Symposium on Aerospace Radiobiology

II. On the Shielding of Cosmic Rays

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THE PROBLEM of protecting space travelers against solar and non-solar cosmic rays is a highly complex one. There exist a number of possible methods whereby some degree of protection may be achieved (e.g., solar-flare forecasting). Of these, *shielding*—"brute-force" shielding—is perhaps the most naive at first sight. There is something to be said however about the latter, for, whatever eventually turns out to be the best method, it is likely that shielding will play *some* role. This alone suffices to justify further consideration of the shielding problem separately.

But the shielding problem is itself fairly complex. This would be so if only for the fact that its complete consideration involves a number of conventionally distinct areas of endeavor. One may say, with some oversimplification, that it is the task of the radiobiologist to find out, by studying the biological effects, how much attenuation of the incident radiation is required, that it is the task of the nuclear physicist to find out how the required attenuation can be achieved by shielding, and that, simultaneously, it is the task of the cosmic-ray physicist to find out what it is that one is trying to shield against in the first place. Certainly not less important is the over-all task of the design engineer, who must decide how a practical shield can come out of all this without doing violence to the many technical limitations.

In its general form, the nuclear physics part of the shielding problem may be stated as follows. Suppose we have a completely specified radiation field in space. (By "completely specified" is meant here that we know at all times the composition—e.g., protons, heavier nuclei, electrons—of the radiation, as well as the energy spectrum—i.e., the flux at each energy—of each of its components.) Let this flux be incident on an enclosure of a specified size, shape, structure, and composition.

We now ask *Question 1a*: What is the resulting radiation field in the enclosure as a function of the shield (wall) thickness? A more appropriate question superseding the preceding one is *Question 1b*: Supposing a space traveler is occupying a specified position in the enclosure, what is the resulting radiation field inside his body, as a function of the shield (wall) thickness? In either question, we ask for a complete specification of the resulting radiation field which, as we shall see, will often be different in composition from the field outside the enclosure. We must also allow for the possibility that the thickness and composition of the shield may not be uniform over the enclosure.

A further question is *Question 2*: Knowing the radiation (flux) field inside the body, what is the corresponding *dose* field?

If we can give answers to *Questions 1b and 2*, we have what is needed for the nuclear physics part of the shielding problem. Combined with the knowledge from cosmic-ray studies and from radiobiology, and taking into account the practical limitations imposed on the design, it will then be possible, in principle, to decide on the optimum shield. Such a grand program, which, at any rate, may not be needed in practice, is not easily tractable without simplification.

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The cosmic-ray problem and the radiobiology problem are discussed in a number of papers elsewhere in this issue. We wish to confine ourselves here to a few remarks on the nuclear physics problem and, in particular, to a simplified version of *Question 1* posed above. Before going further, it should be pointed out that there now exist in the literature a number of recent papers[1,2,8,11,12,14,19,22-24,26-28,30,33] in which the shielding problem in space has been considered, including several discussions of the related but distinct problem of the shielding of nuclear-powered spacecrafts.[13,14,22]

COMPETITION BETWEEN ELECTROMAGNETIC AND NUCLEAR INTERACTIONS

When a proton (or alpha particle or heavier nucleus) enters matter and comes upon a target atom of the shield, it may do nothing or it may do either one of the following two things: It may ionize (or excite) the atom, thereby losing a small part of its energy, and then keeps on going at the reduced energy. This will be called an *electromagnetic* interaction, since only coulomb forces are involved. Or else, the incident proton may undergo a *nuclear* interaction, in which nuclear forces are brought into play. Phenomenologically, the outcome of a nuclear interaction is the disappearance of the incident particle, and the emergence from the site of the interaction of a number of secondaries. What these secondaries are depends on many factors, among which the energy of the incident proton and the nature of the target nucleus. In general, if the incident proton energy is less than 100 Mev or so, the secondaries will be few and weak—perhaps one or two low-energy protons, neutrons, deuterons, alpha particles, or gamma rays. For incident proton energies exceeding 100 Mev or so, the secondaries increase in number and energy. Beyond 500 Mev, another process, called "meson production", intervenes appreciably, so that from there on the secondaries will contain an admixture of energetic pi-mesons as well. Experimentally, one can separate the secondaries from each proton-induced high-energy nuclear interaction into roughly two classes: the low-energy secondaries (less than 100 Mev or so) composed of protons, neutrons, deuterons, tritons, and heavier nuclei; the high-energy secondaries (more than 100 Mev or so, up to the energy of the incident particle itself), composed of protons, neutrons, and the pi-mesons mentioned above. For example, a typical high-energy nuclear interaction induced by a 3 Bev proton in a nucleus of carbon (often mentioned as shield material[23]) may yield six low-energy secondaries and six high-energy secondaries, three of the latter being pi-mesons, perhaps one positive, one negative, and one neutral.

The above cursory description does not do justice to the rapidly accumulating knowledge on high-energy nuclear interactions, and the interested reader should consult the proper references. Some such references exist in the aerospace literature.[11,26,32] More comprehensive descriptions can be found in the cosmic-ray and nuclear-physics publications, such as in the volume by Powell *et al*,[20] and in the series of papers by Metropolis *et al.*[17]

What is the relative likelihood that an incident proton will undergo nuclear or electromagnetic interaction? The detailed answer cannot be given in the space available here. Suffice it to note for our purpose that electromagnetic interactions are much more probable than nuclear ones. However, since in an electromagnetic interaction a proton loses only a small fraction of its energy and then keeps on going, it will have a chance to nuclear interact if it is allowed to go far enough. For a proton of energy less than 150 Mev, the chance of nuclear interaction is not great, for even before it has an opportunity to do so, it will be stopped by the more frequent electromagnetic interactions. For a higher-energy proton, nuclear interaction becomes the more usual fate, provided the shield is thick enough. In Figure 1, we have plotted the fraction a of monoenergetic protons which undergoes nuclear interaction in a carbon shield as a function of the distance x travelled in the shield (upper abscissa). The lower abscissa shows the energies of protons whose ranges are the distances given in the upper abscissa. These ranges are simply taken from the conventional range-energy relations,[34] which give the distance a proton of a given energy will penetrate if no nuclear interaction is possible. Graphs similar to Figure 1 can be constructed for shields of other materials as long as we know the nuclear interaction mean free path for the material. The exact expressions, which are simple exponential functions, are contained elsewhere.[30]

A graph such as Figure 1 makes possible an important decision before considering the actual shielding of a given radiation field, for it tells us what fraction of the incoming radiation will nuclear interact and will, therefore, be attenuated in the way characteristic of nuclear-interacting particles to be described later. For example, at about 600 Mev, some 90 per cent of the incident protons will undergo nuclear interaction if the shield is thicker than about 170 gm/cm², the range. (But if the shield is only 50 gm/cm² thick, then only about 50 per cent of the incident protons will nuclear interact.) If we have, say, 95 per cent or more of the incident protons undergoing nuclear interaction, i.e., if the incident energy exceeds 700 Mev or so, then it may be possible as a first approximation to ignore the presence of the remaining 5 per cent or less of protons which lose energy by electromagnetic interactions only. On the other hand, if we have, say, 20 per cent or less of the incident protons nuclear interacting, i.e., if the incident energy is below about 150 Mev, then it may be possible to neglect the presence of nuclear interactions, and use the conventional range-energy relations alone for

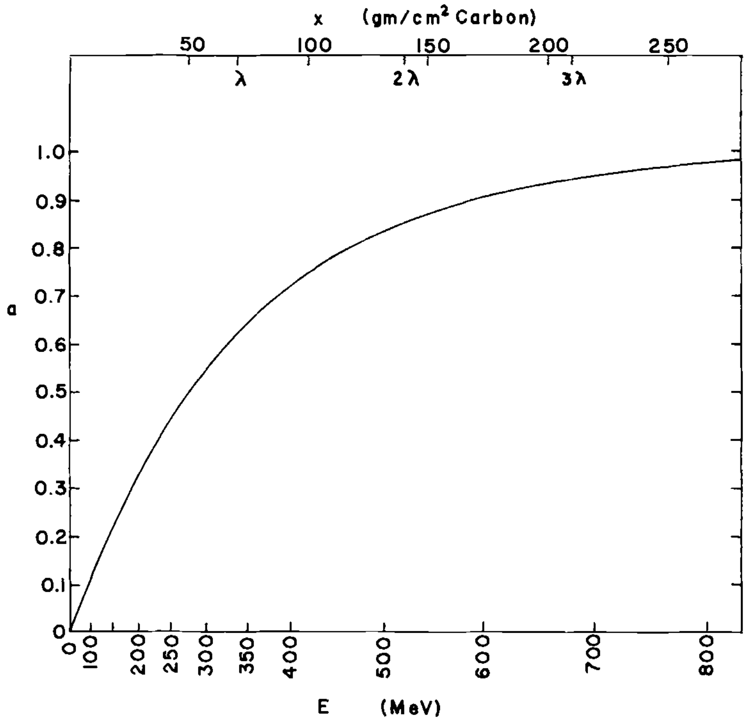

Fig. 1. Fraction a of incident protons undergoing nuclear interaction in a carbon shield *vs.* the path length x traversed in carbon (upper abscissa). The lower abscissa gives the energy $\mathcal{E}$ of a proton whose range is as given in the upper abscissa. The mean free path λ for (inelastic) nuclear interaction in carbon is about 70 gm/cm².

actual shielding estimates. For intermediate situations, it is necessary that nuclear and electromagnetic interactions, each with its own way of attenuating the beam, both be taken into account.

In an actual situation in space, it will be found, during a solar cosmic-ray event for instance, that the bulk of the incident particles are of such small energy (< 150 Mev) that the use of the conventional range-energy relations alone may be sufficient for most purposes. For such cases, the nuclear physics part of the shielding problem is already solved, since accurate and extensive range-energy relations are available.[34] There exists, for example, a work by Schaefer[27] which gives perhaps the most thorough consideration to date to such cases.

If, on the other hand, examination of the energy spectrum of the incident radiation shows that there are enough high-energy ones to require consideration of the nuclear interactions, then, as has been noted previously,[28,30] the problem becomes complicated and our knowledge of the fundamental processes involved quickly becomes inadequate for accurate prediction. Before discussing this further in the following sections, we should note that it is not trivial to consider cases of incident energy spectra for which nuclear interactions are important, since such cases do occur in nature. The normal non-solar interplanetary cosmic-ray spectrum is, of course, an example. Even on the assumption that these non-solar cosmic rays may require little shielding for short trips, one can cite the largest of the solar cosmic-ray events as clear examples where the flux between, say, 700 Mev and 10 Bev, is considerably higher than that due to the non-solar cosmic rays. Further, the high-energy end of the more frequent but smaller solar cosmic-ray events too fall into the "nuclear-interacting" category. All these will have to be shielded against as space travel becomes more commonplace.

THE NUCLEAR CASCADE

What happens to the secondaries emerging from the nuclear interactions described earlier? The low-energy secondaries, because of their short range will, as shown by Figure 1, mainly lose energy by further electromagnetic interactions, and eventually stop in the shield. The high-energy secondaries, on the other hand, will not only lose energy by electromagnetic interactions, but also have a good chance of undergoing nuclear interaction and, as Figure 1 shows, the higher the energy the better this chance. The ability to undergo nuclear interaction is, of course, not limited to the protons; high-energy neutrons and positive and negative pi-mesons are as likely to nuclear interact as the high-energy secondary protons. The only exceptions are the secondary neutral pi-mesons, which decay so rapidly into two high-energy gamma rays that they never have a chance to do anything else. Now each of the nuclear interactions initiated by the high-energy secondaries will produce its own secondaries which, in turn, may further nuclear interact. It is not difficult to see that, following the incidence of a high-energy proton (unless it has the rare luck of avoiding all nuclear interactions), there will arise inside the shield a spray of secondary particles of successive generations, the whole thing being known as a "nuclear cascade." This multiplication process will go on until the secondaries are of too low energy to initiate further nuclear interactions. Since the high-energy secondaries emerge from the site of the nuclear interaction predominantly in the forward direction (i.e., in the direction of the velocity of the incident particle), we see that the nuclear cascade too will develop in this direction. Since, furthermore, this forward collimation is not perfect, the totality of the secondaries in the cascade will diverge more and more from the central axis as the cascade develops.

For a given incident energy, what is the particle flux at a given depth in the nuclear cascade? This is, after all, a version of our *Question 1* for the case where nuclear interactions are important. We will see in the next section that, in contrast to the case where only electromagnetic interactions are important, there are few definite answers to give at present.

ATTENUATION BY NUCLEAR INTERACTION

We will rephrase *Question 1* in the following simplified form: Given a parallel beam of particles incident perpendicularly and uniformly over the face of a plane shield of great thickness, what is the radiation flux at every depth inside the shield? Note that we are asking for the flux *inside* the shield. This is slightly different from asking for the flux *behind* a shield of variable thickness. However, since most of the experimental data available are of the former kind, we will be content with that version. Furthermore, although it is desirable to know the flux of *each* component of the radiation as a function of depth inside the shield, we will confine ourselves here to asking simply for the depth variation of the flux of the *nuclear-interacting component* only. As mentioned earlier, the nuclear-interacting component of a cascade consists of the high-energy secondaries (protons, neutrons, and pi-mesons) with the neutral pi-mesons excluded. To be sure, the nuclear-interacting secondaries are not the only particles giving rise to biologic effects; the low-energy secondaries contribute also. However, it is difficult to obtain a detailed depth variation of the low-energy secondaries without first knowing the depth variation of the high-energy nuclear-interacting secondaries, which sustain the cascade and determine its penetration.

The most extensive attenuation data available are found in studies of the nuclear cascades produced in the atmosphere by primary cosmic rays. However, there is a basic difference between a cascade in the atmosphere and one in condensed matter, such as a shield. While in condensed matter the positive and negative pi-mesons of sufficient energy will nuclear interact, in the atmosphere they will not in general: they will decay before having a chance to nuclear interact. Thus the nuclear-interacting component of the average atmospheric cascade consists mainly of high-energy protons and neutrons. This difference will result in a depth variation of the atmospheric cascade different from that of a cascade in condensed matter. Nevertheless, the data we now have of the atmospheric cascade do give an indication of what we may expect in condensed matter, even though the details may be different.

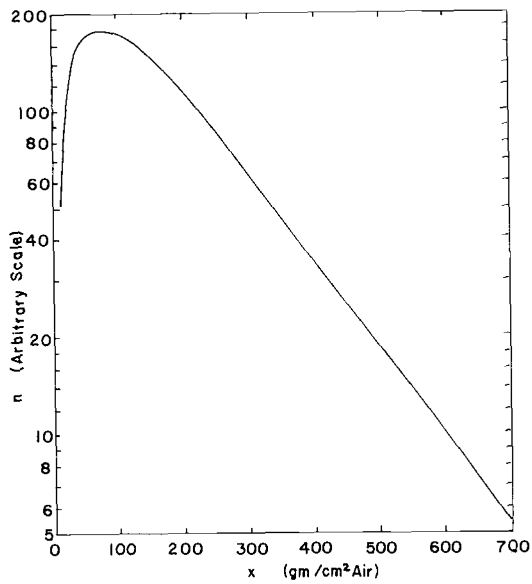

Fig. 2. Slow-neutron counting rate n *vs.* depth x in the atmosphere at the north geomagnetic pole. Incident spectrum: normal nonsolar cosmic rays. (After Neuburg, Soberman, Swetnick and Korff[18]).

Figure 2 shows a representative curve of the slow-neutron intensity as a function of depth in the atmosphere recorded in a balloon flight at the north geomagnetic pole by the New York University Cosmic-Ray Group.[18] The incident radiation in this case is not too different from the normal interplanetary cosmic rays. The principal features of Figure 2 agree with the more difficult direct measurements[25] of the nuclear-interacting component in the atmosphere, as well as with predictions of the theoretical models of the atmospheric cascade.[3,4,7,10,16,25] Any future detailed investigation of the nuclear cascade in condensed matter can be expected to rely heavily on the existing models for the cascade in the atmosphere.

Until recent years, there had been little interest in the nuclear cascade in condensed matter, mainly because there was no important phenomenon which required such knowledge for its interpretation. During the past decade, however, it was realized[32] that certain nuclides normally rare in meteorites were produced as a result of nuclear interactions initiated by cosmic rays when the meteorites orbited in space. These rare nuclides are measurable[31] and they afford an unusual method for studying cosmic rays in space and in time. In order to interpret these meteorite measurements, however, it is necessary to know how the production rate of a given rare nuclide varies with depth in the meteorite, which is (we happily note) after all, condensed matter. In 1953, Martin[15] proposed a simple theoretical model to describe this depth variation, a model which has since been tentatively applied to a number of meteorite measurements.[31] Essentially, what Martin did was to solve a set of linear first order ordinary differential equations similar, but not identical, to the Bateman equations of radioactive series decay. Although his model referred to the depth variation of the production rate of various nuclides, it can be extended to give also the depth variation of the nuclear-interacting component in condensed matter. We have made a number of such calculations using a slightly modified version of Martin's model. Figure 3 shows a typical result for the case of normal non-solar cosmic rays incident perpendicularly and uniformly on a block of iron. The abscissa represents the depth in the iron block and the ordinate shows the flux of the nuclear-interacting component.

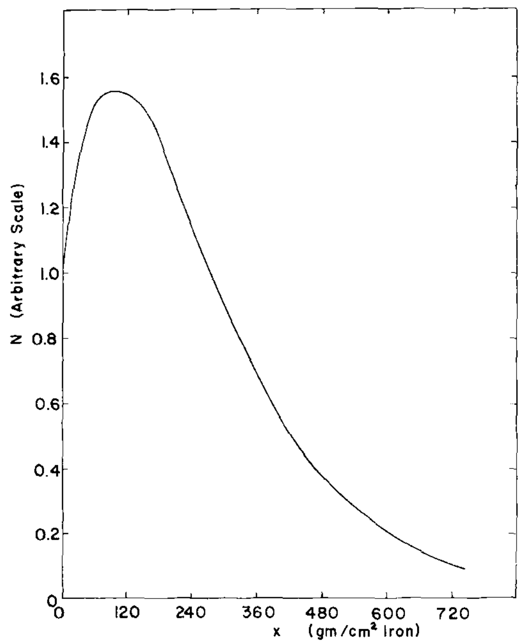

Fig. 3. Calculated flux of the nuclear-interacting component N *vs.* depth x in iron. Incident spectrum: normal non-solar cosmic rays. Calculations based on Martin's model. (This graph is not intended to be used for estimating actual shield thicknesses).

In 1957, Fireman and Zaehringer[9] bombarded an iron target with protons from accelerators up to 6 Bev energy, and measured the depth variation of the production rate of two nuclides of interest in the target. (One would expect that the nuclear-interacting component has a depth variation similar to that of the nuclide production rates.) It is, however, difficult to compare their measurements with Martin's model due to the differences in the geometries. Other experiments of interest are those of Shapiro and Gabrysh[29] and of Bridge and Rediker.[5,21]

The experience gained in the shielding of high-energy nuclear accelerators is of pertinence to our problem. Since the Proceedings[6] of a conference held in 1957 on the shielding of accelerators have been published, there is no need to repeat anything here. In these Proceedings,[6] the reader interested in the shielding problem in space is referred, in particular, to Moyer's useful semi-empirical method of predicting the particle flux behind a given shield, to the Appendix of a contribution by Lindenbaum describing an attenuation experiment by Swartz *et al*,[6] and to some interesting Monte Carlo calculations by O'Neill.[6] It is useful to bear in mind that the weight limitation for a shield aloft is, as a rule, far more stringent than that for a shield on the ground, where the limiting factors are usually space and cost rather than weight. The cosmic-ray shielding problem thus requires a more detailed knowledge of the attenuation curve, including the attenuation at small shield thicknesses.

Recently, Robey[23] and Keller,[11] using differing methods, have made interesting studies of the neutrons emerging from a shield bombarded by cosmic rays.

In a forthcoming experiment designed for studying the structure of the nuclear cascade and for interpreting some of our meteorite measurements, we plan to bombard a block of iron or aluminum one meter in length with high-energy protons. By means of a combination of detection techniques, the development of the nuclear cascade will be followed. Such information, once obtained, would be helpful to the nuclear physics part of the shielding problem.

CONCLUDING REMARKS

We recall that, according to Figure 1, a fraction of the incident beam will undergo nuclear interaction while the remainder will eventually be stopped by electromagnetic interactions alone (i.e., ionization and excitation). Figure 3, however, refers only to the attenuation of that fraction which does undergo nuclear interaction in the shield; the attenuation—in fact, the presence—of the remaining incident particles was ignored completely. We know that if the incident energy spectrum extends below 700 or 800 Mev, this would not be a justifiable procedure. In particular, if the incident spectrum belongs to a solar cosmic-ray event, then the electromagnetically-stopped fraction definitely has to be taken into account. When we do that, there will be superposed on Figure 3 (mainly within the first few tens of gm/cm^2), the attenuation curve due to electromagnetic stopping of the low-energy bulk of the incident spectrum. For example, a 100 Mev proton in the incident beam will, if it escapes nuclear interaction, gradually lose energy by ionization and excitation and persist to a depth of 12 gm/cm^2, its range in iron. In a similar way, conventional range-energy relations show that a 300 Mev proton will penetrate to some 75 gm/cm^2 in iron, 600 Mev to about 230 gm/cm^2, 1 Bev to about 480 gm/cm^2, 2 Bev to about 1200 gm/cm^2, and 3 Bev to about 1800 gm/cm^2 in iron. (Of course, the chance for the 2 or 3 Bev proton to do this is almost nil.) Now the incident cosmic-ray spectrum on the iron in Figure 3 has an average energy of about 3 or 4 Bev. Comparing the attenuation shown in Figure 3 with the 1800 gm/cm^2 range of the 3 Bev proton, we see that, at these energies, the attenuation by nuclear interaction is far more effective than attenuation by electromagnetic interaction. This is not surprising if we recall that, in each nuclear interaction, the energy is *shared* by a number of secondaries.

The virtue of Martin's model, if it can withstand future experimental tests, lies in its simplicity, which is desirable even when large computers are on hand. The nuclear cascade is such an involved phenomenon that any model even slightly more sophisticated than Martin's runs into rather formidable mathematical complexity and, sometimes, impasse. For such complex phenomena, random sampling techniques (e.g., Monte Carlo methods) often turn out to be highly useful *ad hoc* devices.

One of the shortcomings of Martin's model, for example, is that it assumes that all the high-energy secondaries emerge from a nuclear interaction strictly in the forward direction. This is not quite so in actuality, but will be difficult to correct for, without destroying the simplicity of the model. In short, we do not have at present firm knowledge as to how far the results of Martin's model deviate from reality. Figure 3, for instance, may thus be seriously in error, and it is therefore *not* intended to be used as a basis for actual shielding estimates; it has been discussed here mainly for illustrative purposes.

In the final analysis, the complete solution of the nuclear physics part of the cosmic-ray shielding problem depends on an understanding of the nuclear cascade in condensed matter. Utimately, what one would like to have for shielding purposes is a complete set of answers to some mitigated version of the *Questions* 1 and 2 posed at the outset. At present, such a goal is not yet immediately attainable.

SUMMARY

The shielding of cosmic rays in the energy range where nuclear interactions are important is discussed, and some attenuation data are given.

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