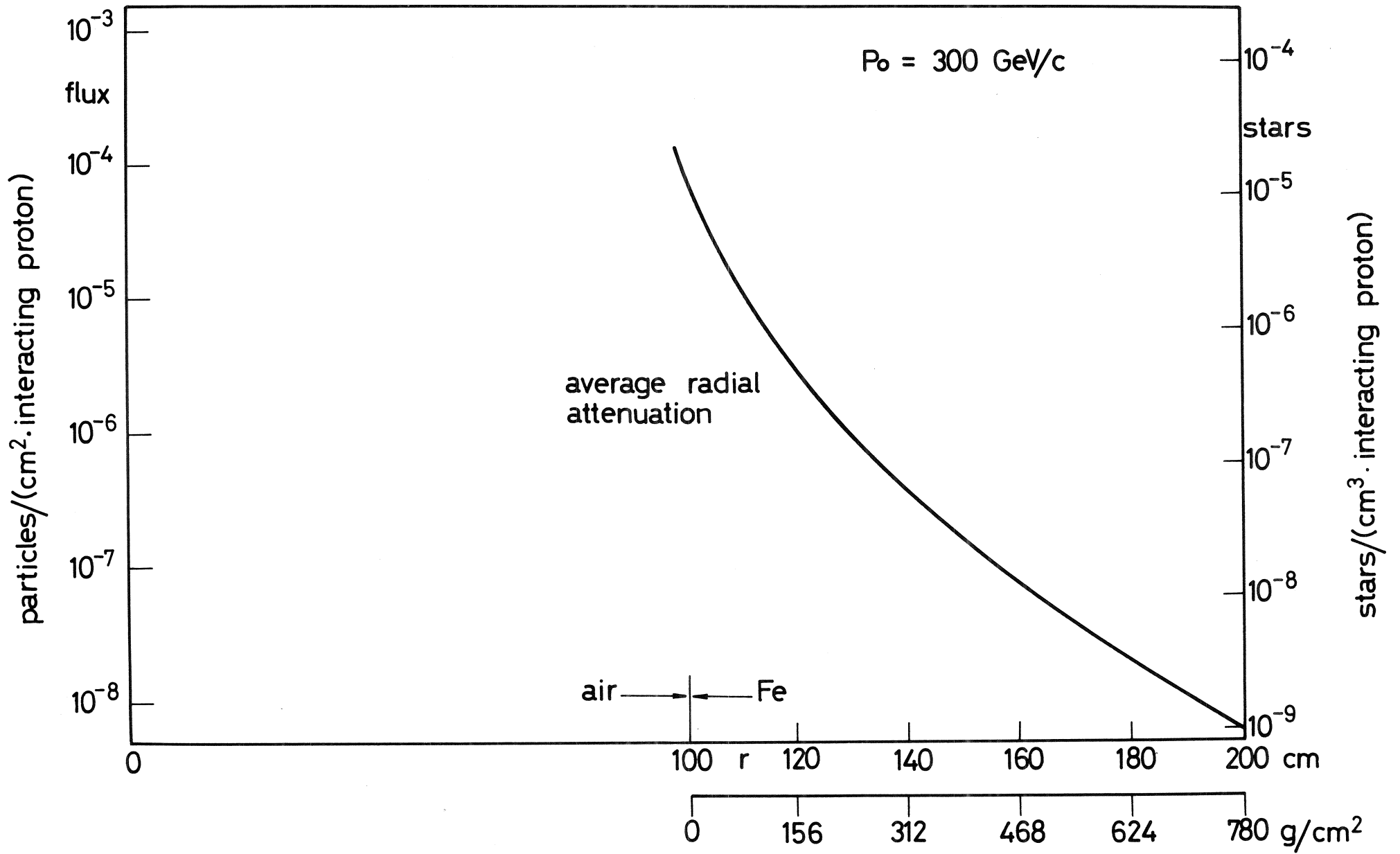


Fig. 4

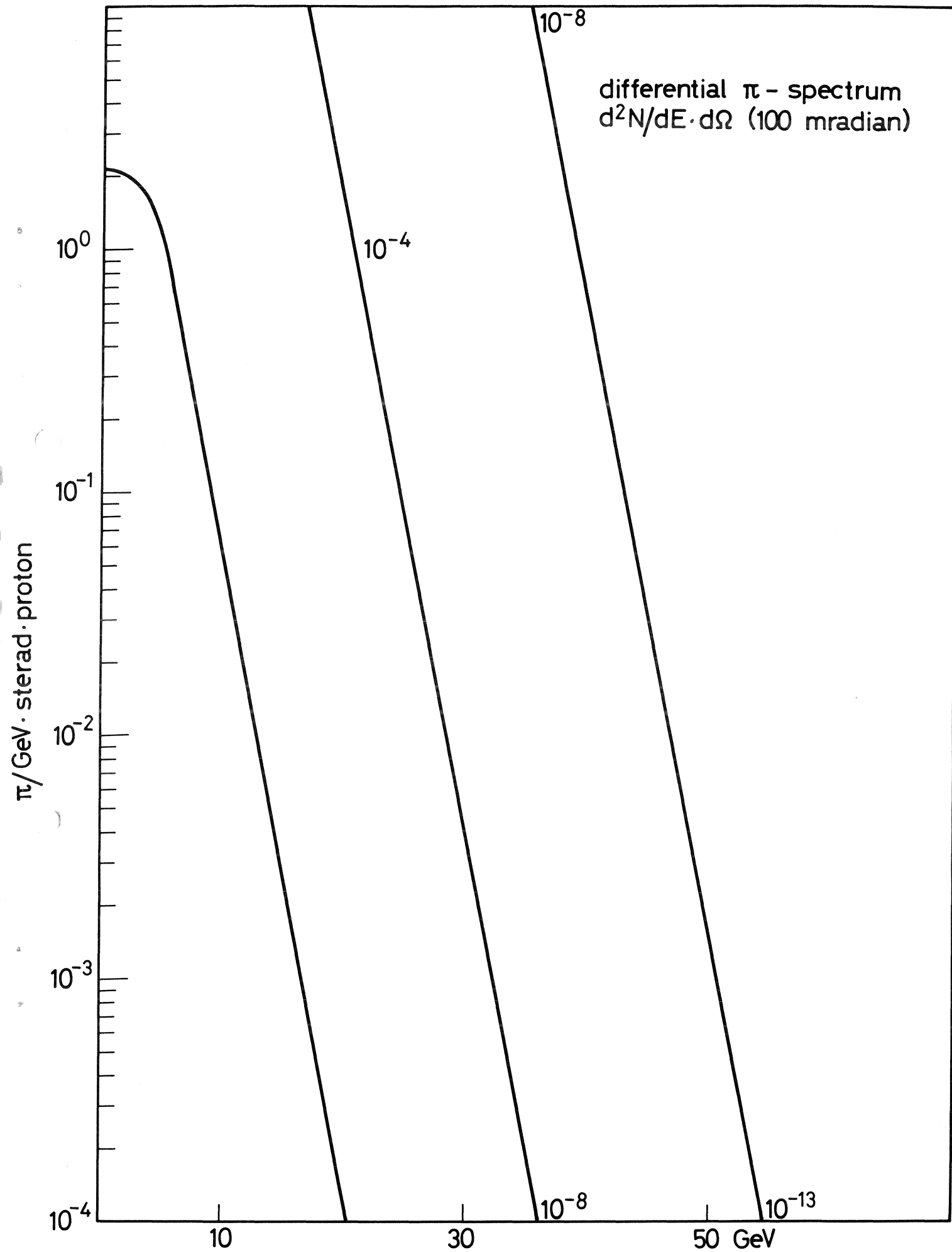


Fig. 5

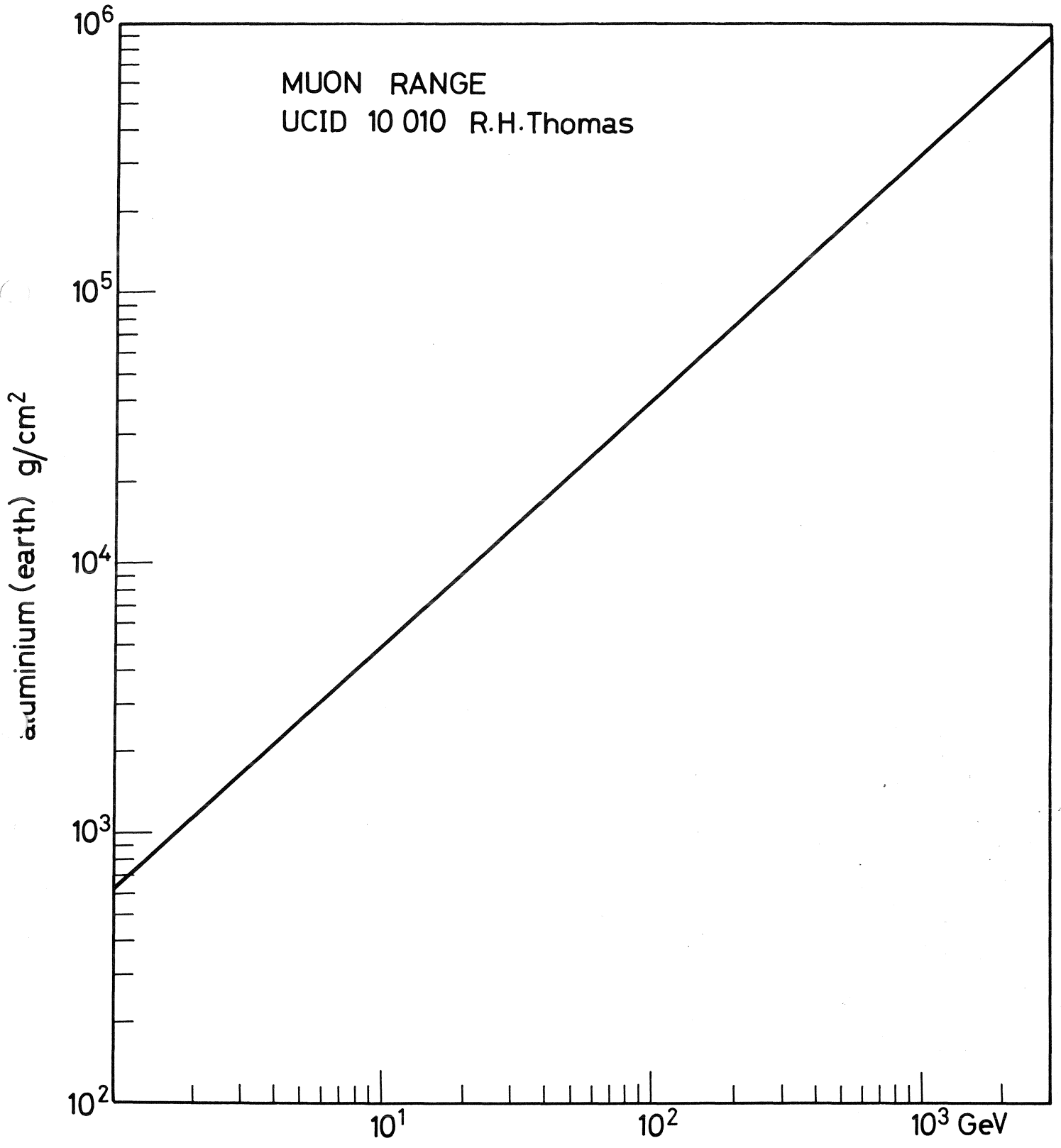


Fig. 6

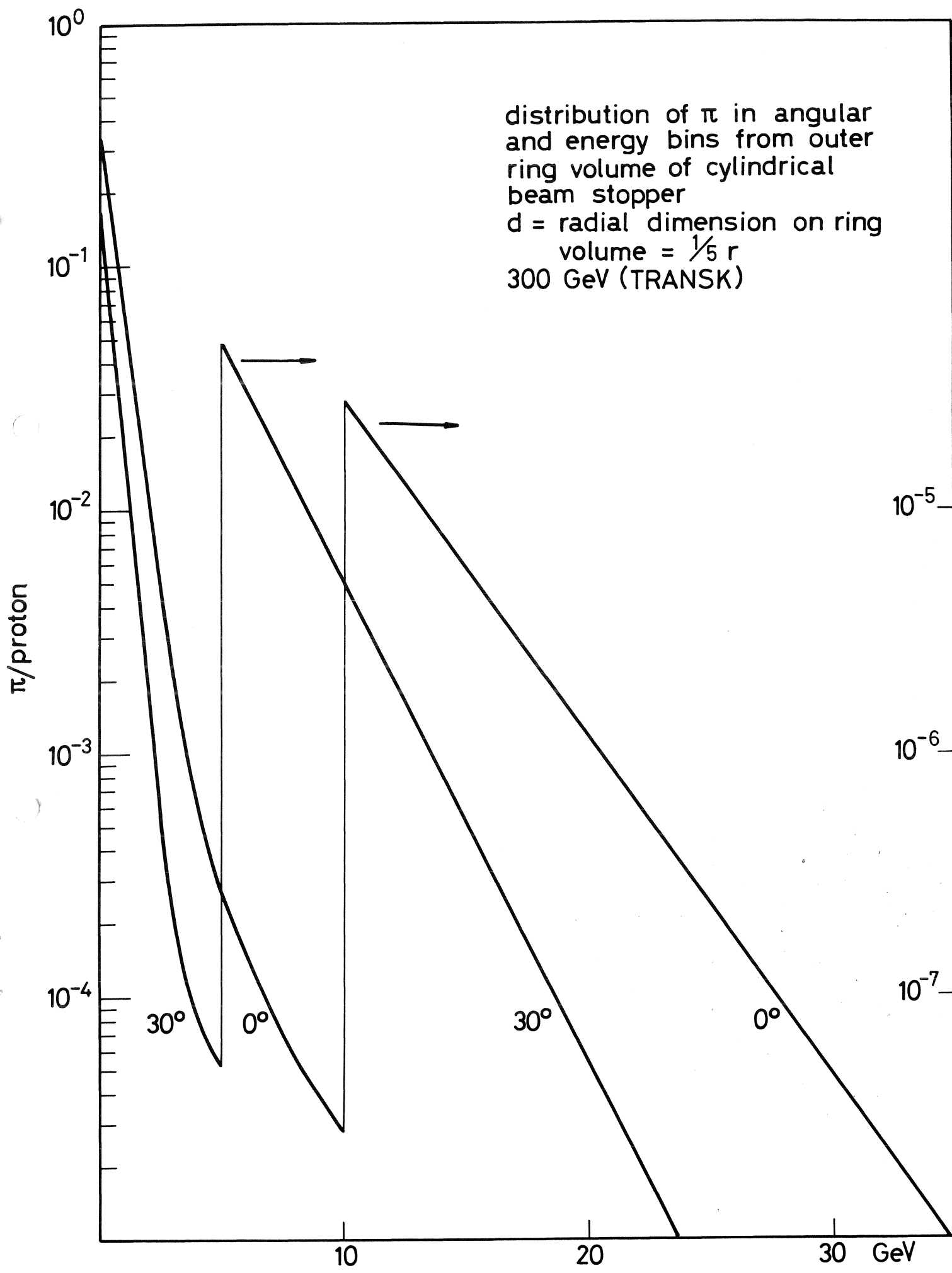


Fig. 7

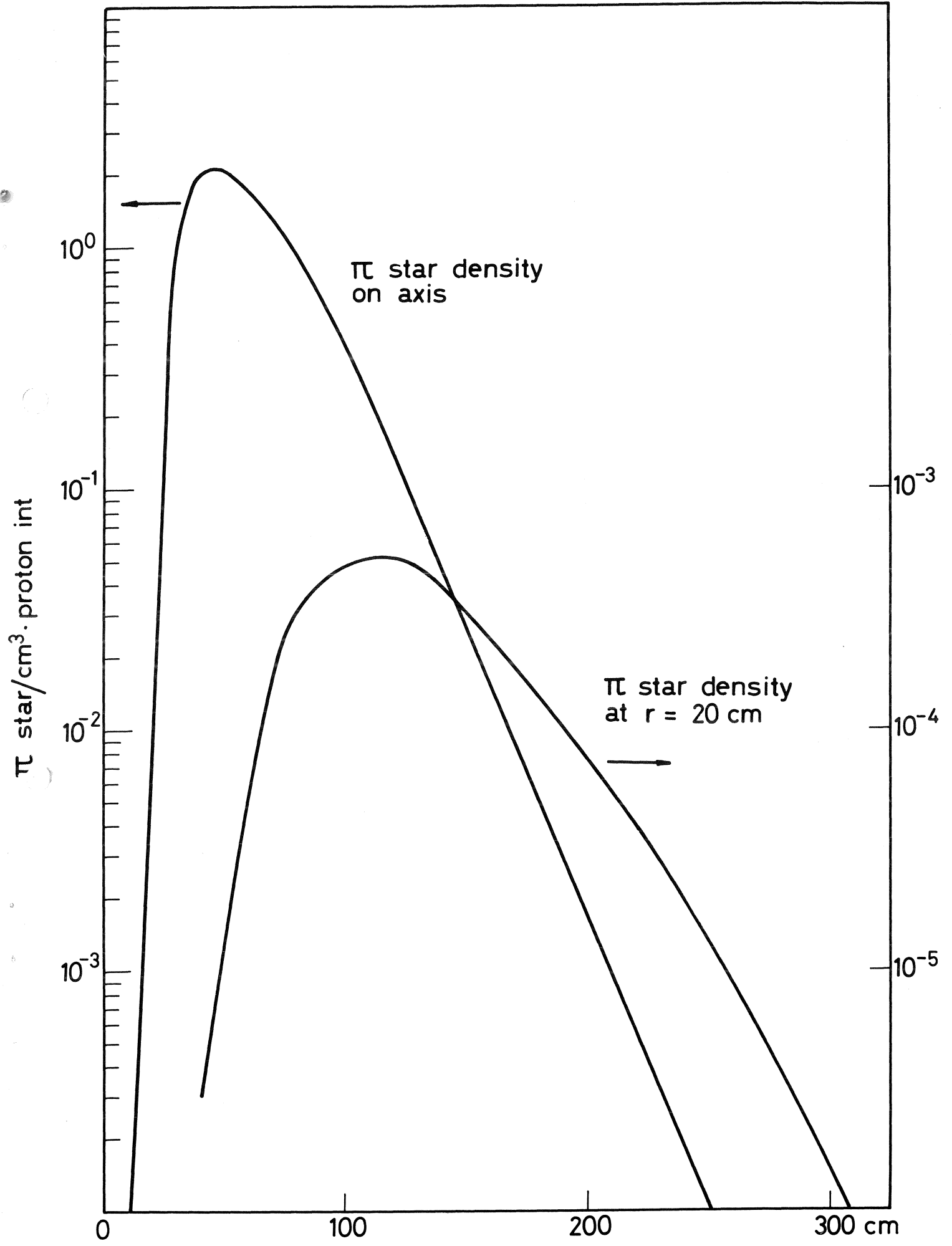


Fig 8

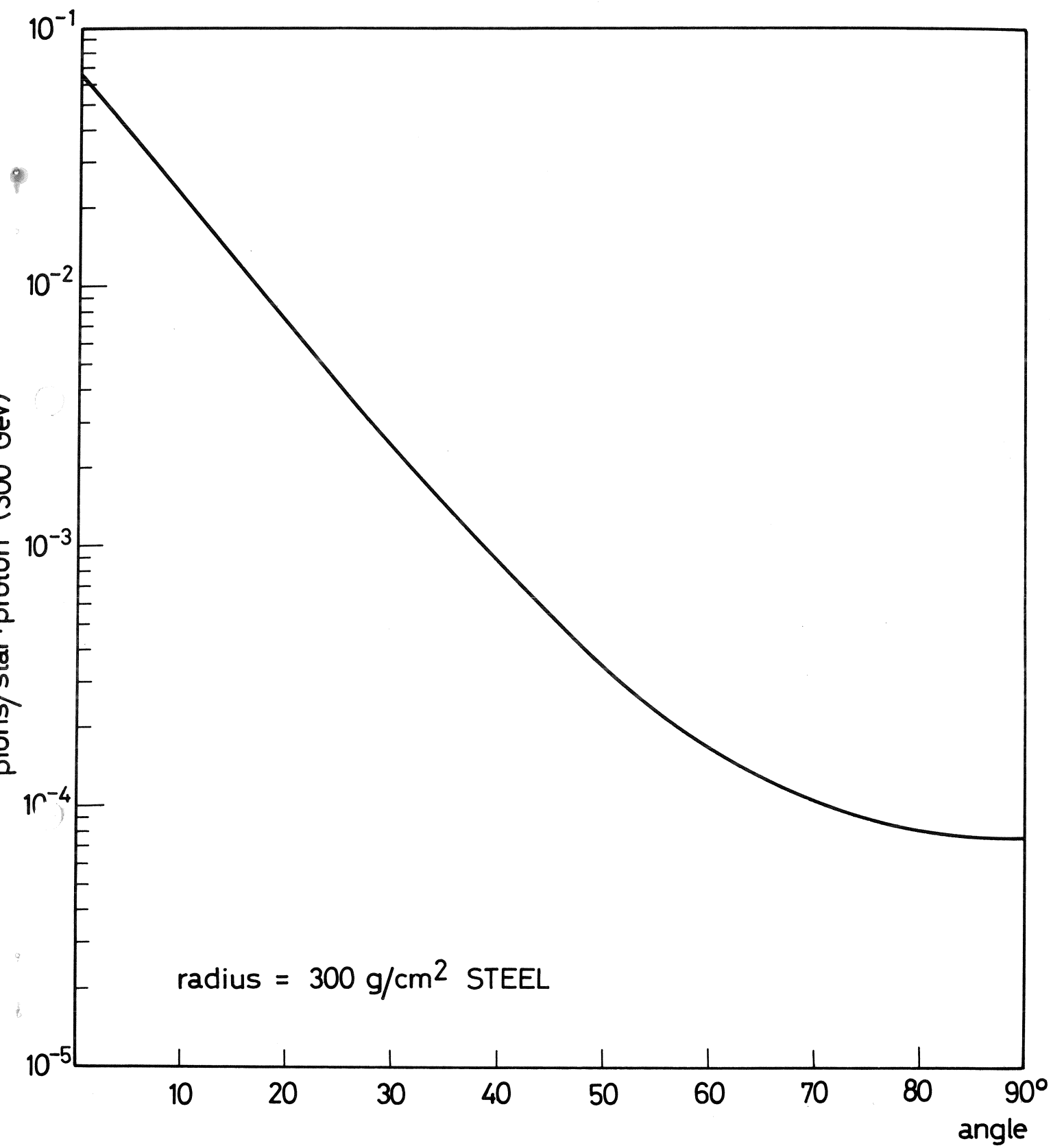


Fig. 9

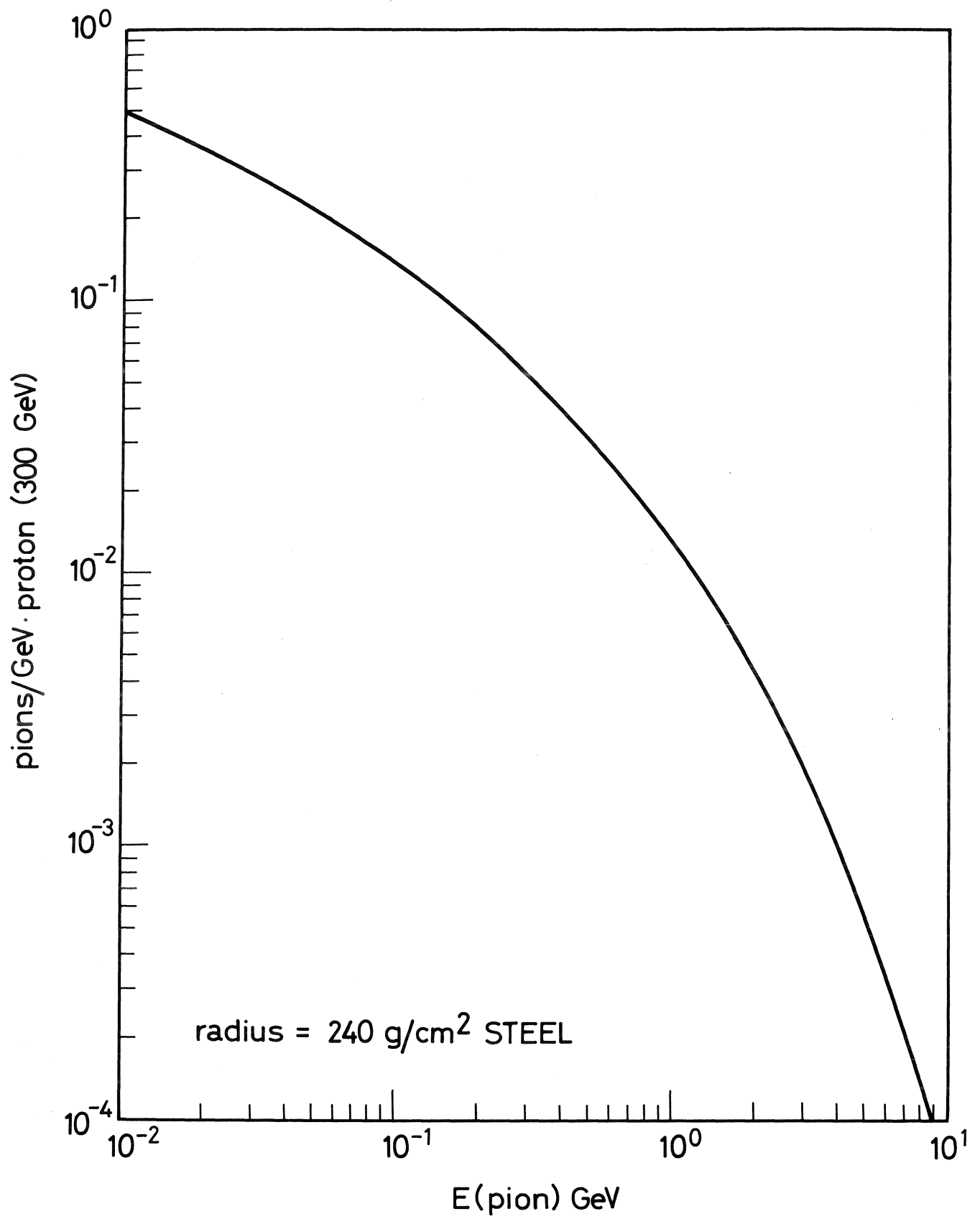


Fig. 10

TABLES

1. Calculated and measured flux densities around PS-ring and primary beam tunnel.
 - +) the measured values (^{11}C) are divided by 3.6 (see explanations in ref. 9 and 13, in order to allow for the different energy ranges,
 - ++) flux densities above 100 MeV obtained from spectra fitting best the responses of series of activation detectors.
2. Shielding estimations from different calculations and various experiments.
3. Energy spectrum of pions under different angles from 300 GeV protons on a Cu-target.