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NUCLEON-MESON CASCADE CALCULATIONS:

THE STAR DENSITY PRODUCED BY A 24-Gev

PROTON BEAM IN HEAVY CONCRETE

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OAK RIDGE NATIONAL LABORATORY

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BY A 24-Gev PROTON BEAM IN HEAVY CONCRETE

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Abstract

The nuclear star density produced by a 24-Gev proton beam in a material having approximately the properties of heavy concrete has been calculated. A comparison has been made with experimental measurements made at CERN, but, since the quantity which could be calculated is not the same as that which was measured, no firm conclusions can be drawn.

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I. Introduction

In a series of recent reports^{1,2,3} (hereinafter referred to as 1, 2, and 3, respectively) nucleon-meson cascade calculations have been presented.

In this report similar calculations are presented for a 24-Gev proton beam incident on heavy concrete. The equations and method of calculation are the same as used in 1. The physical data used is that described in 1 and 2 except for a few changes which were made to make the shielding medium correspond more nearly to heavy concrete. These changes are discussed in Section II. They are relatively minor, and, in general, the properties of the shielding medium are only very approximately those of heavy concrete.

The method of calculating the density of nuclear stars from the cascade is discussed in Section III.

The results are given in Section IV. The star density results are compared with the experimental measurements made at CERN.⁴ However, since the CERN measurements include only those stars formed "on the axis" while the results of a one-dimensional cascade calculation imply an integration over the plane transverse to the beam axis, the calculated and experimental values are not comparable and no firm conclusions can be drawn.

II. Physical Data

In this section a brief discussion of the difference between the physical data used here and that used in 1 and 2 is given.

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1. R. G. Alsmiller, Jr., F. S. Alsmiller, and J. E. Murphy, Neutron-Meson Cascade Calculations: Transverse Shielding for a 45-Gev Electron Accelerator (Part I), ORNL-3289 (1962).
 2. R. G. Alsmiller, Jr., F. S. Alsmiller, and J. E. Murphy, Neutron-Meson Cascade Calculations: Transverse Shielding for a 45-Gev Electron Accelerator (Part II), ORNL-3365 (to be published).
 3. R. G. Alsmiller, Jr., and J. E. Murphy, Space Vehicle Shielding Studies: Calculations of the Attenuation of a Model Solar Flare and Monoenergetic Proton Beam by Aluminum Shields, ORNL 3317 (1962).
 4. A. Citron, L. Hoffmann, and C. Passow, Nuclear Instruments and Methods 14, 97 (1961).

The neutron, proton, and pion multiplicities and secondary energy distributions are the same as those in 1. This data was derived from measurements on cosmic rays in emulsions, and thus is only approximately correct for heavy concrete.

The value of the collision length, λ , defined by

$$\lambda^{-1} = \sum_1 n_i \sigma_{iG}, \quad (1)$$

where

$$\begin{aligned} n_i &= \text{number density of the } i\text{th element in the shielding medium,} \\ \sigma_{iG} &= \text{geometric cross section of the } i\text{th nuclei} \\ &= \pi r_0^2 A_1^{2/3}, \quad r_0 = 1.3 \times 10^{-13} \text{ cm}, \end{aligned}$$

is taken to be that for heavy concrete (38 cm).⁴ All distances are measured in units of this collision length.

The total absorption probability per collision length is taken to be the same as in 1 and 2, i.e., is taken to be that for aluminum. To understand this, note that (Eq. 2.4 of 1)

$$Q_j(E) = \lambda \sum_1 n_i \sigma_{ij}(E) \quad j = N, P, \pi \quad (2)$$

where

$$\sigma_{ij}(E) = \text{the nonelastic collision cross section for the } j\text{th type particle with the } i\text{th nuclei. [The values of } j \text{ (N, P, or } \pi) \text{ correspond to neutrons, protons, and pions, respectively.]}$$

If we multiply and divide by σ_{iG} and assume that the quantity σ_{ij}/σ_{iG} is independent of i we find

$$\begin{aligned} Q_j(E) &= \left(\frac{\sigma_{ij}}{\sigma_{iG}} \right) \lambda \sum_1 n_i \sigma_{iG}(E) \\ &= \frac{\sigma_{ij}}{\sigma_{iG}} \end{aligned} \quad (3)$$

by using Eq. 1. Thus on the basis of our assumption, which is a reasonable approximation, the Q_j 's are independent of the medium and may be taken to be those for aluminum.

The value of the density, ρ , is taken to be that for heavy concrete (3.6 g/cm^3).⁴

The energy loss (by atomic collisions) per collision length, $S_j(E)$, is taken to have the same energy dependence as in 1 but has a different magnitude because of the different values of λ and ρ . To understand this, note that S_j (Eq. 2.1 of 1) is given by

$$S_j(E) = \lambda \sum_i n_i \epsilon_{ij}(E) \quad j = \pi, P, \mu \quad (4)$$

where

ϵ_{ij} = stopping cross section of the ith element for the jth particle specie ($j = \mu$ corresponds to muons).

Utilizing the equation

$$n_i = \frac{N_0 \rho_i}{A_i} \quad (5)$$

where

N_0 = Avagadro's number,

ρ_i = density of the ith element,

A_i = atomic weight of the ith element,

Eq. 4 becomes

$$S_j(E) = \lambda \rho \sum_i \frac{\rho_i}{\rho} \frac{\epsilon_{ij}(E)}{A_i} \quad (6)$$

Assuming that the quantity ϵ_{ij}/A_i is independent of A_i — a reasonable approximation — we find that S_j is proportional to $\lambda \rho$ but is otherwise independent of the medium. Thus, in our calculations we use

$$S_j = \lambda \rho \left[\frac{\epsilon_{ij}(E)}{A_i} \right]_{Al} ; \quad (7)$$

i.e., λ and ρ are given their values for heavy concrete and ϵ_{ij}/A_i is taken to be that for aluminum.

III. Star Density Calculation

In passing through matter the cascade particles — protons, neutrons, and pions — produce nuclear stars, and it is convenient to characterize the cascade by the density of stars produced.

Let us consider the case of a narrow beam of protons incident normally on a slab shield and let

$P(E, \vec{\Omega}, \vec{R})$ = angular proton flux, i.e., the number of protons per Mev per cm^2 per steradian per second,

where

E = particle kinetic energy,

$\vec{\Omega}$ = unit vector in the direction of the particle momentum,

$\vec{R}$ = position vector.

If we define a star to be a nuclear reaction produced by a particle with kinetic energy greater than Γ we have

$$\phi_p(x, r) = \int_{\Gamma}^{E_{\max}} \left[\int P(E, \vec{\Omega}, \vec{R}) d\Omega \right] \sum_i \eta_i \sigma_{iP} , \quad (8)$$

where

ϕ_p = star density produced by protons (i.e., the number of stars produced per second per unit volume at x and r by protons),

x = normal distance into slab shield,

r = radial distance measured normal to the axis defined by the incident beam,

$E_{\max}$ = maximum energy of particles being considered,

η_i = number density of the i th kind of nuclei in the detector being used to measure the star density,

σ_{iP} = nonelastic cross section for protons on the ith kind of nuclei.

In this report the calculations are done in the straight-ahead approximation. This means that there is no lateral spread in the cascade. Physically, of course, the cascade does spread and the calculated quantity, $P(E,x)$, can best be interpreted as an approximation to the total flux integrated over the surface of a plane normal to the incident beam. That is

$$P(E,x) \approx (2\pi) \int_0^\infty r dr \left[\int P(E, \vec{\Omega}, \vec{R}) d\Omega \right] \quad (9)$$

where $P(E,x)$ is obtained from the straight-ahead equations (see 1) when the initial values used are the number of particles per Mev per second incident on the shield. We shall henceforth refer to this quantity as the proton intensity.*,+

Since only the proton intensity is available, we cannot calculate the star density defined in Eq. 8, but, rather, we calculate T_p , given by

$$T_p(\Gamma, x) = \int_\Gamma^{E_{\max}} P(E, x) \sum_i \eta_i \sigma_{iP}(E) dE. \quad (10)$$

*If one considers a very broad beam incident normally on a slab shield, one uses as initial values the number of particles per Mev per cm² per second incident on the shield and then $P(E,x)$ obtained from the straight-ahead equations is an approximation to the total proton flux per Mev, i.e., to the angular proton flux per Mev integrated over all solid angle. If one considers a very narrow beam incident normally on a slab shield one uses as initial values the total number of particles per Mev per second incident on the shield, and then $P(E,x)$ obtained from the straight-ahead equations is an approximation to the total flux integrated over the surface of a plane normal to the incident beam.

+The term intensity has a somewhat different meaning here than in 1 and 2.

This quantity, $T_P(\Gamma, x)$, is the number of stars produced by protons per second per unit distance in the shield. We shall refer to T_P as the star density, but it must be understood to have this special meaning.

In Eq. 3 we multiply and divide by the geometric cross section, σ_{iG} , and we assume as before

$$\frac{\sigma_{iP}}{\sigma_{iG}} = Q_P, \quad (11)$$

where Q_P is independent* of i , to obtain

$$T_P(\Gamma, x) = \frac{1}{\lambda_D} \int_{\Gamma}^{E_{\max}} P(E, x) Q_P(E) dE \quad (12)$$

$$\frac{1}{\lambda_D} = \sum_i \eta_i \sigma_{iG}$$

where λ_D is the collision length in the detector.

In like manner we have

$$T_N(\Gamma, x) = \frac{1}{\lambda_D} \int_{\Gamma}^{E_{\max}} N(E, x) Q_N(E) dE \quad (13)$$

where

$T_N(\Gamma, x)$ = star density produced by neutrons,

$N(E, x)$ = neutron intensity,

$Q_N(E)$ = neutron nonelastic cross section in units of the geometric cross section, and

*In the star density calculation Q_j ($j = N, P, \pi$) is taken to be that for aluminum.

$$T_{\pi}(\Gamma, x) = \frac{1}{\lambda_D} \int_{\Gamma}^{E_{\max}} \pi(E, x) Q_{\pi}(E) dE \quad (14)$$

where

$T_{\pi}(\Gamma, x)$ = star density produced by charged pions,

$\pi(E, x)$ = charged pion intensity,

$Q_{\pi}(E)$ = pion nonelastic cross section in units of the geometric cross section.

The total star density, T , is given by

$$T(\Gamma, x) = T_P + T_N + T_{\pi}.$$

IV. Results

The IBM-7090 code which was used to do the numerical computations cannot handle a truly monoenergetic source, so a suitable continuum was assumed. The energy spectrum used to represent the source is shown in Fig. 1.*

The proton, neutron, pion, and muon intensities are shown in Figs. 2, 3, 4, and 5, plotted against distance, for several energies.**

All energy components of the intensities rise to a peak and thereafter decay. The peaks are quite broad, and the decay, if it is exponential at all, becomes so only at the largest distances considered.

*The method of doing the calculation with this type of source is discussed in Section 2 of Reference 3.

**It should be noted that if these intensities are plotted against energy rather than distance they exhibit an abrupt change in shape in the vicinity of 2 Gev. This change in shape is a reflection of an abrupt change in the secondary energy distributions (i.e., in the energy spectrum of secondary particles produced in a single collision) we are using. See Fig. VI of 1.

Fig. 1. Initial Proton Energy Spectrum vs Energy

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Fig. 2. Proton Intensity vs. Distance

Fig. 3. Neutron Intensity vs. Distance

Fig. 4. Pion Intensity vs. Distance

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Fig. 5. Muon Intensity vs. Distance

The somewhat peculiar shape, at large distances, of the proton curve for $E = 20.25$ Gev is due to the presence of primary protons. Below 950 g/cm^2 the curve represents entirely secondary protons while at larger distances some primary protons have slowed down into this energy region and the curve represents primary as well as secondary protons.

The muon intensity exhibits much the same behavior as the other intensities, but the decay with increasing distance is very much less rapid. Because the muons decay so slowly, it is clear that for purposes of shielding they are of major concern.

The total star density is shown as a function of distance in Fig. 6. To make the plotted star density independent of the number of incident particles, it has been normalized to unity at $x = 0$. Note also that this normalization makes it unnecessary to specify the constant, λ_D , of Eqs. 12, 13, and 14. Because there is ambiguity as to exactly what value of Γ should be used to define a star, results are given for a variety of values.

Also shown in Fig. 6 are the experimental results from CERN.⁴ It must be remembered, of course, that the measured results contain only those stars which are formed on the axis of the cascade and are thus not truly comparable with the calculations.* The calculated curves decay much more slowly than the measured curves, which is as it should be, since the calculated star density includes (in an approximate manner) stars from particles which are not "on axis." Of course, the broad beam experiment includes more stars from particles which are not moving in the axial direction than does the narrow beam experiment; and thus, the broad beam results are closer to the calculations than the narrow beam results.

Figure 7 contains the ratio of the star density produced by neutrons (neutral stars) to the total star density from both the experiment and the calculations. The theoretical value at $x = 0$ is zero while the experimental value is not zero because the incident beam was contaminated by neutrons.

*The measurements differ from the calculations in at least two other respects. In the case of the narrow beam experiment, a 20-Gev beam was used rather than a 24-Gev beam. In the case of the broad beam experiment a 24-Gev beam was used but the shielding material was changed from heavy concrete to earth at 800 g/cm^2 and from earth to ordinary concrete at $1,000 \text{ g/cm}^2$.

Fig. 6. Star Density vs. Distance

Fig. 7. Ratio of Star Density Produced by Neutrons to Total Star Density vs. Distance

Figure 8 contains the ratio of the star density produced by pions to the total star density.

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We would like to thank Dr. F. S. Alsmiller and Dr. C. D. Zerby for many helpful discussions.

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Fig. 8. Ratio of Star Density Produced by Charged Pions to Total Star Density vs. Distance

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