BROOKHAVEN NATIONAL LABORATORY
Associated Universities, Inc.
Upton, L.I., N.Y.

AGSCD-13

MAR 14 1967

RELEASED FOR ANNOUNCEMENT
IN NUCLEAR SCIENCE ABSTRACTS

ACCELERATOR DEPARTMENT
Internal Report

MASTER

SAND AS A SIDE SHIELD FOR 30 GeV PROTONS
STOPPING IN THE BROOKHAVEN AGS

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November 9, 1966

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Introduction

Although the stimulus for the material presented in this report came from the Conversion Program to increase the beam intensity of the AGS, an attempt is made to cast the results in a form more useful to the shielding physicist, rather than to discuss questions relevant only to the conversion effort. The measurements are not limited to the entrance and exit surfaces of the sand shield, but were made in an array of small pipe wells (to be described later) which permitted the detection of particle fluxes and dose rates throughout the volume of the sand cover.

Particle attenuation transverse to the circulating beam in the side shield is much more rapid than would be concluded from direct calculations based upon an interaction length for strongly interacting particles. Such a result is to be expected when one considers the decrease in both particle population density and in average energy as the polar angle from the direction of the circulating beam increases.

The most severe side shielding requirement arises when all of the circulating beam is stopped at some point in the magnet ring. To generate the particle fluxes in the sand, the AGS was operated at 30 GeV and a 0.040 inch beryllium target one half inch long was flipped into the beam at the upstream end of the

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10' long H-10 straight section (see Figs. 16, 17). It has been assumed that all of the circulating beam eventually interacted in this target because of multiple traversals; however, diffraction scattering could eject protons from the target into unstable orbits which would be lost on the vacuum chamber walls. Probably not more than 20% of the original protons are removed in this way.

The fast fluxes, $E > 20$ MeV, were detected by C^{11} activation in polyethylene foils, paraffin and plastic scintillators. Aluminum foils measured the 14 MeV neutron intensity. NTA film recorded protons from 0.35 - 20 MeV, Dupont β - γ films detected these components of the radiation, and Bendix dosimeters recorded total ionization.

One of the aims of these measurements was to penetrate sufficiently deep into the sand to find a depth beyond which the weakly interacting flux dominates over the strongly interacting. If the strongly interacting particles are attenuated by $\sim 100 \text{ g/cm}^2$ and the weakly interacting by $\sim 1000 \text{ g/cm}^2$, then at some critical sand depth, there should be an abrupt change in slope of the particle population density provided the weakly interacting particles are intense enough for detection.

I. The Tunnel Flux

1. Polyethylene Foil Exposure

The principal source of secondary particles whose intensity must be reduced by the side shield is determined by the number of fast secondaries produced in a target collision, the angular distribution of these secondaries and the location of the side shield with respect to the direction of the circulating beam. The population density of these source particles reaching the exposed shield boundary must be known, and of particular importance is the direction of the high energy component. To a lesser extent, the shield must absorb particles arising from leakage around the magnet ring.

To measure the fast flux in the tunnel, polyethylene foils were placed two feet apart upon vertical standards resting upon the tops of the AGS magnets, as shown for stations A through G in Fig. 1. An hour's exposure is sufficient to generate C^{11} (half life 20.4 minutes) in amounts over 90% of its equilibrium value. To calculate the fast particle intensity from the C^{11} decay rate

corrected to the end of the bombardment, a cross section for $C^{12} (p, pn) C^{11}$ must be chosen. This is complicated by the energy spectrum of the fast particles leaving the target. As will be discussed later, the average energy of a secondary is about one GeV, indicating a cross section of 29.0 mb as a reasonable one. The cross section¹ for C^{11} as a function of incident proton energy is shown in Fig. 2; the same cross section was assumed for the reaction $C^{12} (n, 2n) C^{11}$.

The flux density rates were computed from

$$\frac{dN}{dt} = \frac{(dC^{11}/dt)_{t_1}}{KE(1 - e^{-t_1/\lambda})}$$

for steady bombardment beam conditions, where

t_1 = bombardment time in minutes ~ 60

λ = mean life of C^{11} = 29.2 m

E = counter efficiency = 0.737 ± 0.011

K = $A(1-\alpha) \sigma(E) w/m.w.$

A = Avogadro's number $6.0228 \times 10^{23} \text{ mole}^{-1}$

$\sigma(E)$ = the cross section for inducing C^{11} taken as $29.0 \pm 1.3 \times 10^{-27} \text{ cm}^2$

$(1-\alpha)$ = (0.88 ± 0.018) is the correction for the cross section for a 0.004 in. polyethylene foil due to the escape of active hydrocarbon molecules from the foil during bombardment.²

w = foil weight 0.1028 ± 0.0008 grams

$m.w.$ = molecular weight of polyethylene = 14.03 g/mole

K = $(11.26 \pm 0.75) \times 10^{-5} \text{ cm}^2$

1. J.B. Cumming, Ann. Rev. Nucl. Sci. 13, 271 (1963).

2. J.B. Cumming, A.M. Poskanser and J. Hudis, Phys. Rev. Letters 6, 484 (1961).

The numerical result is

$$\frac{dN}{dt} = 230 (dC^{11}/dt)_{t_1} \text{ strongly interacting particles/cm}^2/\text{sec}$$

where $(dC^{11}/dt)_{t_1}$ are the counts/minute corrected for the decay to the end of the bombardment time.

The foils were counted in a well counter whose average background is about 140 counts/minute. Thus, the lower limit for the measurable fast flux is about 5000/cm²/sec.

2. Total Particle Flux and Average Energy

The flux density of secondary particles from the target collisions is essentially a constant over the surface of a cylinder of any radius, inside the tunnel boundaries, concentric with the circulating beam and extending from the target some 30 ft downstream (except in the magnet shadow). (See Fig. 1.) Frisken³ also observed this by hanging sheets of polyethylene transverse to the beam at intervals along the beam. He also inserted polyethylene foils in a carbon absorber, with the results shown in Fig. 3. The results of Hoffman and Sullivan⁴ indicate an isoflux several feet downstream from the target for 19.2 and 10 GeV protons using steel as a side shield. (See Fig. 4.)

Consider a concentric cylinder around the beam, one foot in radius, extending for a distance of 10 feet downstream from the target. Extrapolation of the data at station B on Fig. 6 (see Fig. 8) gives 9.3×10^7 fast particles/cm² for 2.78×10^{11} protons or 3.3×10^{-4} fast particles/cm²/incident proton.

The curved area of a cylinder one foot in radius and 10 feet long is 5.84×10^4 cm²; therefore

$$n_s = 3.3 \times 10^{-4} \times 5.84 \times 10^4 = 19 \text{ particles.}$$

Estimating that an additional 10% pass through the downstream end of the cylinder, it is concluded that about 21 fast particles are associated with each

3. W.R. Frisken, private communication.

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

incident 30 GeV proton interacting in the target, giving an average of 1.4 GeV for each particle, if an equipartition of energy is assumed.

Current knowledge of the multiplicity at 30 GeV indicates about seven fast particles per interaction or about one-third of the multiplicity measured. A larger number can be expected because of the interaction of the secondaries in the vacuum chamber wall, the high energy tail of the evaporation spectrum and the beam loss during the acceleration cycle.

3. Tunnel Background Flux

The tunnel flux is shown in 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 from the target (Fig. 18) are shown in Fig. 5. In regions remote from the lead block there is a constant flux density of about 3×10^5 particles/cm²/sec which is about the same value as seen in Fig. 1 (without shielding) over the H-15 magnet.

This can be explained by assuming a constant flux density (neutron background) of about

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

per incident proton which is tunnel background in the sense that it is independent of shielding in front of the target. Isoflux contours obtained by subtraction of this background are shown on Fig. 6, which also gives the flux density contours in the sand cover with no shielding around the target.

4. The Target as a Point Source

In Fig. 7 the fast particle flux density in the tunnel, Fig. 6, has been plotted in polar form with r , the distance in feet from the target, and θ , the polar angle with respect to the circulating beam, as parameters. 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. Such would not be true if the AGS magnets were contributing a substantial amount of fast secondary flux for any considerable distance downstream. 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 much more rapidly than the inverse square.

5. Angular Distribution around the Target

Let $\varphi(r, \theta)$ express the flux density of fast particles where r is the distance from the target and θ is the polar angle measured from the direction of the circulating beam. From the results of section 4, it seems reasonable to write

$$\varphi(r, \theta) = k f(\theta) / r^2 \quad (1)$$

where $f(\theta)$ gives the functional variation of the particle population density with respect to the polar angle.

The flatness of the isoflux contours as discussed in section 2 and shown in Fig. 6 leads to the empirical expression

$$\left. \frac{\partial \varphi}{\partial z} \right|_y = 0 \quad (2)$$

for some 30 ft downstream from the target. From the figure

$$\frac{\partial \varphi}{\partial z} = \frac{\partial \varphi}{\partial r} \frac{dr}{dz} + \frac{\partial \varphi}{\partial \theta} \frac{d\theta}{dz} = 0 \quad (3)$$

$$\frac{\partial \varphi}{\partial r} = \frac{-2kf(\theta)}{r^3} \quad \frac{\partial \varphi}{\partial \theta} = \frac{k}{r^2} \frac{\partial f(\theta)}{\partial \theta}$$

$$\frac{dr}{dz} = \frac{z}{r} \quad \frac{d\theta}{dz} = -y/r^2$$

which when substituted into (3) leads to

$$\frac{\partial \varphi}{\partial z} = -\frac{k}{r^4} \left[2z f(\theta) + y \frac{\partial f(\theta)}{\partial \theta} \right] = 0 \quad (4)$$

Using $z = y \operatorname{ctn} \theta$,

$$2 \operatorname{ctn} \theta \cdot f(\theta) + \frac{\partial f(\theta)}{\partial \theta} = 0 \quad (5)$$

The solution to (5) is

$$f(\theta) = \csc^2 \theta \quad (6)$$

Therefore,

$$\begin{aligned} \varphi(r, \theta) &= k \csc^2 \theta / r^2 \text{ or since} \\ \csc^2 \theta &= r^2 / y^2 \\ \varphi &= k / y^2 \end{aligned} \quad (7)$$

To check the validity of (7) the data inside the tunnel at station B have been replotted on Fig. 8, which shows $\varphi \sim y^{-2}$ is closely obeyed. The same data on Fig. 8 have been plotted on Fig. 9 for a constant radius of 10 feet which shows $\csc^2 \theta$ is a fairly close fit; however θ^{-2} appears to fit better.

Hoffman and Sullivan⁴, in a side shielding experiment, studied the flux density of fast particles as a function of the polar 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.

The θ^{-2} angular distribution appears to be valid for proton energies of at least $10 \text{ GeV} \leq E_p \leq 30 \text{ GeV}$.

6. Numerical Value of k (Population Density)

In section 2 it was shown that the number of fast secondaries, $n_s = 19$ over the curved surface of a cylinder one foot in radius (concentric with the beam) and 10 feet long. Empirically the particle intensities inside the tunnel can

be expressed as

$$\varphi(r, \theta) = k/(r\theta)^2/\text{cm}^2/\text{incident proton}$$

where $k = 1.5$ if r is measured in feet and θ is in degrees. φ then accounts for the particle fluxes within a factor of 2.

Assume that the 19 fast secondaries are emitted into the downstream hemisphere from the target, excluding the central cone of semi-opening angle, θ_1 . (See Fig. 10.) Therefore

$$2 \pi k \int_{\theta_1}^{\frac{\pi}{2}} \frac{r^2 \cos \theta d\theta}{r^2 \theta^2} = 19 \quad (8)$$

$$\begin{aligned} \int_{\theta_1}^{\frac{\pi}{2}} \frac{\cos \theta}{\theta^2} d\theta &= \frac{\cos \theta_1}{\theta_1} - \int_{\theta_1}^{\frac{\pi}{2}} \frac{\sin \theta}{\theta} d\theta = \frac{\cos \theta_1}{\theta_1} - s_i \left(\frac{\pi}{2} \right) + s_i \left(\theta_1 \right) \\ &= 9.95 - 1.39 + 0.10 = 8.70^* \end{aligned} \quad (9)$$

Putting (9) into (8)

$$2 \pi k \times 8.70 = 19$$

$$k = 0.35$$

Changing from cm and radians to feet and degrees

$$k = 0.35 \times \left(\frac{57.3}{30.48} \right)^2 = 1.22$$

which is to be compared with the 1.5 found empirically.

* Jahnke and Emde: Tables of Functions with Formulae and Curves, Fourth Edition, p. 3 (1945).

II. Particle Fluxes in the Sand

1. Pipe Wells and Instrumentation

To study the transmission of radiation through the existing sand cover of the AGS two inch pipe wells were driven from the sand surface to the tunnel roof directly over magnets H-11, H-13 and H-15 (Fig. 6). These wells nominally extended through 10 feet of sand. Similar wells were also placed in the side sand out to 40 or 50 feet, driven to below the median plane at H-11, H-12, H-13, H-14 and H-15 (Fig. 11). At H-13 an array of wells enabled the sand to be probed 14 feet inside the ring from the inside tunnel wall.

The instrumentation consisted of paraffin, Pilot-B plastic scintillators, NTA film, β - γ film and Bendix pocket dosimeters, which were attached to strings and lowered into the wells to the desired level. The Pilot-B scintillators were used both for C^{11} activation and with a photomultiplier tube. Aluminum foils were also included in the side sand measurements.

In the vertical plane over the circulating beam, paraffin was placed at two foot intervals in the pipes at H-11, H-13 and H-15 (see upper half of Fig. 6). The particle detectors were lowered to the median plane in the side wells.

A plastic scintillator with a photomultiplier tube explored the wells at various levels, thus giving a two-dimensional flux plot through the sand cover during one run of the AGS.

The particle fluxes in the sand were generated in the manner described in the Introduction.

2. Results in the Vertical Plane

Measurements of the strongly interacting fluxes in the vertical plane were done in the manner described in Part I, section 1, and the results are given in Figs. 6 and 12.

A similar experiment was done at CERN⁵ where the earth cover is 3.3 m and density $\sim 2.2 \text{ g/cm}^3$ (AGS sand 1.8 g/cm^3). Instead of pipe wells, 90 cm of shield

5. T. Capone et. al., CERN Report DI/HP/71, February 23, 1965.

top was removed and flux measurements using C^{11} activation made before and after removal. The maximum particle flux was found about 30 feet downstream from the target which agrees with Fig. 6 (see Figs. 1 and 17 of Ref. 5).

The data from their experiments ABC (full earth cover) and KLM (90 cm of earth removed) (Fig. 17, Ref. 5) are presented to compare with the 83 g/cm^2 for the fast particle attenuation length shown on Fig. 12 (this report).

<u>E(GeV)</u>	<u>Φ for 3.87 m *</u>	<u>Φ for 2.97 m *</u>	<u>$\lambda \text{ g/cm}^2$</u>
26.4	76	505	105
19.2	53	305	113
12	26	195	101

* includes tunnel roof concrete

Φ fast neutrons ($\text{n cm}^{-2} \text{ sec}^{-1}/10^{12} \text{ p sec}^{-1}$)

The attenuation length, $\lambda \text{ g/cm}^2$, was computed from

$$\Phi (3.87 \text{ m}) = \Phi (2.97 \text{ m}) e^{-90 \times 2.2/\lambda}$$

The approximately constant value of λ between 12 and 30 GeV incident protons is interpreted to mean that the angular distribution of the secondary particles from the target does not vary markedly from θ^{-2} between these energies.

Pocket dosimeters and γ sensitive film were also placed at the same locations as the foils and the results are shown in Figs. 13 and 14.

3. Particle Intensities in the Median Plane

Since the present sand cover is limited to a nominal 10 feet in the vertical plane over the beam, measurements of the fast particle fluxes were made in the median plane outside the tunnel where sand penetration up to 50 feet could be realized. If the sand fluxes are comprised of two components: (a) a strongly interacting one composed of nucleons and pions with about the same interaction lengths and angular distributions, and (b) a weakly interacting component, muons,

then there should be an abrupt change in slope at some critical sand depth where the weakly interacting component begins to dominate. A search for this phenomenon was one of the principal reasons for wanting deeper sand penetrations. A second reason was to learn whether or not the 83 g/cm^2 for the attenuation of the fast flux would be valid at greater depths.

A. Plastic Scintillators, C^{11} Activation. The plastic scintillators were 2" in length and 1" in diameter, and were machined to weigh $25 \text{ grams} \pm 1\%$. They were calibrated against the polyethylene foils as described in Part I, section 1. The comparison was made with 1.2 feet of sand intervening between the outside of the tunnel wall and the place of detection. The foil gave 765 counts/min. and the scintillator 3.25×10^5 counts/min. corrected for background, decay and counter efficiency.

From Part I, section 1, the fast particle flux intensity from the foil was

$$\Phi_F = 230 \times 765 = 1.76 \times 10^5 / \text{cm}^2 / \text{sec.}$$

Therefore,

$$\Phi_{\text{SCIN}} = \frac{1.76 \times 10^5}{3.25 \times 10^5} \left(\frac{dC^{11}}{dt} \right)_{\text{SCIN}} = 0.54 \left(\frac{dC^{11}}{dt} \right)_{\text{SCIN}}$$

where $(dC^{11}/dt)_{\text{SCIN}}$ is the counts/min. corrected for background, decay and counter efficiency.

A semilog plot of the results is shown in Fig. 15 for radial distances outward on the median plane from various magnets, and a contour map of the same data is given in Fig. 11.

Comparison between the semilog plots, Figs. 12 and 15 does not reveal any significant differences for the particle intensities at corresponding thicknesses of sand. From this it is concluded that the AGS magnet does not contribute to the side and roof shielding for fast particles emerging from the H-10 target. The data from the H-11 side wells have not been included in Fig. 15 because they are influenced by the void created by the access tunnel (see Fig. 11).

B. Na^{24} Activation. Aluminum foils were included with the plastic scintillators to measure the neutrons with energy in the neighborhood of 14 MeV which is the peak for the giant resonance⁶ in the cross section for neutrons bombarding the aluminum making Na^{24} . Analysis of the results leads to the conclusion that uncertainties about the radiation components and their energy spectra in the earth, production thresholds and cross sections for Na^{24} and F^{18} negate the utility of aluminum foils for this kind of measurement in shielding.

C. Scintillation Counters. Fluxes were measured at many points in the earth cover utilizing scintillation counters. The counters consist of Pilot B diphenylstilbene scintillators mounted on the end windows of Type 6199 photomultipliers. Counter gain is controlled by varying the photomultiplier high voltage. Signals developed at the anode of the tube are passed through a limiter circuit and then to a discriminator circuit which registers only those pulses which exceed 100 millivolts of amplitude. The circuitry is capable of counting at rates as high as 100 Mc/sec. Table A summarizes the dimensions of the scintillators. Fig. 19 is a typical response curve for a given counter, showing its sensitivity to a variety of radiations. The counters were calibrated with a known source of 14 MeV neutrons.

Scintillation counter data were always obtained by recording the flux detected at a particular point during targeting, and for an equivalent time when there was no accelerated beam. In the great majority of cases no background was detected. Two methods were utilized to normalize these measurements: The internal beam intensity was monitored for each run, and a second counter was fixed at some point in the earth cover and its output recorded.

Table A
Scintillator Dimensions

<u>Counter</u>	<u>Material</u>	<u>Scintillator</u>		<u>Volume (cm³)</u>
		<u>Diameter (inch)</u>	<u>Length (inch)</u>	
1, 2	Pilot B	1	1-7/8	25.7
3	"	1-1/2	1/4	7.3

6. S.P. Shen, BNL 8721.

The data of Fig. 20 show an intensification of lower energy particles, not detected by C^{11} activation, arising from the absence of one foot of steel in the magnet gap. There is also some indication of a lesser bulge on the side in the direction of the center of the magnet ring; this is most likely due to the target being closer to the inward wall. Eliminating these bulges, the isoflux contours are approximately parallel to the tunnel walls. The data on the median plane outward from the magnet ring are plotted on Fig. 21. The results show a tailing off at about 20 feet of sand.

4. Dose Rates in the Sand

Dose measurements in the sand were made by Kodak NTA film, Dupont 555 and 1290 β - γ film, and with Bendix pocket dosimeters. The films were packaged in a standard BNL film badge container and lowered to the median plane along with the dosimeters as previously explained. The film container has 43 mil cadmium and 64 mil aluminum filters over different areas of the film. An open window is also present. The films were processed and calibrated by the Personnel Monitoring Section of the Health Physics Division at Brookhaven.

A. NTA Film. NTA film will respond to any ionizing particle having an L.E.T. greater than 60 MeV/cm in the film. This limits the muon detection to those with energies less than 3 MeV and protons of less than 20 MeV.⁷ The proton response of NTA film ranges from 0.35 to 20 MeV. The results are shown on Fig. 22. At about 20 feet of sand, the points for H-13 show a change in slope, suggesting a background of weakly interacting particles.

B. Pocket Dosimeters. For the measurement of the total dose at each well location (both in the vertical plane and in the median plane) Bendix condenser ionization chambers (manufactured by the Bendix Aviation Corporation, Cincinnati, Ohio) were used. These dosimeters are in use at the AGS as a quick method for personnel monitoring. The wall of the instrument is thin aluminum and the ionization chamber is encapsulated in near tissue-equivalent plastic. These were charged in accordance with the manufacturer's specifications (- 160 volts).

Calibration runs were made on each of the dosimeters used with gamma rays from Co^{60} , neutrons from a Pu-Be source and minimum ionizing protons in the

7. R.L. Lehman, UCRL Report 9513 (1961).

external beam from the Cosmotron. Previous calibrations made by the Health Physics Division showed that these instruments are tissue-equivalent for neutrons up to ~ 20 MeV. Calibrating the dosimeters using 14 MeV neutrons and comparing the results with a known response from NTA film showed agreement within 20% for the average dosimeter. A quality factor of 6.5 was taken for determining the rem dose for the dosimeters at 14 MeV. Another calibration was made utilizing a 1 GeV proton beam from the Cosmotron. The results showed the pocket dosimeters to be under-reading by a factor less than three; however, the uncertainty about the distribution of the proton intensity across the beam could account for the disagreement.

For the collection of data, one dosimeter was inserted in each well. Because of the rapidity of dose rate fall-off with increasing sand thickness from the circulating beam, three different sensitivities ranging from 600 R to 200 mR full-scale, were used. All instruments were identical in construction, differing only in the size of the capacitor.

The selection of the sensitivity of the dosimeter to be placed in a particular well was calculated from the results obtained previously in the vertical plane. Several dosimeters were buried in the sand in a remote, quiet area to determine any background radiation which may be present in the earth. No discharge was observed on any of these after 48 hours.

The dosimeters were read immediately after the run, which gave a result in roentgens for a 16 hour exposure. The readings were converted to rads by a 0.92 factor and a quality factor of 10 was assumed to obtain the rem dose, which was then normalized.

The results are plotted on Fig. 23 which, as in the case of the NTA film, show a change in slope at about 20 feet of sand. The dose distribution on the median plane in the side sand is shown in Fig. 27.

C. β - γ Film. Dupont SX-249 packets containing type 555 sensitive film and 1290 insensitive film were measured with densitometers after an exposure to 1.6×10^{16} targeted protons. Doses were assigned from calibration of the film by exposure to known gamma sources.⁸ The results are plotted on Fig. 24, which, as in the case of the dosimeters and NTA film, show a change in slope at about 20 feet of sand.

8. F. Lacey and C.F. Swezey, private communication.

5. Attenuation Length in the Sand

If the following figures are examined (Table B) for the half attenuation length for the particle population density or the dose rate, a value of 1.05 feet of sand results, or a mean attenuation length of 1.50 feet of sand.

Table B
 λ_e vs. Detector

<u>Detector</u>	<u>Geometry</u>	<u>Figure</u>	<u>$2.3 \lambda_e$ (ft.)</u>
C^{11}	Vertical	12	3.4 ± 0.2
Dosimeters	Vertical	13	3.3 ± 0.2
γ Film	Vertical	14	2.8 ± 0.15
C^{11}	Horizontal	15	3.6 ± 0.4
Scint. Counter	Horizontal	21	3.7 ± 0.2
NTA Film	Horizontal	22	3.5 ± 0.5
Dosimeters	Horizontal	23	3.8 ± 0.5
γ Film	Horizontal	24	3.45 ± 0.2

$$\lambda_e = \frac{(3.44 \pm 0.33 \text{ feet})}{2.3} \times 30.48 \times 1.82 = 83.10 \pm 7.8 \text{ grams/cm}^2$$

An average density of AGS sand cover is 1.82 g/cm^3 or 114 lb/ft^3 for a 10% mixture content. Fifteen samples were obtained from a variety of locations and depths in the ring top. These densities and moisture content were measured by Dames and Moore.⁹ The moisture content varied from 4% to 17% by weight of the wet weight.

6. An Interpretation of $\lambda_e = 83 \text{ g/cm}^2$

If one plots the decrease in particle intensity or dose rate vs. the distance in sand transverse to the circulating beam direction, a group of points

9. Dames and Moore, Soils Investigation, AGS Magnet Enclosure Structure, May 20, 1966.

results, which may be connected by an approximately straight line on a semi-log plot. The slopes of a set of such plots are essentially the same near the target and about forty feet downstream from it.

The exponential character of these plots is fortuitous in that it is a special combination of the geometry, angular distribution of the secondaries from the target, and the change in interaction length at various inclinations to the circulating beam direction. To interpret 83 g/cm^2 as an interaction length in that it is the mean flight distance of a fast strongly interacting particle between nuclear collisions, is obviously erroneous.

The results from the C^{11} activation were studied, not transverse to the beam, but along lines in the sand which passed through the target (Figs. 6 and 11). Except for scattering, attenuations along these lines are close to the direction along which the fast particles are moving and should show an attenuation nearly equal to the interaction length, provided that there are no significant contributions of particles coming from other sources. The results from this study are shown in Figs. 25 and 26.

Summary

Knowledge of the flux distribution from an internal target at a straight section of the AGS is reasonably well understood. It can satisfactorily be described by the relationship

$$\varphi(\theta, r) = \frac{k}{(r\theta)^2}$$

The side shielding characteristics of the sand cover over the AGS ring have been carefully measured and are consistent with published interaction lengths for strongly interacting particles. There is marginal evidence of a weakly interacting tail beyond 20 feet. It should be emphasized, however, that the energy spectrum and components of the particle population are not well known.

Acknowledgments

This report summarizes the results of an effort involving and supported by a significant number of persons at BNL. The authors particularly wish to

acknowledge the contributions of R.D. Colvett, B.A. Norman, L.F. Phillips, W.R. Tooker, B. Vitale, the staffs of the AGS and Cosmotron, the Accelerator Health Physics group and the Personnel Monitoring group.

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Distr.: AGSCD External

- Notes:
1. Normalized to 2.78×10^{11} protons/second
 2. 30 GeV
 3. Fast flux in particles/cm² sec $\times 10^{-5}$
 4. Data of run No. 7 - 8/12/65
 5. CH₂ foils
 6. 8" vacuum pipe
 7. Errors
 - a. Position: Horizontal $\pm 4"$
Vertical $\pm .5"$
 - b. Relative accuracy $\pm 5\%$

FIGURE 1 - FAST FLUX IN TUNNEL - NO SHIELDING

Excitation function for C^{11} production by protons from carbon. The symbols refer to the work of various authors: $\diamond$ -Cumming (7); $+$ -Hintz & Ramsey (35); ∇ -Cassels et al. (25 and 32); $\star$ -Prokoshkin & Tiapkin (20); $\square$ -Crandall et al. (1); $\times$ -Parikh (18); ∇ -Rosenfeld et al. (21); $\triangle$ -Goebel et al. (24); Δ -Poskanzer et al. (37); $\bullet$ -Cumming et al. (14); $\circ$ -Horwitz & Murray (15); $\square$ -Cumming et al. (4).

FIGURE 2 - EXCITATION FUNCTION FOR C^{11} . FROM REFERENCE 1.

FIGURE 3 - Fast Flux in Carbon Absorber (from Ref. 3).

FIGURE 4 - FLUX DENSITY CONTOURS NORMALIZED FOR 10^5 INCIDENT PROTONS. FROM REFERENCE 4.

- Notes: 1. Normalized to 2.78×10^{11} protons/sec
 2. 30 GeV
 3. Fast flux in particles/cm² - sec x 10⁻⁵
 4. Data of run No. 9 - 9/2/65
 5. CH₂ foils
 6. 8" Vacuum pipe
 7. Errors a. Position: Horizontal $\pm 4"$
 Vertical $\pm .5"$
 b. Relative Accuracy $\pm 5\%$

FIGURE 5 - FAST FLUX IN TUNNEL - LEAD SHIELD

NOTES:

1. Normalized to 2.78×10^{11} protons/sec.
2. 30 GeV
3. Fast flux in particles/cm² - sec.
4. CH₂ foils

5. 8" vacuum pipe

6. Errors - a. Position: Horizontal $\pm 4"$
Vertical $\pm .5"$
b. Relative Accuracy $\pm 5\%$

FIGURE 6 - RESIDUAL FAST FLUX - BACKGROUND SUBTRACTED

FIGURE 8 - FAST FLUX DENSITY VERSUS HEIGHT ABOVE BEAM (y)

$N(\theta) - n/cm^2/sec./2.78 \times 10^{11} \text{ protons/sterad.}/30.48^2 \times 10^{-5}$

FIGURE 9 - Tunnel Fast Flux As A Function Of Angle (θ)

FIGURE 10 - Hemisphere Excluding Central Cone

FIGURE 11 - C^{11} ACTIVATION IN PLASTIC SCINTILLATORS AT THE MEDIAN PLANE

FIGURE 12 - C^{11} From Paraffin - Vertical Distribution In Sand

FIGURE 13 - DOSIMETERS IN SAND COVER-VERTICAL DISTRIBUTION

FIGURE 14 - γ - FILM IN SAND COVER VERTICAL DISTRIBUTION

Roentgens/Hr/ 10^{12} Targeted Protons/sec.

- H - 11
- H - 13
- △ H - 15

- Notes: 1. Data of Run No.1 - 3/17/65
 2. 30 GeV
 3. Special Vacuum Pipe at H-10
 4. Sand begins fourteen feet above the beam

Fig. 16. The H-10 Straight Section

Fig. 17. The H-10 Straight Section

Fig. 18. Absorber at the H-10 Straight Section

FIGURE 19 - SCINTILLATION COUNTER NO. 3 - CALIBRATION CURVES

- H 12
- H 13
- H 14
- △ H 15

FIGURE 24 γ Flux In Side Sand On Median Plane

Notes:

1. Angles with respect to circulating beam direction.
2. r_0 is the distance, in feet, from the target to the 2.5×10^5 contour, Figure 6.
3. Data of Figure 6.
4. Data are not corrected for the inverse square law.

FIGURE 26

λ_e vs. Polar Angle

Notes:

1. 30 GeV
2. Data of run No. 10 - 5/26/66
3. Readings in R/Hr. for 10^{12} protons targeted/sec.

FIGURE 27

Dose Distribution in the Side Sand