How the $Z_c(3900)$ Reveals the Spectra of Charmonium Hybrids and Tetraquarks

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(Received 27 May 2013; published 18 October 2013)

The recently discovered $Z_c(3900)$ meson is a flavor-exotic tetraquark whose constituents consist of a charm quark and antiquark and a light quark and antiquark. We identify such heavy tetraquark mesons as analogs of quarkonium hybrids, with the gluon field replaced by an isospin-1 excitation of the gluon and light-quark fields. Given the identification of $Y(4260)$ as a ground-state charmonium hybrid, lattice QCD calculations of the charmonium spectrum by the Hadron Spectrum Collaboration can be used to estimate the masses of the four lowest spin-symmetry multiplets of charmonium hybrids. We make the assumption that the isospin-1 Born-Oppenheimer potentials, whose energy levels are tetraquarks, have the same shapes as the flavor-singlet Born-Oppenheimer potentials, whose energy levels are hybrids. Given the identification of $Z_c(3900)$ as a charmonium tetraquark, lattice QCD calculations of the charmonium hybrid spectrum can then be used to estimate the masses of the four lowest spin-symmetry multiplets of charmonium tetraquarks.

DOI: 10.1103/PhysRevLett.111.162003 PACS numbers: 14.40.Pq, 12.38.−t, 14.40.Rt

One of the most basic problems of QCD is to identify all the clusters of quarks, antiquarks, and gluons that are sufficiently bound by QCD interactions that they are either stable particles or else sufficiently long-lived to be observed as resonances. The simplest bound clusters are baryons, which consist of three quarks (qqq), and ordinary mesons, which consist of a single quark and antiquark ($q\bar{q}$). The Review of Particle Properties lists dozens of baryons that are well established, hundreds of mesons that are well established, and many more resonances that are less well established [1]. The most general meson allowed by QCD is a cluster whose constituents consist of equally many quarks and antiquarks and possibly also gluons (g). An exotic meson has constituents that are not $q\bar{q}$. Two of the simplest types of exotic mesons are hybrids ($q\bar{q}g$) and tetraquarks ($qq\bar{q}\,\bar{q}$). A manifestly exotic meson has quantum numbers that are incompatible with $q\bar{q}$. A meson is spin exotic if its J^{PC} quantum numbers are in the sequence $\mathbf{0}^{--}, \mathbf{0}^{+-}, \mathbf{1}^{-+}, \mathbf{2}^{+-}, \mathbf{3}^{-+}, \ldots$. (Here and below, a bold-face $\boldsymbol{J}$ indicates exotic quantum numbers.) A meson is flavor exotic if its flavor quantum numbers are incompatible with $q\bar{q}$. Until 2011, no manifestly exotic mesons had been definitively identified.

The recent definitive discoveries of manifestly exotic mesons have come in sectors of QCD that were believed to be the best understood, namely, those containing a heavy quark and antiquark ($Q\bar{Q}$), where Q is a charm quark (c) or a bottom quark (b). These new mesons are flavor-exotic tetraquark mesons, whose constituents consist of a $Q\bar{Q}$ pair and a light quark-antiquark pair. In October 2011, the Belle Collaboration announced the discovery of $Z_b^+(10610)$ and $Z_b^+(10650)$, both of which decay into $\Upsilon(nS)\pi^+$, $n = 1, 2, 3$, and into $h_b(nP)\pi^+$, $n = 1, 2$, [2], revealing their constituents to be $b\bar{b}u\bar{d}$. These flavor-exotic tetraquark mesons have surprisingly narrow widths of about 10 and 20 MeV, respectively. The neutral member $Z_b^0(10610)$ of one of the isospin multiplets (Z_b^-, Z_b^0, Z_b^+) has also been observed [3]. These states have isospin and G parity $I^G = 1^+$ and their preferred spin and parity are $J^P = 1^+$ [4].

During the past year, flavor-exotic tetraquark mesons have also been discovered in the $c\bar{c}$ sector of QCD. In March 2013, the BESIII Collaboration announced the discovery of $Z_c^+(3900)$ through its decay into $J/\psi\pi^+$ [5], which reveals its constituents to be $c\bar{c}u\bar{d}$. The existence of the $Z_c^+(3900)$ was confirmed by the Belle Collaboration [6] and by an analysis of data from the CLEOc Collaboration [7]. The latter analysis provided evidence for the neutral member $Z_c^0(3900)$ of the (Z_c^-, Z_c^0, Z_c^+) multiplet. The measurements in Refs. [5,6] determine the mass of the $Z_c(3900)$ to be 3897 ± 5 MeV and its width to be 51 ± 18 MeV. In June 2013, the BESIII Collaboration announced the discovery of $Z_c^+(4020)$ through its decay into $h_c(1P)\pi^+$ [8,9], which reveals its constituents to be $c\bar{c}u\bar{d}$. Its mass is $4021.8 \pm 1.0 \pm 2.5$ MeV and its width is $5.7 \pm 3.4 \pm 1.1$ MeV. They also observed a state decaying into $(D^*\bar{D}^*)^+$ with a slightly larger mass and a larger width [8,9]. This could be the same state $Z_c^+(4020)$ whose fitted mass and width have been increased by final-state interactions associated with the nearby $D^*\bar{D}^*$ threshold.

The constituents of the tetraquark mesons Z_b and Z_c are clearly revealed by their decay products. However, the structure of these mesons is an open question. The possibilities that were proposed for $Z_c^+(3900)$ in the first two weeks after the announcement of its discovery include a cusp in $D^*\bar{D}$ scattering [10], a charm-meson molecule consisting of D^* and $\bar{D}$ [11–17], a tetraquark consisting of cu and $\bar{c}\,\bar{d}$ diquarks [13,16], and hadrocharmonium consisting of $u\bar{d}$ bound to a color-singlet $c\bar{c}$ core [15,16]. Many more possibilities for Z_b have been proposed. These models are all inherently phenomenological, making no direct contact with QCD. In particular, they are not easily verified through nonperturbative calculations using lattice QCD. In this Letter, I point out compelling candidates for the Z_b and Z_c that can be confirmed using lattice gauge theory. I propose that they are analogs of quarkonium hybrids with the excitation of the gluon field replaced by an isospin-1 excitation of the gluon and light-quark fields.

We begin by discussing quarkonium hybrids. Their existence in QCD without light quarks was demonstrated convincingly by Juge, Kuti, and Morningstar using the Born-Oppenheimer approximation in conjunction with lattice nonrelativistic QCD (NRQCD) [18]. In the Born-Oppenheimer approximation, the Q and $\bar{Q}$ are assumed to move adiabatically in a Born-Oppenheimer (B-O) potential defined by the energy of the gluon field in the presence of static Q and $\bar{Q}$ sources, while the gluon field responds almost instantaneously to the motion of the Q and $\bar{Q}$. The B-O potentials can be labeled by the eigenvalues of $\hat{\boldsymbol{R}} \cdot \boldsymbol{J}_{\rm light}$ and $(CP)_{\rm light}$, where $\boldsymbol{R}$ is the separation vector of the Q and $\bar{Q}$, $\boldsymbol{J}_{\rm light}$ is the angular momentum of the gluon field, and $(CP)_{\rm light}$ is the product of its charge conjugation and parity. It is more traditional to label them Σ_g^+, Π_u, Σ_u^-, etc. Juge, Kuti, and Morningstar used lattice QCD without dynamical light quarks to calculate the B-O potentials [18]. Ordinary quarkonia correspond to bound states of Q and $\bar{Q}$ in the B-O potential for the ground state of the gluon field, which is labeled Σ_g^+. Those bound states form spin-symmetry multiplets: S-wave multiplets with J^{PC} quantum numbers $\{0^{-+}, 1^{--}\}$, P-wave multiplets $\{1^{+-}, (0, 1, 2)^{++}\}$, D-wave multiplets $\{2^{-+}, (1, 2, 3)^{--}\}$, etc. Quarkonium hybrids correspond to bound states of Q and $\bar{Q}$ in B-O potentials for excited states of the gluon field. The lowest excited B-O potentials are labeled Π_u and Σ_u^-. The Π_u potential is deeper, with a minimum near 0.3 fm [18]. In the limit $R \to 0$, the Π_u and Σ_u^- potentials both approach the repulsive $1/R$ potential for a color-octet $Q\bar{Q}$ pair and they are both linear in R as $R \to \infty$ [19]. The energy levels in each of the Born-Oppenheimer potentials can be labeled nL, where n is a radial quantum number and $L = 0, 1, 2, \ldots$ (or $S, P, D, \ldots$) is the quantum number for the sum $\boldsymbol{L}$ of the orbital angular momentum of the $Q\bar{Q}$ pair and $\boldsymbol{J}_{\rm light}$. In the Π_u potential, L is restricted to be 1 or larger, while in the Σ_u^- potentials, all values of L are allowed. The lowest hybrid energy level is $\Pi_u(1P)$, which consists of two spin-symmetry multiplets, $H_1 = \{1^{--}, (0, \mathbf{1}, 2)^{-+}\}$ and $H_2 = \{1^{++}, (\mathbf{0}, 1, \mathbf{2})^{+-}\}$. These two multiplets are degenerate in the leading Born-Oppenheimer approximation, but the degeneracy is broken by the coupling between $\boldsymbol{L}$ and $\boldsymbol{J}_{\rm light}$. Other low energy levels include $\Sigma_u^-(1S)$, which is a single spin-symmetry multiplet $H_3 = \{0^{++}, 1^{+-}\}$, the radial excitation $\Pi_u(2P)$ with multiplets H_1' and H_2', and the orbital excitation $\Pi_u(1D)$ with multiplets $H_4 = \{2^{++}, (1, \mathbf{2}, 3)^{+-}\}$ and $\{2^{--}, (\mathbf{1}, 2, \mathbf{3})^{-+}\}$. For bottom quarks in the absence of dynamical light quarks, the ordering of the lowest energy levels in the leading Born-Oppenheimer approximation is H_1 and H_2, which are degenerate, then H_1', and then H_3 [18].

Juge, Kuti, and Morningstar also used lattice NRQCD with bottom quarks but without dynamical light quarks to calculate the energies of the lowest bottomonium hybrids [18]. The ordering of energy levels in this case is H_1, H_2, H_3, and then H_1'. Because of the absence of dynamical light quarks, the lattice QCD calculations of the B-O potentials and the lattice NRQCD calculations of the spectrum in Ref. [18] are not quantitatively useful for estimating the masses of bottomonium hybrids.

Lattice gauge theory calculations of B-O potentials are complicated by instabilities that are more severe if there are dynamical light quarks [20]. For small separation R of the Q and $\bar{Q}$ sources, there is an instability from transitions to the ground-state potential Σ_g^+ through the emission of two mesons. In the absence of dynamical light quarks, the two mesons must be glueballs, which are relatively heavy. If there are dynamical light quarks, the two mesons can be light mesons, such as $\pi^+\pi^-$. With dynamical light quarks, there is also an instability at large R from transitions to a pair of heavy-light mesons localized near the Q and $\bar{Q}$ sources. If the transition rates for the instabilities are sufficiently small, it may still be possible to define B-O potentials as almost stationary energies of light-quark and gluon fields that are localized near static Q and $\bar{Q}$ sources. Quarkonia and quarkonium hybrids are bound states in B-O potentials for which the gluon and light-quark fields have flavor-singlet quantum numbers. It is also possible to define B-O potentials for which the gluon and light-quark fields have nontrivial flavor quantum numbers, such as isospin 1. The bound states in these potentials would be quarkonium tetraquarks. The calculation of the tetraquark B-O potentials is a challenging problem for lattice QCD. The structure of a tetraquark in the Born-Oppenheimer approximation is qualitatively different from any previous proposals for the structure of the charmonium and bottomonium tetraquarks. I will therefore refer to this possibility as *Born-Oppenheimer tetraquarks*.

In the case of QCD with charm quarks and light quarks, the spectrum of charmonium hybrids can be calculated directly using lattice QCD. Exploratory calculations of the $c\bar{c}$ meson spectrum above the open-charm threshold have been carried out by Dudek *et al.* [21] and extended by the Hadron Spectrum Collaboration [22]. The calculations were carried out at a single lattice spacing and with u and d quark masses that correspond to a pion mass of about 400 MeV. The lowest charmonium hybrid candidates in the calculations of Ref. [22] form the multiplet H_1. The remaining charmonium hybrid candidates could be organized into the spin-symmetry multiplets H_2, H_3, and H_4 [22]. The lowest multiplet H_1 can be interpreted as a constituent gluon with quantum numbers 1^{+-} bound to an S-wave $c\bar{c}$ pair. The supermultiplet consisting of H_2,

H_3, and H_4 can be interpreted as a constituent gluon bound to a P-wave $c\bar{c}$ pair [23]. The Born-Oppenheimer interpretation of these multiplets is that H_1 and H_2 make up the $\Pi_u(1P)$ energy level, H_3 is the $\Sigma_u^-(1S)$ energy level, and H_4 is part of the $\Pi_u(1D)$ energy level. The calculations in Ref. [22] are not definitive, because they were not extrapolated to zero lattice spacing or to the physical values of the u and d quark masses. However, since light quarks are not expected to be important as constituents in charmonium or in charmonium hybrids, the results of Ref. [22] provide plausible estimates for the masses of the charmonium hybrids. The energy splittings between charmonium hybrid states may be less sensitive to the effects of light quarks than their masses.

The results of Ref. [22] are compatible with the identification of $Y(4260)$ as the lowest 1^{--} charmonium hybrid. The $Y(4260)$ was discovered by the *BABAR* Collaboration in 2005 [24] through its decay into $J/\psi\pi^+\pi^-$. It is a plausible candidate for a charmonium hybrid, because it is produced so weakly in e^+e^- annihilation that the resonance is a small peak near a deep local minimum of the cross section into hadrons. The small production rate in e^+e^- annihilation is a consequence of the small wave function for $c\bar{c}$ at the origin that is characteristic of charmonium hybrids. One model-independent prediction for hybrids is that decay into a pair of S-wave mesons is suppressed [25,26]. The dominant decays of charmonium hybrids are therefore expected to be into an S-wave and P-wave charm-meson pair, provided these states are kinematically accessible. The center of the $Y(4260)$ resonance is about 20 MeV below the threshold for $D_1\bar{D}$ and about 80 MeV above the threshold for $D_0^*\bar{D}$, but the latter decay mode is suppressed by a D-wave coupling. Transition decays into charmonium plus light hadrons are also expected to have some suppression from the small overlap between the $c\bar{c}$ wave functions for charmonium hybrids and charmonium. Until the discovery of Z_c, the only decay modes of $Y(4260)$ that were observed were the discovery mode $J/\psi\pi\pi$ [24] and the hadronic transition $J/\psi K\bar{K}$ [27]. The unexpectedly large branching fraction for two-pion transitions to J/ψ was an obstacle to the definitive identification of the $Y(4260)$ as a charmonium hybrid. The discovery of the $Z_c(3900)$ has removed that obstacle by providing the new decay mode into $Z_c\pi$, which contributes to $J/\psi\pi\pi$ through the subsequent decay $Z_c \to J/\psi\pi$.

Having identified the $Y(4260)$ as the lowest 1^{--} charmonium hybrid, we can use the results of Ref. [22] for the splittings between $c\bar{c}$ mesons to estimate the masses of other charmonium hybrids. The results are shown in Table I. The errors are statistical uncertainties only. They do not include the systematic errors associated with the extrapolation to zero lattice spacing or to the small physical masses of the u and d quarks.

Lattice QCD calculations of the $b\bar{b}$ spectrum analogous to those for the $c\bar{c}$ spectrum in Ref. [22] are not feasible with the currently available computer power, but the calculations could be carried out using lattice NRQCD. There is a candidate for the 1^{--} member of the ground-state bottomonium hybrid multiplet T_1. It is the $Y_b(10888)$ observed by the Belle Collaboration as a resonance in e^+e^- annihilation into $\Upsilon(nS)\pi^+\pi^-$ that overlaps with the $\Upsilon(5S)$ [28]. If lattice NRQCD calculations of the splittings between bottomonium hybrid states were available, the mass of the $Y_b(10888)$ could be used as input to predict other bottomonium hybrid states.

TABLE I. Estimates for the masses of charmonium hybrids and charmonium tetraquarks. The bold masses in parentheses were used as inputs. The errors are statistical uncertainties from the inputs and from the lattice QCD results in Ref. [22]. They do not include systematic errors associated with extrapolations to zero lattice spacing and to the physical masses of the u and d quarks. The bold quantum numbers are manifestly exotic.

H_n	J^{PC}	Mass (MeV)	T_n	$I^G(J^P)$	Mass (MeV)
H_1	1^{--}	$(\mathbf{4263 \pm 9})$	T_1	$1^+(1^-)$	3839 ± 41
	0^{-+}	4173 ± 21		$1^-(0^-)$	3748 ± 40
	1^{-+}	4195 ± 23		$\mathbf{1^-(1^-)}$	3770 ± 42
	2^{-+}	4312 ± 24		$1^-(2^-)$	3887 ± 42
H_2	1^{++}	4377 ± 22	T_2	$1^-(1^+)$	3952 ± 41
	$\mathbf{0^{+-}}$	4364 ± 19		$\mathbf{1^+(0^+)}$	3939 ± 39
	1^{+-}	4322 ± 41		$1^+(1^+)$	$(\mathbf{3897 \pm 5})$
	$\mathbf{2^{+-}}$	4373 ± 43		$\mathbf{1^+(2^+)}$	3948 ± 55
H_3	0^{++}	4450 ± 34	T_3	$1^-(0^+)$	4025 ± 49
	1^{+-}	4455 ± 25		$1^+(1^+)$	4030 ± 43
H_4	2^{++}	4470 ± 27	T_4	$1^-(2^+)$	4045 ± 44
	1^{+-}	4475 ± 42		$1^+(1^+)$	4050 ± 55
	$\mathbf{2^{+-}}$	4490 ± 25		$\mathbf{1^+(2^+)}$	4065 ± 42
	3^{+-}	4526 ± 21		$1^+(3^+)$	4101 ± 40

We next consider quarkonium tetraquarks, such as Z_b and Z_c. The Born-Oppenheimer tetraquark interpretation is that they are analogs of quarkonium hybrids with the flavor-singlet excitation of the gluon field replaced by an isospin-1 excitation of the gluon and light-quark fields. The isospin-1 B-O potentials can be labeled by the eigenvalues of $\hat{\boldsymbol{R}} \cdot \boldsymbol{J}_{\text{light}}$ and $(CP)_{\text{light}}$ or, alternatively, by Σ_g^+, Π_u, Σ_u^-, etc. I will make some simple assumptions about these B-O potentials that are very predictive. First, I assume the isospin-1 Σ_g^+ potential is completely unstable with respect to a transition to the flavor-singlet Σ_g^+ potential plus a light meson, so this potential can be ignored. Second, I assume the excited isospin-1 B-O potentials Π_u and Σ_u^- have approximately the same shape as their flavor-singlet counterparts and differ primarily by an energy offset. This is plausible, because as $R \to 0$ they must both approach the repulsive $1/R$ potential for a color-octet $Q\bar{Q}$ pair, while as $R \to \infty$ they should both be linear in R. For each quarkonium hybrid with quantum numbers J^{PC}, there will be a quarkonium tetraquark whose $I^G(J^P)$ quantum numbers have the same J^P, $I = 1$, and $G = -C$. The isospin-1 $\Pi_u(1P)$ energy level consists of the two spin-symmetry multiplets $T_1 = \{1^+(1^-), 1^-(0^-, \mathbf{1}^-, 2^-)\}$ and $T_2 = \{1^-(1^+), 1^+(\mathbf{0}^+, 1^+, \mathbf{2}^+)\}$. The isospin-1 $\Sigma_u^-(1P)$ energy level is the multiplet $T_3 = \{1^-(0^+), 1^+(1^+)\}$. The isospin-1 $\Pi_u(1D)$ energy level includes the multiplet $T_4 = \{1^-(2^+), 1^+(1^+, \mathbf{2}^+, 3^+,)\}$.

Given our assumptions, the energy splittings between the quarkonium tetraquarks associated with an isospin-1 B-O potential should be approximately the same as the splittings between the quarkonium hybrids associated with the corresponding flavor-singlet B-O potential. If we can identify one quarkonium tetraquark, we can use lattice gauge theory results for the mass splittings between quarkonium hybrids to predict the masses of other quarkonium tetraquarks. The bottomonium tetraquarks $Z_b(10610)$ and $Z_b(10650)$ have quantum numbers $I^G(J^P) = 1^+(1^+)$ [4]. They can therefore be identified with two of the 1^+ members of the T_2, T_3, and T_4 multiplets. If lattice NRQCD results for the mass splittings between bottomonium hybrids were available, we could use the assignment of $Z_b(10610)$ to the T_2 multiplet to predict the masses of other bottomonium tetraquarks.

The two charmonium tetraquarks that have been observed are $Z_c(3900)$, which decays into $J/\psi\pi$, and $Z_c(4020)$, which decays into $h_c(1P)\pi$. They have quantum numbers $I^G = 1^+$, but their J^P quantum numbers have not yet been determined. The bottomonium tetraquarks $Z_b(10610)$ and $Z_b(10610)$ both decay into $\Upsilon(nS)\pi$ and $h_b(nP)\pi$. We will assume that the $Z_c(3900)$ and $Z_c(4020)$, which decay into final states that are analogous to those of the Z_b mesons, also have the same quantum numbers $I^G(J^P) = 1^+(1^+)$. They can therefore be identified with two of the 1^+ members of T_2, T_3, and T_4 multiplets. Assigning the $Z_c(3900)$ to the T_2 multiplet, taking its mass as an input, and using the splittings between charmonium hybrid multiplets obtained in Ref. [22], we obtain the predictions for the masses of the charmonium tetraquarks in Table I. If the $Z_c(4020)$ is the 1^+ member of either the T_3 or T_4 multiplet, the estimate of its mass is consistent with the observed value.

Before the discovery of Z_c, several unconfirmed isospin-1 charmonium tetraquarks were observed in B meson decays. The $Z^+(4430)$ was observed through its decay into $\psi(2S)\pi^+$ [29]. Its preferred quantum numbers are $1^+(1^+)$ [30]. Its mass is too high for it to be assigned to any of the multiplets in Table I. It could belong to the one of the radially excited multiplets T_2', T_3', or T_4'. The $Z^+(4050)$ and $Z^+(4250)$ were observed through their decays into $\chi_{c1}\pi^+$ [31]. The mass of $Z(4050)$ is within the range of the T_3 and T_4 multiplets. A P-wave decay into $\chi_{c1}\pi$ would be compatible with the $1^-(0^+)$ member of T_3 or the $1^-(2^+)$ member of T_4.

More than a dozen neutral XYZ charmonium states have been observed [32]. Those that decay into pairs of S-wave charm mesons are disfavored as candidates for charmonium hybrids or tetraquarks. Those that decay into $J/\psi\phi$, such as $X(4140)$ [33], are candidates for $c\bar{c}s\bar{s}$ tetraquarks. The $X(3915)$, which can be produced in $\gamma\gamma$ collisions, decays into $J/\psi\omega$, and has quantum numbers 0^{++} [34], is about 100 MeV lighter than the estimated mass for the neutral isospin partner of the $1^-(0^+)$ member of the T_3 multiplet. An alternative identification of $X(3915)$ as the P-wave charmonium state $\chi_{c0}(2P)$ is disfavored by its not having been observed in the decay mode $D\bar{D}$ [35]. The new XYZ states with quantum numbers 1^{--} that are heavier than $Y(4260)$, such as $Y(4360)$ [36], are candidates for the radially excited charmonium hybrid multiplet H_1'. Thus, aside from $Y(4260)$, none of the neutral XYZ mesons that have been observed can be compellingly identified with any of the charmonium hybrids and isospin-1 tetraquarks whose masses are estimated in Table I.

In summary, the flavor-exotic mesons Z_c and Z_b have been identified as Born-Oppenheimer tetraquarks, which are related to quarkonium hybrids by the replacement of the flavor-singlet excitation of the gluon field by an isospin-1 excitation of the gluon and light-quark fields. Lattice QCD calculations of the charmonium spectrum together with the identification of the $Y(4260)$ as a charmonium hybrid were used to estimate the masses of the lowest spin-symmetry multiplets of charmonium hybrids. The assumption that the isospin-1 Born-Oppenheimer potentials have the same shapes as their flavor-singlet counterparts was used to estimate the masses of the lowest multiplets of charmonium tetraquarks. Aside from $Y(4260)$, none of the neutral XYZ mesons that have been observed have compelling assignments to any of those charmonium hybrid or tetraquark multiplets. This suggests that a rich spectrum of additional quarkonium hybrids and tetraquarks is awaiting discovery.

This research was supported in part by the Department of Energy under Grant No. DE-FG02-91-ER40690.

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