the relation

$$R = CZ^{\alpha}, \tag{24}$$

where Z is the atomic weight and C is a constant, then from the data of Montgomery and Tobey[12] for carbon and aluminum we find α to be approximately 0.5. Using 14.6 for the mean atomic weight of air and 64 for copper we calculate the neutron production rate in copper at 119 mb to be

$$q_c = 0.013 \text{ g}^{-1} \text{ sec.}^{-1}. \tag{25}$$

[12] C. G. Montgomery and A. R. Tobey, Phys. Rev. 76, 1478 (1949).

When compared with the proton production rate at this altitude these data support the view that protons and neutrons are formed in approximately equal numbers in stars.

In conclusion the author wishes to extend grateful thanks to Professor S. A. Korff under whose direction this work was performed, and to the members of the New York University Cosmic-Ray Group: L. G. Collyer, H. A. C. Neuburg, M. Pavalow, W. P. Staker, and M. Swetnick.

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The Penetration and Diffusion of Co^{60} Gamma-Rays in Water Using Spherical Geometry*

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Ionization and Geiger-Müller counter measurements of Co^{60} gamma-rays were made in effectively spherical geometry up to a distance of 252.8 cm (16 mean free paths of the primary radiation) corresponding to an exponential attenuation of the primary radiation by a factor of 8.8×10^{6}. The "build-up factor" was observed to climb up to 33.8 and approached closely the theoretically predicted trend of asymptotic variation $r^{1.4}$. Preliminary information on the spectral distribution of the radiation is included.

I. INTRODUCTION

MUCH experimental work has been done to measure absorption coefficients under narrow beam conditions in which no scattered radiation can reach the detector. In other absorption experiments singly or multiply scattered radiation can reach the detector but the geometry dictated by practical considerations hinders a detailed theoretical analysis of the results.[1] Some data are available from arrangements with simple geometry but only at small distances from the source.[2,3]

Therefore, in connection with the progress on the theory of the penetration and diffusion of x-rays,[4] it seemed advisable to conduct a new experiment in a large mass of water and in simple geometry. The Naval Gun Factory in Washington, D. C., kindly made available its large water tank which is 25 ft. in diameter and 60 ft. deep. Measurements were made using two Co^{60} sources with an apparent strength of 0.33 and 4.75

TABLE I. Data from the 4.75 curie source.

Distance (cm)	46	61	76	91	106	120.5	135.5	150.5	180.5
Mr/min.	125.4	36.6	12.8	4.09	1.39	0.500	17.80×10^{-2}	6.4×10^{-2}	8.3×10^{-3}
Standard error	1.3	0.3	0.2	0.06	0.01	0.009	0.02×10^{-2}	0.2×10^{-2}	—
Build-up factor	4.51	5.98	8.34	9.83	11.65	13.5	15.5	17.6	22.0
Distance (cm)	135.5	150.5	165.5	180.5	195.5	210.5	225.5	240.5	252.8
Counts/sec.[a]	1682	647.4	221.4	82.4	29.92	11.2	4.36	1.64	0.72
Standard error	1	0.8	2.5	0.5	0.08	0.1	0.10	0.01	—
Build-up factor[b]	14.7	17.9	19.2	21.7	23.6	26.2	29.6	32.5	33.8

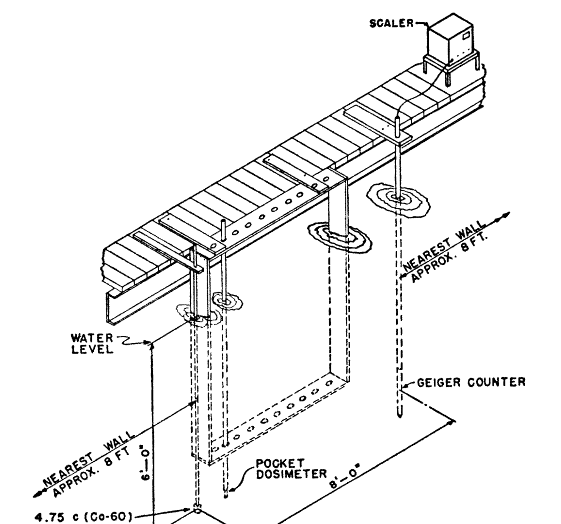
[a] Corrected for coincidence counts and a background of 0.55 counts/sec.
[b] Counter data are scaled to match ionization data in the overlappingregion.

* Work supported by the Applied Mathematics Branch of the ONR.
[1] Kennedy, Wyckoff, and Snyder, J. Research Nat. Bur. Stand. 44, 157 (1950), RP2066.
[2] W. R. Faust, Phys. Rev. 77, 227 (1950).
[3] Levin, Weil, and Goodman, M.I.T. Tech. Rep. 22 (June 15, 1949).
[4] Phys. Rev. 76, 538, 739, 1843, 1885 (1949) and 77, 425 (1950).

curies[5] determined from a calibration in air. Dosage was measured at distances up to 180.5 cm with sealed Kelley-Koett pocket ionization chambers which were calibrated with a 25-mg radium source. A Cu Geiger-Müller counter of the type described by Faust and Johnson[6] was used as detector at distances from approximately 135 to 253 cm.

Figure 1 shows our experimental arrangement which insures effectively spherical geometry. A few measurements at large distances with both source and detector lowered from a depth of 6 ft. to 8 ft. confirmed that the geometry was adequate. Most exposure times were chosen to give a reading of approximately 160 mr. Leakage measurements in the absence of radiation were obtained for each exposure time. Leakage values were erratic and varied from 1 to 6 mr.

The data obtained with the 4.75 curie source are given in Table I. The data show that the dosage decreases with the distance less rapidly than a law of the form $\exp(-\mu_0 r)/r^2$, owing to the building up of secondary scattered radiation. The data are expressed in terms of a *build-up factor*. This factor is the ratio of the observed ionization to the ionization expected from the primary gamma-rays only, disregarding multiple scattering. The estimate of the expected ionization in the absence of scattering is based on (a) the results of measurements in air, where scattering is negligible, and



DISTANCE (CM)	46	61	76	91	106	120	135	150	165	180	195	210	225	240	252
TIME FOR 160 MR	1'	4'	12'	35'	2H	5H	13H	36H	100H						
MR./MIN.	134	37	13	4.1	1.4	.50	.18	.064	.027	008					
COUNTS/SECOND							1343	590	214	82	30	12	5	2	1

FIG. 1. Experimental arrangement.

[5] The apparent strength of a Co^{60} source in curies is determined by the ratio of its action on a standard ionization chamber to the action of another Co^{60} source of negligible self-absorption and of known strength in disintegrations per second. Thus the apparent strength of 4.75 curies means that the source gave a reading of 6.41 roentgen/hr. on a standard chamber at 1 meter distance at an average date during the experiment.

[6] W. R. Faust and M. H. Johnson, Phys. Rev. **75**, 467 (1949).

TABLE II. Percentage absorption by 0.25 g/cm^2 shields with 4.75 curie source.

Distance (cm)	61	91	135.5	Very large (theoretical estimate): Uncorrected for characteristic response of chamber	Corrected for characteristic response of chamber
Al	2.7	1.2	2.8		
Cu	9.9	9.1	17	21	26
Ag	20	20	26	32	40
Pb	23	25	30	38	46

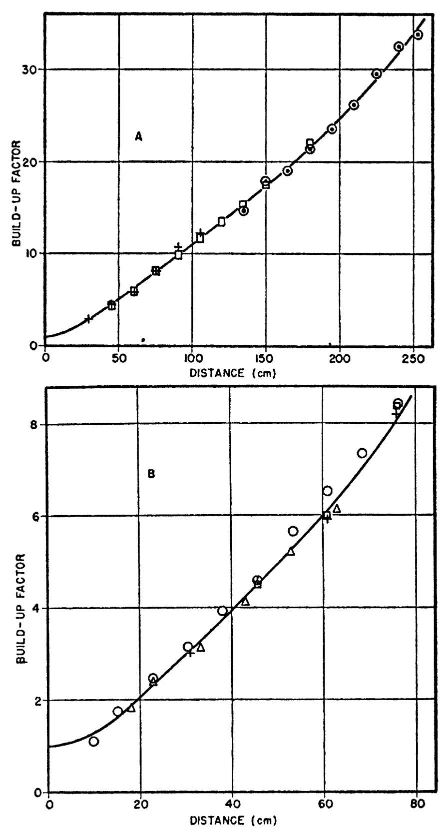


FIG. 2. The build-up factor as a function of distance. (A) Data from the present experiment. (B) Collection of data from various experiments for moderate penetration. + NBS, 0.33 curies, ionization data; □ NBS, 4.75 curies, ionization data; ⊙ NBS, 4.75 curies, counter data; ○ NRL, 0.04 millicurie, counter data; △ MIT, 1.9 curies, ionization data.

(b) a calculated attenuation in water according to the $\exp(-\mu_0 r)/r^2$ law. The calculation took into account the fact that different absorption coefficients pertain to the two Co^{60} lines. Only Compton absorption in water for 1.17 and 1.33 Mev was considered, since the contribution by pair production is of the order of 0.05 percent of the Compton absorption and the photoelectric effect is even smaller.

Figure 2 (A and B) shows data on the attenuation of Co^{60} gamma-rays in water. It is shown in (A) that the build-up factor increases with distance somewhat faster than linearly. At a distance of 252.8 cm the total

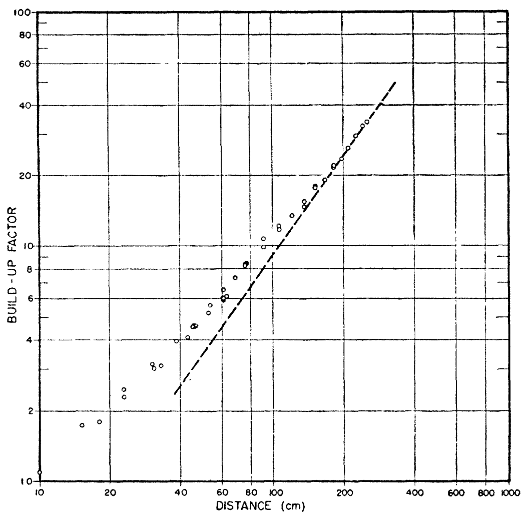


FIG. 3. Logarithmic variation of build-up factor with distance.

gamma-ray intensity is 33.8 times as large as the estimated intensity of the primary component alone. Data from other experiments in spherical geometry[2,3] with comparatively weak Co^{60} sources match our data at small penetration distances, as is shown in (B). Both ionization chamber and counter readings are represented in these data below 80 cm. The curve is extended to zero distance where the build-up factor should be unity.

Theoretical work of Fano, Hurwitz, and Spencer[7] on the asymptotic trend of x-ray intensities, including the effect of small angular deflections, indicates that the build-up factor should increase as r^k at very large distances, and that k should be about 1.4 in this experiment. However, the asymptotic behavior should be approached very slowly as the distance from the source increases.

A log-log plot of build-up factors (Fig. 3) shows a slope increasing with distance from a value of the order of unity at small distances. The dashed line has a slope of 1.4 which appears to match the latter portion of the experimental curve. It is expected, therefore, that the build-up factor will continue to increase beyond 253 cm as $r^{1.4}$ and will never reach a maximum value. This follows from the theory of Bethe, Fano, and Karr[8] according to which the intensity ratio of secondary to primary radiation increases beyond any limit. Spencer and Fano, in a paper to be published shortly, have calculated theoretically the build-up factor throughout the range of Fig. 2A. Their result agrees completely with the experimental data.

Some indication of the intensity of the soft radiation components at large distance from the source was obtained by shielding the ionization chambers with filters of various materials. Preliminary results are shown in Table II. The percentage decrease in the ionization when measured with shielded chambers has been variously used[9] to obtain an indication of the amount of soft radiat on in the spectral distribution. Since the sleeve filters were approximately 0.25 g/cm² thick no appreciable amount of the hardest component was stopped. An indication of the spectral distribution of the radiation expected at very large distances is given by the "NRL distribution" of Karr and Lamkin,[10] that is, by the spectral distribution calculated for an infinite mass of water with a uniformly distributed Co^{60} source. The actual distribution for large penetration would be steeper on the high energy side than the "NRL distribution," since photons that have traveled large distances tend to have been scattered many times with little energy degradation. Nevertheless, the expected absorption by the Cu, Ag, and Pb filters was estimated using the "NRL spectral distribution." The spectral energy density for each photon energy was multiplied by the filter attenuation, the coefficient of energy absorption in air ($\tau+\sigma_a$) and by a correction factor characterizing the spectral response of the ionization chamber.[11] The data in Table II indicate that quality equilibrium has not yet been closely approached up to 135.5 cm from the source. Much further experimental work is needed to complete this phase of the investigation.

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[7] Fano, Hurwitz, and Spencer, Phys. Rev. **77**, 425 (1950). The difference in source geometry does not effect any change in the exponent in this case.

[8] Bethe, Fano, and Karr, Phys. Rev. **76**, 538 (1949).

[9] E. H. Quimby and R. F. McNattin, Am. J. Roentgenology **28**, 236 (1932).

[10] P. R. Karr and J. C. Lamkin, Phys. Rev. **76**, 1843 (1949).

[11] Frank H. Day, *"X-ray calibration of radiation survey meters, pocket chambers and dosimeters,"* Circular NBS (to be published)