The Absorption of Cosmic Rays in Lead at a Depth of 1000 m Water Equivalent

In a previous experiment[1] the absorption of cosmic rays was measured in the coal mines of Dorog at a depth of 957 m water equivalent. For these measurements we used a threefold coincidence telescope. The thickness of the interposed lead layer was at first gradually increased between the central and bottom tube, and only after this thickness had attained 50 cm was the additional lead placed between the upper and central tube also. When similar absorption measurements are made at sea level, as is well known, the intensity sinks rapidly as far as 15 cm Pb and then decreases slowly. In contrast to this at 957 m water equivalent depth we have found[2] that although in the beginning the intensity decreases rapidly as far as 10 cm Pb, this decrease is then succeeded for a greater thickness of lead by an increase of the intensity, which may reach 90 percent of the initial intensity. A second decrease was observable only when the additional lead was placed between the two upper tubes. For the interpretation of this new type of absorption we must assume—as already pointed out in our first paper—that at such great depth only non-ionizing radiation is able to penetrate, which reveals itself by producing ionizing secondary rays along its path. To be able to account for the minimum of the intensity at 10 cm Pb we must assume that the range of the particles emerging from clay or brick layer above the apparatus is shorter, about 10 cm Pb, than the range of the particles produced in the lead, which may be estimated to 25 cm Pb.

Since September 1939, during a period covering 7000 hours, we have been performing similar absorption measurements at a different place in the same mine, at a depth of 941 m water equivalent. The only difference between the apparatus employed at present and that used in the investigations of 1938 is, that at present we place the same amount of lead between the upper and central tube as between the central and bottom tube in every position, and that in 1938 we had 2.5 cm Pb above the upper tube instead of which we now use 70 cm of wood. The results are represented in Fig. 1. We may remark that here the decrease of intensity up to 10 cm Pb followed by an increase

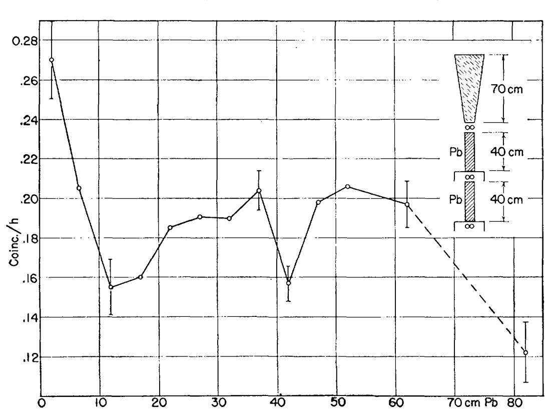

FIG. 1. Absorption of cosmic rays in lead at 941 m water equivalent depth with 70 cm of wood above the apparatus. The vertical lines represent the probable errors of the measurements.

of intensity is again observable. We should like to point out that this second measurement performed at a different place in the mine and more than a year later than the first investigation establishes sufficient evidence for the existence of the minimum at 10 cm Pb. But in Fig. 1 we see a second very sharp decrease with subsequent increase of the intensity between 37 and 47 cm Pb. In order to secure equally well-established evidence for this second minimum, we have several times measured the intensity of the radiation in the minimum and in its neighborhood. In Fig. 2 these results are reproduced. We may remark that the three different curves agree well with each other; the sharp fall of the intensity is found in every case at 42 cm Pb. At every thickness of lead where measurements were several times repeated the values of the intensity found on different occasions lay between the limits of their probable error, even at 42 cm Pb when more than 8 months had elapsed between the first and the last determination.

We may also be able to explain this absorption in a qualitative manner with the same assumption made in connection with the curve found in 1938, namely, that at such great depth only a non-ionizing radiation is present,

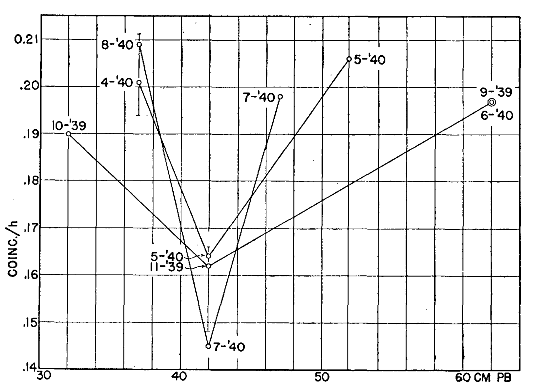

FIG. 2. Minimum of the intensity at 42 cm Pb with the dates when the measurements were performed.

which produces ionizing secondaries with 10 cm Pb range in the clay or brick layer and ionizing secondaries with 25 cm Pb range in lead. With these assumptions we can expect from numerical calculations two intensity maxima, one at 25 cm Pb and a somewhat higher one at 50 cm Pb, with a flat minimum between the two. In order to account for the sharp fall of the intensity at 42 cm Pb we must further assume that in wood another kind of more penetrating particles with well-defined ranges of 40 cm Pb is created. This would also enable us to explain the intensity decrease found at 82 cm Pb. Since the number of the H nuclei is rather abundant in wood it does not seem too far-reaching to postulate that these rays with 40 cm Pb range are perhaps protons, whereas the rays created in clay or lead might rather be of mesotronic nature.

In conclusion the writers wish to express their thanks to Councilor Dr. S. Schmidt and to Manager K. Roth of the Salgótarjáni Coal Mine Company for permitting us to execute experiments in the mines of Dorog, as well as to the engineers of the Company for their kind help. The experiments were performed with the financial support of the Széchenyi Scientific Society, the Hungarian Council for Natural Science and the Hungarian Academy of Science.

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[1] J. Barnóthy and M. Forró, Phys. Rev. **55**, 870 (1939).
[2] See Fig. 2 of the cited article.

The Second Law of Thermodynamics and Irreversible Processes

The two papers by Eckart in the *Physical Review* for August first permit a simple interpretation which amounts to an extension of the second law.

The conventional statement of the second law, when applied to irreversible processes, is that the entropy of an isolated system increases whenever an irreversible process occurs within it. No attempt is made to evaluate how much the increase of entropy may be under such circumstances, and in fact the precise evaluation of irreversible increases of entropy has always been considered to be beyond the power of methods thermodynamic in spirit, and to be rather the proper subject of statistical mechanics or kinetic theory. This accepted impotence of thermodynamics has always struck me as a surprising thing. It would seem that thermodynamics ought to be able to handle any system that is causally determined from the macroscopic point of view, that is, any system which can be adequately described in terms of operations with macroscopic instruments. This means that whenever the readings of the macroscopic instruments are repeated the future behavior of the system as measured with those same instruments repeats. The readings of the macroscopic instruments should then become the parameters for a complete treatment, thermodynamic in an extended even if not in the classical sense. Of course there are many processes which are so complicated that they cannot be adequately described in terms of a number of macroscopic variables small enough to be manageable, as in the efflux of a jet of gas from a nozzle, and it is not to be expected that systems in which apparent irreversibility thus arises from intractable complication will be completely amenable to any treatment. But there are many systems in which irreversible processes occur which are completely describable in terms of a few macroscopic parameters, and such systems should be amenable to an exact treatment, including an exact evaluation of the increase of entropy. Examples of such completely describable irreversible processes are: conduction of heat down a temperature gradient, development of Joulean heat when an electrical current flows against resistance; development of frictional heat when one solid rubs on another or in the interior of a viscous liquid; and when there is diffusion down a concentration gradient.

Sometime ago I proposed that a plausible extension of the second law to such completely defined irreversible processes was to postulate that whenever such a process occurs a corresponding characteristic increase of entropy occurs. Thus when an electric current i flows against a resistance r at absolute temperature θ there is an increase of entropy per unit time of i^2r/θ, and when the amount of heat Q drops by conduction through a temperature range $\Delta\theta$ there is a similar increase of entropy of $Q\Delta\theta/\theta^2$. I applied the equations to thermoelectric phenomena, and showed how the equations of Kelvin could be derived without illegitimately neglecting the irreversible aspects of the phenomena, as had been necessary in all previous treatments. In my book, *The Thermodynamics of Electrical Phenomena in Metals*, several other applications were given, particularly to deducing a relation between the Nernst and the Ettingshausen coefficients. I have also discussed the matter in a forthcoming book on the foundations of thermodynamics.

It is the purpose of this note to point out that Professor Eckart's equations can be written exactly in accord with this postulate of the extended second law. In general one must have: (increase of entropy in the region within a closed surface) plus (entropy which has flowed out of the region across the surface) equals (entropy generated by irreversible processes within the surface). The last term (entropy generated by irreversible processes within the surface) should be capable of precise formulation when the irreversible processes are well defined. Such is the fact in the cases considered by Professor Eckart. In his first paper the irreversible processes are thermal conduction and viscous motion of a fluid. His Eq. (15) on page 269 is:

$$(d/dt)\int\int\int_S m\eta d\tau+\int\int_S (1/\theta)\mathbf{q}\cdot d\sigma$$
$$=\int\int\int_S \{[k(\nabla\theta)^2]/\theta^2+[(\mathfrak{p}\cdot\nabla)\cdot\mathbf{V}]/\theta\}d\tau.$$

In this equation the first term on the left is recognizably the increase in unit time of the entropy of the material within the surface S, the second term is the outward flow of entropy across the surface, the first term in the integrand on the right is the rate of increase of entropy due to irreversible thermal conduction within the region and the second is the increase of entropy due to frictional generation of heat in the viscously moving liquid. The latter is obviously the general expression for the characteristic rate of entropy increase in a moving liquid, and the first is the same as the expression I had already used, $Q\Delta\theta/\theta^2$. In Professor Eckart's second paper, Eq. (26) on page 272 contains the additional terms for the characteristic increase of entropy when there is diffusion in general. Professor Eckart has pointed out to me in correspondence that the expression for the increase of entropy due to diffusion is not separable into the sum of a term due to diffusion down a concentration gradient and another due to diffusion down a temperature gradient, but the two diffusion effects are cross connected. This suggests the necessity for detailed working out of the entropy increases, which is what Professor Eckart has essentially done, and by methods entirely macroscopic. That it can be done, constitutes the justification for the proposed extended formulation of the second law.

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