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Considerations about the radiation shielding for 30 GeV protons.

A. Assumptions.

1) Medical tolerance dose (M.T.D.)

We will be chiefly concerned with the particles of high penetrating powers, i.e. fast ionizing particles and neutrons.

a) Fast ionizing particles.

For these the value is 0.3r/week. For safety, we take 7 x 24 hours a week, which gives 1.8 mr /h (instead of the usual 6 mr/h) or $5 \cdot 10^{-7}$ r/sec. 1 r = 10^9 ion pairs per cm^3 of air. One fast particle makes 50 ionpairs per cm of air. Thus a flux of 10 cm^{-2} sec^{-1} or $10^5 m^{-2} sec^{-1}$ gives the M.T.D, being about 10^3 times the cosmic ray flux at sea level.

b) Neutrons.

Here the tolerance dose is 0.06 r/week or 10^{-7} r/sec. This ionization is measured in an air chamber whose walls consist of hydrogen compounds (Victoreen chamber). The neutrons we will be concerned with are attenuated to 0.1 intensity by 400 g /cm^2 of air. A hydrogen compound of a constitution similar to H_2O will be about 10 times as effective in attenuating, so 40 g / cm^2 will attenuate to 0.1, or in average a neutron loses 6% of its energy per g / cm^2 . After the first few collisions the average energy per neutron will be 10^7 eV, thus the energy loss is 6 x 10^5 eV g^{-1} cm^2. The recoil nuclei produce 2 x 10^4 ion pairs per g / cm^2 of air, or 20 ion pairs cm^3 of air, corresponding to 2 x 10^{-8} r / cm^3. Thus a flux of 5 neutrons cm^{-2} sec^{-1} or 5 x 10^4 m^{-2} sec^{-1} will give the M.T.D. This is half the rate for fast ionizing particles. Because of the uncertainties involved in this estimate we assume 10^4 neutrons m^{-2} sec^{-1} as M.T.D.

2) Laboratory Tolerance.

Here the total flux of particles ought not to be higher than that produced by the cosmic radiation, which is about 10^2 m^{-2} sec^{-1}.

3) The machine.

Particle energy 3 x 10^{10} eV.

Initially a pulse intensity of 10^9 particles per pulse and a pulse frequency of 4 pulses / min were assumed, corresponding to 6.7×10^7 sec^{-1}. As an increase both in pulse intensity and pulse frequency is being considered, an intensity of 10^9 protons sec^{-1} is assumed. The proton beam extracted will have a minimum half angle of opening of 1°.

4) Interaction an absorption processes.

The interaction processes in the range of energies involved are known only from photographic plates exposed to the cosmic radiation at high altitudes. We based ourselves on the paper by CAMERINI, LOCK and PERKINS in "Progress in Cosmic Ray Physics ed. by J.G. Wilson North-Holland Publishing Company, Amsterdam 1952, p. 1 to 59. From this paper we use the following data :

A	fig 1
B	fig 4
C	fig 10
D	tab 3
E	fig 11
F	fig 16
G	fig 17

Protons of 30 GeV lose their energy mostly by nuclear collisions. The collision mean free path will not exceed 150 g / cm^2. The following particles are created :

I π - mesons (1/3 neutral and 2/3 charged).

The distribution in multiplicity for various energies is given by A. All multiplicities below the maximum one have about equal probability. B gives the mean multiplicity as a function of energy. It rises from 0.1 at 500 MeV to 4 at 10 000 MeV with decreasing slope. By extrapolation to 30 GeV one finds 8 charged mesons. In material of low atomic weight the multiplicity might be somewhat lower.

C gives a differential energy spectrum for the mesons. It can be represented by a power law with exponent -1.4 below 1.1 GeV, -2.5 above this value. This spectrum will be influenced to some extent by the similar spectrum of the primary cosmic rays. The mean energy is 10^9 eV per meson according to D; this value does not depend strongly on the primary energy.

The angular distribution is given in E. If x is the ratio of flux per angular interval according to distribution E compared to the same for an isotropic distribution, we get

	$0 - 30^\circ$	$30 - 60^\circ$	$60 - 120^\circ$	$120 - 180^\circ$
x	8.7	1.35	0.34	0.21

II Protons.

These appear in the emulsions as "black" tracks (< 30 MeV) and "grey" tracks (30 to 500 MeV). The first ones will not be of importance because of their short range (< 0.5 g/cm^2). Their multiplicity is 3 to 4 times that of the grey tracks, The multiplicity distribution for both is given in B. At 30 GeV we get about 8 protons per star. The differential energy spectrum according to C falls off with an exponent -1.4; the mean energy is about 10^8 eV according to F independent of star energy. The angular distribution G shows less collimation than E; above 100 MeV 3/4 of the protons are emitted into the forward hemisphere.

III Neutrons.

For these we take the same multiplicities and distributions as for protons; the neutrons below 30 MeV cannot be neglected as the protons are.

Absorption processes.

I Charged π-mesons.

These can produce the same nuclear reactions as the primary protons do, The mean free path is the same. On the other hand they can decay into μ-mesons. The mean free path for decay is determined by the mean life (2.5×10^{-8} sec), the velocity of light and the time dilatation, which is proportional to the energy in terms of the rest energy. (140 MeV).

II Neutral π-mesons.

These will decay with very short mean life into two photons, which start an electron-photon cascade. The development of the cascade in air is governed by the energy in terms of the critical energy of 10^8 eV and by the interaction length of 340 m air.

III Protons.

The grey protons may produce stars as the primaries did. Also they lose energy by ionization. The black protons are quickly stopped by ionization.

IV Neutrons.

These can produce stars as well. Below 30 MeV their energy loss will be by elastic and unelastic collisions only . From cosmic ray observations we get an attenuation to 0.1 in 400 g/cm^2 of air. In Brookhaven an attenuation to 0.01 in 600 g/cm^2 of concrete is fpund. This latter value will depend however on the angle, under which most of the neutrons strike the wall.
We will take the more conservative value of the cosmic radiation.

V. μ- mesons.

These lose their energy by ionization only. As they are fast particles, we get from the value of 50 ion pairs per cm^3 of air a loss of 1.25 MeV/g cm^{-2}. The range distribution is thus given by the energy spectrum. For dense material, where only a small proportion of the π-mesons decays, this spectrum is steeper than that of the π-mesons by a factor 1/E. (energetic π-mesons are less likely to decay). In air, where most of the π-mesons decay, the μ-mesons will have the same energy spectrum as the π-mesons.

B Calculation of the absorption of the proton beam.

This was carried out by two methods, which differ in the assumption about the energy spectrum of the π-mesons.

Method a is based upon the distribution A, extrapolated to 30 GeV. To get an energy distribution, the assumption is made, that the energy is divided equally amongst all the mesons which are created in one interaction. For the interaction of the mesons thus generated, again the distributions A under the same assumption are employed. After this second step, there results a differential energy spectrum $\sim E^{-3}$.

Method b uses the multiplicity distribution B. The energy spectrum C, with an high energy cut-off at 10 GeV and a lower limit 200 MeV, corresponding to a mean energy of 1 GeV is assumed to hold also for the mesons generated by the momochromatic protons. Here, too, two steps are considered, after which multiplication stops being important. This method gives more μ-mesons, less protons and neutrons and a differential energy spectrum $\sim E^{-2.5}$ for the mesons at high energies. The differences in numbers of particles do not, however, exceed a factor of 3.

For safety, we always take the higher of the 2 values for the multiplicities of the various particles and the flatter energy distribution of method b.

1. Beam going directly into earth.

$\rho = 1.5$ g/cm^3
The first 2 steps of interaction take 2×150 g/cm^2 = 2 m
Behind these 2 m we find per incident proton:

20 photons
200 neutrons
0.6 μ-mesons.

The protons are not enumerated because of their short range.
The electron-photon cascade proves to be absorbed in a few m of earth.
The neutrons are attenuated to 43% by 1 m.
The μ-mesons lose 1.9×10^8 eV/m.
As to the angular distribution it is a cautious assumption here, that all of the particles are equally distributed into a cone of half-opening 20°. In so doing we exaggerate the collimation.
The corresponding solid angle is 0.38.
With these data we can calculate table 1. It gives numbers and densities for neutrons and μ-mesons behind various thicknesses. Also included are μ-mesons generated in air with their flatter energy spectrum. We will need these later. The M.T.D. is marked. The thickness needed is determined by the neutrons, it amounts to 16 m In this value the assumption is involved, that the beam strikes the wall perpendicularly. For practical use, the angle of incidence must be considered. Laboratory tolerance (cosmic ray intensity) can be found to be reached at a distance of about 200 m from the wall by application of the $1/r^2$ law.

2. Beam going directly into heavy concrete.

$\rho = 4$ g/cm^3
2×150 g/cm^2 = 75 cm
Initial number of particles per proton.

20 photons
200 neutrons
0.22 μ-mesons.

Neutrons attenuated to 10% in 1 m
μ -mesons lose 5 x 10^8 eV in 1 m
The results are collected in table 2.
Thickness required for M.T.D. determined by neutrons: 8 m.

3. Beam going freely into the air.

$\rho = 1.2 \times 10^{-3}$ g/cm^3
150 g/cm^2 = 1.25 km.
Initial number of particles per proton:

20 photons
100 neutrons
20 μ-mesons
60 gray protons.

Consideration of cascade theory gives an electron-photon cascade of low multiplicity. We can deal with it roughly by assuming the primary photons not to be absorbed in the first 1.4 km
Neutrons attenuated to 50% in 1 km.
μ-mesons lose 1.5 x 10^8 eV/km.
Gray protons have ranges $<$ 150 m.
In air the first step of multiplication is comparatively more important than the second one, because of the decay of most π-mesons. Then here the attenuation by distance is much more effective than by absorption. So it is important, where the apex of the cone of 20° is to be put. To get a safe estimate, we assume the beam to remain entirely collimated up to 1 km (when 56% of the protons will have reacted), and from 1 km onwards all the particles generated are considered to be emitted into the 20°-cone starting at the 1 km distance.
We then get table 3.
M.T.D. reached after 3 km, determined by neutrons.
The effective range may even be greater because of photons produced by neutrons in inelastic collisions.

4. Beam striking the earth bank after going through air for a distance of some 100 m.

In spite of the more μ-mesons created in this case along the air path, it proves to be admissable to use table 1, which gives 16 m.

5. Lateral action of the beam.

First the action of the secondaries created directly by the proton beam will be considered. A place can be protected against these by putting a bank of sufficient thickness between this place and the whole extent of the proton beam. Later we will be concerned with the tertiary particles created by the secondaries in collisions in the air. The protection against these will prove to be much more difficult.

a. Action of secondaries.

Let some apparatus standing in the open air in the experimenting field be hit by the proton beam. The dimensions of the apparatus may be so, that most of the protons and their secondaries emitted into a forward direction interact in the material of the apparatus, but the particles emitted in a sideward direction are allowed to escape into the air. If the apparatus is placed near to a side bank of the experimenting field, part of this secondaries hit this bank. We can apply table 1 with some modifications. The initial number of particles is the same as in table 1, only we double the number of μ-mesons, because some may be generated along the air path between apparatus and bank. Instead of the cone of 20° (solid angle 0.38), into which the particles were emitted in table 1, we have them now distributed over the full solid angle 4π. The distribution of the grey protons is considered here to be isotropical; for the mesons we apply the distribution E. Further we must allow for the different geometrical paths of particles, which penetrate the bank under different angles. Doing so, we find from table 1 a thickness of 11 m required to bring the neutrons down to M.T.D. The laboratory tolerance will be reached at a distance of 200 m from the bank, except in the forward 30°-sector.

If the beam does not strike an apparatus for some 100 m, it will only produce secondaries in the air. Its action on a point outside the bank will then be at least 50% weaker than in the case just considered.

b. Action of tertiaries.

We consider again the apparatus in the beam. From this particles will emerge in all directions. Part of them will also go over the head of a person standing in the "protected" area outside the banks From these secondary beams, tertiary particles will be emitted down on him.

To estimate their density, we need only consider those particles generated in the first interaction, who are able to make more multiplication processes. For small distances (< 50 m) this will be μ-mesons, grey protons and the corresponding neutrons. Their total number, considering the angular distribution E for the mesons, will be about 20 per interaction. The solid angle containing trajectories which run at moderate distances from a point of observation outside the banks is estimated to be $4\pi/20$. For simplicity we combine all the trajectories within this solid angle to one "mean beam" in the vertical plain containing the apparatus and the point of observation at a distance r from the apparatus. The angle this beam includes with the vertical in this plain will be somewhere between zero and a maximum value, given by the direction of the trajectory touching the top of the bank. It will be nearer to the latter value. Let us consider an angle of 30°. Then the horizontal distance r and a portion of the beam of lemgth r form two sides of an equilateral triangle. We consider only the production of secondaries in this portion of the beam, where all its points are at a distance $<$ r to the point of observation. The interaction probability is about 6×10^{-4} m $^{-1}$ with a multiplicity of about 4 neutrons. To find the M.T.D.-distance, we get the equation:

$$10^9 \times 20 \times 1/20 \times 6 \times 10^{-4} r \times 4 \times 1/4\pi r^2 = 10^4$$

$$\underline{r = 20 \text{ m}}$$

Because of the neglect of action from more distant parts of the beam, we better take 30m. Thus one must be at a distance of <u>30 m</u> from the apparatus to get only the M.T.D.. If one makes a safety zone of 30m outside the banks, the bank thickness can be reduced from 11 to 9 m. If the angle between the vertical and the mean beam is larger than 30°, we find the necessary distance by postulating, that the point of observation is outside a cylinder of radius r round the mean beam.

At the end of the experimenting field the safety zone must be larger because more secondaries are emitted in that direction. The factor is 5 to 10, but depends on whether a system of collimators is used to reduce the spread of the beam or not.

For the laboratories we find by a similar estimate (here neutrons only have sufficient ranges to make secondary stars):

$$10^9 \times 10 \times 1/20 \times 6\times10^{-4} r \times 4 \times 1/4\, \pi r^2 = 10^2$$

$$\underline{r = 1 \text{ km.}}$$

To this distance the same consideration apply as to the 300 m above. The big distances thus defined can be reduced perhaps by a factor of 2 by putting the laboratories into the sector between 120 and 240° to the primary beam. As it is hardly possible to restrict the secondary beams to still steeper trajectories than the one considered here, the conclusion must be drawn, that if distances of the order of 1 km are not wanted, either a higher background in the laboratories must be admitted for part of the time, or full intensity experiments must not be carried out in the open air.

C. Practical conclusions.

1. The circular bank. ($\rho = 1.58$ cm^{-3})

The beam will never strike it at right angles. So a thickness of 12 m in all direction seen from the tube under 30° to the horizontal or less will be sufficient. As the beam will escape here only during adjustment or by some failure, it is not likely to go through one particular portion of the bank for a long time. So we might even reduce the thickness to 8 m, which would mean an increase in neutron intensity by a factor of 50.

2. Roof of the circular ditch.

Because of the small curvature of the ditch the beam can escape from it at small angles to the horizontal and produce secondaries in the air at a low elevation above ground. To prevent this, a roof of 2 m of earth is needed, in which the multiplication processes will come to an end.

3. Target room.

It seems advisable to provide heavy concrete shielding up to 6 m thickness. For the roof 0.7 m will be sufficient

4. Experimenting field.

To prevent secondaries from escaping at low angles, the experimenting field must not be made very broad. A field of 100 m length increasing in breadth from 5 to 20 m seems sufficient. The distance from the target where there is no heavy background from scattered particles is limited anyway by the finite opening of the primary beam, which will strike the ground at about 70 m from the target, if it starts at an elevation of 1.5 m above ground. If special experiments in larger distances are desired, it seems advisable to let only the central portion of the beam through a collimator into an area of dimensions similar to those of the first one. Even so, it will be better to carry out full intensity experiments not in the open air, but under some sort of a wide tunnel with walls and roof of 300 g/cm^2. This will greatly reduce the background at great distances. The experimenting field, including the portion under the tunnel, must be surrounded by banks of about 10 m thickness on the side and 20 m at the end. The necessity of a safety zone (30 m on the side, 150 to 300 m at the end) depends on whether full intensity experiments are carried out in the open air. If the beam would finally disappear in a sort of a hole, it would improve matters. The laboratories must be placed in the sector between 120 and 240° from the direction of the primary beam in a distance which depends again on the restriction to full intensity experiments in the open air.

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Table 1·

Attenuation of secondaries from 30 GeV protons in earth

Density 1·5 g/cm^3

1 Total thickness in m (2 m for generation of secondaries included)·
2 number of neutrons·
3 number of μ-mesons·
4 relative number of μ-mesons produced in the air·
5 radius of the 20° cone in m
6 surface, over which the particles are distributed in m^2·
7 density of neutrons in m^{-2}·
8 density of μ-mesong in m^{-2}·
9 relative densities of μ-meson from the air·

	numbers					densities		
1 m	n° 2	μ 3	μ 4	5 m	6 m^{-2}	n° 7 m^{-2}	μ 8 m^{-2}	μ 9
2	2 x10^{11}	6 x10^{8}	6 x10^{8}	0				
3	8·6x10^{10}	6 x10^{8}	6 x10^{8}	1	0·38	2·3x10^{11}	1·6x10^{9}	1·6x10^{9}
4	3·7	2·4	3·8	2	1·52	2·4x10^{10}	1·6x10^{8}	2·5x10^{8}
5	1·6	1·2	2·8	3	3·4	4·7x10^{9}	3·5x10^{7}	8·2x10^{7}
6	6·8x10^{9}	7·8x10^{7}	1·8	4	6·1	1·1	1·3	2·9
7	2·9	4·5	1·34	5	9·5	3·1x10^{8}	4·7x10^{6}	1·4
8	1·2	3·1	9·4x10^{7}	6	13·7	8·8x10^{7}	2·3	6·9x10^{6}
9	5·4x10^{8}	2·1	7·5	7	18·6	2·9	1·1	4·0
10	2·3	1·4	6·0	8	24	9·6x10^{6}	5·8x10^{5}	2·5
11	1·0	1·07	4·8	9	31	3·2	3·5	1·5
12	4·3x10^{7}	7·9x10^{6}	4·0	10	38	1·1	2·1	1·05
13	1·9	6·2	3·5	11	46	4·1x10^{5}	1·35	7·6x10^{5}
14	8·1x10^{6}	5·5	3·2	12	55	1·5	1·00	5·8
15	3·5	4·4	2·7	13		5·5x10^{4}	6·9x10^{4}	4·2
16	1·5	3·6	2·4	14	74	2·0	4·9	3·0
17	6·5x10^{5}	2·9	2·1	15	86	7·6x10^{3}	3·4	2·4
18	2·8		1,9	16	97			2·0
19	1·2		1·7	17	109			1·6
20	5·2x10^{4}		1·5	18	123			1·2

Table 2.

Attenuation of secondaries from 30 GeV protons in heavy concrete.

Density 4 g/cm^3

1 Total thickness in m (1 m for generation of secondaries included).
2 number of neutrons
3 number of μ-mesons
4 radius of 20°-cone in m
5 surface, over which the particles are distributed, in m^2
6 density of neutrons in m^{-2}
7 density of μ-mesons in m^{-2}.

	numbers				densities	
					n°	μ
1	2	3	4	5	6	7
1	$2x10^{11}$	$2.2x10^{8}$	0			
2	$2x10^{10}$	$5.4x10^{7}$	1	0.38	$5.3x10^{10}$	$1.42x10^{8}$
3	$2x10^{9}$	1.5	2	1.52	$1.3x10^{9}$	$9.9x10^{6}$
4	$2x10^{8}$	$5.3x10^{6}$	3	3.4	$5.9x10^{7}$	1.56
5	$2x10^{7}$	2.6	4	6.1	$3.3x10^{6}$	$4.3 x10^{5}$
6	$2x10^{6}$	1.4	5	9.5	$2.1x10^{5}$	1.5
7	$2x10^{5}$	$8.9x10^{5}$	6	13.7	$1.5x10^{4}$	$6.5 x10^{4}$
8	$2x10^{4}$	5.9	7	18.6	$1.1x10^{3}$	3.2
9	$2x10^{3}$	4.2	8	24		1.75

Table 3·

Attenuation of secondaries from 30 GeV protons in air·

Density 1·2 x 10^{-3} g/cm^3

1 Total distance in km (1 km for production of secondaries included)·
2 number of neutrons
3 number of μ-mesons
4 number of cascade-particles (electrons and photons)
5 radius of the 20°-cone in km
6 surface over which the particles are distributed, in m^2
7 density of neutrons in m^{-2}
8 density of μ-mesons in m^{-2}
9 density of cascadeparticlesin m^{-2}

	numbers					density
1	2	3	4	5	6	7
1	1·0x10^{11}	2·0x10^{10}	2x10^{10}	0		
2	5·0x10^{10}	2·0x10^{10}	2x10^{10}	1	3·8x10^{5}	1·32x10^{5}
3	2·5	1·51	-	2	1·52x10^{6}	1·64x10^{4}
4	1·25	1·07	-	3	3·4	3·7 x10^{3}

	densities	
1	8	9
1		
2	5·3 x10^{4}	5·3x10^{4}
3	9·9 x10^{3}	-
4	3·1	-