"Energy Crisis" and Heavy Leptons

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A pair of heavy leptons with a mass of 1.8 GeV can explain the step-function–like behavior of the charge-particle energy fraction in e^+e^- annihilation except for the resonance region around 4.1 GeV. The preliminary result of the e-μ events reported by Perl, in particular the effects of spin alignment, are discussed in terms of this heavy lepton. We comment on a possible way to distinguish the heavy lepton from heavy hadrons.

It has been suggested by several authors[1] that the possible existence of heavy leptons might be responsible for the peculiar phenomena observed in e^+e^- annihilation such as the rising ratio $R = \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$.[2] Another interesting aspect in e^+e^- annihilation is the neutral-particle energy excess, which is often referred to as the "energy crisis."[3] In this paper we discuss the effects of the possible existence of a heavy lepton with a mass of 1.8 GeV on the energy crisis and the rising ratio R. We show that the heavy lepton can explain the step-function–like behavior starting at $\sqrt{S} = 3.6$ GeV in the energy-crisis curve.[3]

More specifically we assume a special kind of heavy leptons which are generally referred to as "sequential heavy leptons."[4] The sequential leptons consist of the heavy charged leptons (L^-, L^+) and the associated massless neutrinos $(\nu_L, \bar{\nu}_L)$. The weak and electromagnetic interactions are assumed to act on e, μ, and L universally. The mass of the heavy lepton is taken as $M_L = 1.8$ GeV. Based on this mass asignment we repeated the evaluation of various decay modes, and the ratio of these decay modes relative to the leptonic one is shown in Table I. A general calculational scheme of this problem has been given by several authors.[5] Here we briefly comment on the basic assumptions and experimental parameters used in this estimation.

(i) The electron and muon masses are neglected.

(ii) Single-particle contributions are estimated on the basis of the parametrization found in Ref. (5). The unknown coupling constants such as A_1 and K^* couplings are estimated by using the second Weinberg sum rule and the Das-Mathur-Okubo sum rule.[5]

(iii) The hadronic continuum is treated by assuming conservation of vector current, asymptotic chiral symmetry, and asymptotic SU(3) symmetry.[4,5] In our calculation, we assume that the hadron continnum starts around 1 GeV and we used the averaged experimental value of $R(S)$ in e^+e^- annihilation,[3]

$$\bar{R} = 1.5 \text{ for } 1.8 \text{ GeV} \geq \sqrt{S} \geq 1 \text{ GeV}. \qquad (1)$$

From the total width given in Table I, the lifetime of this heavy sequential lepton is estimated at $\simeq 3.0 \times 10^{-13}$ sec.

(iv) We estimate the energy fraction carried by charged particles in L decay. This calculation for single-particle contributions is rather straightforward because the decay modes of the parti-

TABLE I. Partial decay rates normalized to the leptonic mode and the energy fraction carried by charged particles. (All the charged particles in the final state are assumed to be pions.)

Decay mode	Ratio	Charged-particle energy fraction
$L \to \nu_L + \nu_e + e$	1.00	0.35
$\nu_L + \nu_\mu + \mu$	1.00	0.35
$\nu_L + \pi$	0.55	0.50
$\nu_L + K$	0.02	0.46
$\nu_L + \rho$	1.20	0.30
$\nu_L + K^*$	0.06	0.25
$\nu_L + A_1$	0.44	0.46
ν_L + hadron continuum	0.97	0.44
ν_L + all hadrons[a]	3.24	0.40
Total rate	5.24	

[a] Sum of all the hadronic modes.

cles involved are well known. In the case of the hadronic continuum, the neutrino carries away the average energy

$$\bar{E} = \int_0^{0.62} E g(E)\,dE \Big/ \int_0^{0.62} g(E)\,dE = 0.45 \text{ GeV}, \qquad (2)$$

where $g(E)$ is the energy spectrum of the neutrino for the *leptonic* decay mode in the rest frame of L [in Eq. (2), scaling is assumed]. The charged hadrons carry approximately 0.59 times the residual energy. It is assumed that all the hadrons in the final state are pions. The energy fraction carried by charged particles in the decay of L thus evaluated is shown in Table I.

On the basis of the above decay properties of the heavy lepton, we next discuss the effects of the heavy lepton on the neutral to charged-particle ratio in e^+e^- annihilation. The energy fraction carried by charged particles for the "background" hadronic events is estimated at

$$r_h(S) \simeq 0.59 \qquad (3)$$

from the experimental data up to $\sqrt{S} = 3.6$ GeV.[3] The observed value of r_{ob} above the heavy-lepton threshold is then given by

$$r_{\text{ob}}(S) = \frac{r_h(S) R_h(S) + r_L \frac{1}{2}\beta(3-\beta^2)\delta}{R_h(S) + \frac{1}{2}\beta(3-\beta^2)\delta},$$

$$\beta \equiv (1 - 4M_L{}^2/S)^{1/2}, \qquad (4)$$

where r_L ($\simeq 0.39$) stands for the averaged energy fraction carried by charged particles for the decay modes hh, $h\mu$, he, and $\mu\mu$ in the L^+L^- decay. Here the μh mode, e.g., stands for the combined process $L^+ \to \mu^+ + \nu_\mu + \nu_L$ and $L^- \to \nu_L +$ hadrons, and the process where L^+ and L^- are interchanged. The parameter δ (0.89) is the total branching ratio for these four decay modes. The experimentally observed ratio $R_{\text{ob}}(S) = \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$ is given by

$$R_{\text{ob}}(S) = R_h(S) + \tfrac{1}{2}\beta(3-\beta^2)\delta. \qquad (5)$$

The theoretical prediction of the energy fraction carried by charged particles obtained from Eqs. (3) and (4) is shown in Fig. 1. The result appears to be consistent with experiment[3] except for the value around $\sqrt{S} = 4.1$ GeV, where $R_{\text{ob}}(S)$ shows a feature characteristic of a hadronic resonance. Our result may indicate that $r_h(S)$ cannot be a constant in this region. In Fig. 1, we counted the eh mode as hadronic events. If a part of this mode is excluded, the result is slightly modified.

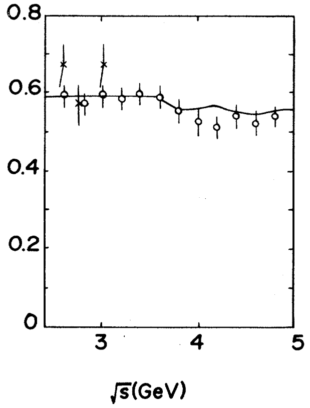

FIG. 1. Energy fraction carried by charged particles [see Ref. (3)]. The prediction given by Eq. (4) is shown by the solid curve.

We note that a slight increase in $R_{\text{ob}}(S)$, starting at $\sqrt{S} = 3.6$ GeV,[2] is well accounted for by Eq. (5). The ratio $R_{\text{ob}}(S)$ at 4.6 GeV, where the effect of the resonance at 4.1 GeV is small, is also consistent with the value given by Eq. (5) with $R_h(S) \simeq R_h(3.6 \text{ GeV}) \simeq 2.55 \pm 0.25$,

$$R_{\text{ob}}(4.6 \text{ GeV}) \simeq 3.2\text{–}4.2. \qquad (6)$$

The rapid increase of $R_{\text{ob}}(S)$ above 4.6 GeV[2] may be due to the opening of new particle-production channels. The rather stable behavior of $r_{\text{ob}}(S)$ around this energy indicates that these particles cannot be the heavy leptons with the conventional decay properties we assumed above.

We next discuss the preliminary experimental result of $e\mu$ events in e^+e^- annihilation reported by Perl.[6] He indicates that a heavy lepton with a mass of 1.8 GeV is consistent with the experimental result. One of the characteristic features of the $e\mu$ events is that the collinearity angle distribution is limited within 90°. If one takes the heavy-lepton interpretation of these $e\mu$ events, some effects of spin alignment on the collinearity angle θ_{coll} are expected.[5] In the following we examine this problem. To simplify the calculation we assume 4π-sr counters and no noncoplanarity cutoffs, which is not the case in the actual experiment. Because of this limitation our result cannot exactly reproduce the experimental situation. We can, however, still discuss the qualitative features of the spin-alignment effects.

The normalized distribution for the process

$$e^+ + e^- \to L^-(P) + L^+(P') \to \mu^-(p) + \nu_L + \bar{\nu}_\mu + e^+(q) + \bar{\nu}_L + \nu_e \qquad (7)$$

is readily evaluated as (after integrating over neutrino variables)

$$d\Gamma=\frac{1}{N}\{T_1+T_2\}\frac{d^3p}{2p_0}\frac{d^3q}{2q_0}\,\delta((P-p)^2-s)\,\delta((P'-q)^2-s')\,ds\,ds', \tag{8}$$

where

$$T_1=\left(\frac{Q^2+2M_L^2}{2M_L^2}\right)(P\cdot p)(P'\cdot q)(M_L^2+2s)(M_L^2+2s'), \tag{9}$$

$$T_2=(M_L^2-2s)(M_L^2-2s')\left\{M_L^2(q\cdot p)-(p\cdot P')(q\cdot P')-(p\cdot P)(q\cdot P)+\frac{Q^2-2M_L^2}{2M_L^2}(p\cdot P)(q\cdot P')\right\}, \tag{10}$$

$$N=\tfrac{1}{128}\pi^2M_L^{10}(Q^2+2M_L^2),\quad Q=P+P', \tag{11}$$

and

$$0\leqslant s\leqslant M_L^2,\quad 0\leqslant s'\leqslant M_L^2,\quad S=Q^2. \tag{12}$$

Here T_2 is the spin-alignment term arising from the parity nonconservation in the weak decay. In writing (8), the calculation was simplified by first taking an average over the direction of the *incident* electrons with the final-state configuration fixed. This is justified if one assumes 4π-sr counters. The distributions of $\cos\theta_{\text{coll}} \equiv -(\vec{p}\cdot\vec{q})/|\vec{p}\,|\,|\vec{q}\,|$ obtained from Eq. (8) for incident energies $\sqrt{S}=4.8$, 6.8, and 8.8 GeV with various cutoffs E_c, $p_0\geqslant E_c$, and $q_0\geqslant E_c$ are shown in Fig. 2. The main features of this calculation are as follows: (i) By reducing the heavy-lepton mass from 2 to 1.8 GeV, the distribution for $\theta_{\text{coll}}>90°$ can be substantially reduced. (ii) The distribution is also rather sensitive to E_c. If one takes $E_c=0.75$ GeV instead of the experimental value 0.65 GeV at $\sqrt{S}=4.8$ GeV, the distribution for $\theta_{\text{coll}}>90°$ is further reduced. (iii) The spin-alignment term gives a contribution of 4-5% to the total distribution. It is positive for $\theta_{\text{coll}}<60°$ and negative for $\theta_{\text{coll}}>60°$ at $\sqrt{S}=4.8$ GeV and $E_c=0.65$ GeV. The effects of the spin alignment are therefore small for this configuration. Under certain conditions, however, the spin alignment becomes important. For example, at $\sqrt{S}=8.8$ GeV and $E_c=3$ GeV it gives rise to about 20% of the total distribution.

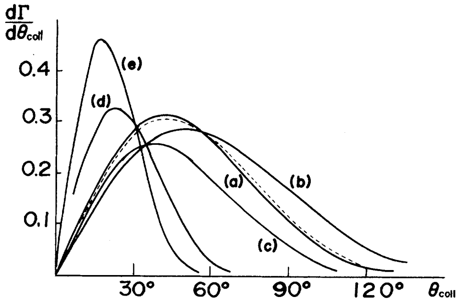

FIG. 2. Normalized collinearity-angle distribution of the $e\mu$ events via a heavy lepton pair without any noncoplanarity cutoffs. Solid curves include the effects of spin alignment. Dashed curve is without the spin alignment term for $\sqrt{S}=4.8$ GeV, $M_L=1.8$ GeV, and $E_c=0.65$ GeV. The values of $\sqrt{S}$, M_L, and E_c in GeV are, for curve *a*, 4.8, 1.8, and 0.65; for curve *b*, 4.8, 2.0, and 0.65; for curve *c*, 4.8, 1.8, and 0.75; for curve *d*, 6.8, 1.8, and 1.2; for curve *e*, 8.8, 1.8, and 1.5.

So far we have attempted to interpret the step-function–like behavior in the energy-crisis curve and the $e\mu$ events in terms of a heavy lepton. It might also be possible to explain these phenomena in terms of heavy exotic hadrons such as charmed or colored mesons. It is therefore very important to find a possible way to distinguish the heavy leptons from heavy hadrons. For this purpose, we come back to Fig. 2. The normalized distribution in Fig. 2 indicates that we have a substantial number of $e\mu$ events even with $E_c=1.2-1.5$ GeV for $\sqrt{S}=6.8-8.8$ GeV. It is generally believed that the strong interaction induces a rather small transverse-momentum cutoff. One can therefore expect that those events with energetic e and μ would not increase so much with increasing $\sqrt{S}$ if the parent particles for e and μ are strongly interacting particles. On the other hand, heavy leptons carry exactly one half of $\sqrt{S}$ for arbitary S. This means that more and more energetic decay products such as e and μ are expected for increasing $\sqrt{S}$. It is, in principle, possible to distinguish heavy leptons from heavy hadrons on the basis of this $\sqrt{S}$ and E_c dependence. A jet of hadrons from the energetic heavy lepton is also expected at high energies.

A discussion of lepton schemes other than the sequential lepton will be given elsewhere.

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Note added.—After submitting our Letter, we recognized the following interesting properties. The following three different cases at $\sqrt{S} = 4.8$ GeV and $M_L = 1.8$ GeV all produce almost identical $\theta_{\rm coll}$ distributions: (i) $M_{\nu_L} = 0$, $E_c = 0.75$ GeV, and $V - A$ current for the heavy lepton (see Fig. 2); (ii) $M_{\nu_L} = 0.5$ GeV, $E_c = 0.65$ GeV, and $V - A$; and (iii) $M_{\nu_L} = 0$, $E_c = 0.65$ GeV, and $V + A$ current for the heavy lepton. A somewhat related observation has been made independently by Park and Yildiz.[7] See also the newer data of Perl *et al.*[8]

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Angular Correlation of Neutrons from Spontaneous Fission of ^{252}Cf

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The *n*-*n* angular correlation for neutrons emitted in spontaneous fission of ^{252}Cf has been measured. Discrepancies are observed when these and other experimental observations are compared with Monte Carlo calculations based on the evaporation model. It is suggested that the discrepancies could be attributed to enhanced neutron emission along the fission axis.

It is well established[1,2] that a large fraction (75–90%) of the neutrons emitted promptly in spontaneous or thermal-neutron fission can be accounted for in terms of evaporation from the fully accelerated fission fragments. However the origin of the remaining 10–25% of the neutron emission remains in question and it has been suggested that these neutrons may be emitted at the instant of scission[1,2] or during the acceleration period of the fragments.[3] Models of the neutron emission rest mainly on experimental observations of the velocity and angular distributions of the prompt neutrons, the angular distributions being referred to the axis defined by the direction of the light fragment.

Another observable in the neutron emission process is the neutron-neutron angular correlation, that is the *n*-*n* coincidence rate as a function of angle between emitted neutrons. Such a measurement was reported for thermal-neutron fission of ^{235}U by De Benedetti *et al.*[4] in 1948. However no further measurement of this observable appears to have been reported since then. The *n*-*n* angular correlation experiment does not require the detection of fission fragments, and hence stronger and thicker sources may be used than in angular distribution measurements. On the other hand, the observations are automatically averaged over all orientations of the fission axis, which implies some loss of detail. The correlation is nevertheless sensitive to the characteristics of neutron emission and provides a useful additional method for testing models of emission process. We have measured the *n*-*n* angular correlation of prompt neutrons from the spontaneous fission of ^{252}Cf. In order to compare results with predictions based on the evaporation model we have also made Monte Carlo calculations simulating our experiment and the measurement of the neutron angular distribution.[1]