incident beams must be of the form

$$P(\theta) \propto 1 + \alpha \cos^2, \quad |\alpha| \leq 1, \tag{2}$$

for any D spin and α must be -1 for spin 0. Figure 3 shows the angular distribution for the $D^+ \to K^-\pi^+\pi^+$ and $D^0 \to K^-\pi^+$ decays. The values of α are found to be -1.04 ± 0.10 and -1.00 ± 0.09, respectively, consistent with the assignment of spin 0 for the D mesons.[13]

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[2] J.-E. Augustin *et al.*, Phys. Rev. Lett. 34, 233 (1975).

[3] A. Barbaro-Galtieri *et al.*, Phys. Rev. Lett. 39, 1058 (1977).

[4] G. Goldhaber *et al.*, Phys. Rev. Lett. 37, 255 (1976); I. Peruzzi *et al.*, Phys. Rev. Lett. 37, 569 (1976).

[5] G. J. Feldman *et al.*, Phys. Rev. Lett. 38, 1313 (1977).

[6] See Ref. 5 for the rationale for this procedure and an example of how it works in practice.

[7] V. Lüth *et al.*, Phys. Lett. 70B, 120 (1977).

[8] G. Goldhaber *et al.*, Phys. Lett. 69B, 503 (1977).

[9] M. Piccolo *et al.*, Phys. Lett. 70B, 260 (1977).

[10] The efficiency for the $K^\mp\pi^\pm$ mode is substantially larger here than in Ref. 9 because less restrictive time-of-flight requirements were needed and because the K and π are more collinear, which results in a larger geometrical acceptance. The ratios of σB values for the three D^0 decay modes are in good agreement with those which can be derived from Ref. 9.

[11] A revised calculation of the external radiative corrections for e^+e^- collinear events has resulted in a 7.5% increase of the evaluated luminosity and in a consequent decrease of the cross sections reported in Refs. 1, 3–9 (A. M. Boyarski, private communication). The revised ψ'' partial width to electron pairs is 345 ± 85 eV.

[12] A possible contribution to the total cross section due to τ production (which could be as large as 7%) has not been explicitly subtracted.

[13] See H. K. Nguyen *et al.*, Phys. Rev. Lett. 39, 262 (1977) for additional experimental evidence on D and D^* spins.

Decays of Heavy Vector Mesons into Higgs Particles

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Estimates are presented for the decay of vector mesons composed of heavy quarks into states containing a Higgs boson. If the decays are kinematically allowed, they are probably experimentally accessible when the quark mass $m_q \gtrsim 4$ GeV.

Present-day gauge theories of the weak interactions require the existence of scalar particles (Higgs mesons) with characteristic properties. Discovery of such particles would be weighty evidence in favor of such theories. Because these mesons are thought to be very weakly coupled, all processes hitherto considered for production and detection gave poor prospects for experimental success.[1] In this Letter I would like to point out that this situation can be much improved if e^+e^- colliding-beam machines produce particles analogous to the J/ψ but with larger mass.[2]

Let us briefly recall the relevant properties of Higgs mesons. For definiteness I shall discuss the original model of Weinberg and Salam[3] with new quarks and leptons added sequentially. In this model the coupling of the Higgs meson H to a quark q or lepton l of mass m is given by

$$\mathcal{L}_{\rm int} = 2^{1/4} G_{\rm F}^{1/2} m H(q\bar{q} \text{ or } l\bar{l}). \tag{1}$$

The close connection between the Higgs coupling strength and the fermion mass is characteristic. It immediately suggests that the use of particles containing heavy quarks in the search for Higgs particles will be profitable. For instance, if the mass m of the quark is 7.6 GeV, then the Higgs coupling already has $\frac{1}{10}$ the strength of the electromagnetic coupling. (Actually, if we remember that quarks are fractionally charged, the ratio is even larger.) The mass of the Higgs particle itself is unfortunately not predicted in the model.

It is easy to compute the ratio of the processes $V \to \mu\mu$, $V \to H\gamma$ (where V is a vector meson formed from quarks of mass m_q), assuming that

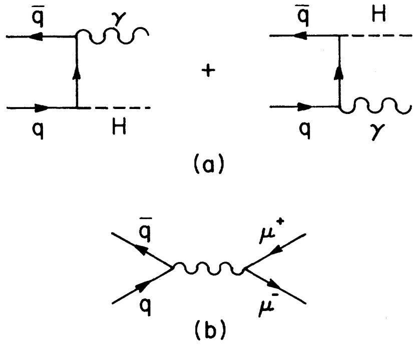

FIG. 1. Comparison of (a) the radiative decay $V\to H\gamma$ and (b) the leptonic decay $V\to\mu^+\mu^-$.

V is weakly bound and that nonrelativistic mechanics is appropriate. Calculation of the Feynman diagrams shown in Fig. 1 yields

$$\frac{\Gamma(V\to H\gamma)}{\Gamma(V\to\mu\mu)}=\frac{G_{\rm F}m_q^2}{\sqrt{2}\,\pi\alpha}\left(1-\frac{m_H^2}{m_V^2}\right)^{1/2}, \qquad (2)$$

which for $m_q = 4.5$ GeV^2 is 0.007 times the phase-space factor. Since colliding-beam machines may produce tens of thousands of V particles and the branching ratio for $V\to\mu\mu$ should be a few percent, it is not inconceivable that the monochromatic photons from $V\to H\gamma$ could be detected.

If several such events are collected, it would be interesting to look at the decay modes of H. We would expect that of known particles, H decays almost exclusively to charmed final states and $\tau^+\tau^-$ pairs,[4] if 9 GeV $\gtrsim m_H \gtrsim$ 4 GeV.[5] The ratio of decays into charm-bearing final states (which might be $D\bar{D}n\pi$, $J/\psi\,\pi\pi,\dots$) to decays into τ's should be about 3 (for three colors) times the square of the mass ratio, i.e., $\sim3\times(1.3)^2/(1.8)^2 \simeq 1.6$. Since $\tau\to e\nu\bar\nu$ and $\tau\to\mu\nu\bar\nu$ each about 20% of the time, we expect $H\to\tau^+\tau^-\to ll'+\nu$'s about 10% of the time, giving the very distinctive decays $V\to\gamma\mu\mu, \gamma\mu e, \gamma ee$ with a monochromatic photon. If neutral heavy leptons[6] exist and have masses $\gtrsim 2$ GeV, they might dominate H decays and lead to spectacular multilepton final states.

Decays of lighter Higgs mesons are discussed in Ref. 1. There is, however, a potentially important process which was not considered in that paper. This is the "loop-annihilation" process depicted in Fig. 2. (It is formally similar to the $H\to\gamma\gamma$ process which was considered.) In this process the Higgs boson couples to a virtual heavy quark which annihilates into two color gluons. Since through this process light quarks may be produced in Higgs decay without the appearance of their small masses, we would expect this to be the dominant process for light-quark production even though it is suppressed by several powers of the strong-interaction coupling. The effective vertex for the loop-annihilation process depicted in Fig. 2 is $HG_{\mu\nu}G_{\mu\nu}$, i.e., of dimension 5. Therefore for a heavy quark q of mass m_q we would expect the Feynman integral to be well enough convergent in the ultraviolet so that the integral is proportional to $1/m_q$ for large m_q. However, the vertex coupling the Higgs to q is also proportional to m_q, so that the total amplitude is *independent* of the m_q when m_q is large. So this process in principle would allow the detection of effects of arbitrarily heavy quarks. It may be calculated with some confidence by use of renormalization-group methods, and in principle allows us to measure experimentally the number of heavy-quark flavors.

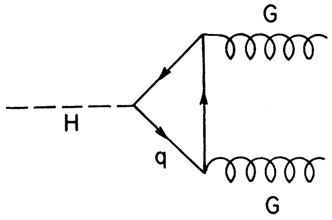

FIG. 2. "Loop-annihilation" contribution to Higgs decay.

The result is[7]

$$\frac{\Gamma(H\to GG)}{\Gamma(H\to\mu\mu)}=\left(\frac{m_H}{m_\mu}\right)^2\left(\frac{\bar{g}^2}{4\pi^2}\right)^2\frac{4}{9(1-4m_\mu^2/m_H^2)^{3/2}}N^2, \qquad (3)$$

where N is the number of heavy-quark flavors. The denominator is directly measurable, but the numerator would have to be determined indirectly by comparing, say, the total $\mu\mu$ branching ratio to that expected from tree-graph processes, or making some plausible conjecture as to how the two-gluon final state is realized physically.

Another, closely related, mechanism for Higgs production is illustrated by the quark diagram in Fig. 3. It is difficult to be quantitative here, but roughly speaking we would expect that the ratio of inclusive decay into Higgs mesons to inclusive decay into real photons to be comparable to the ratio in Eq. (2). If the charge of the quark is $-\frac{1}{3}$, we might even expect the relative rate for inclusive Higgs production to be up a factor $3^2=9$ from Eq. (2). On the other hand, notice that the final hadron state X in $V\to H+X$ has charge con-

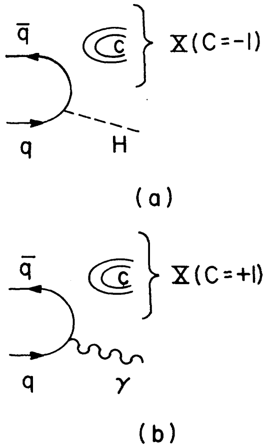

FIG. 3. Comparison of (a) the inclusive decay $V \rightarrow H + X$ and (b) the inclusive radiative decay $V \rightarrow \gamma + X$.

jugation $C = -$, and in some models for "Zweig's rule"[8] would be extra suppressed relative to $V \rightarrow \gamma + X(C = +)$ (I do not expect this, however). In any case, the most likely channel for the Higgs decay with hadrons would be $V \rightarrow H + \omega$.

I have discussed so far only the original Weinberg-Salam model, where all particles acquire mass from a single Higgs multiplet. The coupling of Higgs particles in more complicated models is difficult to survey in a general way. Indeed, the requirements of gauge invariance and renormalizability alone allow any number of scalar particles with almost arbitrary masses and couplings. I will mention one possibility. It is possible that the W bosons acquire the bulk of their mass through Higgs particles which do not couple to quarks (to lowest order). Then the coupling of the quarks to the Higgs bosons which do give them mass would be *larger* than envisaged in Eq. (1). (The vacuum expectation values would be smaller so that the contribution of the "quark-coupling" Higgs to the W mass is smaller, but the product of Yukawa coupling to quarks times vacuum expectation value is fixed to be the quark mass.) For this reason my estimate, Eq. (2), has the nature of a lower bound. It might conceivably be possible to identify the $X(2800)$[9] with such a Higgs particle, although there is at present no sufficient reason for such a radical step.

There is one general relation between the mass m_H of the Higgs particle, the mass m_q of the quark, and the Yukawa coupling g_Y between them, which follows from the requirement that the Higgs self-coupling not be strong.[10] It is

$$m_H \lesssim m_q / 2\pi g_Y. \qquad (4)$$

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[1] J. Ellis, M. Gaillard, and D. Nanopoulos, Nucl. Phys. B106, 292 (1976), and references therein.

[2] Such particles may be suggested by the findings of S. W. Herb *et al.*, Phys. Rev. Lett. 39, 252 (1977).

[3] S. Weinberg, Phys. Rev. Lett. 19, 1264 (1967); A. Salam, in *Proceedings of the Eighth Nobel Symposium on Elementary Particle Theory, Relativistic Groups, and Analyticity, Stockholm, 1968*, edited by N. Svartholm (Almqvist and Wiksell, Stockholm, 1968).

[4] M. L. Perl *et al.*, Phys. Rev. Lett. 35, 1489 (1975), and Phys. Lett. 63B, 466 (1976).

[5] There are arguments by A. Linde, Pis'ma Zh. Eksp. Teor. Fiz. 23, 73 (1976) [JETP Lett. 23, 64 (1976)], and S. Weinberg, Phys. Rev. Lett. 36, 294 (1976), indicating $m_H \gtrsim 4$ GeV. See also P. Frampton, Phys. Rev. Lett. 37, 1378 (1976). However, these arguments involve the assumption that the simple H^4 form of the Higgs interaction survives at high momenta, which may not be correct.

[6] E.g., T. P. Cheng and L.-F. Li, Phys. Rev. Lett. 38, 381 (1977).

[7] The result is readily extracted from the calculation of L. Resnick, M. Sudaresan, and P. Watson, Phys. Rev. D 8, 172 (1973). I have ignored a small correction due to the renormalization of "effective mass."

[8] G. Zweig, unpublished, and in *Symmetries in Elementary Particle Physics*, edited by A. Zichichi (Academic, New York, 1965), p. 192.

[9] J. Heintze, in *Proceedings of the International Symposium on Lepton and Photon Interactions at High Energies, Stanford, California, 1975*, edited by W. T. Kirk (Stanford Linear Accelerator Center, Stanford, Calif., 1975).

[10] For the quark mass we have $m_q = g_Y \langle\varphi\rangle$, while $\langle\varphi\rangle$ is determined by the Higgs mass m_H and self-coupling λ to be $\langle\varphi\rangle = m_H/\lambda^{1/2}$, thus requiring $\lambda/4\pi^2 \leq 1$ leads to Eq. (4).