tons. When the complete potential is deformed, the optical parameters (Table I) found so far to give the best fit to the elastic polarization also produce the best prediction of inelastic asymmetry.

All the curves in Fig. 2 use a central-well deformation parameter of $\beta_2=0.39$ for ^{28}Si and $\beta_2=0.22$ for ^{60}Ni. The deformation parameter of the spin-orbit term is 1.5 times the central-well value, which produces slightly better agreement with the asymmetry data for ^{28}Si. Both real and imaginary parts of the spin-orbit interaction are included, but since $|W_S| \ll V_S$, the imaginary part makes little difference. The curves also include Coulomb-excitation amplitudes,[1] which make little difference in either the asymmetry or the cross section. We find that for all of the calculations made, the predictions of inelastic asymmetry and inelastic polarization are very nearly identical.

In summary we find that, provided the imaginary and spin-orbit terms are included, the collective-model generalization of the optical potential gives a good account of the present inelastic asymmetry data at all but the most forward angles. It is quite possible that a more comprehensive treatment of the spin-dependent interaction will improve matters in this region, and such calculations are in progress.

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‡Graduate Fellow from the University of Tennessee under appointment from the National Science Foundation.

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END TO THE COSMIC-RAY SPECTRUM?

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The primary cosmic-ray spectrum has been measured up to an energy of 10^{20} eV,[1] and several groups have described projects under development or in mind[2] to investigate the spectrum further, into the energy range 10^{21}-10^{22} eV. This note predicts that above 10^{20} eV the primary spectrum will steepen abruptly, and the experiments in preparation will at last observe it to have a cosmologically meaningful termination.

The cause of the catastrophic cutoff is the intense isotropic radiation first detected by Penzias and Wilson[3] at 4080 Mc/sec (7.35 cm) and now confirmed as thermal in character by measurements of Roll and Wilkinson[4] at 3.2 cm wavelength. It is not essential to the present argument that the origin of this radiation conform exactly to the primeval-fireball model outlined by Dicke, Peebles, Roll, and Wilkinson[5]; what matters is only that the radiation exists and pervades the observable universe. The transparency of space at the pertinent wavelengths, and the consistency of intensity observations in numerous directions, give strong assurance that the radiation is indeed universal. The equivalent black-body temperature has been reported as 3.1 ± 1°K[6] and 3.0 ± 0.5°K.[4] For our discussion, we shall consider $T=3.0°$, at which temperature the photon density is 548 cm^{-3} and the mean photon energy 7.0×10^{-4} eV. Although at this temperature the number of photons in the spectral range of the measurements ($\lambda \geq 3.2$ cm) is only 5×10^{-3} of the total, the slope of the spectrum is such that any reasonable extrapolation to shorter wavelengths would yield at least a substantial part of the 3° black-body photon density. Moreover, two indirect confirmations of the existence of the radiation have been reported: One lies in the slope of the isotropic part of the x- and gamma-ray spectrum[7] and the other in the absence of muon-poor air showers above 10^{16} eV.[8]

As the last statement implies, several consequences of the existence of the thermal radiation have quickly been noted. One is to provide a source of x rays and gamma rays by inverse Compton interactions with cosmic-ray electrons.[7,9,10] Another is to make the universe opaque to high-energy photons, above 2×10^{14} eV, because of positron-electron pair creation by photon-photon interactions.[8,11] A third effect is to deplete the density of energetic electrons by the energy losses in the inverse Compton interactions.[7,9] Hoyle[9] also considered the effect of the thermal radiation on cosmic-ray protons, but concluded that the time scale for energy degradation is greater than the expansion time of the universe for all protons up to 10^{21} eV. This conclusion is wrong because he only considered the proton Compton effect and neglected two stronger processes, namely pair creation and photopion production, which we now wish to examine.

The threshold energy for pion production by protons on photons of energy 7×10^{-4} eV (the mean energy of black-body radiation at 3°K) is 10^{20} eV, and some pion production occurs at lesser proton energies because of the high-frequency tail of the photon spectrum. The cross section rises rapidly above the threshold,[12] going through a peak exceeding 400 μb at the $\frac{3}{2}$, $\frac{3}{2}$ resonance (2.3×10^{20}-eV proton energy on 7×10^{-4}-eV photon), and descending thereafter to about 200 μb, about which minor wiggles occur owing to the superposition of higher resonances. With a mean cross section of 200 μb and a photon density of 550 cm^{-3}, the mean path for interaction is $(n\sigma)^{-1}=9\times10^{24}$ cm. However, the distance scale for loss of energy is $L=(E/\Delta E)(n\sigma)^{-1}$, E being the initial proton energy and ΔE the energy loss per interaction. At the threshold for single-pion production, $\Delta E/E$ is only 0.13, but it rises to an average value of 0.22 at the $\frac{3}{2}$, $\frac{3}{2}$ resonance, and continues to rise thereafter as multiple pions are produced or more kinetic energy is given to a single pion. L is therefore on the order of 4×10^{25} cm, and the time scale for energy loss is 10^{15} sec, which is several hundred times less than the expansion time of the universe. L is also more than an order of magnitude less than the distance to the nearest quasar.

There is abundant evidence that above 10^{17} eV, the cosmic rays are not confined to the galaxy; the local intensity is a sample of the flux in a much larger sphere. If the sources of very high-energy particles are uniformly distributed in space and time, the effect of interactions like those described here is to deplete the spectrum by a factor equal to the ratio of the time scale for energy loss to one-third the expansion time. If, on the other hand, the sources of such particles exist only far back in time or at great distances, the depletion is much stronger. It may also be noted that if the primeval-fireball model is correct, going back in time raises the mean photon energy as $(1-t/T)^{-1}$ and the photon density as $(1-t/T)^{-3}$, T being the expansion time; thus the effect may be somewhat larger than our computations on a static model indicate.

It should be noted that the cut in the spectrum due to photopion processes is rather sharp, because of the steepness of the high-frequency tail of the Planck distribution. Only 1 % of the photons have energies exceeding 3 times the mean value; also, close to the threshold the cross section is smaller than 200 μb and the fractional energy loss per interaction is a minimum. Therefore, below 3×10^{19} eV the process should have a completely negligible effect on the proton spectrum. As 10^{20} eV is approached, the effect should rise rapidly; and above 2×10^{20} eV, it should be a factor of several hundred. At present the data above 10^{19} eV are rather sparse, and the highest energy recorded is represented by a single event at 10^{20} eV.[1] A smooth representation and extrapolation of the spectrum gives an integral frequency of about one event on 100 km^2 in one year at energies above 2×10^{20} eV. If this number is cut by a factor of several hundred, owing to the γ-p reaction, the rate will be far too low to be detected by any of the methods yet proposed; even the one event recorded at 10^{20} eV appears surprising.

One cannot save the day for superhigh-energy cosmic rays by calling on heavy nuclei. The threshold for photodisintegration against photons of 7×10^{-4} eV is only 5×10^{18} eV/nucleon, and at 10^{19} eV/nucleon most of the photons can excite the giant dipole resonance, for which the cross section is on the order of 10^{-25} cm^2. At this energy the mean path for photodisintegration is on the order of 2×10^{22} cm, much less than the size of the galaxy. Even nuclei 5 times less energetic would be decomposed in a time short compared with the expansion time of the universe, owing to the high-frequency tail of the black-body spectrum.

Ordinary optical interstellar radiation can also produce γ-p photopions and heavy nucleus disintegrations, at energies 1000 times less than those discussed above; but the intergalactic optical photon density is smaller than that of the 3° radiation by a factor of about 5×10^4, and the mean paths are correspondingly longer. So the effect on the proton spectrum is negligible, but not the effect on the heavy nuclei: Above 10^{16} eV/nucleon the mean time for photodisintegration is an order of magnitude less than the expansion time. Nuclei confined in the galaxy encounter a higher density of optical photons and are fragmented much faster.

In addition to photopion interactions as a source of energy loss to high-energy protons, one should consider pair production by the thermal photons. The proton energy threshold for this reaction against photons of 7×10^{-4} eV is only 7×10^{17} eV. The energy loss in the laboratory system arises primarily from the small longitudinal momentum given to the proton in its rest system. At the threshold the fractional energy loss is $2m/M\simeq10^{-3}$, where m and M are the electron and proton masses. At higher energies the energy loss depends on the relative velocity of the electron and positron and the transverse momentum given to the proton, but the average energy loss in the laboratory is approximately constant, making the fractional energy loss $f\simeq10^{-3}/x$, where x is the ratio of the proton energy to its threshold value. The cross section with no screening is approximately $1.8\times10^{-27}(\ln x-0.5)$ cm^2. Therefore, the scale length for energy loss is given by $L=(nf\sigma)^{-1}\simeq10^{27}\times(\ln x-0.5)^{-1}$ cm. The minimum value of L occurs at $x=4.5$ or $E\simeq3\times10^{18}$ eV and is about half of the Hubble length. Thus, the effect on the primary spectrum is barely significant, creating a small depression (never exceeding a factor of about 3) in the interval 10^{18}-10^{20} eV.

Even this small depletion of the flux above 10^{18} eV, however, followed above 5×10^{19} eV by a stronger depression due to the photopion process, makes the observed[1] flattening of the primary spectrum in the range 10^{18}-10^{20} eV quite remarkable. The injection spectrum of the intergalactic flux must be much less steep than that of the galactic particles which dominate at lower energies.

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