Scalar-Quark Bound-State Interpretation of the $\zeta(8.3)$

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We interpret the $\zeta(8.3 \text{ GeV})$ as the 0^{++} ground state of a scalar-quark ($\sigma\bar{\sigma}$) bound system where σ is a color triplet and has electric charge $|Q| = \frac{1}{3}$. With the use of the quarkonium potential model, the energy of the third (1^{--}) P state is calculated to be within 50 MeV of the Y state. If it falls within the machine energy spread (20 MeV at DORIS) of the Y , all existing data can be understood.

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Recently the Peck *et al.*¹ announced evidence for a state which they call ζ . It has the following properties:

$$M(\zeta) = 8.322 \pm 0.026 \text{ GeV},$$

$$\Gamma(\zeta) < 80 \text{ MeV},$$

$$B(Y \rightarrow \gamma\zeta) = (0.57 \pm 0.28)\%,$$

$$\rho = \frac{B(Y' \rightarrow \gamma\zeta)}{B(Y \rightarrow \gamma\zeta)} < 0.22,$$

$$B(Y \rightarrow \gamma\zeta, \zeta \rightarrow \tau^+\tau^-) < 0.2\%,$$

$$B(Y \rightarrow \gamma\zeta, \zeta \rightarrow e^+e^-) < 0.03\%,$$

where the errors are the sums (by quadrature) of the statistical and systematic errors and the bounds are quoted at the 90% confidence level. Since $Y' \rightarrow Y + \text{anything}$ (mostly $Y\pi\pi$) approximately one-third of the time, one expects the data sample to include 53 ± 13 events of the type

$$Y' \rightarrow Y + \text{anything}, \quad Y \rightarrow \gamma\zeta.$$

The data show no hint of this transition, and Peck *et al.* place the upper bound for his channel at 70 events. Youssef *et al.*² obtain the upper bound

$$B(Y \rightarrow \gamma\zeta) < 0.20\%$$

in an independent experiment.

In this paper we interpret the $\zeta(8.3)$ as the 0^{++} ground state of a scalar-quark-anti-scalar-quark ($\sigma\bar{\sigma}$) bound system. Here the scalar quark σ has zero spin and electric charge $|Q| = \frac{1}{3}$ while its baryon and lepton numbers and weak isospin remain unspecified. It is a QCD color triplet. If we identify it as the supersymmetric partner of a charge $-\frac{1}{3}$ quark, and if R invariance is valid, the experi-

mental constraints³ on the σ allow the mass range $1 \text{ GeV} < M(\sigma) < 7 \text{ GeV}$. This window is compatible with the σ mass we need to explain the ζ , namely $M(\sigma) \sim 4 \text{ GeV}$. If R invariance is broken, then there is essentially no experimental constraint on $M(\sigma)$. Of course we need not identify σ as a particle in a supersymmetric theory. To emphasize this point we refer to the σ as a scalar triplet [as opposed to a scalar quark (s-quark)]. We assume that the σ decay is not strong enough to have an observable effect on the spectroscopic properties of the scalar-triplet-anti-scalar-triplet bound system below the continuum threshold.

Recent studies in the Ψ/J and the Y spectroscopies have determined quite accurately the quarkonium potential that is applicable to the scalar-triplet-anti-scalar-triplet spectroscopy.^{4,5} Since there are no spin-dependent forces in the scalar-triplet-anti-scalar-triplet system, we can reliably and accurately calculate the energy eigenstates and radiative transitions as well as the various decay widths. The S -wave states have $J^{PC} = 0^{++}$ while the P -wave states have $J^{PC} = 1^{--}$. Using the observed mass of the lowest 0^{++} state, $M(\zeta) = M(1S) = 8.32 \text{ GeV}$, together with the QCD-motivated potential,⁵ we find for the excited 0^{++} states $M(\zeta') = M(2S) = 8.88 \text{ GeV}$ and $M(\zeta'') = M(3S) = 9.22 \text{ GeV}$, and for the 1^{--} states, $M(1P) = 8.75 \text{ GeV}$, $M(2P) = 9.11 \text{ GeV}$, and $M(3P) = 9.41 \text{ GeV}$. In Fig. 1 we show the energy-level diagram for these states as well as the D -wave ($J^{PC} = 2^{++}$) states below the continuum threshold. The mass of the scalar triplet is $M(\sigma) \approx 4.3 \text{ GeV}$, and the continuum threshold is around 9.48 GeV . Except for $M(3P)$ our estimates of the resonance masses carry an error of about 40 MeV, attributable to uncertainty in the measured ζ mass of 26 MeV

FIG. 1. The S -, P -, and D -wave states of the scalar quark ($\sigma\bar{\sigma}$) bound system below the continuum threshold. The numbers under the lines are masses in gigaelectron volts, and the dashed lines with arrows are the $E1$ radiative transitions from the $3P$ (1^{--}) state. The numbers in brackets are the branching fractions in percent. They have an uncertainty of a factor of 2.

and to uncertainty in the potential model of about 30 MeV. Because the $3P$ state is so close to continuum threshold, coupled-channel effects introduce an additional uncertainty of about 40 MeV in this case.

Hence we obtain $M(3P) = 9.41 \pm 0.06$ GeV, which is very close to the Y mass at 9.46 GeV. The center-of-mass energy spread at the Y energy is about 20 MeV (full width of a Gaussian distribution) for the DORIS machine.⁶ The $3P$ ($J^{PC} = 1^{--}$) narrow resonance and the Y resonance are not unlikely to coexist within this energy spread. We propose that this accident actually happens. Since the leptonic width of the $3P$ state is much smaller than that of the Y state, the $3P$ state can easily hide under the Y resonance. The apparent transition $Y \rightarrow \gamma\zeta$ is really due to the radiative transition $3P \rightarrow \gamma\zeta$. Since the Y' energy, 10.02 GeV, is way above the continuum threshold of the scalar-triplet-anti-scalar-triplet system, it is immediately clear that the ζ production rate at the Y' resonance is negligibly small. Likewise no ζ particles are expected from the decays of Y 's produced via the channel $Y' \rightarrow \pi\pi Y$. Let us now investigate this

scenario in greater detail.

The leptonic width of a P state is given by⁷

$$\Gamma(nP \rightarrow l^+ l^-) = 24\alpha^2 Q^2 \frac{|R'_P(0)|^2}{M_P^4},$$

where $|Q| = \frac{1}{3}$ and $R'_P(r)$ is the derivative of the P -state wave function. Numerically $\Gamma_{ee}(3P) \approx 30$ eV, $\Gamma_{ee}(2P) \approx 29$ eV, and $\Gamma_{ee}(1P) \approx 24$ eV. Compared to the leptonic width of the Y , $\Gamma_{ee}(Y) \approx 1.2$ keV, the rise in R due to the P -state resonances is only $\frac{1}{40}$ that of the Y state, i.e., $\Delta R \sim 0.2$ at DORIS. With present data the $3P$ state would not make a resolvable contribution to the total cross section regardless of its precise difference in mass from the Y . The hadronic decay of a P state proceeds dominantly via the three-gluon decay mode for which the rate is⁷

$$\Gamma(P \rightarrow 3g) = \frac{160}{9\pi} \alpha_s^3 \frac{|R'_P(0)|^2}{M_P^4} \ln \left(\frac{M_\sigma}{\Delta} \right),$$

where Δ is a cutoff that can be chosen to be of the order of the binding energy. Here we shall simply follow Ref. 7 and make a crude estimate. The radiative transitions between the P - and S -wave states are given by

$$\Gamma(nP \rightarrow mS + \gamma) = \frac{4}{9} \alpha Q^2 \omega^3 |D_{nm}|^2,$$

where ω is the photon energy and D_{nm} is the dipole matrix element. With the coefficient $\frac{4}{9}$ replaced by $\frac{20}{9}$ this formula is also valid for the $nP \rightarrow mD + \gamma$ transitions. When the photon energy is large, the finite-size (retardation) effect should be included in D_{nm} :

$$D_{nm} = (6/k) \langle mS \text{ or } mD | j_1(\frac{1}{2}kr) | nP \rangle,$$

where k is the photon momentum. We can also estimate the hadronic transition rates.⁸ They are quite small. The resulting decay widths are

$$\Gamma(3P \rightarrow l^+ l^-) \approx 30 \text{ eV},$$

$$\Gamma(3P \rightarrow \gamma\zeta) \approx 8.3 \text{ keV},$$

$$\Gamma(3P \rightarrow \gamma\zeta') \approx 7.9 \text{ keV},$$

$$\Gamma(3P \rightarrow \gamma\zeta'') \approx 15.4 \text{ keV},$$

$$\Gamma(3P \rightarrow \gamma + 1D) \approx 0.4 \text{ keV},$$

$$\Gamma(3P \rightarrow \gamma + 2D) \approx 14.6 \text{ keV},$$

$$\Gamma(3P \rightarrow \text{hadrons}) \approx 30 \text{ keV},$$

$$\Gamma(3P \rightarrow \pi\pi + 1P) \approx 1 \text{ keV},$$

$$\Gamma(3P \rightarrow \text{all}) \approx 78 \text{ keV},$$

We emphasize that the three-gluon decay rate has large uncertainties. As a result the various branching ratios may have sizable uncertainties.

In principle the genuine Y state also decays to $\gamma\zeta$ (via $Y \rightarrow \gamma gg, gg \rightarrow \zeta$), but we estimate that this rate is very small, $B(Y \rightarrow \gamma\zeta) \approx 10^{-5}$ to 10^{-4} . To a good approximation we can ignore the actual $Y \rightarrow \gamma\zeta$ decay. The apparent $Y \rightarrow \gamma\zeta$ decay is really due to the decay of the nearby $3P$ resonance. Hence we predict the following apparent branching ratios:

$$B(Y + 3P \rightarrow \gamma\zeta) \approx 0.3\% \text{ at } E_\gamma \approx 1.08 \text{ GeV},$$

$$B(Y + 3P \rightarrow \gamma\zeta') \approx 0.3\% \text{ at } E_\gamma \approx 0.52 \text{ GeV},$$

$$B(Y + 3P \rightarrow \gamma\zeta'') \approx 0.5\% \text{ at } E_\gamma \approx 0.18 \text{ GeV},$$

$$B(Y + 3P \rightarrow \gamma + 1D) \approx 0.01\%$$

$$\text{at } E_\gamma \approx 0.40 \text{ GeV},$$

$$B(Y + 3P \rightarrow \gamma + 2D) \approx 0.5\% \text{ at } E_\gamma \approx 0.10 \text{ GeV}.$$

These branching fractions probably have a factor of 2 uncertainty. The photon energies should be quite accurate. The estimate for the first of these branching fractions is to be compared with the measurement by Peck *et al.* of $(0.57 \pm 0.28)\%$. The decay width of the ζ is roughly 1 MeV and is dominated by hadronic modes (i.e., the two-gluon mode). Therefore the branching fraction $B(\zeta \rightarrow l^+ l^-)$ is negligibly small. The two-gluon decay mode of ζ is compatible with the low-multiplicity ($n_c < 9$) data sample of Ref. 1.

The masses of the fermionic bound state $(\sigma\bar{u})$ and $(\sigma\bar{d})$ are about 4.74 GeV while the bosonic states (σuu) , (σud) , and (σdd) have masses of about 5.0 GeV. Above the continuum threshold the contribution of the scalar triplet to the e^+e^- cross section is very small,

$$\Delta R(e^+e^- \rightarrow \sigma\bar{\sigma}) \sim \beta^3/12,$$

and the onset is very gradual because of the factor cubic in the scalar-triplet velocity β . Observing such a small, slow rise in R is likely to be quite difficult.

There is no $1^{--}(\sigma\bar{\sigma})$ narrow resonance sitting under the $Y(10.02)$ state in the e^+e^- channel. From the genuine $Y, Y' \rightarrow \gamma\zeta$ rate we predict

$$\frac{B(Y' \rightarrow \zeta + \gamma + \text{anything})}{B(Y + 3P \rightarrow \gamma\zeta)} \lesssim 10^{-2},$$

where $Y' \rightarrow \zeta + \gamma + \text{anything}$ includes $Y' \rightarrow \gamma\zeta$ as well as $Y' \rightarrow \pi\pi Y, Y \rightarrow \gamma\zeta$. Hence it is clear why the ζ is not seen at the Y' resonance. In comparison we observe that the ρ factor, $\rho = B(Y' \rightarrow \gamma\zeta)/B(Y \rightarrow \gamma\zeta)$, is estimated to be about 0.8

for a pseudoscalar Higgs particle and $\rho \sim 0.5$ for a scalar Higgs particle.⁹ These estimates have included the bound-state effects. The experimental bound on the ρ factor clearly excludes the pseudoscalar Higgs-particle case. Because of the theoretical and experimental uncertainties, the scalar Higgs-particle case is still a possibility. A more precise experimental determination of the ρ factor can distinguish between the scalar Higgs-particle and the scalar-triplet-anti-scalar-triplet system interpretations.

The center-of-mass energy spread of the Cornell storage ring CESR¹⁰ is about 8 MeV when this machine operates near the Y mass. The corresponding energy spread for DORIS is about 20 MeV. The mass of the $3P$ state could easily be well within the Y resonance peak at DORIS and yet be considerably off the resonance at CESR. In this case CESR experiments taking data at the Y peak would observe a substantially reduced rate for the apparent transition $Y \rightarrow \gamma\zeta$. Indeed, this situation may explain the nonobservation of $Y \rightarrow \gamma\zeta$ by Youssef *et al.* Because of the smaller energy spread at CESR, the $1P$ and $2P$ resonances will have $\Delta R \approx 0.4$ and 0.5 , respectively, to be compared with $\Delta R \approx 0.2$ at DORIS.

In summary, we propose the scalar-triplet bound-state interpretation for the ζ . The only experimental input to our model calculations is the ζ mass. Other quantities can be reliably calculated and are in good agreement with data. This model has many precise, easily testable, and in some cases dramatic predictions. If borne out by experiment, it points to a new direction in our understanding of nature. It will be essential to find out if the scalar-triplet is indeed an s-quark.

Suppose the scalar-triplet is actually an s-quark. Its strong decay to quark + gluino and its electromagnetic decay to quark + photino would in general severely suppress the branching ratio $B(3P \rightarrow \gamma\zeta)$. Hence, it is likely that these s-quark decay modes are suppressed by phase-space and/or by flavor symmetry.¹¹ Since the s-quark cannot be stable³ (its lifetime must be shorter than 5×10^{-8} sec), it may decay via the W -ino, $\tilde{q} \rightarrow \tilde{W}q, \tilde{W} \rightarrow l\tilde{\nu}$. For each quark, supersymmetry requires the existence of two s-quarks, $\tilde{q}_L$ and $\tilde{q}_R$, which are the partners of the left- and right-handed components of the quark. If $\tilde{q}_L$ and $\tilde{q}_R$ are degenerate in mass, the rise in R as well as the apparent branching ratios for the $Y + 3P$ decay given above should be doubled. In particular the apparent branching ratio $B(Y + 3P \rightarrow \gamma\zeta) \approx 0.6\%$.

A comment is in order. Although in the above

discussion we have taken the ζ constituent to be a QCD color triplet, we could, of course, consider alternatives in which it belongs to some other color representation such as **6**, **8**, or **10**. Such a particle is predicted in some composite models. In these cases the potential is stronger than that for quarks or scalar-triplets, and it is possible that the $2P$ state or the $1P$ state has an energy close to the Y mass. If this happens, the present data would be explained in essentially the same way as with the color triplet σ , but many of the predictions (e.g., the P -state energies and the photon lines) would be drastically modified.

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