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MASTER

ACCELERATOR DEPARTMENT
Internal Report

SOURCE OF HIGH ENERGY PARTICLES
FROM AN INTERNAL TARGET IN THE AGS

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1. Preliminary Remarks

All of the measurements herein reported were made with polyethylene foils, hence the particle flux densities is the sum of all the strongly interacting particles above 20 MeV. The data have been normalized to 2.78×10^{11} circulating protons in the AGS. The internal flip target was a beryllium wire one-half inch long and 0.040 inches in diameter. The accelerator was pulsed every 2.8 seconds and the beam energy upon collision with the target was 30.5 GeV.

An eight-inch aluminum cylindrical vacuum pipe was present in the target straight section for all of the data reported.

2. Total Particle Flux and Average Energy

The flux density of secondary particles from the target collisions appears to be a constant over the surface of a cylinder one foot in radius and concentric with the circulating beam. This constancy extends from the H-10 target to the length of the straight section. Frisken¹ observed this from hanging sheets of polyethylene transverse to the beam at intervals along the beam. The contours on Fig. 3 also show this within the limits of

1. W.R. Frisken, private communication.

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drawing error and the results of Hoffman and Sullivan² indicate an isoflux, Fig. 4, several feet downstream from the target for 19.2 and 10-GeV protons using steel as a side shield.

Extrapolation of the line on Fig. 5 to one foot distance from the beam gives 1.10×10^8 fast particles per cm^2 for 2.78×10^{11} protons or

$$4.0 \times 10^{-4} / \text{cm}^2 / \text{incident proton} .$$

The curved area of a cylinder one foot in radius and 10 feet long is $5.84 \times 10^4 \text{ cm}^2$, hence

$$4.0 \times 10^{-4} \times 5.84 \times 10^4 = 23 \text{ particles} .$$

Estimating that an additional 10% pass through the downstream end of the cylinder, it is concluded that some 25 fast particles are associated with each incident 30-GeV proton interacting in the target.

Current theories for strong interactions can account for about seven fast particles per interaction which is about one-third of the multiplicity stated above. A number greater than seven can be expected because of subsequent interactions in the vacuum chamber. The foil detectors are continuously sensitive above 20 MeV which can sense the higher energy portion of the evaporation proton spectrum.

3. Angular Distribution in the Neighborhood of the Target

Let the number of particles per steradian at the polar angle, θ , to the beam be $n(\theta)$. If the number of particles per unit area on a cylinder of unit radius is a constant for the reasons given in Section 1, then from the figure below:

2. L. Hoffman and A.H. Sullivan, Nucl. Instr. and Methods 32, 63 (1965).

$$\frac{n(\theta)}{r^2} \approx \frac{n(\theta)}{x^2} = \text{const}.$$

But

$$\tan \theta = 1/x$$

and

$$n(\theta) \sim \tan^{-2} \theta.$$

Hence for small angles

$$n(\theta) \sim \theta^{-2}.$$

Hoffman and Sullivan² in the side shielding experiment, studied the flux density of fast particles at an angle θ and found it to be proportional to θ^{-n} . They report

$n = 2.3$ for track density in emulsions at 19.2 GeV/c

$n = 2.1$ for C^{11} activation at 19.2 GeV/c

$n = 1.9$ for C^{11} activation at 10 GeV/c.

Validity for the θ^{-n} law is claimed in the angular interval $10^\circ \leq \theta \leq 90^\circ$.

These values are compared with $n = 2.4$ obtained from the angular distribution of pions emitted from proton interactions in LiH at 24 GeV.³

For large angles where $\tan \theta \neq \theta$,

$$n(\theta) \sim \tan^{-2} \theta$$

and $n(\theta) = 0$ for $\theta = 90^\circ$.

3. D. Damgård and K.H. Hausen, Siena Conf. 1963.

The emulsion data shown in Fig. 4 indicate that $n(\theta)$ is rapidly approaching zero as $\theta \rightarrow 90^\circ$ which is the behavior of the $\tan^{-2} \theta$ function as $\theta \rightarrow 90^\circ$. The law appears to be valid in the energy interval

$$10 \leq E \leq 20 \text{ GeV} .$$

It is expected that the law breaks down at lower energies where a more isotropic situation will dominate.

4. Tunnel Background Flux

The tunnel flux is shown on the contours of Fig. 1 with no local shielding in the vicinity of the target. Results from an identical experiment except that a 4' x 4' x 80" lead block was placed immediately downstream the target, Fig. 2. In regions remote from the lead block, there is a constant flux density, $3 - 4 \times 10^5$ particles/cm²/sec which is about the same value as seen on Fig. 1 (without shielding) over the H-15 magnet.

This can be explained by assigning a constant flux density ("neutron sea") of at least

$$\frac{3 \times 10^5}{2.78 \times 10^{11}} \approx 1 \times 10^{-6} / \text{cm}^2$$

per incident proton which is tunnel background in the sense that it is independent of shielding around the target. Isoflux contours obtained by subtraction of 3×10^5 particles/cm² from those shown on Fig. 1 have been drawn on Fig. 3, which also gives the flux density contours in the sand cover with no shielding around the target.

5. Fast Particle Flux in the Tunnel

In Fig. 6 the fast particle flux density in the tunnel (Fig. 3) has been plotted in polar form with r , (the distance from the target in feet) and the polar angle θ with respect to the circulating beam as a parameter. It shows that the fast flux in the tunnel varies as the inverse square of the distance from the target along a constant polar angle. The curve for 10° obeys this law up to about 12 feet downstream where the shadow of the H-11 magnet causes it to fall off more rapidly than the inverse square.

Again considering the data on Fig. 3 and plotting the flux density as a function of θ at a constant r , it is shown on Fig. 7 ($r = 10'$) that the flux density varies closely with θ^{-2} .

Combining the results from Figures 6 and 7, the particle flux density in the tunnel can be expressed, except for the region shadowed by the H-11 magnet, by

$$n(r, \theta) = 4.2 \times 10^{11} / (r\theta)^2$$

or

$$n_1(r, \theta) = 1.5 / (r\theta)^2 \text{ cm}^{-2}$$

per circulating proton where

r is the distance in feet from the target and

θ is the polar angle in degrees from the circulating beam

$$20^\circ \leq \theta \leq 90^\circ.$$

The equation for $n(r, \theta)$ has been derived only in the vertical plane above the beam, however if y is the perpendicular distance from the beam to some point in the vertical plane, then from symmetry around the beam, the flux density upon a circle with y as a radius will be close to a constant.

A further feature of the tunnel flux seems to be in agreement with the side shielding experiment done at CERN. Figure 4 shows that the particle density contours are parallel to the beam for about 500 g/cm^2 downstream from the target. Very likely the opening cone of the fast particle cascade causes the isoflux contours to bend away from the circulating beam in roughly a parabolic fashion as the depth along the beam increases.

This is shown to some extent in the "humping" of the flux contours toward the downstream end of H-11 for the unshielded experiment, Fig. 3. The effect is again shown quite markedly on Fig. 2 with the massive lead shield in place.

6. Absorption Length in the Sand

The isoflux contours in the sand cover shown on Fig. 3 have been replotted on Fig. 8, which shows the falloff of particle intensity as one recedes from the target maintaining a constant angle to the beam. The 20° and 30° lines show some buildup of particles to a depth of about 10' in the sand beyond which the fast particle component of the flux density is probably in equilibrium.

Examination of the slopes of the plots at the bottom of Fig. 8 shows that they increase as the inclination to the beam increases. In other words, the absorption length in the sand decreases as the inclination increases.

Without regard for inverse square law correction, the absorption length

$$L = \frac{0.4343(r - r_o)}{\log_{10} \frac{2.5 \times 10^5}{n(r, \theta)}} \text{ feet}$$

where r_o is the distance in feet from the target to the 2.5×10^5 contour on Fig. 3 and 0.4343 converts $\log_e$ to $\log_{10}$. To convert $L(\theta)$ to g/cm^2

$$0.4343 \times 30.48 \times 1.6 \text{ (sand density)} = 21.18$$

$$L(\theta) = \frac{21(r - r_o)}{\log_{10} \frac{2.5 \times 10^5}{n(r, \theta)}} \text{ g/cm}^2$$

where r and r_o are measured in feet.

The results for $L(\theta)$ are shown on Fig. 9. An absorption length of 150 g/cm^2 at 20° appears higher than would be indicated by the trend of the points for larger angles. This may be due to an extrapolation error for the uppermost contour shown on Fig. 3. However, the 150 g/cm^2 value is not in disagreement with the $185 \pm 20 \text{ g/cm}^2$ reported by Citron et al.⁴ from their study of the nucleon cascade in steel initiated by 19.2-GeV/c protons. Integration of the fast flux transverse to the beam has been included in the result.⁴

4. A. Citron et al., Nucl. Inst. and Meth. 32, 48(1965).

The side shielding experiment of Hoffman and Sullivan² found that "at 20° and 30° the attenuation length is on the order of 100 g/cm², at 40° the attenuation length has dropped to about 60 g/cm²".

It is also seen on Fig. 9 that as the direction in the sand cover approaches 90° (perpendicular to the beam), the absorption length is about 80 g/cm². The "constant value" of 80 g/cm² earlier explained by the Brookhaven group as a consequence of a uniform line source extending from the target to H-13 cannot be reconciled with the plot shown on Fig. 5. The particle intensity over the midpoint of the H-10 straight section falls off somewhat faster than the inverse square law which cannot be consistent with a line source.

The apparent constancy for the absorption length in the sand normal to the beam is a consequence of three mutually compensating factors. The exponential decrease in the flux density as the distance in the sand downstream from the target increases is offset by (1) the increase in particle population from the θ^{-2} angular distribution and (2) the increase in absorption length as θ decreases.

7. Consistency

In Section 2 it was stated that per incident proton there are 23 fast particles through the curved surface of a cylinder one foot in radius and ten feet long. Section 5 states that per incident proton, the tunnel flux density can be expressed as

$$n_1(r, \theta) = 1.5 / (r\theta)^2 \text{ cm}^{-2}.$$

To be consistent

$$\begin{aligned} & 1.5 \int_{\theta_1}^{\pi/2} \int_0^{2\pi} \frac{r \sin \theta d\theta \cdot r d\phi}{(r\theta)^2} \\ &= 9.5 \int_{\theta_1}^{\pi/2} \frac{\sin \theta d\theta}{\theta^2} = 23 (?) \end{aligned}$$

$$\theta_1 = \tan^{-1} \frac{1}{10} \approx 0.1.$$

As $\theta \rightarrow 0$, $\sin \theta / \theta^2 \rightarrow 1/\theta$ and the principal contribution to the integral comes from the region of small θ

$$9.5 \int_{0.1}^{1.57} \frac{d\theta}{\theta} = 9.5 \ln_e 15.7 \approx 26$$

instead of 23.

8. Energy Distribution, $E(\theta)$

In Section 2 it was shown that the average energy of a fast particle was about one GeV. Undoubtedly the particle energy increases with decreasing polar angle with respect to the circulating beam. Some idea of the energy distribution as a function of the polar angle can be obtained from the measurements of the pi spectrum³ emitted from interactions of 24-GeV protons which give a peak in the pi spectrum of 600 MeV at 20° and a peak of 200 MeV at 40° . Scaling these energies by 30/24, the estimated energies for the AGS experiment are:

750 MeV at 20°

250 MeV at 40°

If $E(\theta)$ is the energy as a function of θ we also know that

$$\bar{E} = \frac{1}{\frac{\pi}{2} - 0.1} \int_{0.1}^{\pi/2} E(\theta) d\theta \approx 1000 \text{ MeV}$$

and

$$1.5 \int_{0.1}^{\pi/2} \int_0^{2\pi} \frac{\sin \theta}{\theta^2} E(\theta) d\theta \approx 2800 \text{ MeV}$$

An angular distribution $E(\theta)$ which roughly conforms to the above conditions is shown on Fig. 10.

The writer is indebted to Mr. William Tooker of the Cosmotron Division for his help in the acquisition and reduction of the data.

WHM/jc

1/25/66

Distr.: External

8" VACUUM PIPE

NO SHIELDING

CH₂ FOILS

2.78 x 10¹⁰ /O/SEC.

AUG. 12, 1965

$\frac{1}{4}" = 1'$

FIG. 1

2.78 x 10" P/SEC.

SEPT. 2, 1965

Pb PLUG 4' x 4' x 80"

8" VACUUM PIPE

CH₂ FO'LS

FIG. 2

2.78 x 10" P/SEC.

8" VACUUM

CH₂ FOILS

FIG. 3

Flux Density Contours Normalized for
 10^5 Incident Protons. From Ref. 2.

Figure 4

Figure 5

Figure 6

Figure 7

Fast particle flux density in the
sand cover over the circulating beam.

$$2.78 \times 10^{11} \text{ protons/sec}$$

Angles are measured at the target
from the beam.

r_0 is the distance in feet from the
target to the 2.5×10^5 contour, Fig. 3.

The data are not corrected for the
inverse square law.

Figure 8

Figure 9

Figure 10