The Identification of the Surplus Gamma-Radiation from Granite

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IN a previous paper[1] we expressed the opinion that a new and direct determination of Eve's constant for the gamma-rays from potassium would be necessary in order to find out whether the surplus gamma-radiation from Quincy granite, found experimentally by one of us, could be ascribed to the effect of the gamma-rays from potassium in the granite.

The existing data on the intensity and the penetrating power of gamma-rays from potassium are meager and rather conflicting. The intensity of the gamma-rays from potassium expressed in terms of the equivalent amount of radium (RaC), according to various authors, is given in Table I, together with the calculated mass absorption coefficients.

TABLE I.

Author	1-g potassium equivalent to:	Mass absorption coefficient of gamma-rays from potassium
W. Kolhörster*	5.10×10^{-11} g Ra	0.0250 cm^2/g
W. Mühlhoff**	3.34×10^{-11} g Ra	0.0520 cm^2/g
F. Bêhounek***	1.30×10^{-10} g Ra	0.0513 cm^2/g
L. H. Gray and G. T. P. Tarrant†	1.60×10^{-11} g Ra	0.0477 cm^2/g
E. Gleditsch and T. Gráf††	1.23×10^{-10} g Ra	0.0513 cm^2/g

* W. Kolhörster, Zeits. f. Geophys. **6**, 340 (1930).
** W. Mühlhoff, Ann. d. Physik **7**, 205 (1930).
*** F. Bêhounek, Zeits. f. Physik **69**, 654 (1931).
† L. H. Gray and G. T. P. Tarrant, Proc. Roy. Soc. **A143**, 681 (1934).
†† See reference 4.

Since the latest determination (Gleditsch and Gráf) indicated the correctness of Bêhounek's value, which was heretofore considered as the least reliable, we decided to test the intensity of the gamma-rays from two potassium salts (KCl and K_2SO_4) with the same apparatus that was used in the studies of the surplus gamma-radiation from granite.[2,3]

After the densities of both KCl and K_2SO_4 in powdered form were determined, bags filled with these salts were arranged so as to fill completely one or two quadrants of the space located concentrically between the outer lead cylinder (1 cm thick) surrounding the ionization chamber and the inner wall of our "iron house." This iron house, having a wall thickness of four inches, served only the purpose of excluding the local gamma-rays coming from the walls of the room. A quantity of 50 lb. of KCl and about 75 lb. of K_2SO_4 was sufficient to fill one quadrant of this space.

We also made a series of experiments where two of the quadrants were filled with potassium chloride while the other two were filled with dunite, a material which is practically free of uranium, thorium, and potassium and therefore inactive, as direct gamma-ray tests had shown previously.[1] This experiment showed that the scattering of gamma-rays from the potassium-filled quadrants in the inactive dunite enhanced the effect very little: by only $0.2I$ (ion pairs/cm^3/sec.), as compared with the total ionization of $6.7I$ given by the two potassium-filled quadrants.

For KCl two determinations, consisting of about 50 individual observations, gave, after subtracting the background ($2.7I$), values of $3.68I$ and $3.72I$, respectively. An experiment with two quadrants gave $7.0I$, which is a little lower than $2\times3.7I$ because the material at hand was not quite sufficient to fill the second quadrant completely. We, therefore, took the value for one quadrant (q_1) filled with KCl (and also later with K_2SO_4) and obtained the gamma-ray effect of the concentric layer 15.78 cm thick around the ionization chamber by multiplying the value by four ($4q_1$). A slight correction is necessary since the "open cone" (angle subtended by the electrometer head of the chamber) is not filled with the salt. This correction amounts to $C=0.89$. Extrapolation for an infinite layer of salt is obtained by dividing the corrected value $4q_1/C$ by $(1-e^{-\mu d})$, where μ is the linear absorp-

[1] V. F. Hess and J. D. Roll, Phys. Rev. **73**, 592 (1948).
[2] V. F. Hess, Phys. Rev. **72**, 609 (1947).
[3] V. F. Hess, Trans. Am. Geophys. Union **27**, 670 (1946); V. F. Hess, Norsk Geologisk Tidsskrift **27** (Jan. 1947).

TABLE II.

		KCl	K_2SO_4
Ionization with one quadrant filled with salt,	q_1	$3.70I$	$3.87I$
density of the salt,	ρ	1.125 g/cm³	1.576 g/cm³
thickness of salt layer,	d	15.78 cm	15.78 cm
linear absorption coefficient,	μ	0.0578 cm⁻¹	0.0809 cm⁻¹
exponential factor,	$e^{-\mu d}$	0.402	0.279
potassium content per gram,	M	0.523 g/g KCl	0.448 g/g K_2SO_4

for KCl: $$K=\frac{3.70\times 0.0513}{\pi 0.89(1-0.402)0.523}=0.217I$$

for K_2SO_4: $$K=\frac{3.87\times 0.0513}{\pi 0.89(1-0.279)0.448}=0.220I.$$

tion coefficient of gamma-rays from potassium in the salt, and d is the thickness of the layer.

Thus the ionization due to an infinite concentric layer is given by

$$q_\infty=[4q_1/C(1-e^{-\mu d})].$$

On the other hand, Eve's formula for a concentric layer of infinite thickness gives

$$q_\infty=4\pi K/(\mu/\rho)\cdot M,$$

where K is Eve's constant for potassium, M the amount of potassium per gram of the salt used, and μ/ρ the mass absorption coefficient. Equating the two expressions for q_∞, we get Eve's constant

$$K=[q_1(\mu/\rho)]/[\pi C(1-e^{-\mu d})M].$$

We took for μ/ρ the most recent value of Gleditsch and Gráf[4] 0.0513 cm²/g for gamma-rays from potassium, while our own direct determination with concentric lead shields of 1 cm and 2 cm around the chamber gave 0.0523 cm²/g, which is identical within the limits of experimental error.

The results of the two independent determinations of Eve's constant for the gamma-rays of potassium, for a brass chamber shielded by 1 cm of lead from all sides, are shown in Table II.

A slight correction is necessary due to the fact that the radiating source is neither point shaped nor at a considerable distance, but distributed throughout a relatively large volume quite close to the ionization chamber. As a result, most of the gamma-rays follow oblique paths as they pass through the lead shield around the chamber. The amount by which the ionization within the chamber is reduced by this effect was evaluated by a graphical method and the correction was made as follows:

$$\text{For KCl: } K=0.217\times 1.184=0.257I,$$
$$\text{for } K_2SO_4\text{: } K=0.220\times 1.184=0.260I.$$

The corrected values of Eve's constant agree quite satisfactorily. Since in our apparatus Eve's constant for gamma-rays from radium (RaC) was found to be $2.90\times 10^9 I$/g Ra/cm, we find that the intensity of the gamma-rays from 1 g of potassium is equivalent to $0.2585/2.90\times 10^9 = 0.89\times 10^{-10}$ g Ra. This value is somewhat lower than the most recent value of Gleditsch and Gráf, but it shows clearly that this latter value is essentially correct.

We are now in a position to compute the total ionization produced by gamma-rays from Quincy granite with these revised data at hand and compare it with our experimental findings. For the radium and thorium component we can use our previously published values,[2] taking Eve's constant for radium $K_1=2.90\times 10^9$, for thorium $K_2=440$, and for potassium our own new value $K_3=0.2585$.

(a) Radium component:

$$M_1=1.02\times 10^{-12} \text{ g Ra/g granite};$$
$$\mu_1/\rho=0.045 \text{ cm}^2/\text{g},$$

$$q_a=\frac{12.56\times 2.90\times 10^9\times 1.02\times 10^{-12}}{0.045}=0.832I.$$

[4] E. Gleditsch and T. Gráf, Phys. Rev. 72, 640 (1947).

(b) Thorium component:

$$M_2 = 8.1\times10^{-6} \text{ g Th/g granite};$$
$$\mu_2/\rho = 0.041 \text{ cm}^2/\text{g},$$

$$q_b = \frac{12.56\times440\times8.1\times10^{-6}}{0.041} = 1.094I.$$

(c) Potassium component:

$$M_3 = 0.038 \text{ g K/g granite};$$
$$\mu_3/\rho = 0.0513 \text{ cm}^2/\text{g},$$

$$q_c = \frac{12.56\times0.2585\times0.038}{0.0513} = 2.41I.$$

The total ionization to be expected from an infinite layer of Quincy granite is, therefore,

$$q_a + q_b + q_c = 4.34I$$

if the chamber is shielded by 1 cm of lead.

Our experiments with the same shielded chamber in an underground station and at Fordham, when the iron house was filled with Quincy granite, gave an ionization of $2.70I$. Correction for the "open cone" (explained above) brings this up to

$$2.70/0.89 = 3.03I,$$

and the extrapolation to an infinite layer of granite (assuming the absorption coefficient of gamma-rays in granite $= 0.057$ cm^{-1}, as previously determined[2]) is

$$q_\infty = \frac{3.03}{1-e^{-\mu d}} = \frac{3.03}{0.590} = 5.13I.$$

This is somewhat higher than the computed value. However, the agreement is now quite satisfactory if we consider the uncertainties involved in the determination of the three radioactive components. Furthermore, if instead of using our own experimental value of 1-g potassium equivalent to 0.89×10^{-10} g Ra we would take either one of the two values reported by Gleditsch and Gráf (1.06×10^{-10} or 1.23×10^{-10}), the agreement between the computed value of ionization for Quincy granite and our experimental value would be even better.

We therefore believe that the surplus radiation found by one of us is now satisfactorily explained and identified as coming from the potassium in the rock. It is regrettable that the intensity of the gamma-rays from potassium was underestimated to such an extent by some of the authors in the past. Our investigation confirms preliminary statements of E. Gleditsch and T. Gráf[4] with regard to the consequences involved in the estimates of the contribution of the gamma-rays from potassium in the rocks to the production of heat in the interior of the earth.

The contribution of the gamma-rays from potassium to the ionization of the atmosphere, as estimated by one of us[5] as early as 1934, seems now essentially correct, and it is important to note that this contribution, as seen from our data, exceeds the sum of the ionization by gamma-rays from the uranium-radium and the thorium series.

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[5] V. F. Hess, "Jonisierungsbilans der Atmosphaere", Ergebn. Kosm. Physik 2, 95 (1934).