Flux at Sea Level of Heavy Charged Particles Pair-Produced in Cosmic Ray Showers*

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The flux at sea level of charged particles with mass 300–600 electron masses is calculated assuming the particles to be pair-produced by cosmic ray photons. The cross section for pair production, including the effects of nuclear size, is folded into the distribution of photons predicted by shower theory. Absorption of the produced particles is also considered approximately. The results are well below the experimental upper limit set up by Keuffel and co-workers.

RECENTLY Alikhanian *et al.*[1] have reported the existence of a charged particle of mass 550 electron masses in the cosmic radiation. These particles appeared to lose energy by ionization only, and occurred with an abundance relative to μ mesons of 0.5%. A number of later experiments have thrown doubt on this result. Keuffel *et al.*[2] found an upper limit of 0.2%, while others[3–5] did not detect the particle at all. At present, it appears that if such particles do exist, they occur in cosmic radiation with an abundance too small to have been detected. It is of interest to see whether this low abundance is compatible with their existence. We give here the results of a calculation of the flux of such particles at sea level, assuming that they are produced electromagnetically in pairs by photons in cosmic-ray showers.

If we assume that all showers start at a height h (measured in radiation lengths) above sea level, the total number of positive particles of mass μ produced over the whole atmosphere per cm² per sec is

$$0.79\times 10^{24}\int_{2\mu}^{\infty} dE_0 f(E_0)\int_0^h dx\int_{2\mu}^{E_0}\sigma(k)P(k,E_0,x)dk,$$

where $\sigma(k)$ is the pair-production cross section for a photon of energy k. We assume that the shower develops completely vertically, and hence $P(k,E_0,x)dk$ is the average number of photons with energy between k and $k+dk$ in a shower of total energy E_0 at a depth x below the shower starting point. $f(E_0)dE_0$ is the number of showers occurring per cm²-sec with total energy between E_0 and E_0+dE_0. The numerical factor represents the conversion from radiation lengths to the number of target nuclei per cm².

Most of the production takes place many radiation lengths above sea level. Therefore, the showers are well past their maxima by the time they reach sea level, and the integral over x can be extended to ∞. We then have

$$\int_0^{\infty} dx\, P(k,E_0,x)=g(k,E_0),$$

where $g(k,E_0)$ is what is usually called the photon track length integral. We assume that all showers develop as if they had originated from electrons, in which case the track length is known to be[6]

$$g(k,E_0)=0.57(E_0/k^2).$$

Since the photon-track length decreases rapidly with photon energy, the integral over k can now be extended to ∞. The flux of positive particles is then

$$0.79\times 10^{24}\times 0.57\bar{E}_0\int_{2\mu}^{\infty} dk\,\sigma(k)/k^2, \tag{1}$$

where $\bar{E}_0=\int_{2\mu}^{\infty}E_0 f(E_0)dE_0$ is the total flux of energy going into showers. Greisen[7] has estimated the energy in a shower to be 11 Bev per electron at sea level. In addition, Cocconi[8] has calculated the flux of shower-produced electrons at sea level as 8×10^{-3} per cm² per sec. Therefore, we take

$$\bar{E}_0=0.088 \text{ Bev/cm}^2\text{-sec}.$$

The cross section $\sigma(k)$ is the sum of two parts, incoherent production by the individual protons of the nucleus, and coherent production by the nucleus as a whole. The incoherent part, assuming each proton to act as a free particle, is simply the integrated Bethe-Heitler cross section multiplied by the atomic number Z. The coherent production is complicated by the nuclear size which requires the differential cross section to be multiplied by the square of a form factor $F(q^2)$. For oxygen this form factor, determined from electron

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scattering experiments,[9] may be taken to be

$$F(q^2)=[1-(aq^2/4)]\exp(-aq^2/4),$$
$$a=0.889\times10^{-2}/\text{Mev},$$

where q is the momentum transfer to the nucleus. In order to evaluate the total cross section, it is most convenient to use the form given by Jost, Luttinger, and Slotnick[10] in which only one numerical integration over q is necessary. The major effect of the form factor is to lower the cross section near threshold, where q is largest. The coherent production becomes predominant at $k/\mu\approx10$ and at $k/\mu\approx200$ is approximately the Bethe-Heitler cross section multiplied by Z^2.

It has been assumed that the produced particles have spin $\frac{1}{2}$ and no anomalous magnetic moment. For spin 0 particles the cross sections is of the same order, decreasing at very high energies to 4/7 the cross section for spin $\frac{1}{2}$ particles.[11] For particles with spin $\frac{1}{2}$ and an anomalous magnetic moment, and for higher spins the cross section is generally higher than that used here.[12] In any case, the order of magnitude of the result would not change.

Equation (1) gives the total number of positive particles produced. However, those with insufficient range to reach sea level must be subtracted off. For those positive particles produced at depth x by photons of energy k the fraction with range greater than $h-x$ is

$$c(k)=1-[1/\sigma(k)]\int_0^{E_x}(d\sigma/dE)dE,$$

where $\sigma(k)=\int_0^{k-2\mu}(d\sigma/dE)dE$, and E_x is the kinetic energy corresponding to range $h-x$. $d\sigma/dE$ is the cross section as a function of the kinetic energy of the outgoing positive particle, and except at very high energies is reasonably constant.[13] Therefore, we have taken

$$\int_0^{E_x}(d\sigma/dE)dE=[E_x/(k-2\mu)]\sigma(k),$$
$$c(k)=1-E_x/(k-2\mu).$$

Moreover, in an electromagnetic shower of energy E_0 the flux of photons of energy k reaches a maximum at depth[6]

$$T=1.01[\log(E_0/k)-\tfrac{1}{2}].$$

We have assumed that all production takes place at this depth, so that E_x is that kinetic energy for range $h-T$. E_0 may vary from 10^{12} to 10^{15} ev, while h should be approximately the height of the atmosphere, 25–30 radiation lengths. We have computed the correction factor $c(k)$ assuming the energy losses to be due entirely to ionization. Within this range of values for E_0 and h, the quantity $c(k)$ does not vary by more than 25%, except where the cross section is very small. A set of values which give a median for $c(k)$ is $h=30$ and $E_0=10^{15}$ ev, and these have been used in the computations of the flux.

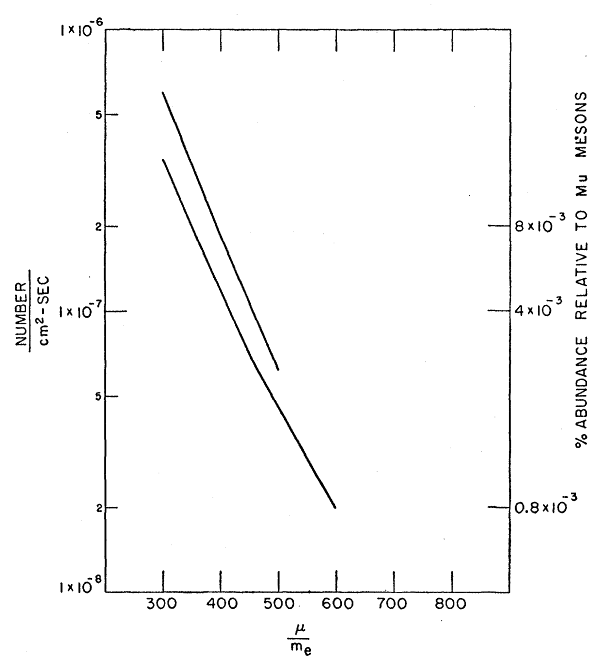

FIG. 1. Flux at sea level of positive particles vs mass of particles in units of electron masses.

The total flux of positive particles is then

$$N=0.79\times10^{24}\times0.57\bar{E}_0\int_{2\mu}^{\infty}dk\,[\sigma(k)c(k)/k^2].$$

This has been evaluated for $\mu=300$, 400, 500, and 600 electron masses. The results are given in Fig. 1. The lower curve represents the flux with the absorption correction $c(k)$ included, while the upper curve is the flux with no absorption. The effect of absorption is to reduce the flux by a factor of 2 to 3. The flux of μ mesons at sea level has been estimated by Cocconi[8] as $2.5\times10^{-2}/\text{cm}^2$-sec, and with this value the relative abundances are those listed on the right side of the graph. In all cases the abundances are well below Keuffel's upper limit. Hence, one would not expect to have found such particles even if they were to exist, unless they were made in some other way, e.g., were decay products of more strongly coupled particles as are the μ mesons.

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