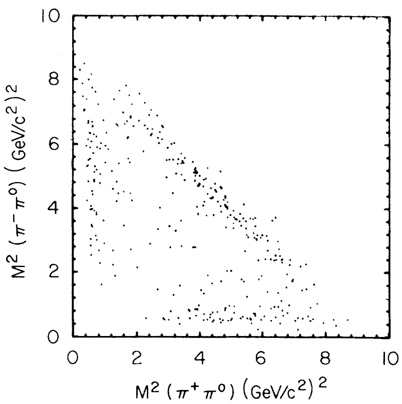

FIG. 4. Dalitz plot for the $\pi^+\pi^-\pi^0$ decay of $\psi(3095)$.

ly seen. For events with $0.600 < M_{\pi\pi} < 0.950$ GeV/c^2, the residual contamination is found to be negligible for $\rho^0\pi^0$ and on the order of 4% for $\rho^\pm\pi^\mp$. The ratio between the production of neutral and charged modes, $\sigma_{\rho^0\pi^0}/(\sigma_{\rho^+\pi^-}+\sigma_{\rho^-\pi^+})$, should be equal to 0.5 for $I=0$, or equal to 2 for $I=2$. The experimental ratio is 0.59 ± 0.17 which clearly favors the assignment $I=0$.

In conclusion the branching ratios for multipion final states strongly indicate odd G parity for the direct hadronic decays of the $\psi(3095)$. The analysis of the $\rho\pi$ decay channel leads to the result $I=0$. We conclude, therefore, that the $\psi(3095)$ has quantum numbers $I^G=0^-$.

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[2]J. J. Aubert *et al.*, Phys. Rev. Lett. 33, 1404 (1974).

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

[4]A. M. Boyarski *et al.*, Phys. Rev. Lett. 34, 1357 (1975).

[5]The direction of the ρ has an angular distribution of $1+\cos^2\theta$ with respect to the beam axis. The angular distribution of the π's from the ρ decay is $\sin^2\theta_{\text{c.m.}}$ with respect to the ρ's direction in the center of mass of the ρ. The normal to the plane containing the three pions of the final state is distributed like $\sin^2\theta_N$ with respect to the beam axis.

Mass of the Higgs Boson*

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The stability of the vacuum sets a lower bound of order $\alpha G_F^{-1/2}$ on the Higgs-boson mass. For the simplest SU(2)⊗U(1) model, this lower bound is $1.738\alpha G_F^{-1/2}$, or 3.72 GeV.

If the gauge symmetry of the weak and electromagnetic interactions is spontaneously broken by the vacuum expectation values of a set of weakly coupled elementary scalar fields,[1] then there should exist a corresponding set of massive scalar particles, one for each elementary scalar field, other than those corresponding to Goldstone bosons. These have come to be known as the "Higgs bosons." This note will present a theoretical lower bound on the Higgs-boson mass.

It is usually said that gauge theories do not put any constraints on the Higgs-boson masses, and that experimental searches must consequently explore all mass ranges, even down to zero mass.[2] This statement is based on lowest-order perturbation theory. If the typical scalar mass in the Lagrangian is of order M and the typical φ^4 coupling is f, then the scalar-field vacuum expectation values $\langle\varphi\rangle$ will be of order $M/\sqrt{f}$, while the Higgs-boson masses will be of order M. We more or less know $\langle\varphi\rangle$, which is of order $G_F^{-1/2}\approx 300$ GeV.[1] But even for fixed $\langle\varphi\rangle$, we can apparently make the Higgs-boson mass $M_H \approx \langle\varphi\rangle\sqrt{f}$ as small as we like, by taking both f and M to be sufficiently small.

However, if we make f too small, the effective potential becomes dominated by gauge vector-boson loops and this argument breaks down. These one-loop diagrams are of order $e^4\varphi^4$, where e is a typical gauge coupling constant. Hence there is an effective lower bound on f of order e^4, and we expect a lower bound on the Higgs-boson mass of order $e^2\langle\varphi\rangle$, or several GeV.

To make this precise, let us consider any gauge theory with only a single scalar Higgs boson,[3] as in Ref. 1. The effective potential is then a function $V(\varphi)$ only of the modulus $\varphi^2 \equiv \sum_i \Phi_i^\dagger \Phi_i$ of the scalar multiplet Φ_i. We assume that $V(\varphi)$ can be calculated perturbatively, but to take into account the possibility that the φ^4 coupling is very weak, we include one-loop as well as zero-loop terms. It then takes the form[4]

$$V(\varphi) = -\tfrac{1}{2}M^2\varphi^2 + f\varphi^4 + (64\pi^2)^{-1}\,\mathrm{Tr}(3\mu_\varphi^{\,4}\ln\mu_\varphi^{\,2} + M_\varphi^{\,4}\ln M_\varphi^{\,2} - 4m_\varphi^{\,4}\ln m_\varphi^{\,2}), \tag{1}$$

where μ_φ, M_φ, and m_φ are, respectively, the zeroth-order vector, scalar, and spinor mass matrices for a scalar-field vacuum expectation value φ. We can safely drop the M_φ term, because if M_φ is as large as the vector-boson masses it is very much larger than the lower bound we are trying to derive. We will also drop the m_φ term, because all the fermions we know are much lighter than the intermediate vector bosons. (This is the only term that would be affected by strong interactions.) The potential may then be put in the form

$$V(\varphi) = -\tfrac{1}{2}M^2\varphi^2 + B\varphi^4\ln(\varphi^2/M_f^{\,2}), \tag{2}$$

where M_f is a mass parameter chosen to absorb all φ^4 terms in $V(\varphi)$, and B is a positive dimensionless constant of order e^4,

$$B \equiv (3/64\pi^2\varphi^4)\,\mathrm{Tr}\,\mu_\varphi^{\,4} = (3/64\pi^2\langle\varphi\rangle^4)\textstyle\sum_v \mu_v^{\,4}, \tag{3}$$

with the sum running over all intermediate vector bosons. This potential has a local minimum at a point $\langle\varphi\rangle$ given by[5]

$$\langle\varphi\rangle^2[\ln(\langle\varphi\rangle/M_f)^2 + \tfrac{1}{2}] = M^2/4B \tag{4}$$

and the Higgs mass is

$$M_{\mathrm{H}}^{\,2} = v''(\langle\varphi\rangle) = 8B\langle\varphi\rangle^2[\ln(\langle\varphi\rangle/M_f)^2 + \tfrac{3}{2}]. \tag{5}$$

It may now appear that for given values of the "known" quantities $\langle\varphi\rangle$ and B, we can give $M_{\mathrm{H}}^{\,2}$ any value we like by a suitable choice of f, or M_f. However, not all these solutions are physically acceptable. The potential at the point (4) has the value

$$V(\langle\varphi\rangle) = -B\langle\varphi\rangle^4[\ln(\langle\varphi\rangle/M_f)^2 + 1] \tag{6}$$

and this must be less than $V(0)=0$ if the local minimum is to be an *absolute* minimum.[6] With the logarithm thus constrained to be greater than -1, Eq. (5) yields the lower bound

$$M_{\mathrm{H}}^{\,2} \geq 4B\langle\varphi\rangle^2 = (3/16\pi^2\langle\varphi\rangle^2)\textstyle\sum_v \mu_v^{\,4}. \tag{7}$$

For instance, in the $\mathrm{SU}(2)\otimes\mathrm{U}(1)$ model[1] with a single scalar isodoublet, $\langle\varphi\rangle$ is $2^{-1/4}G_{\mathrm{F}}^{\,-1/2}$, or 247 GeV, and (7) becomes

$$M_{\mathrm{H}}^{\,2} \geq \frac{3\sqrt{2}G_{\mathrm{F}}}{16\pi^2}(2\mu_W^{\,4} + \mu_Z^{\,4}) = \frac{3\alpha^2(2+\sec^4\theta)}{16\sqrt{2}G_{\mathrm{F}}\sin^4\theta}, \tag{8}$$

where θ is the weak mixing angle. Even with θ unknown, M_{H} has the lower bound $1.738\alpha/\sqrt{G_{\mathrm{F}}}$, or 3.72 GeV. For $\theta \simeq 35°$ as suggested by experiment, the lower limit on m_{H} is 4.9 GeV. As noted by Ellis, Gaillard, and Nanopoulos,[2] a Higgs boson this heavy would decay chiefly into heavy leptons and charmed hadrons, with a very small branching ratio to $\mu^+\mu^-$ pairs.

Similar arguments apply to theories with several Higgs bosons, but the results are less useful. In general, one can show that

$$(M_{\mathrm{H}}^{\,2})_{ij}\langle\Phi_i\rangle\langle\Phi_j\rangle \geq (3/16\pi^2)\textstyle\sum_v \mu_v^{\,4}. \tag{9}$$

If we assume for simplicity that there are no gauge-invariant scalar fields, then this yields a lower bound on the *heaviest* Higgs-boson mass

$$M_{\mathrm{H,\,max}}^{\,2} \geq (3C/16\pi^2)\textstyle\sum_v \mu_v^{\,4}/\sum_{v'}\mu_{v'}^{\,2}, \tag{10}$$

where $C = O(e^2)$ is the smallest eigenvalue of the gauge algebra Casimir operator $\theta_\alpha\theta_\alpha$.

However, there are reasons to suspect[7] that the spontaneous breakdown of the weak gauge symmetries may be described by an effective field theory which has all bare masses zero, in the sense of Coleman and Weinberg.[4] In this case, even if there are many Higgs bosons, it is possible actually to calculate the masses and couplings of the *lightest* one, in terms of other masses.[7] In an $\mathrm{SU}(2)\otimes\mathrm{U}(1)$ model with any number of scalar isodoublets, the mass exceeds the lower bound (8) by just a factor $\sqrt{2}$ (or somewhat more, if the scalar loop graph is appreciable). For $\theta \simeq 35°$, this would give $m_{\mathrm{H}} \simeq 7$ GeV.

If the light Higgs boson has a mass of order 5–10 GeV, the best place to produce it may be in a neutrino reaction.[8] For a center-of-mass energy E between M_{H} and μ_W, the light Higgs boson would tend to be emitted from the exchanged intermediate vector boson line. Aside from numerical phase-space factors, the probability of producing the Higgs boson would be of order $G_F E^2$.

I am grateful for valuable conversations with S. Coleman and E. Gildener.

Note added.—After this paper was submitted for publication, I received a Lebedev Physics Institute report by A. D. Linde (to be published) in which similar conclusions are presented. Linde calculated the lower bound only for Abelian gauge theories, but his estimate for the more realistic SU(2)⊗U(1) theory agrees with the results given here.

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[3]These are the theories [described in Sect. VII of S. Weinberg, Phys. Rev. D 7, 1068 (1973)] in which the scalar fields form a representation of the gauge group which is transitive in a sphere.

[4]S. Coleman and E. Weinberg, Phys. Rev. D 7, 1888 (1973). The same result was subsequently derived by a different method by S. Weinberg, Phys. Rev. D 7, 2887 (1973).

[5]For $M^2<0$, this has two real roots; the local minimum is at the larger root. For $M^2 \geq 0$ there is one real root.

[6]S. Coleman (unpublished) has given an argument that any vacuum which corresponds to a local but nonabsolute minimum will be unstable.

[7]E. Gildener and S. Weinberg, to be published.

[8]D. Cline, private communication.

Search for Charmed Mesons and Baryons*

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Data from a 15-GeV/c π^+d experiment have been used to search for both short- and long-lived narrow resonances. No statistically significant high-mass narrow resonance has been observed up to a mass of 5 GeV. There is a single long-lived V that remains unexplained. Cross-section limits (95% confidence level) of 0.7 μb for the long-lived possibility and 2 to 4 μb for the short-lived possibilities have been obtained.

Since the discovery of the $J(\psi)$ and ψ' narrow resonances,[1] there has been a lot of speculation whether these resonances are the manifestation of a new quantum number called charm.[2] If charm exists then it should be possible to form meson and baryon resonances which contain the charm quantum number. The least massive of the charmed mesons and baryons should decay weakly, implying long lifetimes and narrow widths.

There are many predicted decay modes for these resonances[3] but to date only a few experimental searches have been reported. There has been one experiment looking for long-lived charmed mesons[4] with a sensitivity several orders of magnitude lower than ours. There are a few other experiments which search for short-lived high-mass narrow resonances with negative results.[5-7] Only one experiment has reported one possible event which could be a charmed baryon.[8] In our experiment, in addition to searching for long-lived charmed particles, we also searched for narrow high-mass resonances among such final states as $K^{\pm}\pi^{\mp}$, $K^0\pi^+\pi^-$, $K^{\pm}\pi^+\pi^{\mp}$, K^-p, K^+n, etc.

The data of this experiment[9] come from an exposure of a 15-GeV/c rf-separated π^+ beam to