Weak Current in Harari's Heavy-Quark Model*

S. Pakvasa, W. A. Simmons, and S. F. Tuan
Department of Physics and Astronomy, University of Hawaii at Manoa, Honolulu, Hawaii 96822
(Received 16 June 1975)

We show that by adding a $V+A$ heaviness-changing current to Harari's proposed current, the good results of Harari as well as of De Rújula, Georgi, and Glashow are retained. In addition, our proposal explains the observed y anomaly in $\bar{\nu}$ interactions. Other consequences of the model are also discussed.

A new quark model, consisting of a light triplet (u, d, s) of one $SU(3)_L$ and a heavy antitriplet (t, b, r) of another $SU(3)_H$ with charges $(\frac{2}{3}, -\frac{1}{3}, -\frac{1}{3})$ and $(\frac{2}{3}, -\frac{1}{3}, \frac{2}{3})$, respectively, which leads to the value $R=5$ above the threshold for production of heavy particles in e^+e^- scattering—in excellent agreement with data[1] at 7 GeV—has been proposed by Harari.[2] He assigns $J(3105)$ to a unitary singlet of the $SU(3)_H$ and assigns $\psi'(3695)$ and $\psi''(4200)$ to $I=0$ and $I=1$ members of an octet. This model makes the striking prediction for leptonic widths that $\Gamma_\varphi:\Gamma_J:\Gamma_\psi = 2:6:3$, in good agreement with experiment.[3] Note also that ψ'' is expected to have the same leptonic width as the $\rho(760)$. We extend the model by borrowing the idea of De Rújula, Georgi, and Glashow[4] of adding a new $V+A$ piece to the weak current thus producing an enhancement of $\Delta I=\frac{1}{2}$ nonleptonic transitions through the cross terms between $V-A$ and $V+A$ in the current-current interaction.

Harari[2] chooses the charged $V-A$ weak current to be of the form

$$J^+ = (u, t, r)_L A \begin{pmatrix} \bar{d} \\ \bar{s} \\ \bar{b} \end{pmatrix}_L . \quad (1)$$

If we treat $\int J^+ d^3x$ as the generator of the weak SU(2) algebra, the neutral component J^0 has $\Delta S=0$ if matrix A is chosen to be orthogonal. We modify this current by adding a $V+A$ term,

$$J^{+\prime} = J^+ + (u, t, r)_R B \begin{pmatrix} \bar{d} \\ \bar{s} \\ \bar{b} \end{pmatrix}_R . \quad (2)$$

Now we require $\int J^{+\prime} d^3x$ to generate the weak SU(2) algebra and again, if B is chosen to be orthogonal, the neutral component $J^{0\prime}$ remains $\Delta S=0$.

In both the Harari[2] and De Rújula–Georgi–Glashow models gauge-theory anomalies are present which make the theories unrenormalizable.[5] However, if we add to the current in the Harari model the simplest term analogous to that of De Rújula, Georgi, and Glashow,[4] which is an $r\bar{d}$ term of $V+A$ type, then the anomalies cancel. This corresponds to

$$B = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix}$$

and does not generate $\Delta S \neq 0$ neutral currents.

We proceed next to consider a more general form for B. With the requirement that the $r\bar{d}$ term of $V+A$ structure be dominant, the most general form is

$$B = \begin{pmatrix} 0 & \sin\chi & \cos\chi \\ 0 & \cos\chi & -\sin\chi \\ 1 & 0 & 0 \end{pmatrix}. \quad (3)$$

$\sin\chi$ must be quite small because there is a term $\sin\chi u(V+A)\bar{s}$ and a large value of $\sin\chi$ would thus upset the success of Cabibbo theory in Λ^0 β decay. There is the intriguing possibility of making χ small and imaginary and hence of explaining CP nonconservation following Mohapatra.[6] We shall neglect χ and take B in the form

$$B = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{pmatrix}. \quad (4)$$

For matrix A we adopt Harari's choice

$$A = \begin{pmatrix} \cos\theta & -\sin\theta & 0 \\ \cos\varphi\sin\theta & \cos\varphi\cos\theta & -\sin\varphi \\ \sin\varphi\sin\theta & \sin\varphi\cos\theta & \cos\varphi \end{pmatrix}. \quad (5)$$

Our choice of A and B corresponds to three left-handed and three right-handed doublets transforming under the weak SU(2) and we would need two new leptonic doublets to cancel anomalies.

Note that the amplitude leading to the mechanism of Ref. 4 for enhancement of $\Delta I=\frac{1}{2}$ is $\sin\varphi\, \bar{d}rr\bar{s}$, so we need to take $\sin\varphi \simeq 1$, in contrast to Harari.[2] All of the consequences of the $V+A$ interaction for nonleptonic decays of hyperons and kaons discussed in Ref. 4 remain valid here.

In our model there is heavy-particle $(H\neq 0)$ production from both incident neutrinos and antineutrinos with equal strength (assuming that valence quarks dominate). The y distributions for neutrinos and antineutrinos behave like $(1-y)^2$ and 1, respectively. Hence the onset of heavy-particle production will be seen more easily for incident antineutrinos than incident neutrinos since the usual $V-A$ distributions are 1 for ν and $(1-y)^2$ for $\bar{\nu}$. This is exactly what is observed.[7] Note that these predictions are significantly different from other models. In models like those of Sarma and Rajasekaran,[3] the quasielastic production of a single charmed baryon by incident antineutrinos arises from a $(V-A)$-type interaction and thus goes like $(1-y)^2$, while in the model of Ref. 4 it is forbidden.

The decays of the predicted $H=1$ heavy mesons in our model are different from those in Ref. 2 for two reasons: first, the fact that $\sin\varphi \simeq 1$, and second, the presence of the additional $V+A$ term in Eq. (2) which engenders a variety of transitions. Wherever Harari predicts nonstrange final states, we expect both strange and nonstrange final states. Our modified current equation (2) has $\Delta H = -\Delta Q$ in the $V+A$ part and therefore $\Delta H = 2$ terms in the nonleptonic Hamiltonian. Hence R^- $(=b\bar{u})$ decays semileptonically into nonstrange bosons via $V+A$ and into both strange and nonstrange nonleptonic final states in our model. This decay pattern helps the (K/π)-ratio problem in passing through the region of "charm" threshold. The proliferation of heavy mesons[2] $(H=1)$ along with this plethora of decay modes should make it difficult to observe the heavy mesons as peaks in invariant-mass plots of final charged particles in e^+e^- collisions. The small production cross section for each such peak should alleviate somewhat the so-called "multiplicity crunch" problem ($\langle n_{\rm ch}\rangle \sim 4$ only) just above the expected "charm" threshold.

The branching ratio of semileptonic decays to hadronic decays of heavy mesons does not have a $\tan^2\theta$ factor in our model. Therefore this ratio is expected to be significantly larger than in conventional charm models.[9] Because of this possibly enhanced leptonic branching ratio, it will be extremely interesting to look for a substantial $e\bar{\mu}$ signal which can arise in e^+e^- annihilation from the pair production of P^{++} $(=r\bar{s})$ with $J^P = 1^-$ via $e^+e^- \to P^{++}\bar{P}^{++} \to$ leptons.

This model, like other charm models, also predicts events of the type $\nu + p \to \mu^- +$(heavy baryon) which may have been observed recently.[10]

Considerations similar to those in Ref. 4 indicate that there is no suppression of the common decay modes of Q^0 $(=b\bar{s} \pm r\bar{u})$ and $\bar{Q}^0$ $(=\bar{b}s \pm \bar{r}u)$ so that mass difference and decay-rate difference between $Q_1^0 = (Q^0 + \bar{Q}^0)$ and $Q_2^0 = (Q^0 - \bar{Q}^0)$ can be quite large. (Q^0, $\bar{Q}^0$ mixing can be large also due to the direct $\Delta H = 2$ terms in our weak-interaction Hamiltonian.) Hence "wrong" semileptonic decays of Q^0 could have a substantial branching ratio to the normal semileptonic decays, and "wrong" dileptons $(\mu^- l^-)$ can be produced at rates comparable to normal dileptons[11] in neutrino interactions. By the same token, well above the threshold for pair production of Q^0, we expect trilepton production, i.e., $\mu^- l_1 l_2$ in ν_μ reactions and $\mu^+ l_1 l_2$ in $\bar{\nu}_\mu$ reactions, where $l_1 l_2$ is any pair from μ^-, μ^+, e^-, e^+. All modes should have comparable rates.

We would like to emphasize once more that a detailed investigation of the y anomaly in ν and $\bar{\nu}$ reactions can confirm or demolish the proposal for weak current made here.

Note added.—It should be noted that the enhanced leptonic branching ratios in our case would also lead to a higher rate for $p + p \to l +$anything than in a conventional charm model (c.f. Ref. 9). In deep inelastic neutrino scattering, we predict that $\sigma^{\bar{\nu}}/\sigma^{\nu}$ drops to a little above $\frac{1}{4}$ (just as in Ref. 4) when the r threshold is passed and then rises close to 1 well above the threshold for r, b, and t.

A detailed discussion of the consequences of the model for the weak neutral current (which is pure vector and hence gives $\sigma_n^{\bar{\nu}}/\sigma_n^{\nu} = 1$), x and y distributions expected in the y anomaly, and the dimuon phenomena will be given in a forthcoming paper.

*Work supported in part by the U. S. Energy Research and Development Administration under Contract No. AT (04-3)-511.

[1]SLAC-LBL collaboration, as reported by G. Goldhaber, at the $N\bar{N}$ Symposium, Syracuse, New York, May 1975 (to be published).

[2]H. Harari, SLAC Report No. SLAC-PUB-1568, 1975 (unpublished).

[3]SPEAR data on ψ and ψ', as discussed also in Ref. 1.

[4]A. De Rújula, H. Georgi, and S. L. Glashow, Phys. Rev. Lett. 35, 69 (1975).

[5]C. Bouchiat, J. Iliopoulos, and Ph. Meyer, Phys. Lett. B38, 519 (1972); D. Gross and R. Jackiw, Phys. Rev. D 6, 477 (1972).

[6]R. N. Mohapatra, Phys. Rev. D 6, 2023 (1972).

[7]A. Benvenuti *et al.*, Phys. Rev. Lett. 34, 597 (1975); A. Mann, Bull. Am. Phys. Soc. 20, 635 (1975), and to

be published.
[8]K. V. L. Sarma and G. Rajasekaran, Tata Institute Report No. TIFR/TH/75-19 (to be published); J. W. Moffat, to be published; T. Goto and V. S. Mathur, to be published.
[9]M. K. Gaillard, B. W. Lee, and J. Rosner, Rev. Mod. Phys. 47, 277 (1975).
[10]E. G. Cazzoli *et al.*, Phys. Rev. Lett. 34, 1125 (1975).
[11]A. Benvenuti *et al.*, Phys. Rev. Lett. 34, 419 (1975); D. Cline, Bull. Am. Phys. Soc. 20, 635 (1975), and to be published.

High-Momentum Hadrons from e^+e^- Reactions: Spectra, Particle Ratios, and Multiplicities*

T. L. Atwood, B. A. Barnett, L. V. Trasatti,† and G. T. Zorn
University of Maryland, College Park, Maryland 20742

and

M. Cavalli-Sforza, G. Goggi, G. C. Mantovani, A. Piazzoli, B. Rossini, and D. Scannicchio
Istituto di Fisica Nucleare, Università di Pavia, Pavia, Italy, and Istituto Nazionale di Fisica Nucleare, Sezione di Pavia, 27100 Pavia, Italy

and

D. G. Coyne, G. K. O'Neill, and H. F. W. Sadrozinski
Princeton University, Princeton, New Jersey 08540
(Received 7 July 1975)

We present results from a study of high-momentum inclusive hadron production in electron-positron interactions at $\sqrt{s}=3.8$ and 4.8 GeV. Comparison of the momentum spectra at these energies shows no scaling violation in the region x $(=E/E_{\rm beam}) > 0.7$. At $\sqrt{s}=4.8$ GeV the K/π ratio for hadrons with momenta >1.1 GeV/c is 0.27 ± 0.08, and the average number of charged hadrons is 3.6 ± 0.3 for those events which have at least one charged hadron with momentum greater than 1.1 GeV/c.

This paper presents results from an experiment which measured the inclusive cross section for hadron production in e^+e^- interactions. Measurements were made at e^+e^- center-of-mass energies of 3.8, 4.8, 5.0, and 5.1 GeV at the SPEAR facility of Stanford Linear Accelerator Center (SLAC). The experiment occurred prior to the discovery[1] of the ψ (J) particles, so the data do not add direct information about these particles. It has been observed that R, the ratio of the cross section for "$e^+e^- \rightarrow$ hadrons" relative to "$e^+e^- \rightarrow \mu^+\mu^-$," increases[2] from ≈ 2.5 to ≈ 5 around 4 GeV, and we present data below and above this energy. This report will deal with events having a particle with a momentum greater than 1.1 GeV/c, where our particle identification is best and our backgrounds least. Data for lower particle momenta will be presented later. The data samples at $\sqrt{s}=5.0$ and 5.1 GeV together were only about 15% of that at $\sqrt{s}=4.8$ GeV. These have all been combined and will be referred to as $\sqrt{s}=4.8$ GeV.

The main element of the apparatus (Fig. 1) was a single-arm magnetic spectrometer set at 90° to the e^+e^- beams and subtending about 1% of 4π steradians. The magnetic field was vertical and rather uniform at ≈ 4.2 kG; the total $\int B\,dl$ was ≈ 11.8 kG m. Particle positions were measured by proportional wire chambers[3] or scintillation counters. The event trigger required a charged particle passing through the spectrometer in coincidence with the passage of the e^+e^- bunches through the interaction region.

The experiment achieved $e/\mu/\pi/K/p$ identification of the spectrometer particle by a combination of a threshold Cherenkov counter, shower counters, range measurement, and time of flight. The Cherenkov counter was filled with 90 lb/in.^{2} (gauge) of propane. Its pion threshold was 1.05 GeV/c, and it unambiguously separated $e/\mu/\pi$ from K/p above 1.2 GeV/c. This particle identification was aided by time-of-flight (TOF) measurements between 1.1 and 1.2 GeV/c. The Cherenkov pulse height was also helpful in distinguishing electrons from pions above 1.05 GeV/c, but electrons were identified primarily by a five-