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Photodisintegration of Ultrahigh-Energy Cosmic Rays by the Universal Radiation Field

F. W. STECKER
Theoretical Studies Branch, NASA Goddard Space Flight Center, Greenbelt, Maryland 20771
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We have carried out a detailed calculation to determine the effectiveness of the universal radiation field in disintegrating ultrahigh-energy cosmic-ray nuclei. We conclude that this process cannot lead to a pure-proton interpretation of the air-shower observations above 10^8 GeV. Photodisintegration by the universal radiation is unimportant on time scales of 10^{10} yr or less for helium nuclei below 10^{10} GeV and for iron nuclei below 10^{11}-GeV total energy. Photodisintegration by dilute starlight photons in intergalactic space is unimportant on time scales of 10^{10} yr or less at all energies.

IN a recent paper,[1] we made a detailed study of the effect of photomeson production by the universal radiation field on ultrahigh-energy cosmic rays. Greisen[2] and Zatsepin and Kuz'min,[3] who first proposed the significance of this effect, also pointed out that the universal radiation field can disintegrate cosmic-ray nuclei of 10^{10}-GeV energy and above. The purpose of this paper is to take account of the details of the photodisintegration process and to analyze the results for implications on the origin and propagation time of the ultrahigh-energy cosmic rays.

In Ref. 1, we showed in a detailed calculation that cosmic-ray protons of energies less than or equal to 6×10^{10} GeV can exist for 10^{10} yr (the age of the universe) against attenuation by photomeson production. It was also shown that the lifetime of a 10^{11}-GeV proton is of the order of 10^9 yr and that protons of all energies have lifetimes of at least 5×10^7 yr, long enough to reach us if produced within the local supercluster region.

An event of 10^{11}-GeV energy was detected by Linsley,[4] along with the detection of six other events having energies greater than or equal to 2×10^{10} GeV.[5] Recently, Andrews *et al.*[6] have detected an event of energy $\geq5\times10^{10}$ GeV. As we concluded in Ref. 1, such observations are not incompatible with the existence of the universal blackbody radiation field, but only with the implicit assumption that ultrahigh-energy cosmic rays are primordal. These assumptions are compatible with the existence of these cosmic rays with ages up to 10^9 yr, and which may be reaching us from distances as great as 300 Mpc (10^9 light yr).

We now present a similar discussion of the implications of photodisintegration by the universal radiation field. Letting ϵ' denote the energy of a blackbody photon in the rest frame of an ultrahigh-energy cosmic-ray nucleus, and letting $\sigma(\epsilon')$ denote the cross section of a nucleus of type i for photodisintegration, the lifetime of the nucleus is given by (cf. Ref. 1)

$$\tau_i(E_i)=2\gamma_i^2\hbar^3\pi^2c^2\left[\int_{\epsilon_{\text{th}}'/2\gamma_i}^{\infty}\frac{d\epsilon}{e^{\epsilon/kT}-1}\int_{\epsilon_{\text{th}}'}^{2\gamma_i\epsilon}d\epsilon'\epsilon'\sigma_i(\epsilon')\right]^{-1}. \tag{1}$$

In previous discussions,[2,3,7] photodisintegration has been stressed for Fe nuclei where the cross section is large. However, recent analyses,[5,8] although not airtight, favor the hypothesis that cosmic rays of energies $\geq10^8$ GeV are purely protons. Such conclusions can be explained by photodisintegration, as suggested by Linsley,[5] only if all heavier nuclei can be broken down into individual nucleons. As one considers lighter and lighter nuclei, the photodisintegration cross section becomes smaller and smaller. Indeed,[9] the photodisintegration cross section of a nucleus of atomic number A is proportional to $A^{4/3}$. We consider here as extreme cases, photodisintegration of He and Fe nuclei. We treat here, in detail, the photodisintegration of helium nuclei. We consider in particular the well-studied processes

$$\gamma+\text{He}^4\rightarrow\text{He}^3+n \tag{2}$$

and

$$\gamma+\text{He}^4\rightarrow\text{H}^3+p, \tag{3}$$

keeping in mind the fact that reactions (2) and (3) must be followed by the further breakup of He^3. Thus, lifetimes for the complete breakup of He nuclei are at least twice as long as those calculated here.[10]

The data on reactions (2) and (3) have been compiled by Gorbunov,[11] as shown in Fig. 1. Equation (1) was

[1] F. W. Stecker, Phys. Rev. Letters **21**, 1016 (1968).
[2] K. Greisen, Phys. Rev. Letters **16**, 748 (1966).
[3] G. T. Zatsepin and V. A. Kuz'min, Zh. Eksperim. i Teor. Fiz. Pis'ma v Redaktsiyu 4, 114 (1966) [English transl.: JETP Letters 4, 78 (1966)].
[4] J. Linsley, Phys. Rev. Letters **10**, 146 (1963).
[5] J. Linsley and L. Scarsi, Phys. Rev. Letters **9**, 123 (1962); J. Linsley, *ibid* **9**, 126 (1962); and in *Proceedings of the 1963 Cosmic Ray Conference, Jaipur, India*, edited by R. R. Daniel *et al.* (Commercial Printing Press, Ltd., Bombay, India, 1963).
[6] D. Andrews, A. C. Evans, R. J. O. Reid, R. M. Tennent, A. A. Watson, and J. G. Wilson, Nature **219**, 343 (1968).
[7] N. M. Gerasimova and I. L. Rozental', Zh. Eksperim. i Teor. Fiz. **41**, 488 (1961) [English transl.: Soviet Phys.—JETP **14**, 350 (1962)].
[8] R. Cowsik, Can. J. Phys. **46**, S142 (1968).
[9] J. M. Blatt, and V. F. Weisskopf, in *Theoretical Nuclear Physics* (Wiley-Interscience, Inc., New York, 1952).
[10] Above 10^{12} GeV, photomeson production on He probably dominates over photodisintegration. However, since no events have been detected at such energies, we need not consider this process in detail.
[11] A. N. Gorbunov, Phys. Letters **27B**, 436 (1968).

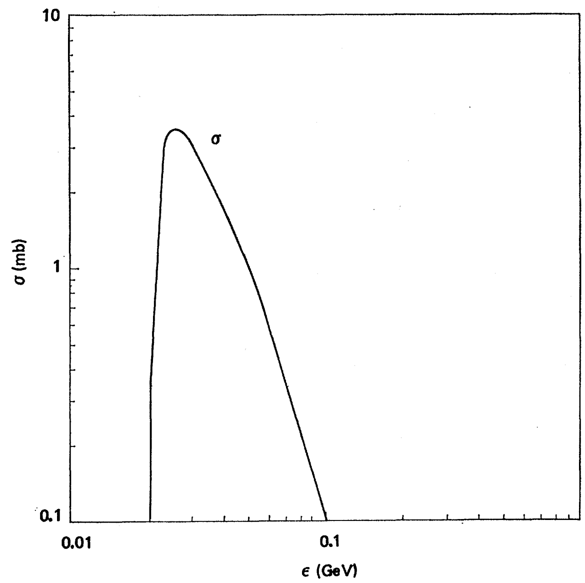

FIG. 1. Total cross section for the processes $He^4(\gamma,p)H^3$ and $He^4(\gamma,n)He^3$ as a function of γ-ray energy in the He rest system.

solved numerically making use of these cross sections and the results are given in Fig. 2 along with the lifetimes of protons against attenuation by photomeson production as given in Ref. 1. We have also considered the lifetimes for processes (2) and (3) as generated by dilute metagalactic starlight photons with a mean temperature of 5000°K and a radiation density of 10^{-14} erg/cm^3, as given by Allen.[12] Recent calculations by Garmire[13] have yielded even lower estimates of the metagalactic starlight photon density. With such optical photon densities, the minimum lifetimes for He photodisintegration are of the order of 10^{11}–10^{12} yr for He and 10^{10} yr for Fe.

One can see from Fig. 2 that photodisintegration of He by the universal radiation field occurs only above 10^{10} GeV even for propagation times of the order of 10^{10} years. Considering more likely propagation times as discussed in Ref. 1, we find photodisintegration of He only above energies of $(2–3)\times10^{10}$ GeV. Thus, photodisintegration by microwave and dilute optical metagalactic photons cannot account for the presumed absence of multinucleon nuclei between 10^8 and 10^{10} GeV. The dashed curve in Fig. 2 shows the photodisintegration lifetime for Fe calculated by scaling the He cross section by $A^{4/3}$. Fe is affected at higher energies than He because the Lorentz factor γ is 14 times lower for an Fe nucleus than for an He nucleus of the same total energy. Photodisintegration of Fe is found to be significant above 10^{11} GeV.

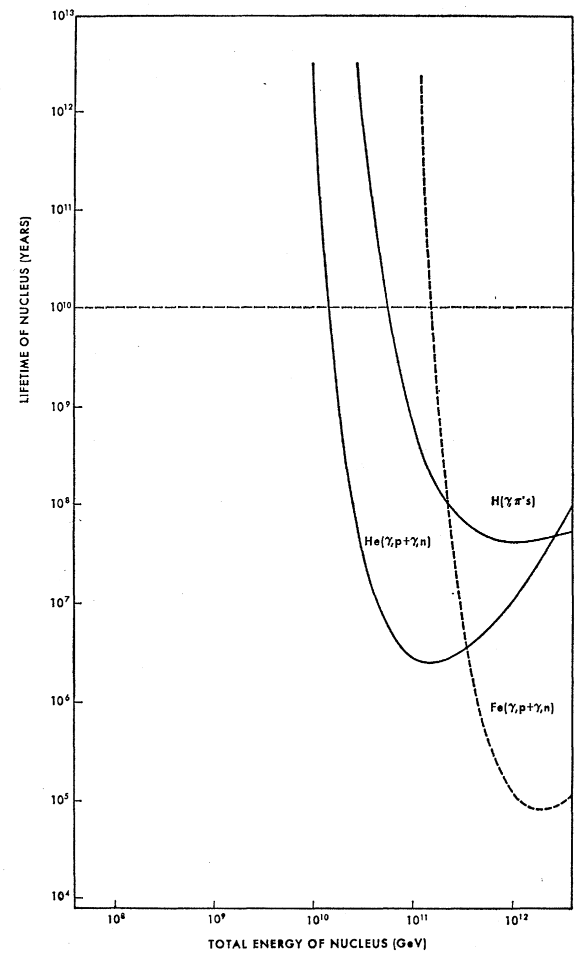

FIG. 2. Characteristic lifetimes for He and Fe nuclei against photodisintegration and for protons against photomeson production as a function of energy.

It may still be possible to obtain adequate photodisintegration for complete breakup if a large flux of infrared photons exists in metagalactic space. Recent preliminary observations between 0.4- and 1.3-mm wavelengths by Shivanandan *et al.*[14] indicate the presence of a photon flux two orders of magnitude higher than to be expected from a 3°K blackbody background. If this flux is universal, it may help account for the possible absence of multinucleon nuclei above 10^8 GeV.

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[12] C. W. Allen, in *Astrophysical Quantities*, (Athlone Press, London, 1963) 2nd ed.

[13] G. Garmire, in *Proceedings of the Ninth International Conference on Cosmic Rays, London, 1965* (The Institute of Physics and The Physical Society, London, 1966).

[14] K. Shivanandan, J. R. Houck, and M. O. Harwit, Phys. Rev. Letters **21**, 1460 (1968).

If the extragalactic ultrahigh-energy cosmic rays cannot undergo complete photodisintegration during propagation, then we must look for an alternative explanation of the results of Linsley and Scarsi. The most natural alternative which comes to mind is the possibility that these cosmic rays were exposed to a strong photon field at their source. Indeed, powerful radiation fields may have been associated with the acceleration process. Photodisintegration during the acceleration of cosmic rays has recently been considered by Kinsey[15] in his study of the survival of heavy cosmic-ray nuclei in supernova explosions.

ACKNOWLEDGMENTS

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[15] J. H. Kinsey, Goddard Report No. NASA X-611-68-352, 1968 (unpublished).

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Advanced Effects in Particle Physics. I

PAUL L. CSONKA

Institute of Theoretical Studies, University of Oregon, Eugene, Oregon 97403

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The relation between causal sequence and time sequence of events is investigated. A theory is constructed which is able to describe the interaction of particles with arbitrary quantum numbers, and in which the elementary interaction is time-symmetric between effect and cause: The effect may precede as well as follow the cause. It is shown that in a many-particle universe, under certain conditions, effects mostly follow the cause, but that this phenomenon is a function of the coupling constants. The direction of time is correlated with the distribution of particles in four-dimensional space. The "velocity of time" (related to the average change of entropy per collision) is introduced and found to be almost zero for an almost empty universe. It is suggested that the causal chain may be closed in our universe. An experiment is described which may be able to test these ideas. In one of the appendices two generalizations of the optical theorem is given, the first of which is valid even if unitarity is not.

1. INTRODUCTION

THE concepts of time sequence and causal sequence of events are of basic importance in science. The relation of these two is restricted by the usual principle of causality, according to which no effect can precede its cause. We shall refer to this principle as the "principle of retarded causality." It is perhaps because of their fundamental role that these concepts are not fully understood at the present time. In an attempt to better understand them, in this paper we shall drop the restrictive assumption of retarded causality, and construct a theory in which an effect may both follow or precede its cause.

The first difficulty one encounters in carrying out such a program is a difficulty of language, and perhaps it is permissible to devote here one paragraph to this problem. So widely is the principle of retarded causality accepted today, that it has even penetrated our language. In this context, it is sufficient to recall that, for example, "outgoing (or resultant) state" is sometimes used in the sense "state following the incoming state," while at other times it is used to mean "state caused by the initial state." For this reason, without carefully redefining some phrases or inventing new ones, our language is no longer capable of describing a world in which effect may precede its cause. Because of this lack of precision, the concepts of time and causal sequences have partially merged. In other words, it is easy to consider it "self-evident" that any state Ψ_f, caused by an incoming state Ψ_i, must follow Ψ_i in time, essentially because we refer to Ψ_f as the "final state." In fact, some consider it inconceivable that it should be otherwise. The confusion which can result from the unconscious merging of two concepts can perhaps be illustrated even more strikingly by recalling an example in which our own prejudices are not involved, namely, the merging of the concepts of "north" and "downstream" in ancient Egypt.[1] This lack of precision is known to those who studied the writing of the ancient Egyptians; its sources and consequences are briefly described in Appendix A. The next paragraphs contain an outline of some of the ideas to be discussed in the paper.

Although very widespread today, it was only relatively recently that the principle of retarded causality gained general acceptance. In ancient times one customarily considered the universe to be analogous to some huge organism. For this reason, for centuries, it was acceptable to explain certain phenomena in terms of emotions, e.g., by saying "the universe abhors emptiness." Since living organisms, such as humans, were

[1] Stele of King Tuthmosis I, translated in J. H. Breasted, *Ancient Records of Egypt* (Russell & Russell, Inc., New York, 1906) Vol. 2, p. 31.