Evaluation of Present-day Knowledge of Cosmic Radiation at Extreme Altitude in Terms of the Hazard to Health

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SUMMARY

THE FACT THAT the intensity of cosmic radiation increases rapidly from its small value at sea level to higher altitudes raises the question of a possible hazard to health in flight at extreme altitudes. Among the abundant experimental data on cosmic radiation are only a few which can be used for an evaluation in terms of the actual biological dosage at different altitudes. This biological dosage rate increases from its sea level value of 0.1 milliroentgens per day to a maximum of 15 mr./day at 70,000 feet altitude in northern latitudes. Beyond this altitude the dosage rate decreases due to the decrease in the number of collision processes of the primaries with the air molecules.

For a full criticism of these dosage values it has to be realized that the ionization from cosmic radiation is produced largely by particles of a higher specific ionization than x-rays and beta particles. The milliroentgen equivalent-man values therefore will be markedly higher than the equivalent-physical values. Present knowledge does not yet permit one to give a reliable numerical value for this conversion factor.

Beyond 70,000 feet altitude the situation is completely different. A new component has been discovered in these regions, the heavy nuclei rays. They have a relatively small penetrating power and do not occur therefore below 70,000 feet. They consist of atomic nuclei of higher atomic numbers which are stripped of all their orbital electrons. They carry the tremendous amount of kinetic energy of more than 2 billion electron-volts per atomic number. Their specific ionization is much higher than any other hitherto observed value. The mechanism of absorption in matter is of the same type as that of alpha particles but magnified by a factor of 1,000. Their range in living tissue reaches values of 10 centimeters in comparison of 50 microns for alpha particles. An estimation of their possible biological action indicates that they might represent a serious hazard to health.

I. INTRODUCTION

Cosmic Ray Research and Aviation Medicine. Aim of Investigation.—It is a well-known fact that the intensity of cosmic radiation at sea level is extremely minute and that it takes the most sensitive instruments the physicists have at their disposal to measure it. However, it is also known that the intensity increases rapidly with increasing altitude. It was just this fact which led the first investigators to the as-

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sumption that this radiation was coming to the earth from outer space.

Considering the possibility that future types of aircraft may travel routinely at very high altitudes, it seems worthwhile to investigate to what radiation doses the pilots and passengers of such high flying planes will be exposed. Cosmic ray research today has developed into the most important branch of nuclear physics. The reason is that cosmic radiation is hitherto the only source which provides us with elementary particles of energies in the billion electron-volt range. The study of nuclear reactions released by such particles of extremely high energy has furnished most valuable information for our concepts of nuclear forces.

One might assume that the abundance of experimental data on cosmic rays which is set down today in the scientific periodicals would also furnish ample information on the relatively simple question of the biological effect which might be expected from the different components of cosmic radiation. But this is a wrong conclusion. The attention of the experimenters and theoreticists in cosmic ray research is directed exclusively to the study of the nuclear phenomena and to the difficult task of bringing some order into the embarrassing multitude of experimental observations. The biophysicist who is seeking for an answer to the question of the biological effect and a possible hazard to health from cosmic radiation can obtain only very little information from these nuclear studies. What he needs is exact numerical data on the total and the specific ionization of cosmic radiation at different altitudes. But the nuclear physicists concentrate their studies more and more on the single nuclear reaction and are deviating more and more from normal conditions by piling up inches of lead around their instruments and by arranging ingenious coincidence measurements to restrict the instrument response to rays from a certain direction only or to simultaneously arriving rays over a certain area. Under these circumstances the biophysicist is easily embarrassed by his colleague of aviation medicine when this latter asks the direct question to what radiation doses a pilot will be exposed at different and at extremely high altitudes.

It is the aim of this investigation to give a survey of those experimental data which permit an evaluation in terms of the hazard to health. It will turn out, however, for the reasons pointed out above, that accurate numerical values are available at present only for a rather limited part of the full problem. Therefore, the second part of this report discusses the tentative conclusions which can be drawn for that part for which a clear-cut answer is not yet possible.

The assumption that the hazard to health from cosmic radiation might become a serious problem outside the air blanket of the earth has first been discussed by Ch. F. Gell.[4] He points out that the interpretation of the collision processes of the new type of radiation in living matter represents still an unsolved problem.

II. BRIEF OUTLINING OF PRESENT KNOWLEDGE OF COSMIC RADIATION

The Primary Radiation.—Before proceeding with the discussion of the strict subject it is, of course, necessary to give a short summary of present-day knowledge of cosmic radiation. The expert in this field will agree at once that even the mere enumeration of the main experimental facts is entirely inconsistent with the purpose of this report. Therefore, it has to be emphasized beforehand that the following survey is incomplete and oversimplified in many respects because it is limited to those data which are pertinent to the special problem of the hazard to health.

From outer space a very penetrating radiation whose origin is completely unknown is coming to the earth. Outside the air blanket of the earth the primary radiation seems to consist predominantly of protons. Besides the protons, heavier positively charged particles are found in a smaller percentage. We do not know but we have to admit the possibility that, in addition to these charged particles, uncharged ones, e.g., high-energy gamma quanta are present in the primaries. The most important and really astounding fact about the primaries is their tremendously high energy which they carry in the form of kinetic energy. The average energy of the primaries equals 20 billion electron-volts, i.e., twenty thousand million electron-volts.*

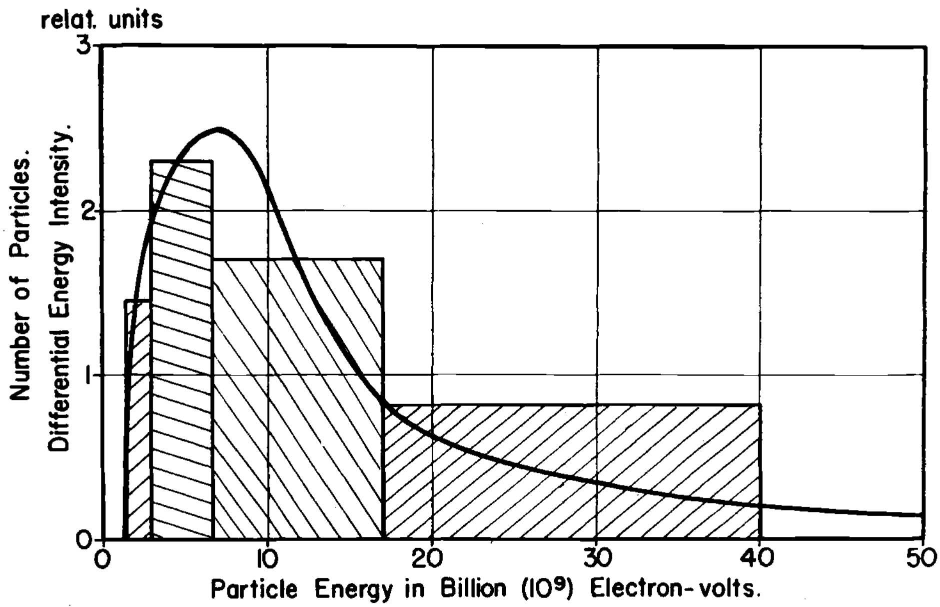

Fig. 1. Energy distribution of the primary particles of cosmic radiation (measurements of Millikan and co-workers).

Figure 1 gives an idea about the energy distribution of the primary protons. It has to be emphasized, however,

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*For those readers who are not familiar with the nomenclature of the physicists the energy unit, electron-volt, has to be explained. One says a proton or electron or any other elementary particle has an energy of one million electron-volts or e-volts when the kinetic energy of the particle is equal to that of an electron which has been accelerated by an electric field of one million volts. This could be accomplished, e.g., in an x-ray tube with a one million volt operating voltage.

that the curve in Figure 1 has not been measured point by point. Present-day experimental technique, of course, is not yet able to carry out a detailed spectral analysis at 90,000 feet altitude. We can derive from our pilot balloon recordings only certain average values over larger spectral areas which are indicated in the graph by the rectangles. The curve itself has been calculated by combining these integral experimental data with some theoretical considerations.

Two facts at least are fairly definite about the energy distribution of the primaries. One is that the energy is cut off at about 1 billion e-volts. We do not find particles with energies below this threshold in the primary radiation. The second fact is that there seems to be no limit of energy on the right side of the spectrum. There is no doubt that the curve approaches closer and closer zero at higher and higher energies. That means, the number of particles becomes smaller and smaller, but the point where the curve actually reaches zero must be very far beyond the limit of the graph. We have strong experimental evidence for the existence of particles with energies of 10^{17} e-volts, i.e., one hundred million times one billion volts. One might hesitate to believe this fantastic figure and it is, of course, outside any question that this figure is based on a very wide extrapolation. It certainly will have to be revised on the basis of future new concepts of the nuclear forces which the study of these astounding phenomena will bring.

The first mentioned fact that the spectrum at small energies is cut off at about one billion e-volts makes it necessary to mention at least briefly one large field of the theory of cosmic radiation, that is, the influence of the sun's and earth's magnetic fields. Both these fields extend in their range over distances many times larger than the actual size of the heavenly bodies in which they originate. If we assume that the sun carries a magnetic field similar in its spatial structure to that of the earth its strength even at the earth's orbit would be about 1 per cent of its value at the sun's surface. Fast moving, electrically charged particles will undergo deflections in such magnetic fields according to the basic laws of electromagnetism. If charge, mass, and velocity of the particles and the strength of the magnetic field are known it is an easy task to calculate the particle orbits. The higher the velocity (or better, the kinetic energy) of the charged particle the less is the deflection it will undergo. Thus there must exist a minimum particle energy which is necessary to enable the particle to "penetrate" a given magnetic field. The cut-off in the energy spectrum of the primary protons at one billion volts is in excellent quantitative conformity with these considerations. Moreover, the theory postulates that this minimum energy shows a strong dependence of the magnetic latitude. Particles whose original direction of travel is in the equatorial plane of the magnetic dipole field undergo maximum deflection; those traveling exactly in the magnetic axis undergo no deflection at all. This strong dependence of cosmic ray intensity on the geomagnetic latitude has been proved experimentally. This will be shown in detail in Part III in the discussion of Figure 2.

Besides the protons another type particle occurs in the primaries which has not been discovered until very recently. The experimental technique in cosmic ray research at extremely high altitude has used the nuclear emulsion with great advantage for about two years. This new technique offers a much better possibility for analyzing the specific ionization than did the cloud chamber, and the very first balloon ascents to 90,000 feet which brought up nuclear emulsions added at once a new sensational discovery to the many with which cosmic ray research has already presented us. The analysis of the nuclear plates revealed a new component of the primaries, the so-called heavy nuclei rays. We have not yet proceeded very far in the studies of this new component but some basic facts can already be stated.

For our special problem here the most important fact is that the specific ionization of the heavy nuclei is very high and exceeds that of alpha particles in a certain section of the path by a factor greater than 100. The penetrating power of the heavy nuclei rays, though immense considering their very high energy dissipation, is small in comparison to the protons of the primary radiation. This is due to the just mentioned high specific ionization and has an ominous consequence for their biological efficiency.

The recordings in the nuclear emulsion permit an accurate analysis of the three important magnitudes for full identification of the particles: the penetrating power, the specific ionization, and the number of recoil electrons per unit path length. This evaluation has revealed that the particles are atom nuclei of higher atomic number which are stripped of all their orbital electrons. Even a first analysis of the spectral composition could be accomplished. This composition is shown in Table I. For a full appraisal, however, of the share in the total energy of the heavy nuclei rays Table I is inadequate. For this purpose it is necessary to have additional information on the energy spectrum of these particles in the same manner as it was given in Figure 1 for the proton component of the primary radiation. At the present, the scarce experimental data do not yet furnish sufficient information to establish this energy spectrum for the heavy nuclei component. There is, however, some evidence that the heavy nuclei carry equal amounts of energy *per nucleon*,† i.e., the energy of a heavy nucleus ray is to be found by multiplying the basic energy value per nucleon by the factor 2 Z where Z is the atomic number. As to this basic energy per nucleon only a rough estimation is possible at the present. It leads to a magnitude of a few billion e-volts per nucleon. If this value is corroborated in the course of further experiments we face the fact that the

TABLE I. THE COMPONENTS OF THE PRIMARY COSMIC RADIATION

		Relative number	Percentage
Protons	H—Nuclei	4,000	80
Alpha particles	He—Nuclei	1,000	20
Heavy nuclei	C, N, O—Nuclei	35	0.7
rays	Nuclei $Z > 10$	10	0.2

Absolute Intensity at 120,000 feet:

Total:	0.12	Particles per second per
Heavy Nuclei:	0.001	Square Centimeter per Steradian

†Nucleon is a general term for proton and neutron. Since modern theory of the intranuclear forces assumes that protons and neutrons can exchange their identities in the nuclear bond it was useful to introduce a common name for both particles.

energy share of the heavy nuclei in the total incoming flux is much greater than the relative number of particles. As will be pointed out later this would put the whole problem of hazard to health in flight in extra-atmospheric regions on an entirely new basis.

Another very important consequence has to be drawn from the data on the penetrating power of the heavy nuclei rays. In this question again only a first approximation is possible. The recordings of heavy nuclei rays hitherto collected show consistently that the heavier the particle, the less its penetrating power. This is, of course, in full conformity with the theoretical expectation. The experimental material is not yet sufficient to derive any sort of general law for the penetrating power and its dependence on the atomic number and the energy. But some limiting values can already be established. The lightest nuclei ($Z=3$ to $Z=8$) which are the most penetrating ones can reach a maximum depth of the air ocean of 70,000 feet altitude. At this altitude they have penetrated, coming from outer space, an air mass of 48 grams per square centimeter. In the interval, from 70,000 to 90,000 feet which represents a layer of 30 grams per square centimeter the number of particles increases substantially. At the same time particles with higher specific ionizations, i.e., heavier ones are are found in increasing number.

The absorption of the heavy nuclei rays in matter does not follow an exponential law but is of the alpha particle type with a definite range for any given atomic number and energy. Thus the altitude range between 70,000 and 90,000 feet seems to represent the end part of the full range of the lighter and softer component of the heavy nuclei rays. The few observed heavier ones are extreme cases in the Gaussian distribution for the straggling phenomenon. If this still hypothetical interpretation is correct we have to expect a further marked increase in the number and energy of the heavy nuclei particles beyond 90,000 feet.

Interaction of the Primaries with the Air Blanket.—When the primary particles of cosmic radiation enter the air blanket of the earth they undergo collision processes with the atom nuclei of the air. The study of these collision processes has revealed that the mechanism of a nuclear reaction released by a particle in the billion e-volt energy range is completely different from the reaction in the million volt range, i.e., the range of nuclear fission and nuclear disintegration of the artificial radioactive isotopes. It is difficult to bring some sort of order into the multitude of new nuclear processes which the cosmic ray research has yielded.

The fundamental difference between nuclear reactions in the million e-volt range and those in the billion e-volt range is that the energy of the primary particle in the billion volt range is not dissipated in one elementary process but is distributed in an initial nuclear disruption to several secondary particles each of which carries a large enough fraction of the primary energy to release another such nuclear disruption, and so on. By this mechanism the primary energy is dissipated to a large number of secondaries before the energy level has decreased below the threshold for nuclear disintegrations and the normal process of dissipation of the energy into ionization work begins.

Such a sequence in which the energy of the primary particle finally is distributed over a large number of secondaries is called a shower. A shower is basically different from the well-known chain reaction which takes place in an atomic pile or in atomic fuels or explosives. Today, cosmic radiation is the only means to obtain and to study shower processes.

By no means do we yet have a complete picture of the mechanism of shower production, but there is no doubt that many different types of nuclear reactions are represented in a shower. We can classify the showers into two groups: the penetrating showers and the soft showers. The latter ones are often also called cascade showers. The penetrating showers consist of heavy particles: protons, neutrons, and mesons. The cascade showers consist of electrons, positrons, and gamma particles. The mechanism of the latter type, the cascade showers, can be clarified fairly well. In these showers the energy is continuously alternating between two forms. A high energy electron produces a gamma quantum in the well-known bremsstrahlung process. This gamma particle produces in the pair production process an electron—positron pair each of which in turn undergoes a bremsstrahlung process and so on. These cascade showers sometimes grow to a tremendous size covering an area of several thousand feet in diameter and comprising many millions of particles.

III. CONVERSION OF THE EXPERIMENTAL DATA INTO TERMS OF THE RADIATION EFFECT ON LIVING TISSUE

The Total Ionization.—If we now try to evaluate these data for our specific problem of the hazard to health we must consider how we can convert the numerical data on the intensities of the different components of cosmic radiation into biological dosage units. We know fairly certainly today that the action of all kinds of penetrating radiations on living matter begins with the same primary physical process: ionization. Therefore, the measuring unit for the biological efficiency of a penetrating radiation, the roentgen unit, has been based on the measurement of the ionizing power of the radiation. The ionizing power of different kinds of radiations is very different. It is different even for the same type of particle at different velocities. The magnitude in terms of which we measure the ionizing power of a radiation is the so-called specific ionization, i.e., the number of ion pairs produced per centimeter path length. The specific ionization for all particles is low for high velocities and increases substantially when the particle slows down. More details on this mechanism are given in Part B of the appendix.

The roentgen unit does not take into account any differences in the spatial distribution of the generated ion pairs which result from these large differences in the specific ionization. It is based solely on the integral value of the total ionization produced in a standard mass of air (or tissue). This disregard of the microscopic "graininess" of the ionization is entirely correct for the comparison and measurement of x-rays in a wide range of quantum energies and of gamma quanta. But it does not hold for mesons, protons, and alpha particles. Just these particles represent a high percentage in the cosmic radiation. This point and its consequences for our specific problem will be discussed later. To obtain a first fairly good basis for the biological dosage from cosmic radiation the total ionization is entirely sufficient.

It is not possible to calculate the total ionization by adding the ionization intensities produced by the different components of the secondary cosmic radiation because we have no accurate data on these intensities. The most immediate way out of this difficulty would be the direct measurement of the total ionization at different altitudes. But measurements of the total ionization have not been very highly appreciated by the cosmic ray experimenters. Indeed, in a phenomenon consisting of so many different and intricate elementary processes it seems a priori preposterous to try to gain a better insight by collecting integral data on the overall energy. Under these circumstances it must be considered a very happy coincidence that one of the leading experts on cosmic ray physics, Millikan[1,6,7] contrived an ingenious mathematical method to separate the curves of total ionization at different altitudes and latitudes into certain discrete energy ranges which should prove or disprove a special hypothesis on the origin of the cosmic radiation. Millikan needed for his evaluation a very accurate measurement and invested very large funds, time, and experimental skill in this task. Thus we have at our disposal extensive and detailed data on the total ionization from sea level to 90,000 feet and from the equator to 60° latitude. All we have to do is to convert the ionization units of Millikan's curves into biological dosage units. The details of this mathematical procedure are given in Part A of the appendix. Figure 2 shows the resulting curves. The left vertical scale of the graph is based on the value 1.0 for the total ionization from cosmic radiation at sea level. The values of the vertical scale give directly the relative dosages to which living tissue will be exposed at the corresponding altitude.

The marked dependence of the radiation dosages on the latitude which is especially pronounced at higher altitudes is due to the influence of the geomagnetic field on the charged primary particles which has been discussed above. It is interesting to note that this strong dependence on latitude at high altitude is practically entirely effaced at sea level. This is due to the multiple scattering processes in the shower production and the resulting direction changes of the scattered radiation.

The relative values of the left scale in Figure 2 are, of course, somewhat unsatisfactory and one may ask to what actual dosage rates in milliroentgens per day they do correspond. It is not very difficult to convert the ionization units of Millikan's original measurements into milliroentgens. The vertical scale on the right side of Figure 2 gives the milliroentgen values obtained this way. But it has to be emphasized that this scale in some respects is very misleading.

To see this we have to go back for a

moment to the fundamental considerations which led to the creation of the biological radiation unit, the roentgen. The general applicability of this unit is based on the presupposition that the biological effect of a penetrating radiation of any kind is dependent only on the total ionization which it produces per gram living tissue. In the time since the introduction of this unit reliable evidence has been obtained, however, that this is an oversimplification. When we compare the biological effects of two kinds of radiations which differ greatly in their specific ionization we find that equal roentgen doses, i.e., equal total ionizations per gram tissue do not produce equal effects. The most significant difference in this respect exists between alpha rays and gamma rays. Present-day practice in radiation safety measurements multiplies roentgen dosages of alpha rays by the factor 10 to make them comparable with x-ray or gamma ray dosages. The reason for this higher efficiency of alpha rays lies in the very non-uniform ion distribution which they produce microscopically in the tissue due to which the ionizations are concentrated along certain "paths of destruction." This important new insight which we have acquired since the creation of the roentgen unit has to be considered in

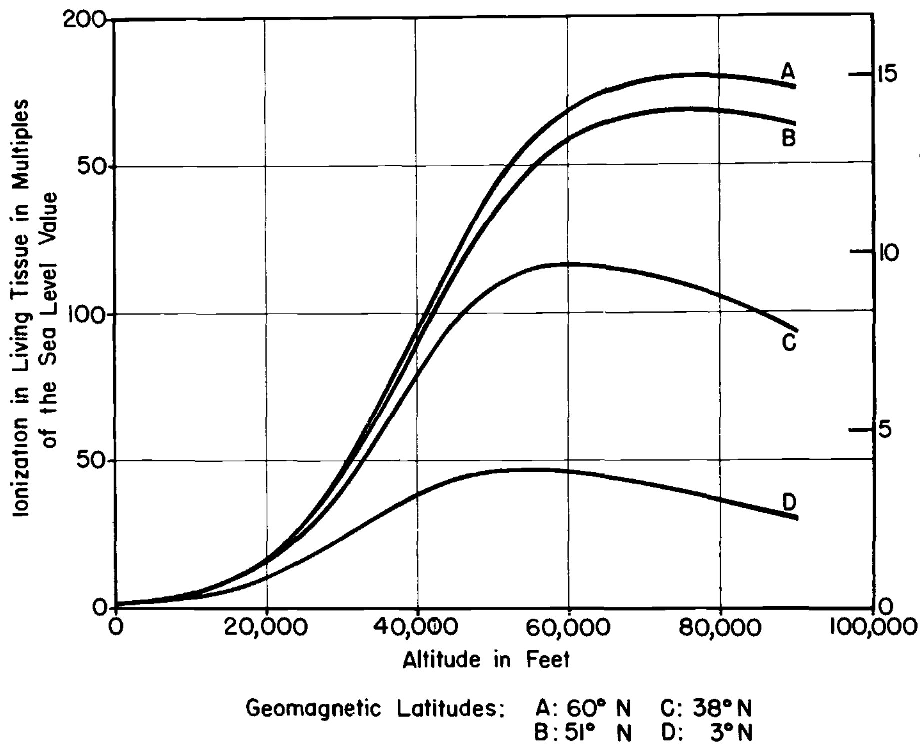

Fig. 2. Altitude dependence of ionization in living tissue from cosmic radiation (based on measurements of Millikan and co-workers).

evaluating the curves of total ionization of cosmic radiation. We remember from the discussion of the mechanism of shower production that there is a continuous change in the kind and in the velocities of the particles when we proceed from the top of the atmosphere to sea level. At very high altitude heavy primary particles are almost exclusively the carrier of the total energy whereas in deeper regions more and more electrons become admixed and lower and lower velocities are predominant. Concomitantly with these changes the specific ionization changes continuously. In other words there is a variable factor by which the milliroentgen dose rates have to be multiplied to obtain the correct biological dose rates, the "milliroentgen equivalent man," as we call this today.

What is this factor and what is its relation to altitude is logically the next question. But this question cannot be answered yet because our experimental material for the quantitative distribution of the total energy to the different components in the cosmic radiation is still much too fragmentary.

There is, however, the possibility for a first approximation in the altitude range from sea level to about 70,000 feet. We have today a rather extensive supply of experimental cloud chamber and nuclear emulsion photographs which present an excellent opportunity for the measurement of the specific ionization of the different particles of cosmic radiation. The evaluation of this material shows consistently that there does not occur within the designated altitude range any type of particle which has a greater specific ionization than alpha particles. We can even say that within this altitude range all cosmic ray particles stay well below the alpha particles in their specific ionization. For alpha particles, the biological efficiency has been studied very carefully by many investigators and with a large variety of biological objects. Thus, we can be quite sure and confident that the factor for the milliroentgen dosages of the cosmic radiation stays in any case below 10 which is the factor for conversion of the "equivalent physical" into the "equivalent man" for alpha particles. This is at least a first tentative basis and a conservative limit for the altitude range up to 70,000 feet. The question, of course, remains whether this limit stays below the tolerance dose. The curve shows that the "equivalent physical" values go up to 15 milliroentgens per day. If we assume a factor of 5 or 8 —we should assume 10 to stay on the safe side—for the conversion into "equivalent man" values we see that the full tolerance dose is reached and even surpassed.

This is not a very pleasant aspect. For a thorough appraisal of the situation we have to consider two facts. One is that the official definition of the tolerance dose actually is rather arbitrary. It is a common phrase to say that present tolerance dose has been defined by careful extrapolation of experimental data on the radiation effects with various biological test objects. However, opinions differ among the experts about this "carefulness." One thing at least is quite certain: the tolerance dose has been defined many years ago in a stage of scientific and technical development in which it was the general opinion that the number of people who actually would be exposed to radiation would always be small and confined to special professional groups representing a very small percentage of the total population. Since we entered the "atomic age" this situation has changed fundamentally and our radiation safety regulations should be established under the assumption that the full population can be continuously exposed to the tolerance dose without endangering the health and hereditary constitution of the living and the future generations. It is characteristic that in all establishments of the AEC the tolerance dose has been changed from its hitherto effective value of 100 milliroentgens per day to the smaller value of 300 milliroentgens per week.

A special part of the problem is the possible damage to the genetic material which will show up only in coming generations. It is not in line with this paper to enter a detailed discussion but the author wants to remind the reader of the urgent warning which H. J. Muller, who was awarded the Nobel prize for his pioneer work in radiation genetics, has published recently.[8] He points out that our present practice and the common attitude even in medical and biological circles is irresponsible.

The Heavy Nuclei Rays.—Still worse prospects turn up when we proceed to the evaluation of the experimental data on the heavy nuclei rays. These experimental data as has been pointed out above are still fragmentary. Therefore, we can win a first outlining only in regard to the biological effects of this newly discovered radiation.

It has been mentioned above (Part II; see also appendix, Part C) that the basic mechanism of interaction with matter for the heavy nuclei rays is similar to that of alpha particles. In fact it would be better to reverse this statement: the basic similarity of this mechanism as it is revealed in the nuclear emulsion recordings is our crucial argument that these new rays are atom nuclei of higher atomic numbers travelling at tremendous speed. Thus, the difference between them and ordinary alpha particles from natural radioactive substances is only a quantitative one though tremendous in magnitude. The fastest and most spectacular way of giving a clear conception of this difference is to compare point by point the stopping processes in living tissue of an alpha particle and a heavy nucleus ray. The discussion here might be limited to the immediate description of the two graphs in Figure 3. All mathematical details are given in Part C of the appendix. The left graph shows the well known curve of the specific ionization along a track of an alpha particle calculated in this example for the stopping power constants of living tissue and related to the structural units of tissue. We have chosen an alpha particle of 9.5 million e-volts of energy, i.e., one of the most energetic of the naturally occurring. This has been done purposely to avoid any exaggeration of the great difference between the two types of rays in discussion. But the calculations of the total dose of natural radioactivity in living tissue have to be based on an average value of 50 microns range or 6 million e-volts respectively. The heavy nucleus ray whose stopping process in living tissue is portrayed in

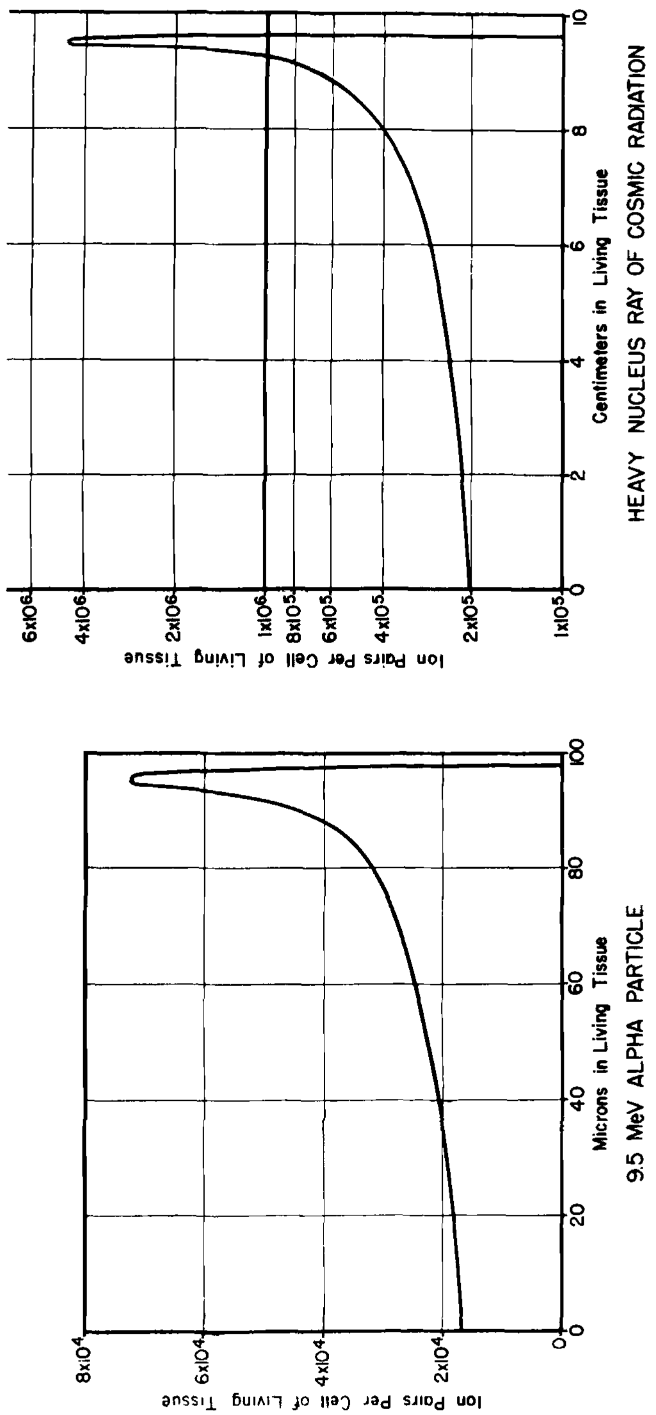

Fig. 3. Specific ionization along particle tracks in living tissue.

the right graph is one of the very few which recorded their full length in the photographic emulsion by penetrating a stack of plates several inches in depth. If one examines the units of the horizontal scales in Figure 3 thoroughly one sees that the graphs represent a giant and a dwarf. The heavy nucleus has a penetrating power in living tissue of 9.5 centimeters; the value for the alpha particle is 0.01 centimeter or 1/1,000 the length of the heavy nucleus track. The ion pair deposits per cell for the heavy nucleus begin with 200,000 and increase to a peak of 4,400,000; the corresponding value for the alpha particle are 17,000 and 72,000. The total energy which the heavy nucleus dissipates in the tissue is 92 billion e-volts, corresponding to 2.8 billion ion pairs; the values for the alpha particle are 9.5 million e-volts and 290,000 ion pairs.

The decisive question, of course, is how to establish a basis for an estimation of the biological effect of the heavy nuclei rays. It is obvious from the just discussed difference in the primary physical reactions released in tissue that they have to be considered an entirely new type of radiation in regard to the biological effect. No natural or artificial radiation source of any kind available in our laboratories can produce a combined specific ionization and penetrating power which could be compared to the heavy nuclei rays of cosmic radiation. Therefore, we can at the present try only an extrapolation from what we know about the biological effects of the common types of penetrating radiations. But as this extrapolation has to reach over a rather wide range it is basically speculative. This has to be emphasized before proceeding in the discussion.

Two main trains of argument can be pursued in this extrapolation. On the one hand, we can calculate from the recordings of the heavy nuclei rays the total ionization which they produce in living tissue. On the other hand, we can compare the different types of radiation with different specific ionizations and can study the difference in their biological efficiency for equal values of the total ionization and then try to derive from this "curve" the efficiency factor for the heavy nuclei by extrapolation.

A very fortunate circumstance in this evaluation is the fact that we have at our disposition today rather accurate values on the natural concentration of alpha active substances in the living organisms and on the lower limit of the concentration which has to be considered toxic. Thus we are not dependent on the entirely arbitrary official tolerance dose of 100 milliroentgens per day or 300 mr per week.

It is a well-established fact that all living organisms contain a definite concentration of radioactive substances. All plants and animals, by taking in air, water, and nutrients, incorporate such substances stemming from radioactive admixtures in the minerals of the soil. For the human organism this natural radioactivity of the tissue has been measured accurately.[10] Its concentration shows a certain rather narrow stray range and some differences in its distribution over the different parts of the organism but for our purpose we can assume the average value of 5×10^{-13} gram radium element per 1 gram living tissue. For a total body weight of 70 kilograms this corresponds to a total activity of 3.5 x 10^{-8} gram radium or 0.035 microgram. On the other hand we know from a thorough study of cases of radium poisoning that a total amount of 1 microgram radium if definitely anchored in the organism represents a serious health hazard. It causes through slow accumulation of the radiation effects severe damage in the bone marrow and lung tissue and finally death. The safety limit for a definitely anchored alpha radiating substance is taken as 0.1 microgram radium for the total body.

If we now compare these figures with the corresponding ones for the heavy nuclei rays of cosmic radiation we obtain values which are compiled in Table II. The mathematical details are given in Part C of the appendix. The data in Table II show that already the total ionization of the heavy nuclei radiation surpasses the safety limit for alpha irradiation. The justification for comparing the figure for alpha irradiation from inner sources is given by the fact that the heavy nuclei rays penetrate the human skin without any noticeable energy loss whereas alpha particles would come to a complete stop in the uppermost dead layers of the skin if administered from an outside source. It has to be borne in mind, of course, that the clinical symptoms of the radium poisoning caused by an amount of alpha-active substance inside the organism of the above given magnitude are of the slowly developing type. It takes months for the first observable changes in the blood test to develop and even a longer time for the other heavier damages. Nevertheless, the special mode of action of the heavy nuclei rays in the living tissue classifies them as alpha-type radiation and it would be a gross mistake to judge their harmfulness on the basis of the tolerance dose for x- and gamma radiation from other sources.

TABLE II. COMPARATIVE FIGURES OF DOSAGES FOR THE HEAVY NUCLEI COMPONENT AND FOR THE NATURAL AND THE MAXIMUM PERMISSIBLE CONCENTRATION OF ALPHA ACTIVITY IN LIVING TISSUE

	Natural radio-activity of living tissue	Max. permissible concentration of radio-activity in living tissue	Heavy nuclei component of cosmic radiation at 90,000 feet
Number of particles per sec. per gram living tissue	0.02	0.055	0.0015
Number of cells hit by one particle	5	5	5,000
Number of cells hit per sec. per gram living tissue	0.1	0.28	1.5
Number of ion pairs formed in one cell of living tissue by one particle	30,000	30,000	~ 150,000
Total number of ion pairs per sec. per gram liv. tissue	3,000	8,400	~ 225,000
Total dosage rate in milliroentgens equival. physical per 24 hours	0.125	0.35	~ 9

Seriously aggravating the situation is the above mentioned second circumstance that the ionization density along the particle track in the tissue is much greater for the heavy nuclei rays than for alpha rays. Therefore the biologically effective dose of the heavy nuclei is greater by an unknown factor than that of alpha particles of the same total ionization. The ion pair figures of Table II have to be multiplied by this unknown factor to give the actual comparable biological doses. An estimation as to the numerical value would be entirely speculative. Our knowledge of the role of the specific ionization for the biological effect is not yet detailed enough so that we could proceed to the derivation of a general law which could be extrapolated for our problem here.

As a first beginning and a rough tentative estimation we distinguish today four types of radiation in regard to the specific ionization. They are given in Table III in the order of increasing specific ionization. If we administer doses of these different radiations equal in the total ionization per gram tissue, i.e., equal in roentgen units we have to multiply the roentgen values by the factors of the table to obtain comparable biological doses. For mesons present-day experimental data on their biological effects are almost entirely missing. But their specific ionization is measured very accurately (see Part D of the appendix) and so we know that they will range between the beta rays and protons in their biological efficiency.

Quite generally, we must be aware that the factors in Table III are rough thumb-rule figures born out of the emergency that the experimenters working with piles and cyclotrons needed some clues for the safety measurements. Much research work has still to be done before we can describe the influence of the specific ionization on the biological efficiency of a radiation in accurate quantitative terms.

TABLE III. CONVERSION FACTORS FROM PHYSICAL INTO BIOLOGICAL DOSAGE UNITS FOR THE DIFFERENT TYPES OF IONIZING RADIATIONS

Type of radiation	Factor for converting roentgen equiv. physical into R equiv. man
X-rays, beta-rays, gamma rays	1.0
Mesons	?
Protons and neutrons	2.5 — 4.0
Alpha particles	10
Heavy nuclei rays $Z<10$	?
Heavy nuclei rays $Z>10$	??

Thus, this discussion of the biophysical qualities of the heavy nuclei rays ends with a major question unanswered.

Without doubt we must not fear that human beings at 90,000 feet altitude will be killed instantly or within a short time by the heavy nuclei rays. The effect might rather be of the slowly accumulating type which makes the clinical picture of the radium poisoning so uncanny and dreadful.

If we look at the situation in a wider scope we must realize that the heavy nuclei component of cosmic radiation represents a harmful environmental influence which during the evolution of life was entirely missing. All the "man made" penetrating radiations which some of us proudly list among man's greatest achievements actually have existed and been acting ever since life began. The natural radioactivity and the cosmic radiation at sea level provide them in a much wider spectral range than man will ever be able to produce them and these "man made" radiations appear altogether like a child's toy in comparison to these deadly atomic projectiles which man encounters now as he is planning to travel in outer space.

Another unsolved problem may be mentioned in this connection. We do not yet know whether the natural background of penetrating radiation due to natural radioactivity and cosmic radiation to which all life is continuously exposed plays any basic role in the living cells for the maintenance of life. The remarkably small gap between the natural concentration of radioactivity in living matter and the lower limit of toxic concentration might indicate that the natural content is not incidental but essential for life. But our knowledge of the primary processes which follow immediately the absorption act in the protoplasm is much too poor for any reasonable discussion of this problem. As a matter of fact we do not know anything about these first stages of the reaction of living matter following the formation of ion pairs by penetrating radiation.

From the general consideration that the response of the living cell to the most minute physical stimuli is astoundingly precise it seems a justifiable conclusion that life, in the same way it has adjusted to gravity, temperature, air pressure and all the other environmental influences, has established a well balanced equilibrium also to the penetrating radiations. If this would prove true the heavy nuclei rays would represent a very heavy disturbance of this equilibrium. But these ideas are at the moment purely speculative.

Before concluding the discussion it must be emphasized once more that in regard to the heavy nuclei rays this report can give only a preliminary and very fragmentary picture which certainly will be out-dated very soon. Many reasons, moreover, point in the direction that the situation is portrayed very conservatively in the right hand graph of Figure 3 and that the numerical data in this example probably give the conditions at the lower end of the energy spectrum of the heavy nuclei rays. The one fact that this ray has been recorded at about 90,000 feet altitude makes it a conclusive inference that the particle has traversed already 18 grams per square centimeter residual air mass from infinite to 90,000 feet altitude. That means that it had dissipated already an energy of the order of 100 billion e-volts before it entered the stack of plates in the gondola of the pilot balloon. We have to realize that the region between 70,000 and 90,000 feet represents the maximum depth of the air ocean for the heavy nuclei rays to which the lightest ones, i.e., the least harmful ones for living matter can penetrate. This view point is strongly corroborated by recent experiments (Bradt and Peters[2]) which indicate that our present conception of the spectral range of the heavy nuclei component is very incomplete and that the full spectrum encountered in free space embraces much higher values than the recordings on which this report has been based disclose.

APPENDIX

A. *Some Remarks on the Conversion of the Total Ionization in Milliroentgen Units.* —The measurements of the total ionization of the cosmic radiation at different altitudes from which the curves of Figure 2 have been calculated have been collected by Millikan and coworkers.[1,6,7,9] They used an ionization chamber with steel walls of ½ millimeter thickness which was carried up by a pilot balloon. A summary of that part of the results which is of interest for our purpose is given in the second paper.[1] The original curve is reproduced in Figure 4. In converting the units of the ordinate, ions/cm.^{3}/sec./atm. to milliroentgens per second, it has to be kept in mind that the authors use the term "ions" in the meaning of "ions collected on one electrode of the electroscope." Consequently, in regard to the actual ionization it means ion pairs. The conversion itself then can be carried out easily and immediately as the ionization is already related to one cm.^{3} and 1 atm. pressure, i.e., to unit air mass.

All altitude recordings in cosmic ray research are related to pressure units and not to the altitude in feet. Two reasons favor this practice. First, the altitude in a pilot balloon ascent is measured by measuring the air pressure which is telemetered or recorded. Therefore, it is more correct to relate the registrations directly to the pressure and to bypass thus entirely the somewhat problematic altitude-pressure relation. Second, all interaction processes of the cosmic ray particles with the air atoms, such as shower production, scattering, and absorption are dependent on the penetrated mass of air. This again makes the pressure which is nothing else than the weight or mass of the air column from infinity to the point of measurement (per unit cross section) the appropriate magnitude for measuring the altitude. For handling conversion calculations with the radiation constants (scattering coefficients, radiation units, etc.) it is especially convenient to give the air mass in meters of a water column of the same weight. The full atmosphere equals 10.33 meters water or 91 centimeters lead. The conversion of the abscissa of Figure 4 in feet altitude has been carried out according to the tables of the National Advisory Committee for Aeronautics.[11]

It might be emphasized that the maxima of the curves of the total ionization in the 50,000 to 70,000 feet range in Figure 2 are, of course, not maxima of the total energy flux of the cosmic radiation. What passes through a maximum is only the percentage

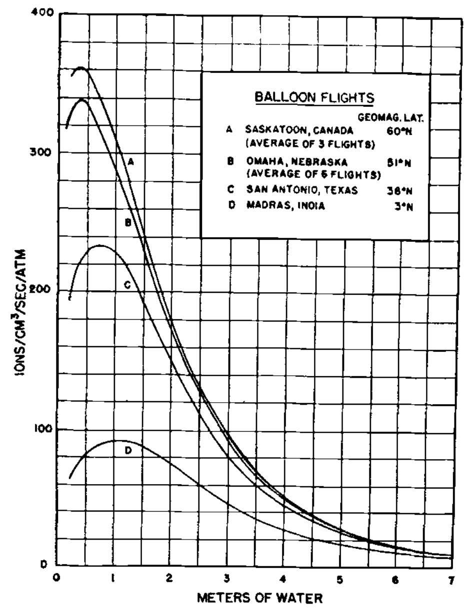

Fig. 4. (Measurements of Millikan and coworkers).

of this total energy which is transformed into ionization work per unit mass layer of the atmosphere. As the biological effect, in quite the same way, is dependent only on the amount of energy turned into ionization work per unit mass, maximum ionization at the same time means maximum biological dosage and the curves therefore give the true relationship for the biological effect.

B. *The Specific Ionization of the Different Components of the Cosmic Radiation and Its Significance for the Biological Effect.*—The roentgen unit is based on the measurement of the total ionization which is produced by the radiation per unit mass (of air or tissue respectively). No additional specifications are provided in the definition of the r-unit which take into account the differences in the micro-structural distribution of the

TABLE IV. SPECIFIC IONIZATION IN LIVING TISSUE FOR PROTONS, 200-MESONS, AND ELECTRONS

Particle energy in million e-volts	Primary ion pairs produced on a path of 10 microns length in living tissue		
	Protons	200-Mesons	Electrons
0.03			410
0.06			225
0.1			150
0.3		3.350	75
0.6	11,200	2,000	55
1	7,380	1,350	51
2.5	3.570	660	55
5	2,190	360	58
10	1,230	215	61
25	590	110	65
50	345	80	69
100	210	63	72
250	110	55	74
500	75	57	80
1,000	61	68	83
2,000	55	60	87

primary ionizations. The reason for this lack is a historical one: When the roentgen unit was defined by international agreement the scientific experience as well as the therapeutic application of ionizing radiations were limited to x-rays, beta-, and gamma rays. The primary process of ionization of these three kinds of radiation is very similar, almost identical because the ionization of x- and gamma rays is produced by electrons (i.e., beta rays) released in collisions of the gamma quanta with orbital electrons of the atoms of the absorber.

The studies of the biological reactions produced by alpha rays, later on those produced by neutrons, proved that the biological effect is dependent not only on the amount of ionization produced in the tissue but also on the spatial distribution of the primary ion pairs. Radiations which generate very closely spaced columns of ion pairs (alpha particles and protons) have a greater biological efficiency than radiations with a more uniform ion distribution. We do not yet fully understand at the present the role of the specific ionization (i.e., the number of ion pairs per unit path length of a ray) in the biological action. It might be even better to say that we know very little about it. How complicated the problem is might be illustrated by the remark that different biochemical actions in the living cell show a different dependence on the specific ionization. For some genetic actions, e.g., things are exactly reversed: a higher specific ionization makes radiation less effective.[5,8]

Present-day radiation safety practice has taken into account this phenomenon of a decisive influence of the specific ionization by introducing an additional specification for the roentgen unit. We distinguish today the roentgen-equivalent-physical and the roentgen-equivalent-man. The former is identical with the normal roentgen unit of the official international definition; the latter gives the actual biological efficiency of a radiation and is obtained by multiplying the normal roentgen value with an intensifying factor in case of a radiation of higher specific ionization. Table III gives the conversion factors for the main types of radiation. It might be emphasized that these values are tentative figures which cannot yet pretend to be sufficiently tested on sufficient experimental material.

For the problem of health hazard from cosmic radiation these considerations have the following consequence. The curves of Figure 4 which give the total ionization for different altitudes and those of Figure 2 which give basically the same relation converted into biological terms do not take into account the fact that the radiation at different altitudes is composed of different particles which have a marked difference in their specific ionizations. At high altitudes protons are the predominant component; at greater depths of the air ocean (lower altitudes) the meson and electron components take over the ionization work; and finally at sea level the primary protons are entirely missing. At the present we are not yet able to give a quantitative analysis of the percentage of the different particles in the total flux of cosmic radiation at different altitudes. Besides this it would be necessary to know also the full energy spectrum of each kind of particle because the specific ionization depends strongly on the particle energy. Thus, for the moment, we have to content ourselves with the rough approximation given in Table III.

As a first step to a more accurate

calculation fairly exact data on the relation between specific ionization and particle energy have been collected. Table IV gives these values for the main types of cosmic ray particles which occur between sea level and 70,000 feet altitude. In studying the table one must realize that in regard to the biological action the ionization by electrons in the range of a few hundred kilovolts energy is the classical case on which the definition of the roentgen unit has been established. The comparison to the other particles shows that at the lower end of the energy scale the specific ionization of the mesons and especially that of the protons is considerably higher. It is not possible to disregard this effect and to decide the radiation safety problem solely on the basis of the milliroentgen-equivalent-physical values of Figure 2.

On the other hand, the specific ionization for alpha particles in the one to ten million e-volts range equals 17,000 to 70,000 ion pairs per 10 microns living tissue. The lowest value of this range is higher than the highest for protons and mesons. Hence it is safe to conclude that the conversion factor in any case will be smaller than the factor for alpha particles, i.e., smaller than 10.

It is worthwhile to mention that for higher energies the specific ionization becomes equal for all three particle types. This is due to the fact that the specific ionization in a given absorber depends on the particle charge and the particle velocity only and therefore must be equal for protons, mesons, and electrons of the same velocity. Due to the different masses and the relativistic mass increase at higher energies the relation between kinetic energy and velocity is somewhat complicated.

C. *Specific and Total Ionization of the Heavy Nuclei Rays.*—The right-hand curve in Figure 3 portraying the specific ionization per cell of living tissue along the track of a heavy nucleus ray is based on an evaluation of data given by Freier, Lofgren, Ney, and Oppenheimer.[3] They give a reproduction of three sections of the recording of a heavy nucleus ray in nuclear emulsion. This ray penetrated a full stack of photographic plates and its path could be traced through many emulsion layers of adjacent plates. The full recorded length corresponds to 9.2 grams per square centimeter. This gives a penetrating depth of 9.2 cm. for living tissue. As the authors point out the evaluation of the photographic recordings in terms of ionization is as yet possible only by approximation because the tremendous values of grain density are far outside the range of density covered by all hitherto known kinds of rays. No interpolation therefore is possible but wide extrapolation has to be performed. In the mentioned reproduction the authors give the tracks of alpha particles of thorium for comparison. For an estimation of what the "path of destruction" of this heavy nucleus ray would look like if it had traversed living tissue the recording in the emulsion has to be transposed in a recording in living tissue. We have tried this in the following way. A careful comparison of the thorium alpha tracks with the beginning part of the heavy nucleus track shows that the specific ionization is at least ten times greater for the latter. For one who is familiar with microdensitometric measurements this figure seems too small but it might be used in order to refrain strictly from any exaggeration. This factor 10 gives a value of 200,000 ion pairs per cell for the initial part of the heavy nucleus track in living tissue. The further calculation does not bring additional major uncertainties into the evaluation because it is based only on the very accurately recorded full range of the heavy nucleus (9.2 grams/cm.^{2}) and the very reliably established law that the specific ionization of an elementary particle is proportional to Z^2 and $1/B^2$ (Z=atomic number; B=ratio of the particle velocity to that of light). The calculation under these premises results in a total energy of ninety-two billion e-volts. This figure is higher than that of Freier and co-workers (fifty-four billion e-volts) but is in better agreement with the general observation that the energy for the heavy nuclei rays in the 90,000 feet altitude range is about one billion e-volt per nucleon. Freier and co-workers emphasize that they estimate conservatively the lower limits in all their extrapolations.

D. *Numerical Data on Protection Layers from Heavy Nuclei Rays.*—Some brief remarks have to be added concerning the problem of protection from heavy nuclei rays. The question, of course, remains yet undecided to what extent such protection is necessary. In any case this necessity is limited to altitudes beyond 70,000 feet because this altitude represents the maximum depth to which the lightest of the "heavy" nuclei rays can penetrate. These lightest ones are, at the same time, the least harmful ones in regard to the biological efficiency. It has been shown above that the heavy nuclei rays resemble entirely the alpha particles in regard to the mechanism of energy dissipation in traversing matter. That means, they travel in straight lines and have a definite range which depends on the initial kinetic energy. This makes the calculation of the thickness of a protection layer very simple. The stopping power of different substances for high energy atomic nuclei is somewhat dependent on the atomic weight of the substance of interest. This dependence, however, is rather insignificant and can be disregarded for this rough estimation. The calculation then can be carried out under the assumption that equal masses per unit cross section exert equal absorption. We obtain the figures for the necessary protection layers by the following considerations: The air pressure at 70,000 feet equals 48 grams per square centimeter. This air layer of 48 gr./cm.^{2} is sufficient for total absorption of all heavy nuclei because we do not find any more below this altitude. Thus, to accomplish full protection in space outside the air blanket it takes a protection layer of the same weight, i.e., e.g., a layer of aluminum of 18 centimeters thickness. With this value we stay absolutely on the safe side because the intensity of the heavy nuclei rays is definitely zero at 70,000 feet. If one assumes that the intensity at 80,000 feet is still tolerable the necessary protection is reduced to 29 grams/cm.^{2} or 10.5 cm. aluminum. This assumption is reasonable because in the range between 70,000 and 80,000 feet the lighter component is predominant and the total number of incoming rays is approaching zero. But the recordings hitherto collected indicate that the increase in the number of particles as well as in their energy, i.e., atomic number, is very rapid. Thus, the figure of 10.5 cm. aluminum or its equivalent in other material probably is the minimum requirement for protection in outer space.

Smaller weights, of course, are necessary if protection has to be provided for a limited altitude range only. For a ceiling of 90,000 feet, e.g., and the above mentioned assumption that the intensity at 80,000 feet is still tolerable a protection layer corresponding to the air pressure difference between 90,000 and 80,000 feet is necessary. This is 29 grams/cm^2 minus 18 grams/cm.^{2} or 4 centimeters of aluminum.

Another point which has to be discussed here is the directional effect. Between 70,000 and 90,000 feet the heavy nuclei rays come predominantly from the vertical direction. Protection within this altitude range therefore is necessary only above the volume to be protected. But this directional effect is a secondary phenomenon caused by the absorption in the air which for oblique directions is much higher due to the longer way of the particle. The recordings at higher altitudes indicate that outside the air blanket the intensity shows a uniform distribution for all directions. Hence in free space protection has to be provided for all sides.

Considering the estimated figures and the weights which they imply the protection from heavy nuclei rays might become the most difficult problem to be overcome in running manned ships at altitudes at the upper end of or outside the air blanket.

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