Heavy-particle production by cosmic rays

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We calculate the production of heavy charged or strongly interacting particles by cosmic rays and find that any sufficiently light stable ones should be detectable in static terrestrial searches. Stable or nearly stable heavy hadrons would also be visible with a distinct signature in delayed-particle cosmic-ray experiments.

I. INTRODUCTION

Numerous unified models of elementary particles suggest that there may exist species of hadrons or charged leptons other than those already known. It is entirely possible that some of these new particles may be stable or nearly stable ($\tau \gtrsim 10^{-8}$ sec). Present accelerator experiments indicate that no such particles exist with masses less than about 4 GeV[1]; the next generation of accelerators should extend this search through their capability of pair-producing particles with masses of up to 15 GeV. At least in the immediate future, more massive particles can be found only if they are remnants from the early universe or are produced by interactions of cosmic rays. Only absolutely stable heavy particles produced in the early universe would have survived to the present, and conventional models of the early universe indicate[2] that such particles should be readily observable in forthcoming static terrestrial searches. Even if no heavy particles were created in the presumably high temperatures of the early universe, a small terrestrial abundance could still result from the interactions of cosmic rays with the earth's atmosphere. Stable or nearly stable heavy particles produced in this way might also be directly detectable in cosmic-ray experiments.

In this paper we consider various features of the production of possible heavy (nearly) stable particles by cosmic rays. We also discuss some of their properties. Throughout this paper we aim to provide only order-of-magnitude estimates since significantly more accurate predictions would require a knowledge of cosmic rays and particle interactions not yet available.

II. HEAVY-PARTICLE PRODUCTION

A. Charged-heavy-lepton production cross sections

Charged heavy leptons ($L^\pm$) which cannot come from the decays of weakly decaying heavier hadrons should be produced dominantly in the process

$$hN \to L^+ L^- X \quad (h = p, \pi, \ldots) . \tag{1}$$

(The reaction $\gamma N \to L^+ L^- X$ should not contribute significantly to cosmic-ray $L^\pm$ production.) The Drell-Yan model[3] for (1) depicted in Fig. 1 provides a very adequate description of muon pair production at accelerator energies. In view of the scaling properties of this model, the extrapolation to cosmic-ray energies is not very drastic. The cross section for the production of $L^\pm$ with mass m by hadrons of energy E incident on nucleons at rest is given in this model by

$$\sigma(hN \to L^+ L^- X) \simeq \frac{4\pi\alpha^2}{3s} \int_{4m^2}^{\infty} dQ^2 \frac{(1-4m^2/Q^2)^{1/2}}{Q^2} \times \left(1 + \frac{2m^2}{Q^2}\right) C(s, Q^2) ,$$

$$C(s, Q^2) = \tfrac{1}{3} \int_{Q^2/s}^{1} dx \sum_{i=u,d,s,\ldots} e_i^2 [G_{q_i/h}(x) G_{\bar{q}_i/N}(x') + G_{\bar{q}_i/h}(x) G_{q_i/N}(x')] , \tag{2}$$

$$s = 2M_N E ,$$

$$x' = \frac{Q^2}{sx} ,$$

where $G_{q_i/A}(x)$ is the probability that the quark q_i (with charge e_i) occurs in the hadron A with a fraction x of its momentum. We use quark dis-

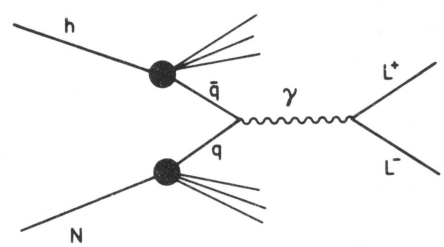

FIG. 1. The Drell-Yan picture for massive-lepton-pair production.

tributions which give a satisfactory description of recent data[4] on $pp \to \mu^+\mu^- X$, but our conclusions do not depend on their detailed form or Q^2 dependence.[5] Note that since π (but not p) contains valence antiquarks the cross section near threshold for $h=\pi$ is somewhat larger than that for $h=p$.

B. Heavy-hadron production cross sections

There is no universally accepted model for heavy-hadron (H) production. However, a simple model[6] based on lowest-order quantum-chromodynamics (QCD) perturbation theory probably provides an adequate estimate. This model is consistent with present limits on the production of charm by protons and photons. The subprocesses contributing to heavy-hadron production in the model are shown in Fig. 2; the most important is $GG \to Q\bar{Q}$ (G is a vector gluon, and Q the new quark presumably associated with any new type of hadron). Writing the differential cross section for these

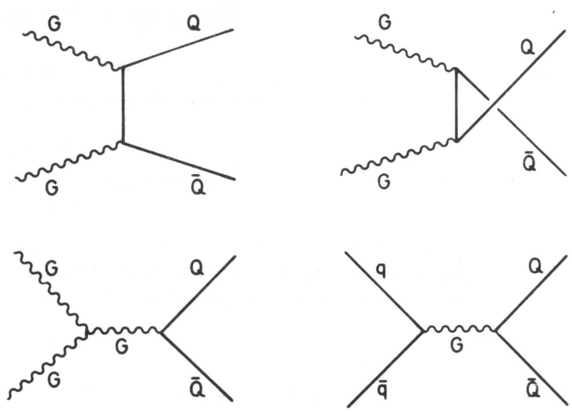

FIG. 2. QCD subprocesses contributing to heavy-quark production.

subprocesses as $d\sigma(ij \to Q\bar{Q})/d\hat{t}$, one finds[6] that the invariant production cross section for H by a hadron h incident with energy E on a nucleon at rest is given by

$$E_H \frac{d^3\sigma(hN\to HX)}{d\vec{p}_H} \simeq \frac{1}{\pi}\int_{x_{\rm min}}^{1} dx \int_{x'_{\rm min}}^{1} dx' \sum_{i,j} G_{i/h}(x) G_{j/N}(x')\, \mathfrak{F}(x,x',s,t,u)\,,$$

$$\mathfrak{F}(x,x',s,t,u) = \int \frac{dz}{z^2} D_{H/Q}(z) \frac{d\sigma(ij\to Q\bar{Q})}{d\hat{t}}(\hat{s},\hat{t},\hat{u})\,\delta(\hat{s}+\hat{t}+\hat{u}-2m_Q^2)\,,$$

$$s=(p_h+p_N)^2 = 2m_N E,\quad t=(p_h-p_H)^2 = -2E(E_H-p_H'') + m_H^2,\quad u=(p_N-p_H)^2 = -2m_N E_H + m_H^2\,,$$

$$\hat{s}=xx's,\quad \hat{t}=xt/z,\quad \hat{u}=x'u/z,\quad x_{\rm min}=\frac{2m_H^2-u}{s+t},\quad x'_{\rm min}=\frac{2m_H^2-xt}{xs+u},\quad P_H''=\frac{\vec{p}_h\cdot\vec{p}_H}{|\vec{p}_h|},\quad \vec{p}_H^{\,\prime\prime}=\vec{p}_H - p_H''\frac{\vec{p}_h}{|\vec{p}_h|}\,, \tag{3a}$$

where $D_{E/Q}(z)$ is the probability that the final H carries a fraction z of the momentum of the Q from which it evolved. We take

$$D_{H/Q}(z) = 3(1-z)^2. \tag{3b}$$

Since this "fragmentation function" is normalized to unity, the total H-production cross section becomes

$$\sigma(hN\to HX) \simeq \int_{4m_H^2/s}^{1} dx \int_{4m_H^2/sx}^{1} dx' \sum_{i,j} G_{i/h}(x) G_{j/N}(x') \int_{\hat{t}_{\rm min}}^{\hat{t}_{\rm max}} d\hat{t}\, \frac{d\sigma(ij\to Q\bar{Q})}{d\hat{t}}(\hat{s},\hat{t},\hat{u})\,,$$

$$\hat{t}_{\substack{\rm max\\ \rm min}} = \left(\frac{2m_H^2-\hat{s}}{2}\right) \pm \tfrac{1}{2}[\hat{s}(\hat{s}-4m_H^2)]^{1/2}. \tag{4}$$

Our results are not sensitive to the form of the gluon momentum distribution assumed.[5] Note the similarity of Eq. (4) to the (successful) Drell-Yan model cross section for leptons given in Eq. (2). However, because it is dominantly gluons rather than quarks and antiquarks which react to produce the $Q\bar{Q}$ pair, the cross sections for this process are almost identical when it is initiated by protons and by pions.

C. The cosmic-ray flux

The last two sections were devoted to a discussion of the production cross sections for heavy leptons and hadrons; to find their cosmic-ray production rates we must convolute these cross sections with the cosmic-ray flux through the atmosphere. An approximate empirical formula for the flux of hadrons of energy E at a depth x (in kg m^{-2}—sea level corresponds to $x \simeq 10^4$) is[7]

$$\phi(E,x) \simeq 10^5[E\,({\rm GeV})]^{-2.6} \times \exp[-x({\rm kg\,m^{-2}})/1300]\ {\rm m^{-2}sec^{-1}\,GeV^{-1}}. \tag{5}$$

This flux contains both pions and nucleons; the presence of pions will increase the heavy-lepton production rate by a factor of about 2. Secondary hadron production in the atmosphere [which is accounted for by the form of the exponential in Eq. (5)] increases all production rates by a factor of about 1.3. The total flux of a particle produced with cross section $\sigma(E)$ by a cosmic ray of energy E is then simply

$$F \simeq \int_{E_{\min}}^{\infty} dE\, 1.3\phi(E,0)\sigma(E)/\sigma_{\text{tot}}(E)\,, \qquad (6)$$

where $\sigma_{\text{tot}}(E)$ is the total hN cross section.

D. Production rates

In Fig. 3 we have plotted the expected direct pair-production cross section for heavy leptons of several masses as a function of the energy of the incident hadron.[8] Figure 4 shows our prediction for heavy hadrons. It is clear from Fig. 3 that the flux of heavy leptons would probably be very small, unless they could be generated in a hadron decay, in which case their flux would be simply the flux for that hadron multiplied by its branching ratio to the heavy lepton. When these cross sections are convoluted with the total cosmic-ray flux according to Eq. (6), we find the total flux of heavy hadrons and leptons as a function of their mass given in Fig. 5. Tolerable fits to these fluxes are given by

$$\begin{aligned} F_{\text{leptons}} &\simeq 4\times10^{-6}[m\ (\text{GeV})]^{-5.3}\ \text{m}^{-2}\text{sec}^{-1}\,,\\ F_{\text{hadrons}} &\simeq 9\times10^{-2}[m\ (\text{GeV})]^{-5.8}\ \text{m}^{-2}\text{sec}^{-1}\,. \end{aligned} \qquad (7)$$

These results are not affected drastically by requiring that the incident hadron energy exceed some minimum. For example, with a cutoff of 10 TeV, the hadron flux is reduced significantly only for masses below about 5 GeV.

Far above threshold our predictions for heavy-hadron production (Fig. 4) are rather insensitive to the details of our model. Close to threshold,

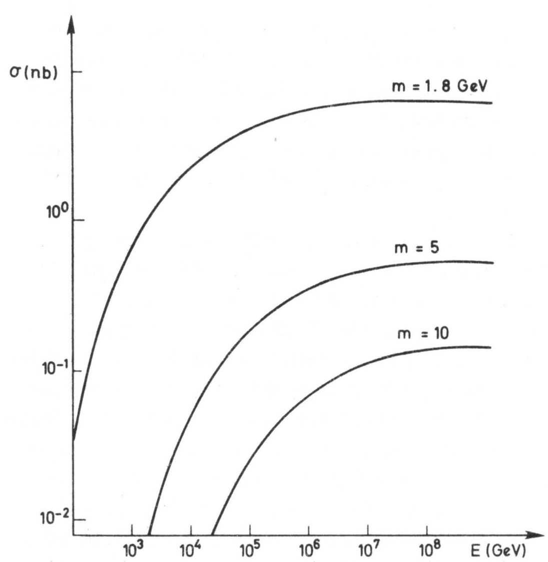

FIG. 3. Cross section for proton-proton collisions to produce a pair of heavy charged leptons with various masses as a function of the incoming proton energy E.

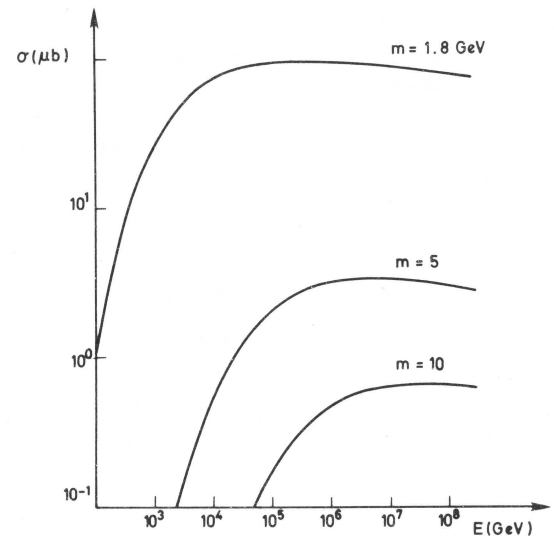

FIG. 4. Cross section for proton-proton collisions to produce heavy hadrons of various masses as a function of the incoming proton energy E.

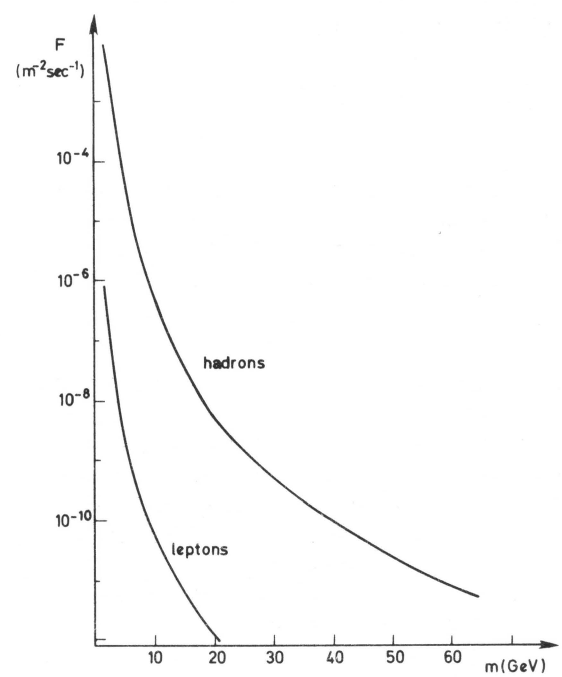

FIG. 5. Total flux of stable heavy hadrons and directly produced charged leptons generated by cosmic-ray particles in the atmosphere, based on a logarithmic extrapolation of the observed rise in σ_{tot}.

however, the predicted cross section depends strongly on, for example, the assumed form of the gluon distribution. Since it is in this threshold region that most accelerator searches for heavy hadrons have been performed, we can make no meaningful comparison of their limits with the predictions of our model.

III. PROPERTIES OF NEW PARTICLES AND TERRESTRIAL SEARCHES

A. Stable heavy leptons

Charged heavy leptons will interact mainly electromagnetically. The range of such stable heavy leptons after production should therefore be about

$$R_L \simeq 5\times 10^3[E_L^{\text{lab}}\,(\text{GeV})]\ \text{kg m}^{-2}. \tag{8}$$

Heavy leptons should mostly be produced nearly at rest in the center-of-mass system. Their mean energy in the earth's frame would therefore be about $10m_L^2/m_N$ since the L production rate is largest when the incident cosmic ray has an energy $\simeq 200m_L^2/m_N$. Hence their range (in water) should be about $5[m_L^2\,(\text{GeV}^2)]m$. Lighter $L^\pm$ ($m \leqslant 10$ GeV) will therefore stop in the oceans (the L^+ forming "water" and the L^- perhaps "ammonium" ions). Heavier ones will stop deep in the earth; they might be found in lava. The abundance of light L^+ in ocean water should be given in terms of the flux F [Eq. (7)] by[9]

$$\frac{n_{L^+}}{n_{\text{nucleons}}} \simeq 5\times 10^{-17}\,[F\,(\text{m}^{-2}\text{sec}^{-1})] \simeq 10^{-22}\,[m\,(\text{GeV})]^{-5.3}. \tag{9}$$

Since terrestrial searches may reach a sensitivity of one new particle in ~10^{29} nucleons (of sea water)[10] they should be sensitive to new stable heavy leptons with masses up to about 20 GeV.

B. Heavy hadrons

Heavy hadrons would undergo secondary interactions in the atmosphere after production. The strong interactions of possible heavy hadrons are essentially unknown; we expect their cross sections to be similar to those of light hadrons.[11] We estimate that $\sigma_{\text{tot}}(HN) \simeq 10$ mb at high energies and that the average inelasticity $\langle\eta\rangle$ of an HN collision is about 0.3, and expect these guesses to be correct to within a factor of 2.

Semistable heavy hadrons (with lifetimes $\gtrsim 10^{-8}$ sec) could only be detected in delayed-particle cosmic-ray experiments[1,12] (see Sec. IV); stable ones are, however, also amenable to direct terrestrial searches. The mean range of stable hadrons of energy E is given very approximately by

$$R_H \simeq \frac{\log[E\,(\text{GeV})]}{\log[1/(1-\eta)]}\,\lambda\ , \tag{10}$$

where λ is their interaction length. Heavy hadrons, like heavy leptons, tend to be produced nearly at rest in the center-of-mass system [typically the fractional longitudinal momentum (x_F) distribution for heavy hadrons produced far above threshold is $\exp(-20x_F)$], so that their mean energy in the earth's frame is about $10m_H^2/m_N$. Using this and the above-mentioned estimates for σ and η, we find that $R_H \simeq 50$ m in water, equivalent to about five times the atmospheric depth. Neutral and negatively charged heavy hadrons should be captured in nuclei when they stop, but positive ones should capture an electron to form a hydrogenlike atom (as do positive pions). The concentration of possible heavy hadrons in the form of ocean water would therefore be approximately

$$\frac{n_H}{n_{\text{nucleons}}} \simeq 4\times 10^{-18}\,[m\,(\text{GeV})]^{-5.8}\ , \tag{11}$$

so that terrestrial searches in sea water could detect stable heavy hadrons with masses up to ~100 GeV. Searches might also be considered in substances such as ocean sediments and moon rock in which the concentration of these particles would not have been so diluted (the concentration of a 10 GeV stable heavy hadron in a core from ~10 m below the lunar surface could be as great as one in 10^{17} nucleons).

IV. DELAYED-PARTICLE COSMIC-RAY SEARCHES

The basic principle of a delayed-particle cosmic-ray experiment[1,12] is to search for particles which traverse the apparatus after the main part of an air shower has passed. Two measurements are usually made on these particles: their delay relative to the shower front and the energy that they deposit.

We consider an experiment under 8000 kg m^{-2} of the atmosphere, and with an effective area of 1 m^2, and we specialize our discussion to the production of hadrons; heavy leptons would probably be produced at a rate too small to be detected by present experiments and would deposit insufficient energy to register in a calorimeter. Very-high-energy primary cosmic-ray protons tend to interact within the top 1000 kg m^{-2} of the atmosphere, about 15–20 km above the experiment, so any heavy hadrons produced will interact on average about twice before reaching the apparatus. They will as a result have an average energy of ~$5[m_H\,(\text{GeV})]^2$ GeV at that point, with, however, a considerable spread about this mean value.[13] If, instead of our previous estimates of $\sigma_{tot}(HN)$ and η we took H to interact like a kaon, it would have an average energy of $\sim[m_H\ (\mathrm{GeV})]^2$ GeV, a possibility which we consider to be a lower bound. Since a particle with $\gamma = E_H/m_H$ will be delayed by a time $\Delta\tau \sim 1600\ \mathrm{h(km)}/\gamma^2$ nsec relative to a particle with $\beta = 1$ over a distance h, the delay time for heavy hadrons would be $\Delta\tau \sim 400\ [m_H\,(\mathrm{GeV})]^{-2}$ nsec. This result is, however, sensitive both to the average H energy and to η: we find empirically that $\Delta\tau \overset{\propto}{\sim} E_H^{-2}(1-\eta)^{-4}$ with only slight dependence on $\sigma_{tot}(HN)$. (The apparent correlation between $\Delta\tau$ and E_H should, incidentally, be washed out by fluctuations.) Since we expect heavy hadrons to be produced with $\langle p_T\rangle \simeq m_H/2$ (and therefore within the shower cone), an experiment with perfect detection efficiency might then observe $\sim 3\times 10^6\ [m\ (\mathrm{GeV})]^{-5.8}$ heavy hadrons per year.[14]

Thus, for example, if there is a stable hadron[15] with a mass of around 5 GeV then the experiment considered above should observe $\lesssim 500$ such particles per year; their average delay time should be about 20 nsec and their energy around 100 GeV. Even if this particle has a lifetime $\sim 10^{-7}$ sec, it should still enter the apparatus at a detectable rate. Note that the detection of such a long-lived particle, if identified with a meson containing the b quark, would rule out the Kobayashi-Maskawa six-quark CP-violation model.[16]

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[1]Limits from hadroproduction experiments depend on assumptions about heavy-hadron production cross sections; the limits quoted here are based on e^+e^- collisions where the cross section is presumably well known. For a recent review see L. W. Jones, Rev. Mod. Phys. 49, 717 (1977).

[2]S. Wolfram, Phys. Lett. B (to be published). See also related studies by Ya. B. Zeldovitch, L. B. Okun', and S. B. Pikel'ner, Usp. Fiz. Nauk 87, 113 (1965) [Sov. Phys.—Usp. 8, 702 (1966)]; B. W. Lee and S. Weinberg, Phys. Rev. Lett. 39, 165 (1977); D. A. Dicus, E. W. Kolb, and V. L. Teplitz, *ibid.* 39, 168 (1977).

[3]S. D. Drell and T.-M. Yan, Ann. Phys. (N. Y.) 66, 578 (1971); for a more recent treatment see E. L. Berger, invited talk at the Vanderbilt Conference, 1978 (unpublished); C. Quigg, Rev. Mod. Phys. 49, 297 (1977).

[4]S. W. Herb *et al.*, Phys. Rev. Lett. 39, 252 (1977) and references therein.

[5]We use the quark distribution functions of Ref. 6 and a gluon distribution function proportional to $x^{-1}(1-x)^5$.

[6]J. Babcock, D. Sivers, and S. Wolfram, Phys. Rev. D 18, 162 (1978).

[7]S. Hayakawa, *Cosmic Ray Physics* (Wiley, New York, 1969), p. 349; also the model of M. Hillas (private communication from E. W. Kellermann).

[8]Muon-electron pairs produced in pp collisions may be used as a signal for charm production. This source will undoubtedly swamp any signal in this channel due to heavier hadronic flavors; our calculations indicate that the background to charm from $\tau^+\tau^-$ production will also be negligible (less than 10^{-4}). This result is in agreement with previous similar calculations, for example, those of R. Bhattacharya, J. Smith, and A. Soni, Phys. Rev. D 13, 2150 (1976).

[9]P. F. Smith and A. H. Spurway, Rutherford Laboratory Report No. R1-73-023 (unpublished). These values are based on integration over the lifetime of the oceans.

[10]H. J. Rose, private communication.

[11]Bound states of two heavy quarks (such as the ψ), however, should and do have cross sections significantly smaller than hadrons containing light quarks.

[12]G. B. Yodh, University of Maryland report 1978 (unpublished).

[13]Unlike ionization losses, strong-interaction losses are caused by only a small number of interactions, which are rather inelastic. The fluctuations of the ranges of about the mean will therefore be much larger.

[14]There have been reports of delayed particle production in cosmic rays. See S. C. Tonwar, S. Naranan, and B. V. Sreekantan, J. Phys. A 5, 569 (1972) and references therein, and J. A. Goodman, R. W. Ellsworth, A. Ito, J. R. MacFall, F. Sidhan, R. E. Streitmatter, S. C. Tonwar, P. R. Vishwanath, and G. B. Yodh, Bull. Am. Phys. Soc. 23, paper No. 511 (1978).

[15]R. H. Cahn, Phys. Rev. Lett. 40, 80 (1978).

[16]The scheme of M. Kobayashi and K. Maskawa [Prog. Theor. Phys. 49, 652 (1973)] could not accommodate such a long-lived $b\bar{q}$ state. A lifetime $\gg 10^{-13}$ sec would require such a new hadron to have a mixing angle significantly smaller than the Cabbibo angle.