Relativistic effects in the decay $V \to H^0 \gamma$

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The influence of relativistic effects on the width of the radiative decay $V \to H^0 + \gamma$ has been studied. These effects substantially reduce the width predicted by the nonrelativistic quark model.

An active search has recently been undertaken for light Higgs bosons (H^0 bosons) in the radiative decay of vector bottomonium,[1,2] $\Upsilon(9.46)$. The experimental planning has been based on the width predicted for this decay by the nonrelativistic quark model[3]:

$$R = \frac{\Gamma(V \to H^0 + \gamma)}{\Gamma(V \to \mu^+ \mu^-)} = \frac{G_F M_V^2}{4\sqrt{2}\pi\alpha}\left(1 - \frac{M_H^2}{M_V^2}\right), \tag{1}$$

where M_V and M_H are the masses of vector quarkonium and of the H^0 boson, respectively.

As Ellis *et al.*[4] have emphasized, however, radiative corrections[5] and effects of the mixing of H^0 and P-even states of bottomonium[6,7] lead to a significant decrease in the ratio R. It is accordingly extremely important to study how relativistic effects influence this ratio. Such effects may also prove important, since an examination of the bottomonium mass spectrum reveals that the mean value of v^2/c^2 in $\Upsilon(9.46)$ is not small: $\langle v^2/c^2 \rangle \simeq 0.1$.

In the present letter we are reporting the results of calculations carried out to incorporate relativistic effects in the decay $V \to H^0\gamma$. In evaluating the relativistic effects we have considered Higgs bosons with masses satisfying the relation $M_V - M_H \gg \alpha_S^2 M_V$. We can therefore ignore diagrams associated with the incorporation of quantum-chromodynamics (QCD) corrections, since (as Vysotsky[5] has shown) at these values of M_V the contribution of these diagrams to the ratio R is relatively small, $\simeq 35\%$. We have treated the particle $\Upsilon(9.46)$ as a pure $1\,^3S_1$ state, since the admixture of other states in $\Upsilon(9.46)$ is negligibly small in all the models which describe the bottomonium mass spectrum with the QCD interaction between quarks (Ref. 8, for example).

The calculations were carried out in the infinite-momentum system obtained by a "boost" along the z axis. In this system we have $k_0 = -k_z = (M_V^2 - M_H^2 - \mathbf{k}_\perp^2)/4p$, where k is the momentum of the γ ray, and $p \to \infty$ is the momentum of the bottomonium. Of the time-ordered diagrams of the noncovariant perturbation theory describing the process $V \to H^0\gamma$ (Fig. 1), only that in Fig. 1a survives in this system. The nature of the vertex of the $V \to q\bar{q}$ transition in the infinite-momentum system can be found by working from the results of Ref. 9, where a general method was found for constructing transition vertices of this sort, corresponding to definite values of the spins, the orbital angular momenta, and the total angular momenta of the quarks in the rest system of

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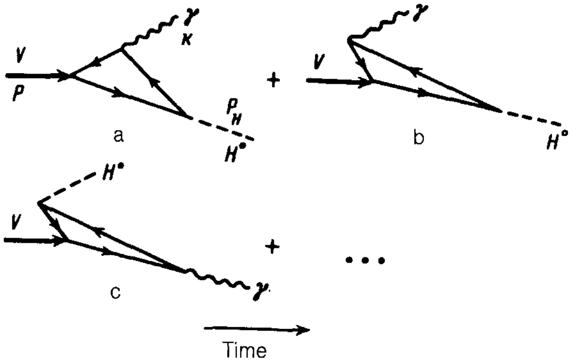

FIG. 1. Diagrams of noncovariant perturbation theory for the decay $V \to H^0 + \gamma$.

the meson. For clarity, we give here only the first two terms in the expansion of our results in powers of p^2/m^2 (p is the momentum of the quark in the rest system of the bottomonium, and m is the quark mass):

$$R = \frac{G_F m^2}{\sqrt{2}\pi\alpha}\left(1 - \frac{M_H^2}{M_V^2}\right)\left(\frac{M_V^2 - M_H^2}{4m^2 - M_H^2}\right)^2 I \ , \tag{2}$$

$$I = 1 + \frac{\Delta}{3} - \frac{10}{3}\,\frac{\Delta}{1 - M_H^2/(4m^2)} \ , \tag{3}$$

$$\Delta = \int \frac{p^2}{m^2}\,\varphi(p^2)p^2 dp \ / \int \varphi(p^2)p^2 dp \, , \tag{4}$$

where $\varphi(p^2)$ is the radial part of the wave function of the quarks in the bottomonium.

It can be seen from (2)–(4) that incorporating relativistic corrections on the order of p^2/m^2 leads to a *decrease* in R. This effect is accentuated by the circumstance that the numerical value of Δ is greater than the mean value of p^2/m^2 in Υ, which is quite large in the bottomonium system. Also tending to reduce the ratio R is the factor $[(M_V^2 - M_H^2)/(4m^2 - M_H^2)]^2$, since the condition $M_V < 2m$ holds in all the models describing the bottomonium mass spectrum. The term containing $\Delta/(1 - M_H^2/(4m^2))$, in (3) (the term which actually causes the decrease in R) increases with increasing M_H (we recall that our analysis is valid for $M_V - M_H \gg \alpha_S^2 M_V$, i.e., for bottomonium with $M_\Upsilon \simeq 9.4$ GeV or essentially for $M_H \lesssim 7.5 - 8$ GeV), and it leads to an even greater decrease in R because of relativistic effects.

Figure 2 shows the results of numerical calculations of the ratio R without a series expansion in the ratio p^2/m^2. These curves correspond to the values found by Kulshreshtha[10] for the mass of the b quark and for the wave function $\varphi(p^2)$. The results change only slightly when we take these values from other studies.

We thus see that incorporating relativistic effects in the mechanism for the radiative production of the H^0 boson in the decays of vector quarkonium leads to a pronounced decrease in the width of this decay. For bottomonium we find that the ratio R decreases by a factor of about two at $M_H \lesssim 4$ GeV or a factor of three or four for $M_H \simeq 6$–8 GeV (Fig. 2).

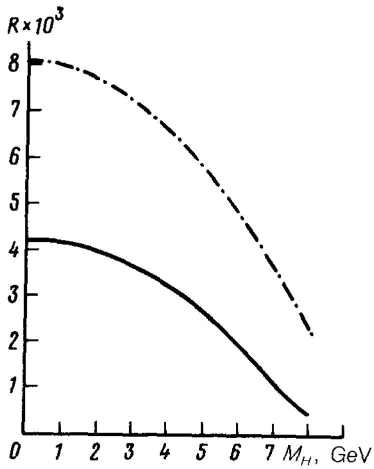

FIG. 2. The ratio R versus the mass of the Higgs boson, M_H. Dot-dashed line—nonrelativistic approximation [expression (1)]; solid line—with relativistic effects.

Relativistic effects may also be significant in the radiative decays of toponium, where we would expect the mean value of v^2/c^2 to be roughly the same as in bottomonium.[10]

In summary, relativistic effects lead to a strong suppression of R. As we have already mentioned, incorporating radiative corrections to the process $V \to H^0 + \gamma$ works in the same direction.[5] The results found here lend strong support to the assertion[4] that the conclusion, based on experiments, that there are no light Higgs bosons with $M_H \lesssim 10$ GeV in the radiative decays of Υ is premature.

We wish to call upon the experimentalists to find a definitive resolution of this problem by substantially improving the sensitivity of experiments on monochromatic γ rays in the decays of bottomonium.

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