Heavy-Quarkonium Decay into $Z+$ Higgs Boson as a Scalar/Pseudoscalar Discriminant

James Pantaleone
Physics Department, University of California at Riverside, Riverside, California 92521

Probir Roy[(a)]
Department of Physics, University of Texas, Austin, Texas 78712
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The heavy-quarkonium decay ${}^3S_1(Q\bar{Q}) \to Z+$Higgs boson, a feasible process for Higgs-boson searches, is shown to be highly sensitive to the structure of the $HQ\bar{Q}$ vertex. A study of the angular distributions of the Z decay products can distinguish between the scalar or pseudoscalar form of this vertex and provide important information on the electroweak-symmetry-breaking mechansim.

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The Higgs-boson spectrum of the electroweak theory remains unobserved and as yet many possible extensions of the standard model are allowed. There exist schemes[1] with additional Higgs fields and alternative scenarios with composite spinless particles.[2] These theories contain physical spin-zero states (henceforth generically called Higgs bosons H) which, assuming CP invariance, act as scalars *or* pseudoscalars *vis-à-vis* fermions[3] at the tree level. If and when such a state is discovered, the knowledge of the form of its interaction vertex with any fermion pair will provide important information on the nature of the symmetry-breaking mechanism.

Heavy-quarkonium decays into final states containing Higgs bosons offer interesting avenues of exploration in this direction. The Wilczek[4] process, ${}^3S_1(Q\bar{Q}) \to \gamma+H$, has been theoretically well studied while experimentally the single-photon spectrum from the Υ has provided useful information on the absence of a very light Higgs boson. However, both the branching ratio and the angular distribution are the same for a scalar or a pseudoscalar $HQ\bar{Q}$ vertex of the same coupling strength. Of course, the corresponding coupling constants would, in general, be different in a nonminimal Higgs-boson scenario. However, these then become quite model dependent and the lace of *a priori* knowledge of the parameters (e.g., mixing angles) of the model would inhibit any scalar/pseudoscalar discrimination. Without information on the photon linear polarization[5,6] (which is not foreseeably forthcoming) such a discrimination would be difficult in the Wilczek process.[7,8]

In this Letter we consider the decay of a heavy-vector-quarkonium state (of mass greater than m_Z+m_H) into $Z+H$ in a "beyond the minimal standard-model" scenario. The quark Q could be the top[9,10] if its mass does not exceed m_b+m_W. On the other hand, it could be the lighter member of a possible fourth-generation doublet [although such a doublet with a light neutrino is excluded by recent experiments at the SLAC Linear Collider (SLC) and the CERN e^+e^- collider LEP] or an extra heavy $SU(2)_L$ singlet (of any generation) as suggested in certain superstring-inspired E(6) models[11] provided it couples to a Higgs boson light enough to be in the final state. Such a process has already been discussed by several authors[12] as a feasible means for a Higgs-boson search. However, its extreme sensitivity to the form of the $HQ\bar{Q}$ vertex had not been noticed and that is the focus of the present work.

Three tree-level Feynman diagrams contribute to the decay amplitude ${}^3S_1(Q\bar{Q}) \to Z+$Higgs scalar to the lowest order of perturbation theory. These correspond to the exchange of a virtual Q in the t and u channels as well as to the exchange of a virtual Z in the s channel. However, the last diagram is absent when H is a pseudoscalar since there is no tree level $ZZH(0^-)$ vertex.[1] Graphs with a virtual Higgs boson in the s channel are not relevant since they only contribute to the decay of ${}^1S_0$ and ${}^3P_0$ quarkonium states. We take the $HQ\bar{Q}$ and HZZ couplings to be, respectively, X_Q and X_Z times their values in the minimal (one doublet) Higgs-boson version of the standard model. In that model $X_Q=X_Z=1$, while in extensions thereof the X's depend on ratios of vacuum expectation values and mixing of physical-Higgs-boson masses. It is convenient to introduce the following dimensionless constants

$$r_Z \equiv (m_Z/2m_Q)^2, \quad r_H \equiv (m_H/2m_Q)^2, \qquad (1)$$
$$F \equiv X_Z r_Z (1-r_Z)^{-1}, \quad G \equiv X_Q (1-r_Z-r_H)^{-1}.$$

We can now write the lowest-order decay amplitude T for ${}^3S_1(Q\bar{Q}) \to Z+H$ in terms of the above quantities as

$$T(0^+) = Ag_{vQ}\epsilon_{Q\bar{Q}} \cdot [F\epsilon_Z + G(\epsilon_Z^0 \mathbf{w} - \epsilon_Z w^0)], \qquad (2a)$$

$$T(0^-) = Ag_{vQ}G\epsilon_{Q\bar{Q}} \cdot [\epsilon_Z \times \mathbf{w}]. \qquad (2b)$$

Equations (2a) and (2b) refer to the scalar and pseudoscalar cases, respectively. A is a known constant, independent of model or kinematic parameters. Also, $\epsilon_{Q\bar{Q}}$ and ϵ_Z are the quarkonium and Z polarization vectors, respectively, while $\mathbf{w}$ (w^0) is the momentum (energy) of the emitted Z divided by the quarkonium mass $2m_Q$, $|\mathbf{w}| = [(w^0)^2 - r_Z]^{1/2}$, $w^0 = (1+r_Z-r_H)/2$.

It is interesting to note that Eqs. (2) depend only on the Z vector current in the $ZQ\bar{Q}$ vertex through the corresponding coupling g_{vQ}, there being no contribution from the Z axial-vector current. Thus this process is similar to the Wilczek process[4] ${}^3S_1(Q\bar{Q}) \to \gamma + H$. The latter has similar diagrams with t- and u-channel exchanges of a virtual Q. However, because the Z is a massive vector boson it has a longitudinal degree of freedom which is unavailable to the photon in the Wilczek process. For the case when H is a 0^+ scalar, this mass gives rise to an additional s-channel Z-exchange diagram (not present in the Wilczek decay). Also, the decay products of the Z provide an extra handle for studying the ${}^3S_1(Q\bar{Q}) \to Z + H$ decay.

Let $\Gamma(0^+)$ and $\Gamma(0^-)$ stand for the partial width $\Gamma[{}^3S_1(Q\bar{Q}) \to Z + H]$ in the scalar and pseudoscalar cases, respectively. Then[12]

$$R \equiv \Gamma(0^+)/\Gamma(0^-)$$
$$= \tfrac{3}{2}[(Gw^0 - F)^2 - \tfrac{1}{3}|\mathbf{w}|^2(G^2 - F^2 r_Z^{-1})]/G^2|\mathbf{w}|^2 . \qquad (3)$$

The size of R depends on the specific Higgs-boson model, through the ratio X_Z/X_Q, and on kinematic parameters. In the limit of a very heavy quarkonium when the Z is relativistic, $r_Z + r_H \ll 1$, F vanishes for X_Z/X_Q of order unity so that the relative model dependence disappears and $R \to 1$; as in the Wilczek process. Then the width for the Wilczek process is 12 ($\tfrac{3}{4}$) times $\Gamma({}^3S_1(Q\bar{Q}) \to Z + H)$ for $a + \tfrac{2}{3}$ ($-\tfrac{1}{3}$) charged heavy quark. However, for a not so relativistic Z, $R \gg 1$ typically, because of the overall factor of $|\mathbf{w}|^2$ in the denominator. The only time that R is less than 1 is if there is a large cancellation between Gw^0 and F. This can occur if r_Z is of order 1 and if X_Z/X_Q has a particular value. (The nominal value of X_Z/X_Q for a minimal standard-model Higgs boson is 1, which turns out to be close to the value at which this cancellation occurs.) Therefore, a comparison of the measured values of the partial widths may be able to discriminate between a scalar and a pseudoscalar Higgs boson for a particular range of kinematic and model parameters.[12]

The "parity" of the Higgs boson from heavy-quarkonium decay can be determined more directly by studying the angular distribution of the decay products. For ${}^3S_1(Q\bar{Q}) \to \gamma + H$, the photon is emitted with an angular distribution of $1 + \cos^2\theta$ for both a scalar and pseudoscalar Higgs boson. However, the orientation of the polarization of the photon is orthogonal for the two cases. It has been proposed[5,6] to measure this polarization by observing the plane of the electron positron for the corresponding Dalitz-decay process (since the electron-positron pair are preferentially emitted perpendicular to the vector-boson polarization axis). Then the parity of the Higgs boson could be determined. However, the rate for this process is down by a factor of $\alpha_{\rm em}/\pi$ from the original Wilczek rate so that a very large quarkonium sample would be required to implement this test. Thus, it is far more reasonable to examine the very similar decay ${}^3S_1(Q\bar{Q}) \to Z + H$. The Z will always decay in the detector so that any observation of this decay can be used to measure the polarization of the Z and hence the parity of the Higgs boson.

We consider the case where the Z decays into a fermion-antifermion pair with momenta $\mathbf{q}_+$ and $\mathbf{q}_-$. The momentum of the Z is then given by $2m_Q\mathbf{w} = \mathbf{q}_Z = \mathbf{q}_+ + \mathbf{q}_-$. To specify the orientation of the Z decay products, we also define the vector $\mathbf{q}_\perp \equiv (\mathbf{q}_Z \cdot \mathbf{q}_-)\mathbf{q}_+ - (\mathbf{q}_Z \cdot \mathbf{q}_+)\mathbf{q}_-$, which lies in the plane of the final-state fermion pair and is perpendicular to $\mathbf{q}_Z$. The heavy-quarkonium state is produced in an electron-positron collision with its polarization vector parallel to the beam axis, so this direction is also known. Using these three vectors, the angular distribution of the fermion-antifermion pair for a pseudoscalar Higgs boson can be computed to be

$$\frac{1}{\Gamma}\frac{d^2\Gamma}{d\cos\theta\, d\varphi} = \frac{3}{32\pi}(1 + 3\cos^2\theta + 2\sin^2\theta\sin^2\varphi) . \qquad (4)$$

For a scalar Higgs boson we find

$$\frac{1}{\Gamma}\frac{d^2\Gamma}{d\cos\theta\, d\varphi} = [-\sin^2\theta|\mathbf{w}|^2(G^2 r_Z - F^2) + (Gw^0 - F)^2(r_Z/2)(3 + \cos^2\theta + 2\sin^2\theta\cos^2\varphi)]/Y ,$$
$$Y \equiv 8\pi[r_Z(Gw^0 - F)^2 - (|\mathbf{w}|^2/3)(r_Z G^2 - F^2)] . \qquad (5)$$

Here θ is the angle between the beam axis and $\mathbf{q}_Z$, while φ is the azimuthal angle between the beam axis and the $\mathbf{q}_\perp, \mathbf{q}_Z$ plane, as illustrated in Fig. 1.

The scalar and pseudoscalar decay distributions differ characteristically in both θ and φ. This is evident from the three-dimensional plots shown in Fig. 2. For the pseudoscalar case [Fig. 2(a)], not only does the φ distribution peak at $\varphi = \pi/2, 3\pi/2$, but it is correlated there with a saddle-point behavior in θ; in contrast, at $\varphi = 0, \pi$ there is a two-way minimum with respect to θ and φ. For the scalar case [Fig. 2(b)], with the choice $m_Q = 80$ GeV and $m_H = 40$ GeV, the Z is moderately nonrelativistic and one observes a two-way minimum at $\varphi = \pi/2, 3\pi/2$ while a two-way maximum is seen at $\varphi = 0, \pi$.

Consider also the φ distribution after integrating over the polar angle θ. This is a measure of the direction of polarization of the Z. The emission rate for a pseudoscalar Higgs boson goes as $1 + \tfrac{2}{3}\sin^2\varphi$. For a scalar Higgs boson, the general form is $C - \tfrac{2}{3}\sin^2\varphi$, where C is a positive quantity that depends on kinematic- and model-dependent factors, becoming $\tfrac{5}{3}$ when the Z is very rela-

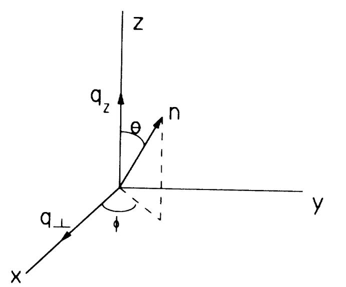

FIG. 1. Coordinate system for $Q\bar{Q} \rightarrow Z+$Higgs boson with $Z \rightarrow$ two massless fermions. $\mathbf{n}$ is the beam axis, $\mathbf{q}_Z$ is the Z momentum direction, and $\mathbf{q}_\perp$ is a vector lying in the plane of the massless fermion momentum but which is perpendicular to $\mathbf{q}_Z$.

tivistic. However, because of the opposite signs and the large coefficient of the $\sin^2\varphi$ term, the φ distributions for the two cases are always quite distinct and will unambiguously indicate the parity of the Higgs boson. This is in agreement with the results for the virtual-photon-decay case discussed previously.[5,6]

We come now to the θ distribution after integrating out the azimuthal angle φ. The emission rate here for a pseudoscalar Higgs boson goes as $1+\cos^2\theta$, the same as that for the Wilczek process. However, for a scalar Higgs boson, the general form is $1+\beta\cos^2\theta$, where β is a quantity that depends on kinematic- and model-dependent factors. The dependence of β on kinematics is such that β approaches 1 for a relativistic Z while it vanishes at threshold where the Z velocity vanishes, for all values of X_Z/X_Q. This is illustrated in Fig. 3 where β is plotted against the quarkonium mass. Thus unless the Z is highly relativistic, the θ distribution can also unambiguously indicate the parity of the Higgs boson.

A necessary condition for any heavy quarkonium, produced at a future e^+e^- machine, to be a practical Higgs-boson source is that the beam-energy resolution δW multiplied by the quarkonium width be sufficiently small. For LEP 2 the present plan is to have $\delta W = (5-0.21\sqrt{s}+0.007s)$ MeV, where s is the center-of-mass energy in GeV^2, which is much too large to conduct any Higgs-boson studies off of a toponium. On the other hand, the quarkonium of a new heavy quark with suppressed weak decays could still produce copious numbers of Higgs particles at this machine. Specifically, let us take Q to be a $-\frac{1}{3}$ charge $\mathrm{SU}(2)_L$ singlet without mixing to any light quark and calculate the number of $Z+H$ final states from $1\,{}^3S_1(Q\bar{Q})$ decay, given an integrated luminosity of 500 pb^{-1} at LEP 2 (the results are approximately the same for Q being a $-\frac{1}{3}$ charge fourth-generation quark). For $m_Q = 100$ GeV and $X_Q = -X_Z = 1$, we estimate a signal of about 900 scalars or 70 pseudoscalars as compared with the background from $Z^* \rightarrow Z+H$ decay[13] of 350 for scalar or 0 for pseudoscalar Higgs boson. Our parity test should then be quite feasible.

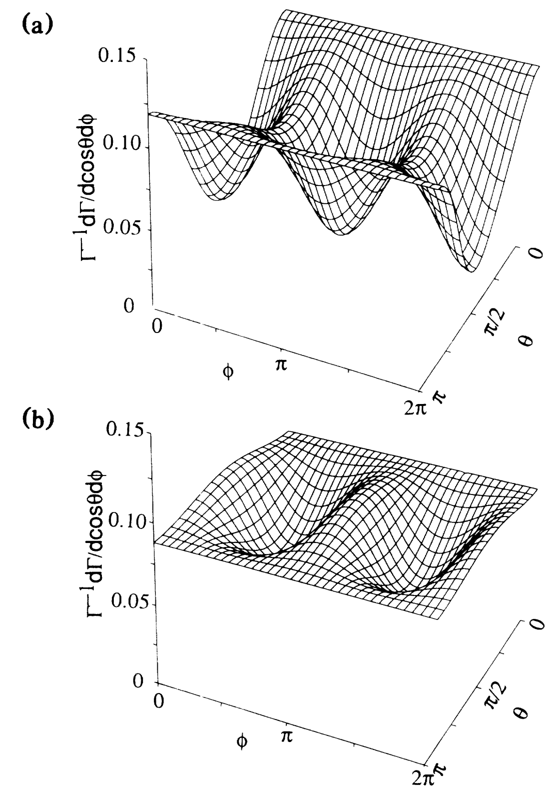

FIG. 2. Three-dimensional plot of $\Gamma^{-1}d\Gamma/d\cos\theta d\varphi$ for (a) the pseudoscalar-Higgs-boson case, Eq. (4), and (b) the scalar-Higgs-boson case, Eq. (5), with $m_Q = 80$ GeV and $m_H = 40$ GeV.

In summary, a study of the decay ${}^3S_1(Q\bar{Q}) \rightarrow Z+H$ should lead to the determination of the fermionic parity of the Higgs boson H. The decay rate for this process is typically comparable to, and can be much larger than, the similar decay ${}^3S_1(Q\bar{Q}) \rightarrow \gamma+H$. While the $\gamma+H$ decay provides no direct[8] information on the parity of

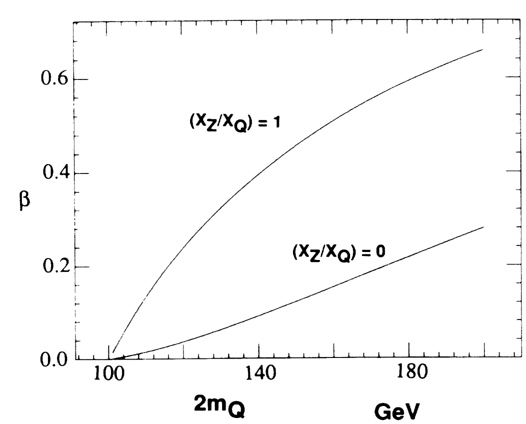

FIG. 3. Plot of β, defined in the text, as a function of the quarkonium mass, for a Higgs-boson mass of 10 GeV and for two values of X_Z/X_Q: 0 and 1.

the Higgs boson, the $Z+H$ decay provides several independent such measures. For a nonrelativistic Z, a comparison of the two partial widths may enable one to distinguish a scalar Higgs boson from a pseudoscalar one. A study of the behavior of $\Gamma^{-1} d\Gamma/d\cos\theta\, d\varphi$ will always allow this discrimination. In particular, the polar distribution of the emitted Z with respect to the beam axis is a discriminant unless the Z is highly relativistic. The azimuthal orientation of the plane of the decay products of the Z, with respect to the beam axis, provides an unambiguous, fail-safe measure of the Higgs-boson parity.

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[a]On sabbatical leave (1989–90) from the Tata Institute of Fundamental Research, Bombay, India.

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