Now recalling that this term (18) is to be subtracted from the others including Eq. (2), we note that the term involving $\ln(\lambda_{\min}{}^2/m^2)$ in these elements will cancel. The reason for this is clear: in both elements the infrared terms come from the emission of long wave-length (small $\boldsymbol{k}$) quanta. For small $\boldsymbol{k}$ the intermediate state $\boldsymbol{p}-\boldsymbol{k}$ is very nearly a free particle state and the self-energy operator

$$\int C(J^2)d^4J\gamma_\nu(\mathfrak{p}-\mathfrak{k}-\mathfrak{J}+m)\gamma_\nu/[(\boldsymbol{p}-\boldsymbol{k}-\boldsymbol{J})^2-m^2]J^2$$

arising in Eq. (1) is very nearly Δm appearing in (16).

VII. THE FOURTH-ORDER SELF-ENERGY

The fourth-order contribution to the self-energy is found by adding Eqs. (2), (10), and (15) and subtracting (18) from the result. We find for the self-energy

$$m(e^4/4\pi^2)\{-(19/8)\ln^2(\lambda^2/m^2)+(7/12)\ln(\lambda^2/m^2)\}. \quad (19)$$

It is encouraging, from the point of view of the theory, that this result behaves as $\ln^2(\lambda^2/m^2)$ in the leading term, and no stronger dependence upon λ exists. However, there is no cancellation between terms which would make the fourth-order self-energy finite, independently of λ. The contribution from the vacuum polarization term is quite strong; and it must therefore be taken into account here, and presumably therefore in any processes involving virtual quanta.

It has been suggested[6] that the self-energy might be represented as a summable series in Δm [second-order self-energy, Eq. A (21)] which would converge for large λ. Neither the relative signs nor the sizes of the coefficients of our result (19) seem to indicate much hope of this.

The statement made by Feynman just before Appendix A of reference 4 seems fully justified. The extreme complexity of the integrations required in any but the simplest higher order processes is apparent by comparison to those evaluated here.

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[6] G. Racah, Phys. Rev. 70, 406 (1946).

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On the Origin of the Cosmic Radiation

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Experimental evidence of the isotropy of the cosmic radiation of energy above 10^{13} ev is given. The interpretation of this result leads one to infer that the more energetic particles of the cosmic radiation are not of solar origin, but come from the whole galaxy. On the other hand, a local origin seems necessary for the particles of moderate energy (10^9–10^{10} ev).

During the months from August, 1950, to February, 1951, experiments have been performed in a salt mine, at a depth equivalent to 1600 m (geographical latitude 42°N) in order to study various properties of the cosmic radiation underground.[1] The ionizing particles were detected by the fourfold coincidences of a vertical telescope shielded by 14-in. Pb (sensitive surface of the counters 30×30 sq. in., maximum distance between counters 22 in.). The temperature inside the mine is constant throughout the year within a few hundredths of a degree. The operation of the apparatus was excellent; no counters had to be replaced during the experiment.

In 4154 hours of effective running 20,450 coincidences have been recorded (average rate 4.92 per hour) on a running tape, and their time distribution has now been analyzed in correlation with the solar time and the sidereal time. Within the statistical errors ($\sim$3 percent), no correlation of the rate of coincidences with either the solar time or the sidereal time has been found.

This result can be of interest in connection with the problem of the origin of the cosmic radiation. In fact, our experiments have indicated that the ionizing particles observed underground are mu-mesons produced in the atmosphere by primaries of energies from 10^{13} to 10^{14} ev; the absence of time correlation for the mu-mesons provides, therefore, experimental evidence of the isotropy of the more energetic particles of the primary cosmic radiation.[2–4] The statement about

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[1] A preliminary report of these experiments has been given at the New York meeting of the American Physical Society. See Phys. Rev. 82, 294 (1951).

[2] Auger, Daudin, Denisse, and Daudin, Compt. rend. 228, 1116 (1949).

[3] A. Daudin and J. Daudin, J. phys. et radium 10, 394 (1949).

[4] A variation with sidereal time of the frequency of the extensive showers at mountain altitudes has been reported by

the nature of the particles underground and their correlation with the primary radiation is based on the following facts: (a) the absorption in lead of the particles underground is equal to the absorption deduced from the well-known intensity *versus* depth curves. This shows that the particles observed underground arrive there losing energy all along the way mostly by ionization, and leads one to infer that they were produced with an average energy of about 10^{12} ev; (b) all the ionizing particles underground are accompanied above ground, in the air, by extensive showers containing at sea level on the average 500 to 1000 electrons each. Hence, the production of the particles observed underground must be due to primaries having energies of the order of 10^{13} to 10^{14} ev per nucleon, since otherwise the accompanying shower would not reach the surface of the earth. A primary energy per nucleon of at least the same order of magnitude is obtained, if one accepts the energy-multiplicity relation in the nucleon-nucleon collisions predicted by Fermi.[5]

We can thus make the statement that the particles of the primary radiation with energies from 10^{13} to 10^{14} ev arrive at the earth isotropically, within an accuracy of about 3 percent.

Not considering the possibility of an isotropic source of cosmic radiation spread uniformly over the whole galaxy, the only known mechanism which can give rise to the isotropy of such particles in space is their curling due to the action of irregular magnetic fields, extended over regions larger by some order of magnitude than the radius of curvature, ρ, of the path of the particles,

$$\rho = E/300H \text{ cm (energy } E \text{ in ev, magnetic field } H \text{ in gauss).}$$

An upper limit for the intensity of a magnetic field surrounding the solar system is believed to be $H = 10^{-5}$ gauss. This gives $\rho = 10^{16}$ to 10^{17} cm. The average distance between the stars in the region of the galaxy in the neighborhood of the sun is several light years, 10^{18} to 10^{19} cm, i.e., of the same order of magnitude as the distance which the particles of 10^{13} to 10^{14} ev have to sweep in order to be sufficiently stirred by a field of 10^{-5} gauss. Therefore, it seems likely that at least the more energetic particles of the primary cosmic radiation are not confined to the solar system, but come also from other stars. Possibly the whole galaxy contributes to their production. A galactic origin of the more energetic band of the cosmic radiation, say, above 10^{13} to 10^{14} ev, very likely implies that the length of the path of these particles in the galaxy is at least of the order of 10^{25} to 10^{26} cm. If the density of the interstellar matter is equal to 10^{-24} g cm^{-3}, this length corresponds to a thickness of at least 10 to 100 g cm^{-2}.

Assume that the galaxy is a sphere of radius R and that cosmic rays are produced at its center by a source of strength S.[6] The effect of the curling of the paths of the charged particles by the irregular magnetic fields is equivalent to the effect of an isotropic elastic scattering with mean free path $\lambda \approx \rho$. The diffusion equation in this case is the Laplace equation:

$$\tfrac{1}{3}\lambda v \nabla^2 n + S\delta(r) = 0,$$

where v is the velocity and n the density of the particles at a distance r from the center of the galaxy. With the condition that $n = 0$ when $r = R$, the solution is

$$n = A\left(\frac{1}{r} - \frac{1}{R}\right),$$

where A is a constant. To find the ratio

$$1 + a = \frac{I(0)}{I(\pi)} = \frac{\text{intensity of the radiation coming from the center of the galaxy}}{\text{intensity of the radiation coming from the opposite direction}},$$

assume that the flux per unit surface and unit solid angle of the particles at a point at a distance r from the center is given by the expression,

$$F(\theta) = f + g\cos\theta,$$

where θ is the angle between the tangent to the trajectory of the particle at the point considered and the line connecting that point to the center; g represents the anisotropy of the radiation at the distance r. Thus,

$$1 + a = (f+g)/(f-g) = \sim 1 + 2(g/f)$$

and

$$a = 2g/f.$$

Furthermore,

$$n = 4\pi f/v.$$

The net outward flux, $I(0) - I(\pi)$ can be obtained both from the expression for the flux, $F(\theta)$, and from the diffusion equation. In the first case,

$$I(0) - I(\pi) = 2\pi \int_0^\pi g\cos^2\theta \sin\theta d\theta = \frac{4\pi}{3} g.$$

In the second,

$$I(0) - I(\pi) = -\frac{1}{3}\lambda v \nabla n = \frac{1}{3}\lambda v \frac{A}{r^2} = \frac{4\pi}{3}\lambda f \frac{R}{r(R-r)}.$$

Equating the two results one obtains

$$g/f = (\lambda/r)R/(R-r)$$

Auger *et al.* (see reference 2). Later (see reference 3), the same group found that the fluctuations observed could be correlated with the fluctuations of the temperature of the atmosphere, hence did not provide evidence for a sidereal effect.

[5] E. Fermi, Prog. Theor. Phys. **5**, 570 (1950).

[6] This is not an oversimplified picture, since most of the galactic matter is concentrated near the center of the galaxy, and the sun is quite far from it. See, for example, A. Unsöld, Z. Astrophys. **26**, 176 (1949).

and finally

$$\lambda/r=(a/r)(1-r/R).$$

The number of "collisions" a particle must suffer before diffusing through a distance r is

$$N=(r/\lambda)^2,$$

hence, the length of the path of the particle in the galaxy before reaching the distance r from the center is

$$s=2\pi\lambda N=2\pi r(r/\lambda)=4\pi r/[a(1-r/R)].$$

From our measurements, $a\leqslant 3\times10^{-2}$, and assuming for r the value of the distance of the sun from the center of the galaxy, $r=3\times10^{22}$ cm, and $r/R=0.5$, one obtains

$$\lambda\leqslant 2\times10^{20}\ \text{cm}\quad\text{and}\quad s\geqslant 3\times10^{25}\ \text{cm}\equiv 30\ \text{g cm}^{-2}.$$[7]

If, among the primary particles, there are heavy ions, their probability of colliding with the interstellar matter will be quite high, their mean free path for nuclear collision being of about 20 g cm^{-2}. This means, first, that the number of heavy ions which reach the earth is much smaller than the number of ions formed at the center of the galaxy; second, that the charge spectrum of the ions is a continuous one, because in the interactions with interstellar matter all kinds of fission nuclei are formed. The first argument does not apply to the protons, because even if they lose some energy in each collision they will gain energy in the interaction with the irregular magnetic fields, as shown by Fermi.[8]

If this picture is true, we can anticipate that the charge spectrum of the high energy band (above 10^{13} to 10^{14} ev) of the cosmic radiation is very different from that observed for moderate energy particles (10^9 to 10^{10} ev). Namely, it will not show the deficiency of Li, Be, B atoms observed by Bradt and Peters,[9] and the relatively high abundance of heavy ions.

This point needs experimental check. No data are thus far available.

The value found previously for λ determines a lower limit for the intensity of the irregular magnetic fields in the galaxy:

$$H_{\min}=10^{14}eV/300\lambda=\sim10^{-9}\ \text{gauss}.$$

The isotropy observed could be considered as a proof of the existence of such fields in the galaxy.

If these fields exist, the particles of the cosmic radiation of moderate energy, e.g., 3×10^9 ev, will move along orbits with a radius of curvature

$$\rho=10^{16}\ \text{cm}=\lambda_1,$$

and if they too come from the center of the galaxy, the length of their path before reaching the earth will be at least

$$s_1=2\pi r(r/\lambda_1)=\sim10^{30}\ \text{cm}\equiv10^6\ \text{g cm}^{-2}.$$

On the other hand, the fact that the cosmic radiation of moderate energy has a charge spectrum quite rich in heavy nuclei and probably very poor in Li, Be, B nuclei strongly suggests, as shown by Bradt and Peters,[9] that these particles have not crossed a thickness of material larger than ~1 g cm^{-2}. The only way out seems to be to assume that the moderate energy particles do not come from very far, but are locally generated by the sun. It may be that they are mostly trapped in the closed orbits of the magnetic field of the sun: in this case their life-time, as shown by Kane, Shanley, and Wheeler,[10] would be of the order of 10^4 years, and the thickness of matter crossed smaller than 1 g cm^{-2}.

In conclusion, the picture we propose is the following. The less energetic particles of the primary cosmic radiation, up to energies of about 10^{10} ev, come from the sun. They are mostly captured by the planets, with a lifetime of 10^4 years. Their charge spectrum reflects the composition of the region of the sun in which they were produced. Their isotropy is insured by their interaction with the magnetic fields of the sun, the earth, and possibly of the planets, as shown by Kane, Shanley, and Wheeler.[10]

The more energetic band of the primary cosmic radiation (energies above 10^{13} to 10^{14} ev) is not produced in the solar system, but comes from the whole galaxy. It consists of the particles which have leaked out from the trapping fields of the producing stars and have possibly undergone further acceleration in the cosmic space. These particles disappear, partly destroyed by collisions with interstellar matter, and partly by diffusing out of the galaxy; anyway their lifetime is at least of the order of 10^8 years and their charge spectrum does not maintain the peculiarities of the composition of the stars from which the particles come.

An intermediate region of energies must be present, whose characteristics are intermediate between those of the two extreme bands.

With a picture of this kind, the density δ of the energy of the cosmic radiation in the galaxy would essentially be the density of the energy of the particles with energy above, say, 10^{13} ev; with the usual 1.8 power spectrum, $\delta=6\times10^{-15}$ erg cm^{-3}; with a lifetime of 10^8 years this corresponds to an output of power 10^6 times smaller than the power going into electromagnetic radiation. The argument of Richtmeyer and Teller[11] against a galactic origin of the cosmic radiation thus loses some of its weight.

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[7] Smaller values for λ and larger values for s would be found if, instead of a spherical galaxy, one assumed a disk-like one, as it actually is.

[8] E. Fermi, Phys. Rev. **75**, 1169 (1950).

[9] H. L. Bradt and B. Peters, Phys. Rev. **80**, 943 (1950).

[10] Kane, Shanley, and Wheeler, Revs. Modern Phys. **21**, 51 (1950).

[11] R. D. Richtmeyer and E. Teller, Phys. Rev. **75**, 1729 (1949).