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ABSORPTION OF GAMMA RAYS FROM RADIUM IN AIR

by

D.F. URQUHART

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ABSTRACT

Measurements of the absorption of gamma radiation in air have been made, under conditions designed to simulate those encountered in airborne radioactive surveys. The large thicknesses of air involved were replaced by thicknesses of a few inches of water.

A study of the literature showed that varying values of absorption coefficients were quoted. The values obtained agree with some of those previously published.

1. INTRODUCTION

The interpretation of radioactive anomalies obtained by airborne surveys, requires a knowledge of the gamma ray absorption which occurs in the air between the ground and the aircraft. In normal surveys the aircraft may fly at heights between 50 ft. and 500 ft.

There are three main natural sources of gamma radiation which can be detected at these heights; the daughter products of radium (Ra226), daughter products of thorium (Th232), and potassium (K40).

The mechanism of gamma ray absorption is well understood and absorption coefficients in air for gammas of any given energy may be calculated from published equations and tables. The absorption coefficient for the single 1.5 Mev gamma ray from K40, therefore presents no problem. The gamma spectra of the radium and thorium series are extremely complex and are not known precisely. Many energy components are present in the spectra and the relative abundance of the gammas of different energies is not known exactly; precise calculation of the absorption coefficients is therefore not possible. Moreover the energy spectrum changes with distance from the source, so the absorption coefficient is also a function of the distance from the source.

An empirical formula has been suggested for the calculation of the absorption coefficient for radium gammas (Cook, 1952). Direct measurements in air present practical difficulties, due to the great distances involved.

It has been shown, however, (Spiers, 1956) that the gamma ray mass absorption coefficients are practically the same for air and water. This immediately suggests the possibility of obtaining "type" airborne radioactive anomalies by model experiments using water as the absorbing medium. Since the mean free path for the gamma rays for uranium is about 400 ft. in the air and only 5 inches in water, the dimensions of the model would be to scale of about 1:900 which is quite a convenient size for laboratory experiments. One serious difficulty however, is that the size of the sodium iodide crystal used for the detector cannot be made small compared with the dimensions of the model.

In order to check the possibility of making model experiments of this kind, some preliminary experiments were carried out in the radiometric laboratory by I.McDermott (University vacation student) during the 1957-58 university vacation period. These experiments were directed mainly towards observing the changes in the gamma ray spectrum and the absorption coefficient, after passing through different "thicknesses" of water.

The results obtained for the absorption coefficients do not agree very well with published figures due mainly to the problem already mentioned of the detector not being to scale. However, it should now be possible to design an experimental arrangement for the model experiments which will approach the required conditions.

In trying to assess the significance of the results obtained from these preliminary experiments, some time has been spent in looking through the available literature on the subjects of gamma rays from radium. A summary of the information so obtained is included in this report in addition to the results obtained by the water scattering experiments.

2. PRELIMINARY MODEL EXPERIMENTS

(i) Introduction.

The arrangement of source and detector used for the experiments is shown to full scale in Fig.1. and a block diagram of the complete instrumental arrangement is shown in Fig.2.

The smallest sodium iodide crystals at present available here are $\frac{3}{4}$" diameter crystals which are to be used in bore-logging detectors. The quality of these crystals is not high and was therefore not suitable for these preliminary experiments where good resolution was required for the gamma spectra measurements. The crystal used was $1\frac{1}{2}$" dia. by 1" long.

The single channel analyser was used to obtain the gamma ray spectra and used as a simple discriminator for the integral bias curves.

A point source of radium was used for all the experiments and thicknesses of water up to 8 inches were used. This corresponds to a distance in air of about 600 ft. In all experiments the results were corrected for geometry by factors determined experimentally, by making measurements in air. In air, the change in count rate observed, as the detector is moved away from the source is due almost entirely to the changing geometry for distances of the order of a few inches.

Preliminary tests indicated that reasonably reliable stability could be assumed after the apparatus had been switched on for an hour or so. At the beginning and end of each experiment, the discriminator bias levels were checked against a pulse generator whose pulse heights could be controlled in steps of 0.1 volt from 0 to 50 volts. The pulse generator was connected to the discriminator and the pulse heights increased until, for a fixed discrimination bias, the scaler started to count. The reading on the pulse generator was then taken as the true bias for the particular discriminator setting. When used as an analyser, the channel widths were checked from time to time, but these were found to be constant so far as it was possible to detect with the apparatus used. However, the channel width changed considerably during the "warming up" period of about one hour. The photo-multiplier tube was used in conjunction with a sodium iodide crystal and good contact between the two was achieved by smearing the surfaces in contact with silicone jelly. The tube and crystal were lagged with "Scotch" electrical tape, and preliminary tests showed that complete insulation of the tube from light was obtained. It was found necessary to keep the scaler cool by blowing a draught of air into it by means of an electric fan since the count rates became erratic under hot conditions.

In addition to the above precautions, the tube was clamped into a fixed position, its orientation being kept constant during any experiment in order to avoid any possible magnetic effects. Count rates were found to vary slightly with orientation of tube. The tube was handled carefully during adjustments lest mechanical jarring might alter the behaviour of the tube.

Before carrying out the experiments the bias voltage scale of the single channel analyser was calibrated in terms of gamma ray energy, measured in Mev. This was done by using the photo peak of $Cs137$ (0.669 Mev.) and the peaks of Co60, (1.17 and 1.33 Mev). The E.H.T. for the photomultiplier tube and the amplifier gain were adjusted to give a scale of approximately 30 volts per Mev.

Fairly strong sources were used throughout the experiments so that background corrections were negligible in most of the measurements.

For these experiments the factor for converting distance in water to equivalent distance in air was taken to be μ (water)/ μ (air) =921, where μ = total linear absorption coefficient for the average energy of the radium gammas (0.8 Mev). This ratio was found to be practically independent of energy over the range of 0.1 to 3 Mev.

The mean free path has been taken to be $1/\mu$ (387 ft. in air and 5.04 inches in water).

(ii) <u>The effect of scattering in water on the spectrum of the gamma rays from radium.</u>

The results of this experiment are shown in the curves of Fig.3. The spectrum was measured with the detector at distances of 2,4,6 and 8 inches from the source (see Fig.1.), the water level in the tank being adjusted to about the middle of the photomultiplier tube for each position of the detector. The spectrum was also measured at 2 inches from the source in air. All curves have been adjusted for the changing geometry between source and detector by the method mentioned earlier. The curves have also been corrected for instrumental drift which was inevitable due to the long time required (about 4 hours) to take the counts for each spectrum. The counts were taken at intervals of 2 volts from 5 volts to 80 volts with the analyser set to a channel width of 0.5 volts.

It can be seen from Fig.3 that the main photo-electric peaks (all due to Ra C) can be distinguished quite clearly for distances up to 8 inches in water or up to 600 ft. in air. At greater heights (several mean free paths) it can be expected that the peaks will gradually disappear into the Compton continuum.

This result may have an application in airborne survey work as a means of distinguishing between uranium and thorium; similar to the method used in the laboratory for assaying. For example, a single channel analyser could be used to observe the 2.6 Mev gamma ray from thorium as well as the total count rate above a bias level of say 0.5 Mev.

However, the low count rate obtained in the 2.6 Mev channel would probably make the scheme quite impracticable for fast flying aircraft although it could be useful in a helicopter.

(iii) <u>The effect of scattering on the absorption coefficient.</u>

The object of this experiment was to determine the effective value of the absorption coefficients for the gamma rays from radium and the variation in this coefficient to be expected for different heights in air.

This was done initially by using the analyser as a simple discriminator set to a bias level of 0.4 Mev. The discrimination level for an airborne scintillometer is likely to be about this value.

A set of readings was obtained for the count rate in air, and water for distances from source to detector between 2 inches and 8 inches at intervals of 0.5 inches.

By taking the ratio of the count rate in water to the count rates in air for each distance, values for the fractional change in gamma ray flux with distance were obtained directly.

These results are shown in Fig.4. From values of n/n_0 taken from this curve, it was possible to calculate values of the true composite linear absorption coefficient (μ'_a) from the experimental equation:

$$n=n_0 e^{-\mu'_a h}$$

Values of μ'_a are shown as a function of h (distance in air) in Fig.5.

Further experiments were then made to determine the ratio n/n_0 for different settings of bias level and for different thicknesses of water. From these results μ'_a was again calculated and plotted as a function of h in Fig.5. Fewer readings were taken for these curves so they could not be plotted with the same certainty as for the 0.4 Mev bias curve.

The empirical formula used by Cook (1952) showing μ'_a as a function of h is also shown in Fig.5. However, Cook assumed an average energy of 1.8 Mev for the gamma rays from uranium which is certainly far too high. The mean value for this energy should be about 0.8 Mev and when this value is used in Cook's equation higher values of absorption coefficient are obtained (see Fig.5).

The experimental curves of Fig.5, undoubtedly give values of μ'_a which are too low - particularly for low values of h and for low values of bias. This is due to the crystal being large in relation to the distance between source and detector so that the geometry is very favourable to receiving back scattered radiation. In fact it was found that the count rate in water was greater than the count rate in air when the crystal was less than 1 inch from the source. This difficulty could be largely overcome by an improved experimental set up. This will be discussed at the end of this report.

However, for values of h greater than 500 ft. the values of μ'_a for the 0.4 Mev curve of Fig.5 are probably fairly reliable.

Since the back scattered radiation will have been scattered through a large angle most of this radiation will be at a low energy level so that the scattering will be less serious for the curves for higher bias levels.

3. PUBLISHED VALUES OF GAMMA RAY ABSORPTION COEFFICIENTS AND GAMMA RAY ENERGIES FOR THE URANIUM SERIES.

(i) Introduction.

In papers on airborne radioactive survey methods by D.H. Pierson and E.Franklin (1951) and J.C. Cook (1952), different values of air absorption coefficient are quoted for the gamma rays from radium. Pierson and Franklin use a value of 10×10^{-5} cm.$^{-1}$ and Cook a value of 3.3×10^{-5} cm.$^{-1}$ for a height in air of 500 ft. Values quoted in some text books

also show some disagreement. For example, Hevesy and Paneth (1938) quote a value 4.64 x 10^{-5} and Bleuler and Goldsmith (1952) quote a value of 3.46 x 10^{-5} cm.$^{-1}$.

The two main difficulties in arriving at a correct value are as follows:-

(a) Values of absorption coefficients for a detector which accepts no scattered radiation (total absorption coefficient) may be confused with absorption coefficients for a detector which accepts all the scattered radiation as well as the direct radiation (true absorption coefficient).

(b) It is difficult to determine an effective mean value of energy for the different gammas from radium due to the complexity of the spectrum. For example two authors, Cook (1952) and Eichholz et al (1952), consider most of the radiation from RaC to consist of the two high energy components 1.76 and 2.19 Mev, whereas the 0.6 Mev ray from RaC has an intensity more than twice that of either the 1.76 or 2.19 Mev rays. Cook assumes an average energy of 1.8 Mev whereas the actual mean value is probably closer to 0.8 Mev.

(ii) Definitions and published values of absorption coefficients.

The absorption of gamma rays is discussed in most books on nuclear and radiation Physics and a comprehensive treatment is given by Bethe and Ashkin 1952.

Absorption takes place by three main processes -

(a) photo-electric absorption; important for elements of high atomic number and for low energies.

(b) Compton scattering; important at medium energies and relatively independent of atomic number.

(c) pair production; important only for high energies.

For absorbers of low atomic number such as air and water, photoelectric absorption and pair production may be neglected for the energy range which is involved in the radiation from uranium and thorium (about 0.1 to 3 Mev). Absorption in those media may be considered to be due entirely to Compton scattering.

Values obtained theoretically or experimentally for the Compton absorption coefficient depend a good deal on whether the detector is considered to accept all or none of the scattered radiation in addition to the direct radiation. Confusion on this point has been partly avoided by H.E.Johns and J.S.Laughlin (1956), who have defined three separate Compton absorption coefficients.

Consider a collimated beam of monoenergetic gamma rays (energy E. Mev per Photon) in which no photons pass through 1 cm^2 per sec. After passing through xcms of an absorbing material the intensity (total energy passing through 1 cm^2 per sec), is measured by a detector at P. Three different absorption coefficients may now be defined depending on the properties attributed to the detector.

(a) Total Compton absorption co-efficient.

If the detector accepts only the direct rays and rejects all scattered rays, then:-

$$I = I_0 e^{-\sigma x}$$

where $I_0 = n_0 E$ = intensity of the beam incident on the absorber.

$I = n E$ = intensity measured at P.

n = number of direct photons per cm^2 per sec. at P.

σ = Total Compton absorption co-efficient (cm^{-1})

(b) True Compton absorption co-efficient.

If the detector accepts all the direct radiation + all the scattered radiation then

$$I = I_0 e^{-\sigma_a x}$$

where $I_0 = n_0 E$

$I = n_0 E'$

E' = effective mean energy of the direct and scattered rays arriving at the detector.

σ_a = True Compton absorption co-efficient (cm^{-1})

(c) Scatter Compton absorption co-efficient.

If the detector accepts all the scattered radiation and no direct radiation, then -

$$I = I_0 e^{-\sigma_s x}$$

where $I_0 = n_0 E$

$I = n' E''$

n' = number of scattered photons per cm^2 per sec. arriving at the detector.

E'' = effective mean energy of the scattered photons.

σ_s = Scatter Compton absorption co-efficient.

then clearly

$$\sigma = \sigma_a + \sigma_s$$

For energies outside the range 0.1 to 3 Mev and for absorbers of high atomic number additional absorption coefficients must be considered for photoelectric absorption and pair production. It is proposed to use the same notation as adopted by H.E. Johns and J.S. Laughlin.

τ = photoelectric absorption coefficient (cm^{-1})

K = pair production absorption coefficient (cm^{-1})

We may now define the combined absorption coefficients when the three processes are operating simultaneously.

$$\mu = \sigma + \tau + K$$

$$= \sigma_a + \sigma_s + \tau + K$$

where μ = Total absorption coefficient

$$\mu_a = \sigma_a + \tau + K$$

where μ_a = True Total Absorption Coefficient

For the purpose of this report the composite absorption coefficients for a multi-element spectrum have been distinguished by a dash (e.g. μ'_a for the radium spectrum).

For the practical case of an airborne scintillometer observing non-collimated radiation from a surface uranium deposit, the True Compton absorption coefficient (σa) appears to be the one which most closely approaches the conditions met in practice. However, the scintillation detector differs from the ideal detector used in the definition of σa, in two important respects.

(a) The scintillation detector measures the number of photons per cm^2 per sec which have energies above a certain minimum value (the discrimination level of the scintillometer). It does not measure intensity of radiation, defined as the total energy passing through 1 cm^2 per sec. ($n_o E'$).

(b) Some of the gamma photons from a surface deposit which have energies, at ground level, above the scintillometer discrimination level will be degraded, by scattering, at higher altitudes to energies below the discrimination setting and will therefore not contribute to the total count rate.

These two properties of the scintillometer will however, tend to compensate, since property (a) will tend to give a lower absorption coefficient at high altitudes (e.g. 500ft.) than the theoretical value, and (b) will tend to give a higher value.

To what extent these two factors will compensate is difficult to determine theoretically without a laborious mathematical treatment. However, this can probably be determined within the practical requirements of airborne

prospecting, by further laboratory experiments using a more refined water model.

Recent theoretical values of the absorption coefficients are shown in Figs. 6 and 7 for air and water. These graphs have been reproduced from curves published by Johns and Laughlin (1956). The authority given for these curves is G.R. White (1952).

These graphs show the absorption coefficients expressed as mass absorption coefficients with dimensions, $cm^2\ gm^{-1}$, the linear forms of the coefficients are obtained simply by multiplying by the density of the medium (0.0012 for air).

It is interesting to note that the true absorption coefficient in air and water (σa) is fairly constant over the energy range 0.1 to 3.0 Mev. No great error is likely to be made therefore in taking a simple arithmetic mean (weighted according to the relative intensities) for the effective mean energy of the gamma rays from radium, in order to determine the theoretical mean absorption coefficient for the radium spectrum.

From published data it appears that the mean energy from the uranium spectrum is about 0.82 Mev which gives (from Fig.6) a theoretical value of $3.6 \times 10^{-5}\ cm^{-1}$ for the true absorption coefficient. Moreover, since this coefficient changes but little with energy (0.1 to 3 Mev) it can be assumed that this theoretical absorption coefficient will be practically constant for distances in air up to 600 ft. at least. This is compared with the experimental results in Fig.5.

Other useful graphs for all absorption coefficients for aluminium and lead are also given by Johns and Laughlin and these are reproduced in Figs. 8 and 9.

(iii) Published values of gamma ray energies for the uranium series.

A list of energies and relative intensities of the gamma rays from the uranium series for energies above 0.1 Mev is shown in Table 1.

This table has been prepared from values published by Hollander, Perlman and Seaborg (1953) and Evans (1947).

TABLE 1.

THE GAMMA RAYS FROM THE URANIUM SERIES

Transition	Average No. of quanta per disintegration N	Energy per photon (E) MEV	Total photon energy (ne) MEV
$UX_2 \rightarrow U_2$	0.020	0.8	0.016
$R_a \rightarrow R_n$	0.012	0.18	0.002
$R_aB \rightarrow R_aC$	0.115	0.241	0.036
	0.258	0.294	0.073
	0.450	0.350	0.157
$R_aC \rightarrow Rac'$	0.658	0.609	0.400
	0.095	0.766	0.073
	0.080	0.933	0.074
	0.191	1.12	0.214
	0.073	1.24	0.090
	0.066	1.38	0.091
	0.051	1.52	0.077
	0.234	1.76	0.412
	0.015	1.82	0.027
	0.073	2.20	0.161
	0.037	2.42	0.089
TOTAL	2.429		1.996

Average photon energy = $\frac{\Sigma nE}{\Sigma n}$ = 0.82 Mev.

4. CONCLUSIONS

From the experiments and survey of the literature which have been made the following conclusions may be drawn.

(i) The water model should be modified to reduce the effects of back scattering. This could probably be done by taking the following precautions.

(a) Use a smaller crystal (e.g. $\frac{3}{4}$" dia. x 1" long)

(b) Shield the sides of the crystal by about 2 inches of lead to prevent the entry of scattered radiation through the sides of the crystal.

(c) Place the source right at the bottom of the tank so that there is no water behind the source.

(d) Mount the tank as far as possible from the floor, walls and ceiling of the room.

(e) The walls of the tank should be kept as thin as possible. Glass may be a more suitable material to use for the tank.

(ii) If a scintillometer can be assumed to be an ideal detector, the value 3.6×10^{-5} cm^{-1} can be taken as a suitable value for the absorption coefficient for altitudes up to 600 ft. at least.

(iii) If it is found that the scintillometer cannot be regarded as an ideal detector the value of absorption coefficient which should be used for different altitudes and different levels of discrimination can probably be determined using the improved water model. Alternately it may be possible to find a discrimination level for which the scintillometer approaches the ideal detector at any given height.

(iv) If a small, good quality crystal can be obtained it should be possible to determine by means of the water model, whether or not it is feasible to use an energy discrimination method in an aircraft to distinguish between uranium and thorium.

(v) If the improved water model is found to be successful it may be useful to set up a more elaborate model with a moving detector in order to obtain "type anomalies" for different shapes and strengths of radioactive sources.

(vi) It has been shown that the photoelectric peaks in the radium spectrum can be distinguished quite clearly at heights up to 600 feet in air.

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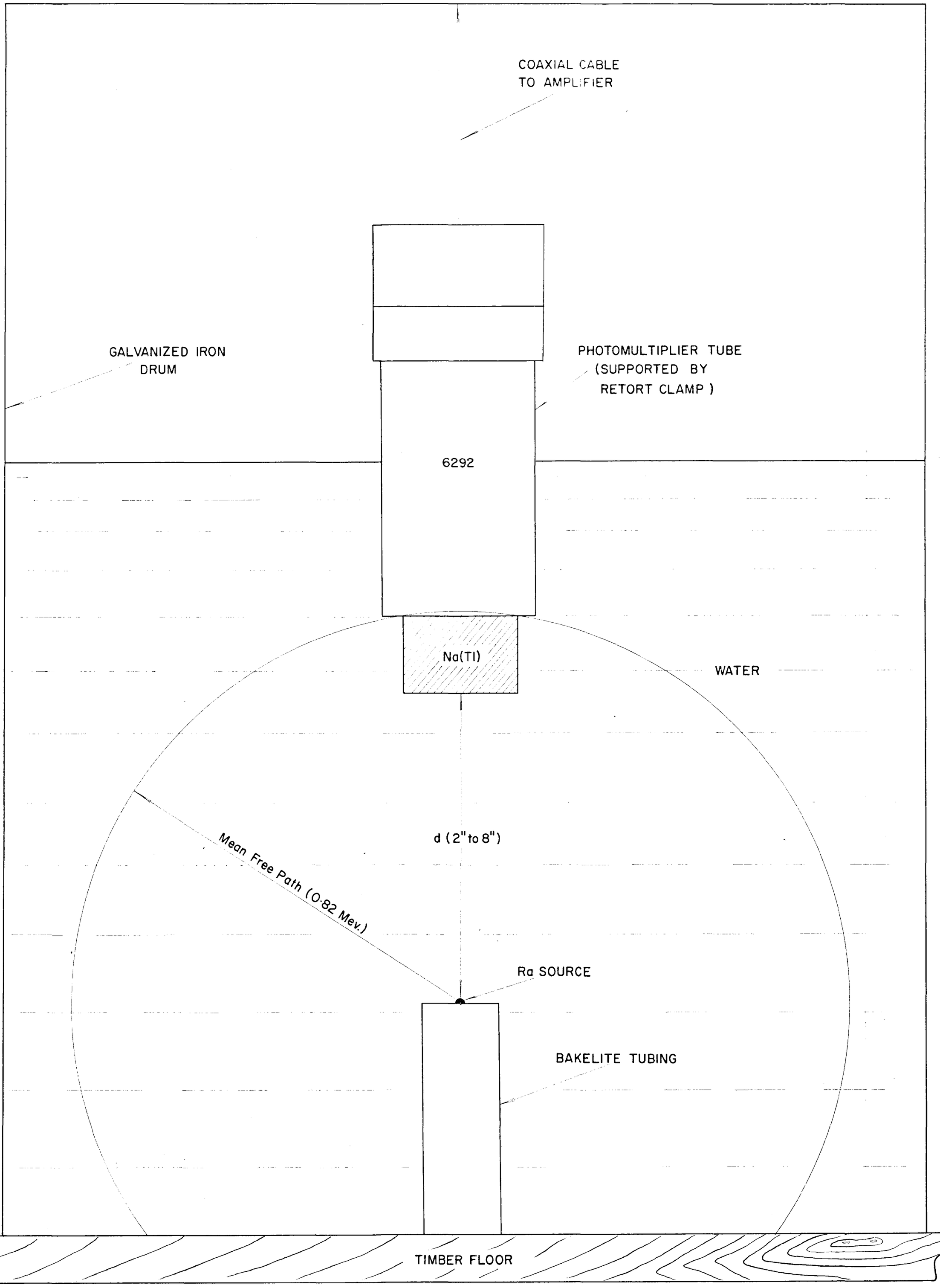
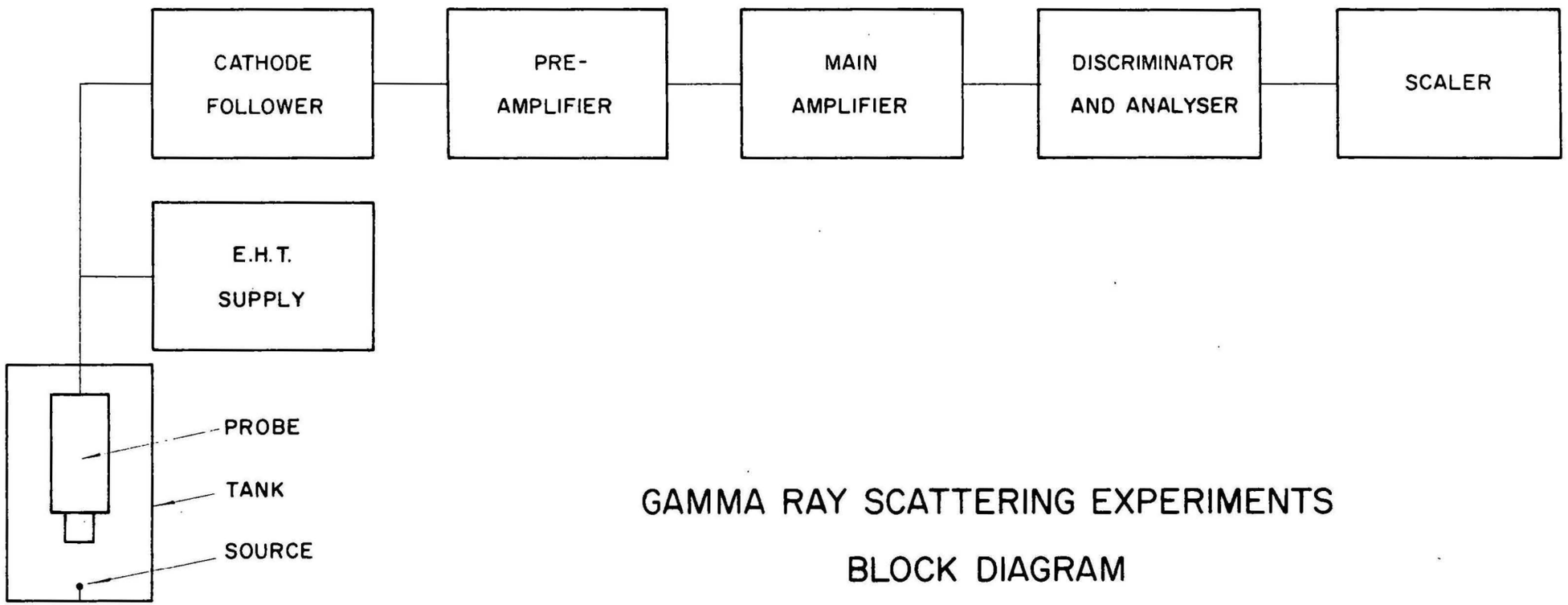


MEASUREMENT OF GAMMA RAY ABSORPTION IN WATER

SCALE 1:1



GAMMA RAY SCATTERING EXPERIMENTS

BLOCK DIAGRAM

PLATE 2

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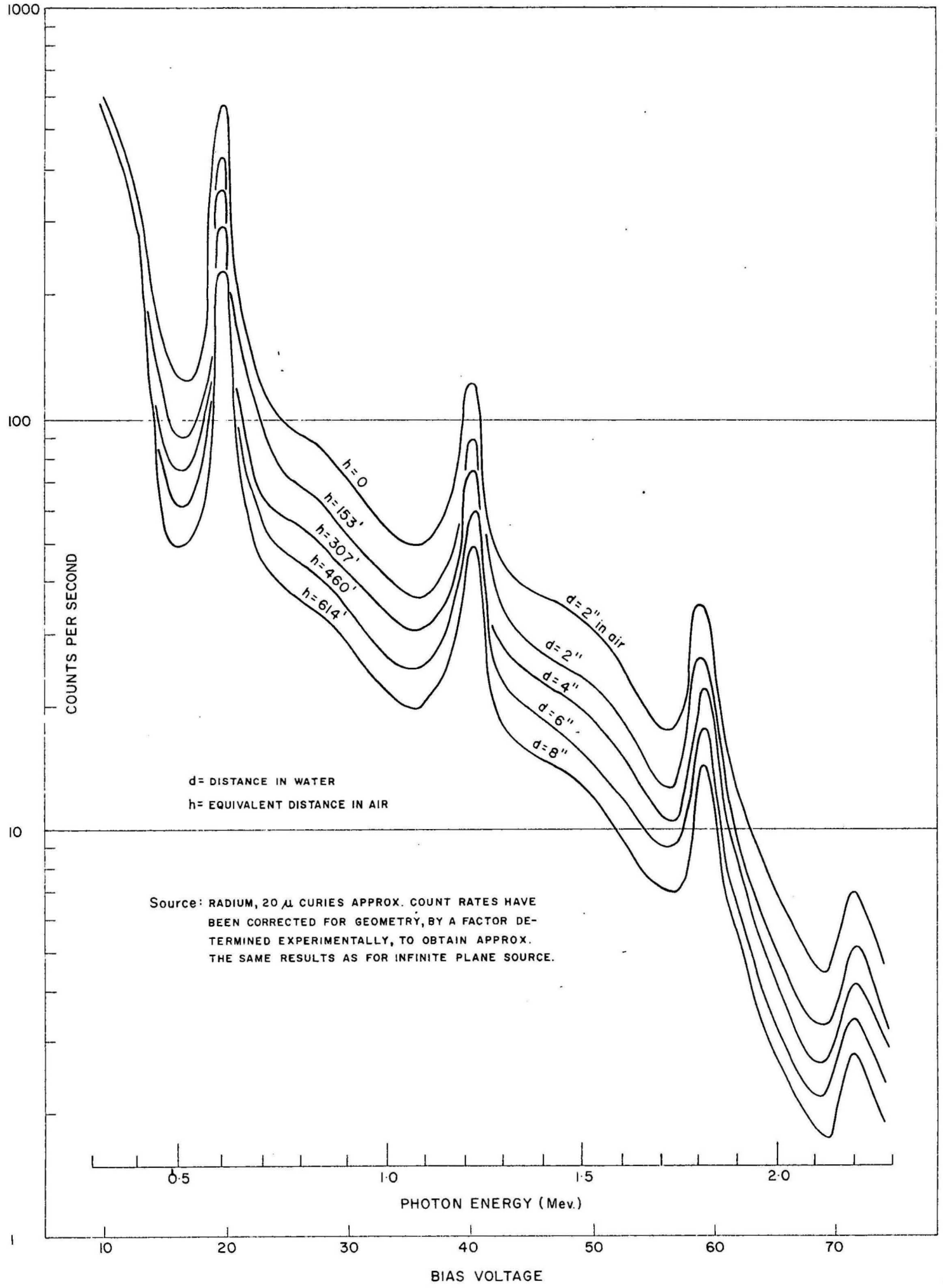
To accompany Records, 1959 No. 46

PLATE 3



THE EFFECT OF SCATTERING, IN WATER, ON THE SPECTRUM OF THE GAMMA RAYS FROM RADIUM

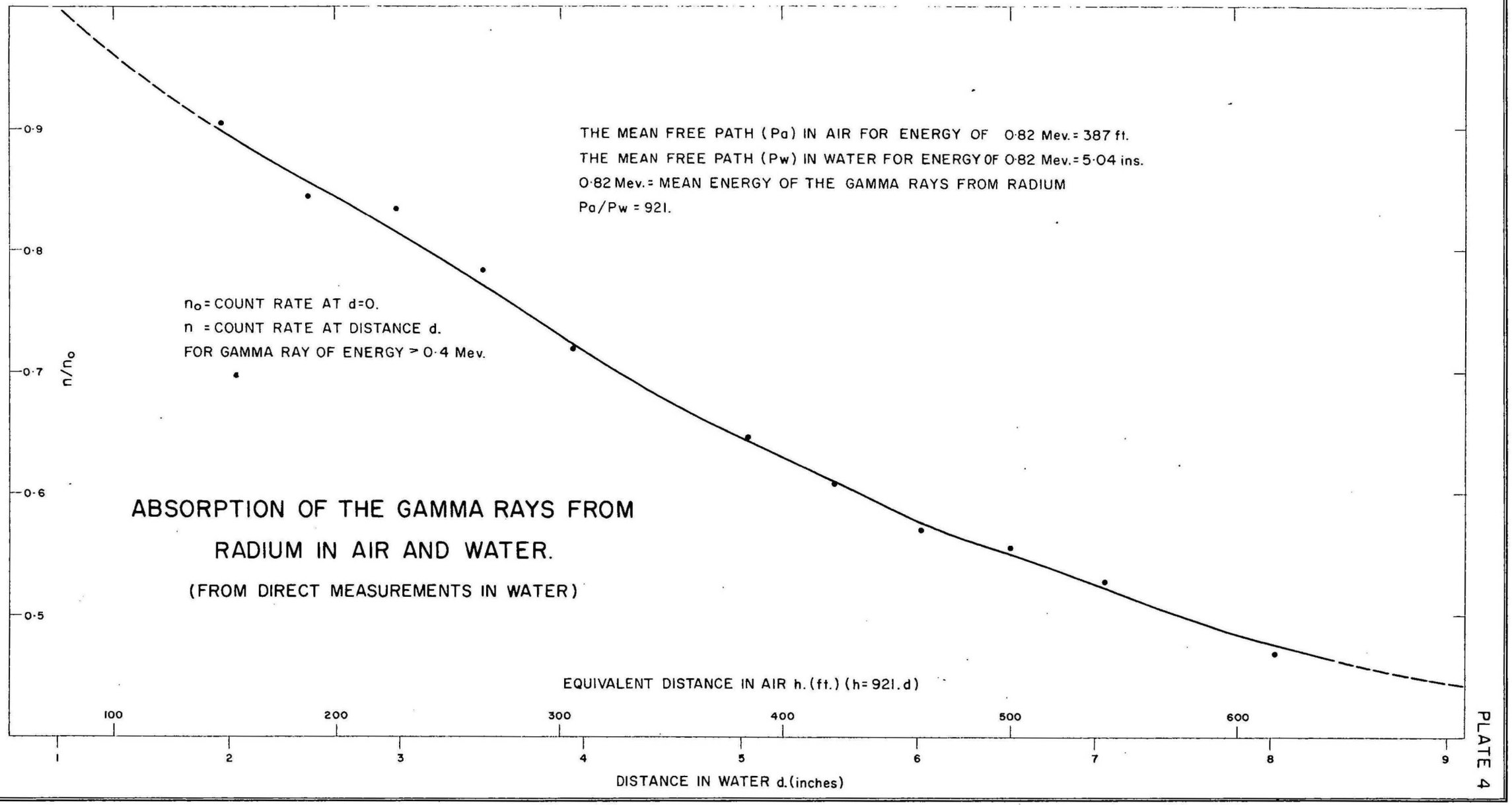


PLATE 4

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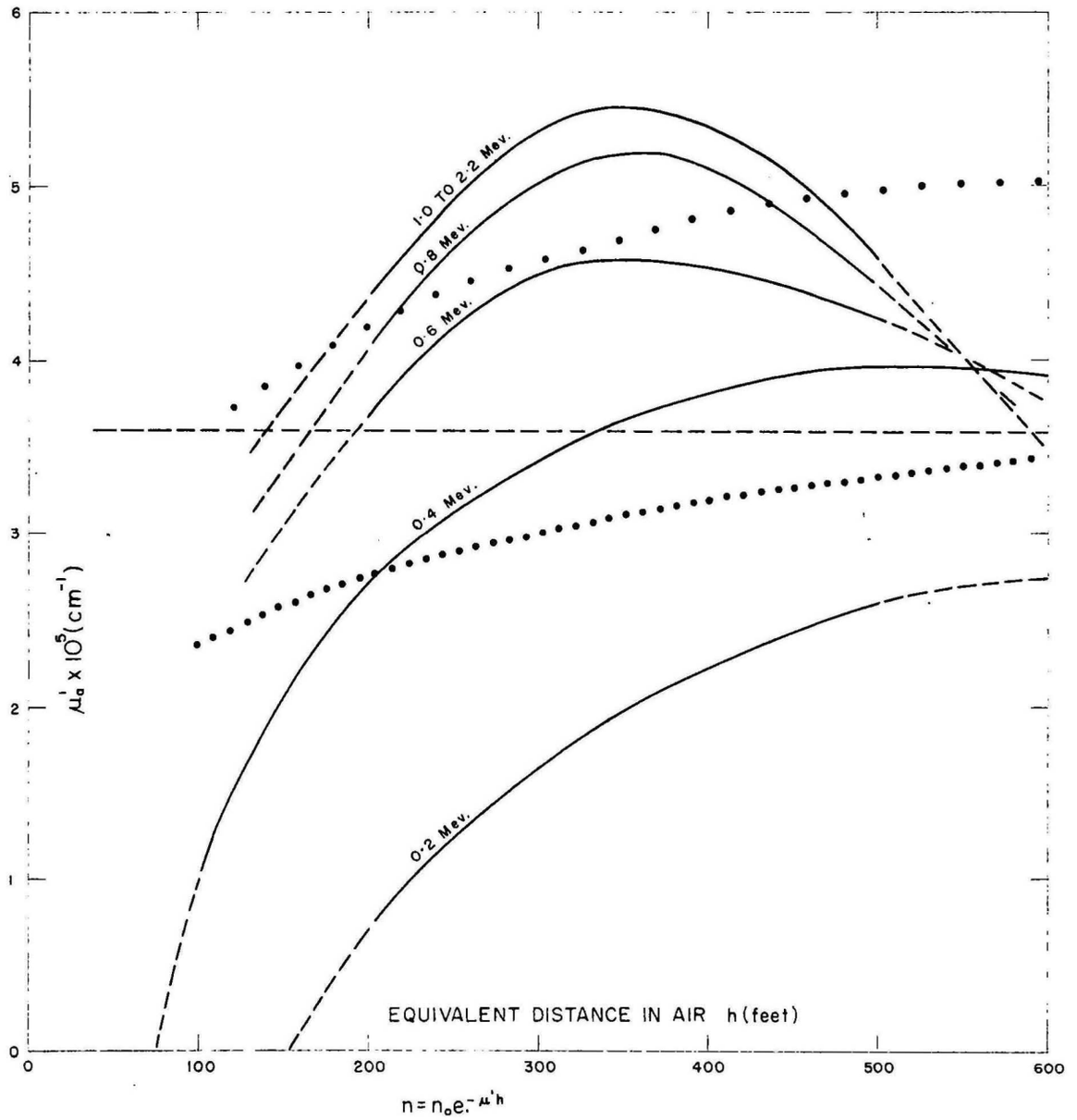
To accompany Records 1959, No 46

PLATE 5



EMPIRICAL FORMULA USED BY J.C.COOK. GEOPHISICS. OCT. 1952 P. 689 ASSUMING AN AVERAGE ENERGY OF 1·8 Mev.

COOK'S FORMULA FOR AN AVERAGE ENERGY OF 0·8 Mev.

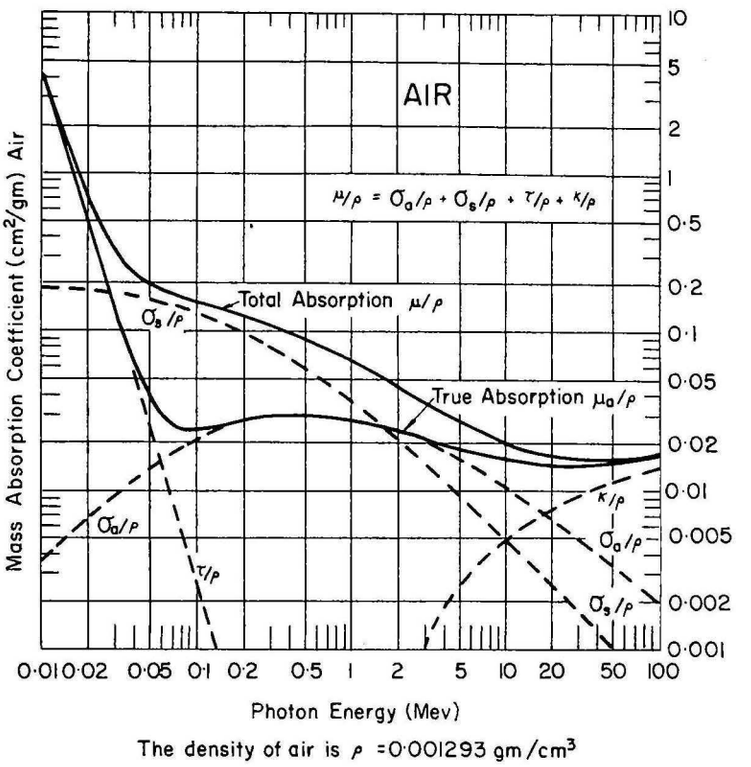
FROM LABORATORY EXPERIMENTS ON ABSORPTION IN WATER. (FOR BIAS LEVELS 0·2 TO 2·2 Mev.)

THEORETICAL ABSORPTION COEFFICIENT, FOR IDEAL DETECTOR.

COMPOSITE AIR ABSORPTION COEFFICIENT FOR THE GAMMA RAYS FROM RADIUM

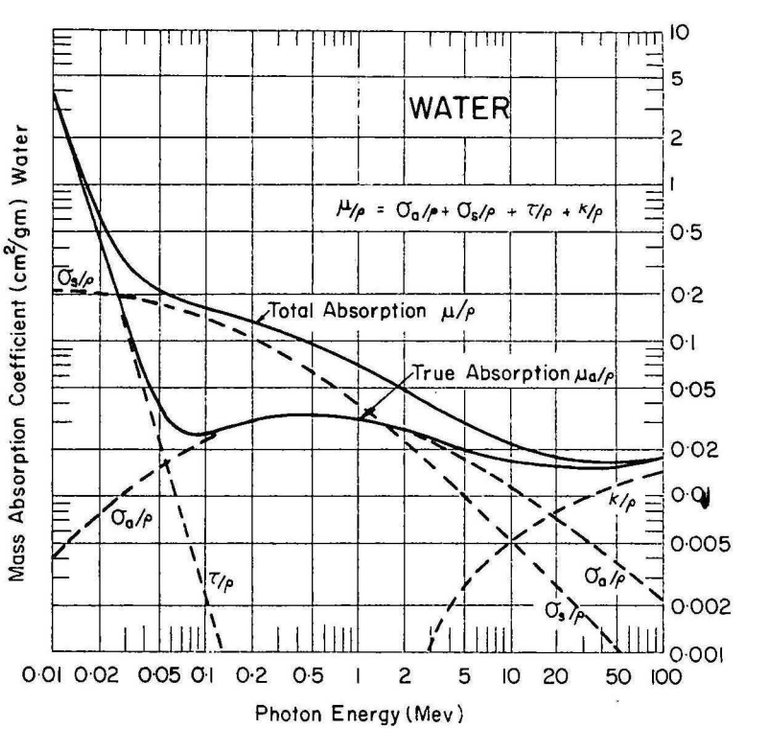
Geophysical Section, Bureau of Mineral Resources, Geology & Geophysics. 786

To accompany Records 1959, No 46.

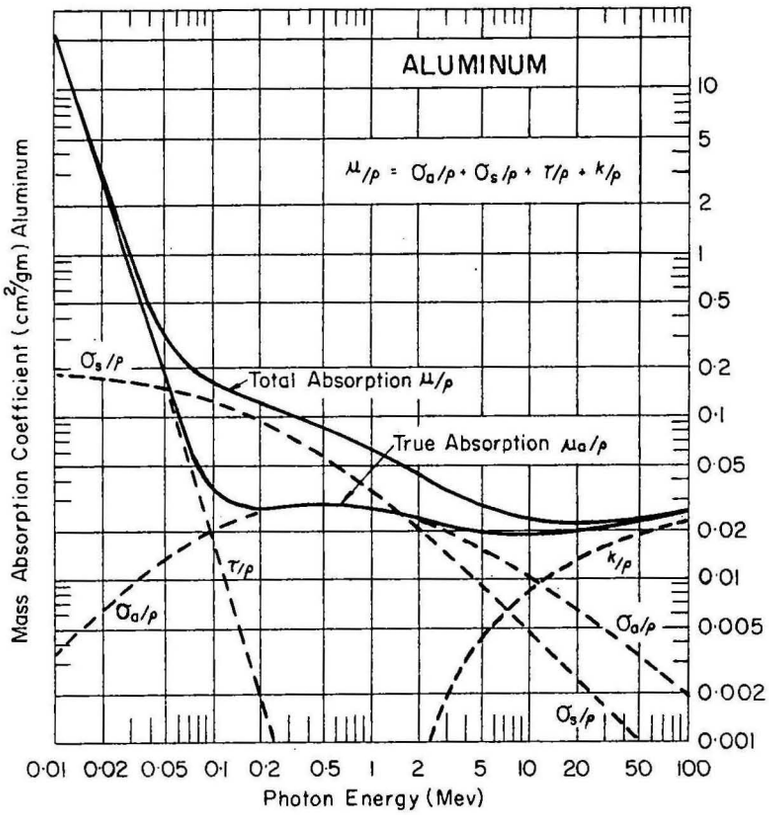


The density of air is $\rho = 0.001293\ gm/cm^3$

MASS ABSORPTION COEFFICIENTS FOR AIR AS A FUNCTION OF PHOTON ENERGY

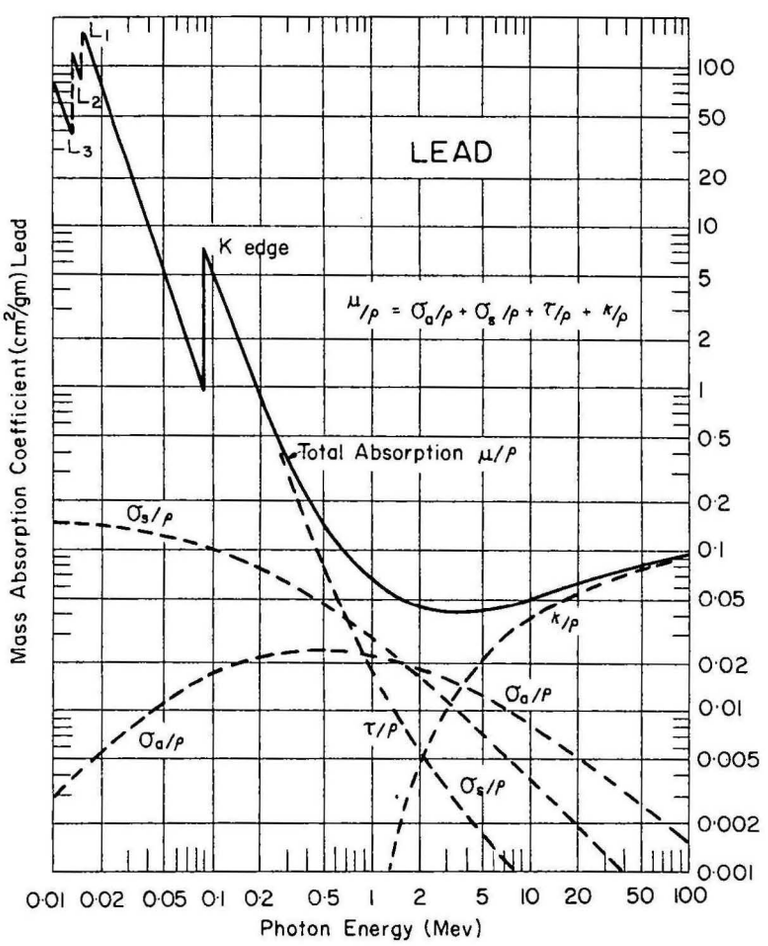


MASS ABSORPTION COEFFICIENTS FOR WATER AS A FUNCTION OF PHOTON ENERGY



The density of aluminum is $\rho = 2{\cdot}70\ gm/cm^3$

MASS ABSORPTION COEFFICIENTS FOR ALUMINUM AS A FUNCTION OF PHOTON ENERGY



The density of lead is $\rho = 11{\cdot}35 gm/cm^3$

MASS ABSORPTION COEFFICIENTS FOR LEAD AS A FUNCTION OF PHOTON ENERGY