simple. Qualitatively, however, a comparison of these two results implies a large nucleon cross section (∼ geometric) for scattering and absorption of hyperons in the energy region 10 to 60 Mev.

D. Probability of Hyperfragment Formation

We observed 46 hyperfragments from the K^- stars and no hyperfragments from an estimated 115 Σ^- stars, including zero-prong events.[36] If one assumes that every Σ absorption yields a Λ^0 via reaction (3), then the hyperfragment formation probability is $(46/700)=6.6\%$ for K^- stars and 0/115 for Σ^- stars. The Λ^0's produced either directly or indirectly from the nuclear capture of K^- mesons appear to have a higher probability of emerging in the form of a hyperfragment than do the Λ^0's, produced by the nuclear capture of Σ^- hyperons.

[36] There is some possibility of experimental bias in this comparison. The mean number of prongs from Σ^- stars is much less than from K^- stars, and hence the identification of hyperfragments that have very short ranges ("double centers" is more difficult in Σ^- events than in K^- events.

Since the total energy available to the nucleus in K^- absorption is much larger than in Σ^- absorption, this result implies that the process of hyperfragment formation is more like a boiling off of nuclear matter containing a Λ^0 than like a pickup process by the Λ^0 as it leaves the nucleus.

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Acceleration of Cosmic-Ray Particles among Extragalactic Nebulae

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It is proposed that cosmic-ray particles can be accelerated by the Fermi mechanism acting among galaxies in clusters in the same way that Fermi originally proposed for interstellar clouds in our own galaxy. When applied to the local group of galaxies this mechanism does not lead to an appreciable increase in energy over the limit attainable in our own galaxy. However, the conditions in a highly concentrated cluster such as the Coma cluster lead to maximum energies in the range 10^{18}–10^{20} ev. Some implications of these results are discussed.

CURRENT theories of the acceleration of cosmic-ray particles suggest that if the original Fermi mechanism[1] or some variations and refinements of it[2–4] are invoked, a reasonable upper limit to the energy which a particle can gain in our galaxy lies in the range 10^{15}–10^{16} ev per nucleon. If the effects of diffusion and structure in the magnetic field are taken into account, Thompson[5] has shown that energies of the order of 10^{17} ev may be attained. It is the purpose of this paper to point out that the Fermi mechanism may well operate among extragalactic nebulae,[6] and the ultimate limit on the energy is probably determined only by the conditions inside clusters of galaxies and to some extent by the age of the universe.

Observations from a number of directions can be used to estimate the probable conditions of acceleration. The clustering tendencies of galaxies have been realized in recent years to be of great importance (see the work of Shane and Wirtanen[7] and Zwicky[8]). Also work by Zwicky[9] has shown that much material exists in regions lying between galaxies. Detection of 21-cm radiation from the Coma cluster of galaxies[10] and from the Cygnus radio source[11] which consists of two galaxies in interaction shows that there is a large amount of neutral hydrogen associated with these galaxies. These masses

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[2] E. Fermi, Astrophys. J. **119**, 1 (1954).
[3] Morrison, Olbert, and Rossi, Phys. Rev. **94**, 440 (1954).
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[7] C. D. Shane and C. A. Wirtanen, Astron. J. **59**, 285 (1954).
[8] F. Zwicky, *Proceedings of the Third Berkeley Symposium on Statistics* (University of California Press, Berkeley, 1956), Vol. III, p. 113, and earlier references given there.
[9] F. Zwicky, Naturwissenschaften **29**, 344 (1956).
[10] D. S. Heeschen, Astrophys. J. **124**, 660 (1956).
[11] A. E. Lilley and E. F. McClain, Astrophys. J. **123**, 172 (1956).

are of the same order as the total masses of the systems themselves.[10,12] It can be expected that a considerable amount of ionized hydrogen is present as well. Furthermore, both normal and abnormal galaxies which are radio sources show in very many cases large radio halos which surround the optically brightest regions.[13–15] On the well-founded assumption that this is synchrotron radiation, we can deduce from these halos that the systems contain large volumes of low-density gas and weak magnetic fields. The presence of these extended systems means that the internal hydromagnetic velocities must be high ($\sim$100 km/sec); otherwise they would collapse towards their centers. The existence of such extended regions may be a very widespread phenomenon in which in the majority of cases in normal galaxies the radio emission is too weak to be detected. Also a number of intergalactic star clusters in the local group of galaxies have been discovered in recent years.[16] Finally, the presence of the [O II] line λ3727 in the spectra of many elliptical galaxies[17] shows that even in these systems gas is often present in appreciable quantities.

The velocity dispersion of galaxies within clusters ranges from $\sim$100 km/sec in the local group of galaxies[18] to $\sim$2000 km/sec[9,17] in highly condensed and heavily populated clusters such as the Coma and Corona clusters. The 21-cm observations of Heeschen[10] show a dispersion $\sim$1000 km/sec in the velocities of neutral hydrogen clouds in the Coma cluster; this value is compatible with the velocity dispersion of galaxies within this cluster, though the clouds may exist either within or without the galaxies of the cluster.

We shall consider the maximum energies that may be achieved by a proton moving (i) in the local group of galaxies, and (ii) in a large condensed cluster such as the Coma cluster. In order to do this we shall make the hypothesis that the space between the galaxies is pervaded by a weak magnetic field and a very low density of matter, both of which must be far lower than the corresponding values in the interstellar gas of our galaxy. The mean density ρ must lie in the range $10^{-24} \gg \rho > \rho'$, where ρ' is the mean density in the space between clusters ($\rho' \simeq 6\times10^{-29}$ g/cc). We shall also suppose that all galaxies contain some gas and magnetic field. In this case we can consider the acceleration in the same way that Fermi originally did, if we replace the conditions due to the interstellar clouds in our galaxy by the conditions due to the galaxies in a cluster. An extra limitation on the duration of the acceleration, t, will now be that t must be less than the age of the universe. Thus if we suppose that the universe is represented by an evolutionary cosmology, $t<1/H$ where H is the Hubble constant. We shall put $1/H \sim 6\times10^9$ years, a value near to that obtained from the red-shift data, though there is increasing evidence that our own galaxy is $\sim 10^{10}$ years old.* If the steady-state cosmology is assumed this limitation has no validity.

(i) If E_1 is the injection energy of protons for acceleration in the local group, then the maximum energy attainable, E_m, is given by

$$E_m = E_1 \exp\{(v/c)^2 N\}, \tag{1}$$

where N is the number of collisions which are made. Thus

$$t \simeq N\lambda/c < 1/H, \quad \text{or} \quad N_m = c/(\lambda H). \tag{2}$$

E_1 must be the highest energy to which particles may be accelerated in our galaxy and still escape, either by following lines of force which form natural escape paths from the galactic disk to the halo and hence to the intergalactic medium,[13,19] or because their spiralling radius becomes comparable with the radius of a spiral arm. Thus we put $E_1 = 10^{15}$–10^{17} ev. For the local group, $v = 100$ km/sec and λ, the mean separation between colliding centers, $\simeq 10^5$ parsecs $= 3\times10^{23}$ cm. Thus from (2) we find that $N_m = 1.9\times10^4$, and $E_m = E_1 \exp(0.002) \simeq E_1$. We can conclude from this result that if the original Fermi mechanism is applicable, acceleration of cosmic rays among galaxies of the local group will not lead to higher particle energies than those already attainable in our own galaxy, unless the mean distance between colliding centers is not the mean distance between galaxies but it is a distance very much smaller than this. This would imply that in the intergalactic medium within such a cluster there is very fine structure in the low-density gas and magnetic field, with a characteristic length $\sim$100 parsecs. This would appear to be highly improbable. Even a more efficient mechanism similar to that proposed by Thompson[5] in which field irregularities lead to energy gain from large fluctuations within galaxies without reflection would not lead to the production of energies appreciably greater than E_1.

(ii) It has been shown by Zwicky[20] that in the Coma cluster in which about 800 member galaxies have been

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[15] G. R. Burbidge and E. M. Burbidge, Astrophys. J. **125**, 1 (1957).
[16] A. G. Wilson, Publs. Astron. Soc. Pacific **67**, 27 (1955); G. O. Abell, Publs. Astron. Soc. Pacific **67**, 258 (1955).
[17] Humason, Mayall, and Sandage, Astron. J. **61**, 97 (1956).
[18] M. L. Humason and H. D. Wahlquist, Astron. J. **60**, 254 (1955).

* The value of $1/H$ given by Humason *et al.*[17] is 5.4×10^9 years, so that, for example, the age and thus the time for acceleration in a particular model (Einstein-de Sitter) is $2/3H = 3.6\times10^9$ years. By effectively putting the age $= 6\times10^9$ years for the purposes of this argument we are somewhat arbitrarily attempting to resolve the dilemma of the conflict between the age of our galaxy determined by dating star clusters and the presently determined value of H, in favor of the cluster-dating method. On the other hand, any distances given in this paper have been obtained from the red-shift-distance relation given by Humason *et al.*[17]

[19] L. Davis, Phys. Rev. **96**, 743 (1954).
[20] F. Zwicky, Astrophys. J. **86**, 217 (1937); Astrophys. J. **95**, 555 (1942).

counted, the density distribution of the galaxies follows that of the molecules in an isothermal gravitational gas sphere. Thus although the mean distance apart of the galaxies in such a cluster is $\sim 2\times 10^5$ parsecs, there is a tremendous concentration towards the center. Hence about half of the galaxies are contained in a volume having a diameter of about 9×10^5 parsecs, while the total diameter of the cluster is about 4×10^6 parsecs. The mean separation of these inner members is $\lesssim 10^5$ parsecs, while nearer to the center the separations begin to approach the average sizes of galaxies themselves. The effect of this concentration together with the high random velocities (2000 km/sec) means that collisions between galaxies become frequent.[21] For example, the calculations of Spitzer and Baade show that a galaxy passing within about 2.2×10^4 parsecs of the center of the cluster will make between 79 and 490 collisions (depending on the cross section which is assumed) in a time of about 6×10^9 years. The collisions will tend to sweep the gas, dust, and magnetic field out of the systems, though the effect of glancing collisions will be that in a single collision not all of the galaxies will be swept clean. Also some of the gas may fall back into the systems after the collision is over. The gas swept out in this way may tend to condense into new galaxies, or fall towards the center and begin to condense into stars. The point which we wish to emphasize here is that the collisions together with the concentration towards the center will tend to increase the number of scattering centers for cosmic-ray particles trapped in this region. Thus a mean separation of scattering centers $\sim 10^4$ parsecs would not appear to be improbable. In this case, we have from (2)

$$N_m = 1.9\times 10^5,$$

and if $v = 2000$ km/sec,

$$E_m = E_1 \exp(8.4) = E_1 \times 4.4\times 10^3.$$

Thus if E_1 lies in the range 10^{15}–10^{17} ev, $E_m = 4\times 10^{18}$ -4×10^{20} ev. If the nucleon is to gain energies as high as those estimated above without being destroyed by nuclear collision, the mean density of the material ρ is given by

$$\rho \lesssim 1.66\times 10^{-24} H/(\sigma c),$$

and if $\sigma = 3\times 10^{-26}$ cm^2, $\rho \lesssim 9\times 10^{-26}$ g/cc. Although this density limit is far lower than the mean density in the disk of our galaxy, it may be comparable with the density in the halo,[13] and it is higher than that in the intergalactic medium in clusters where the nucleon will spend most of its life.

A further limitation on the energy gain will be obtained because when the radius of a spiraling proton in the cluster becomes comparable with the size of the scattering center, i.e., the galaxy with which it collides, the mechanism of acceleration breaks down. In galactic magnetic fields of 10^{-5} or 10^{-6} gauss, these radii are 10^2–10^4 parsecs or 10^3–10^5 parsecs, for protons in the energy range 10^{18}–10^{20} ev. Since the size of a galaxy is of the order of 10^4 parsecs, it is clear that energies near 10^{20} ev are the maxima attainable by this mechanism. A proton can either escape from the inner parts of a cluster by moving about magnetic field lines which naturally lead it to the outer parts and thence to the intergalactic medium between clusters, or else it will escape when its spiralling radius becomes comparable with the size of the inner part of the cluster. This latter condition is fulfilled if the magnetic field in the outer part decreases to a value $\lesssim 2\times 10^{-7}$ gauss (for a 10^{20}-ev particle).

We conclude that nucleon energies of 10^{18}–20^{20} ev per particle may be attained by acceleration among galaxies and the remnants of galactic collisions in the inner parts of highly concentrated clusters. If this is the only mechanism by which such energies can be attained[22] then if such particles are detected by extensive air-shower experiments, we may conclude that they have arisen in clusters of galaxies other than our own since this is far too loose an aggregate to accelerate particles appreciably above the energies that can be attained in our own galaxy. The nearest cluster which is highly effective is the Coma cluster which lies at a distance of 3.7×10^7 parsecs. (The Virgo cluster which lies at a distance of only 6×10^6 parsecs has a large number of members. However, it is not highly condensed and it seems that the upper limit to the energies which might be attained there is $\sim 10^{18}$ ev.) If more distant clusters are also of importance, it should be remembered that if particles are accelerated in clusters for which the red shift is large the maximum energies which may be detected will be lower than those from the Coma cluster, both because of the red-shift effect, and also because in an evolutionary cosmology they have had less time in which to be accelerated in that cluster.

If this mechanism is operative, we would not expect that above $\sim 10^{18}$ ev the spectrum of cosmic radiation necessarily has the same form as that observed due to particles accelerated in our galaxy. If an isotropic distribution of such high-energy particles is found, it may be due either to the effect of a large number of clusters covering an appreciable volume of the universe, or alternatively to the effect of intergalactic magnetic fields on particles escaping from one or two nearby clusters.

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[21] L. Spitzer and W. Baade, Astrophys. J. **113**, 413 (1951).

[22] B. Rossi (private communication) has indicated that energies $\sim 10^{18}$–10^{19} ev have been detected in experiments carried out at Massachusetts Institute of Technology.