Recent $\psi(2s)$ and χ_c results from BES

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Abstract

Recent results on $\psi(2s)$ and χ_c decays from BES are presented, including: the branching fraction for $\psi(2s) \to \tau^+\tau^-$; branching fractions for $\psi(2s)$ hadronic decays into vector-pseudoscalar and vector-tensor mesons; branching fractions for J/ψ,$\psi(2s)$ decays to strange-axialvector plus pseudoscalar mesons; branching fractions for $\psi(2s)$ decaying to baryon-antibaryon pairs; the total width of the χ_{c0}; and the branching fractions for χ_c decays to $\pi^+\pi^-, K^+K^-, p\bar{p}$ final states.

1 Introduction

The BES collaboration has previously reported a precision measurement on τ lepton mass[1] and several results on studies of the $J/\psi, \psi(2s), \tau, D_s$ and D[2]. BES has collected 9 million J/ψ, 3.6 million $\psi(2s)$ events and 22.3 pb^{-1} τ, D_s, D data samples. The BES detector has recently been upgraded with significant improvements to the particle ID and secondary vertex finding capabilities, the momentum resolution and the solid angle coverage.

Since BES has a a larger sample of $\psi(2s)$ events than any previous experiment, we are able to carry out a number of investigations of various $\psi(2s)$ decay channels, and to study properties of other charmonium states, such as the J/ψ, χ_c, etc. In this talk I will concentrate on the results that are measured for the first time, or that represent substantial improvements in precision.

2 BES detector

The BES detector is described in reference [3]. The principal sub-detectors of BES are the central drift chamber (CDC), the main drift chamber (MDC), the barrel and endcap shower counters (BSC, ESC), the barrel and endcap time of flight counters (BTOF, ETOF), the 0.4 T solenoid magnet, muon counters (MUC) and a luminosity monitor (LUM). We briefly describe those elements that are relevant to the analyses described herein. The CDC consists of four cylindrical layers of sense wires that are used for trigger purposes. Charged particle tracks are measured in the cylindrical MDC, which covers 85% of the 4π solid angle and provides a momentum resolution of $\sigma_p/p = 0.017\sqrt{1+p^2}$, p in GeV/c. The MDC also provides dE/dx easurements with a resolution of 8.5% that are used for particle identification. The BTOF consists of 48 scintillation counters covering 76% of 4π solid angle and provides time of flight measurements with a resolution of 330 ps. Between the BTOF and the coil of the solenoid is the BSC, consisting of 24 alternating layers of 0.5 radiation-length lead sheets and self-quenching streamer mode tubes. The solid angle coverage is about 80% of 4π and the energy resolution is $\sigma_E/E = 0.22/\sqrt{E(GeV)}$. Finally, muons with momentum greater than 550 MeV/c are identified in the three-layer iron flux return that is instrumented with proportional tubes that provide spatial resolutions of $\sigma_z = 5cm$ and $\sigma_{r\varphi} = 3cm$ over 65% of 4π.

3 $\psi(2s)$ decay measurements

3.1 Branching fraction for $\psi(2s) \to \tau^+\tau^-$

We measure the branching fraction for $\psi(2s) \to \tau^+\tau^-$ decay to be

$$B(\psi(2s) \to \tau^+\tau^-) = (3.5 \pm 0.5 \pm 0.6) \times 10^{-3}.$$

The expectation for $e - \mu - \tau$ universality is

$$B_{ee} = B_{\mu\mu} = B_{\tau\tau}/0.3885,$$

where the effect of the limited available phase space for the $\tau^+\tau^-$ mode is included. Our measurement for $B_{\tau\tau}$, together with the PDG value of $B(\psi(2s) \to e^+e^-) = (8.8 \pm 1.3) \times 10^{-3}$ and $B(\psi(2s) \to \mu^+\mu^-) = (7.7 \pm 1.7) \times 10^{-3}$[4], are in good agreement with $e - \mu - \tau$ universality.

3.2 Hadronic $\psi(2s)$ decays

3.2.1 Branching fractions of $\psi(2s)$ decays to VP and VT mesons

There is a long-standing puzzle in J/ψ and $\psi(2s)$ decays into vector plus pseudoscalar exclusive final states. In 1983, the Mark II Collaboration reported that the decays $\psi(2s) \to \rho\pi$ and $K^{*\pm}K^{\mp}$, two dominant hadronic decay modes for the J/ψ, were not observed in a sample of 1.02×10^6 $\psi(2s)$ decays [5]. The Mark II results for the ratios of branching fractions of $\psi(2s)$ and J/ψ for these final states: $Q_{\rho\pi} < 0.0063$, $Q_{K^*\overline{K}} < 0.011$, badly violate the perturbative QCD expectation that for any final hadronic state h, the ratio Q_h scales as the ratio of the 3-gluon widths, which are proportional to the leptonic widths. Dividing by the full widths yields:

$$Q_h \equiv \frac{B(\psi(2s) \to h)}{B(J/\psi \to h)} = \frac{B(\psi(2s) \to ggg)}{B(J/\psi \to ggg)} = \frac{B(\psi(2s) \to e^+e^-)}{B(J/\psi \to e^+e^-)} = (14.7 \pm 2.3)\%,$$

where the updated values of leptonic branching fractions from Particle Data Group [4] are used. About ten years ago, the Crystal Ball experiment observed that two other decays of the $\psi(2s)$ into VP final states, $\gamma\eta$ and $\gamma\eta\prime$, are anomalously suppressed [6]. However, the Crystal Ball results have never been formally published. The Mark II $\psi(2s)$ decay measurements were not revisited until the 1995 Beijing Lepton Photon Symposium, where the BES collaboration reported preliminary results of an analysis of 1.27 million $\psi(2s)$ events (one-third of the data sample used for the results reported here), giving branching fractions for $\psi(2s)$ decays into a vector and a pseudoscalar mesons, $\rho\pi$, $K^{*\pm}K^{\mp}$, $K^{*0}\overline{K^0} + c.c.$ [7]. At the same meeting, the BES group also reported the first measurement on the branching fractions of $\psi(2s)$ decay into the vector-tensor final states, ωf_2 and ρa_2. These were found to be substantially suppressed compared to PQCD extrapolations from the corresponding J/ψ decays. In contrast, the BES group reported reasonable agreement with PQCD expectations for $\psi(2s)$ decays to baryon-antibaryon pairs.

Recently BES has systematically studied hadronic $\psi(2s)$ decays to VP, VT,AP,VS, TP, VV, $B\overline{B}$ final states with a sample of 3.6 million $\psi(2s)$ events collected from 1993 to 1995. The number of $\psi(2s)$

events is determined from J/ψ production in $\psi(2s) \to \pi^+\pi^- J/\psi$ decay where the J/ψ production is inferred in the recoil from the $\pi^+\pi^-$ system. With this high statistics study, BES has made substantial progress on the study of the charmonium hadronic decay puzzle. We observe that the PQCD-motivated "15% rule" is basically followed in the decay modes $K^*(892)^0\overline{K}^*(892)^0$, $b_1\pi$, $\phi f_0(980)$, $\gamma f_2(1270)$,$B\overline{B}$ and most of the more-than-two-particle decays that were studied. Anomalous suppressions are observed in VP and VT final states. The results are listed in Table 1. The following conclusions can be extracted:

1. We set new 90% CL upper limits for the $\rho\pi$ and $K^{*\pm}K^{\mp}$ decay modes of:

$$B(\psi(2s) \to \rho\pi) < 2.9 \times 10^{-5},$$
$$B(\psi(2s) \to K^{*\pm}K^{\mp}) < 3.2 \times 10^{-5}$$

   that are significantly lower than the corresponding upper limits set by Mark II group [5]. Using the PDG values of branching fractions of J/ψ decays to the corresponding final states, the limits on the ratios of branching fractions become:

$$Q_{\rho\pi} < 0.0023, \quad Q_{K^{*\pm}K^{\mp}} < 0.0064,$$

   which are more than factors of 60 and 20, respectively, below the PQCD predictions. This confirms the previous observation of VP suppression of $\psi(2s)$ decays and shows that it persists at even higher levels of sensitivity.

2. We report here the first measurement of the $\psi(2s)$ decay to $K^{*0}\overline{K}^0 + c.c.$ final states (VP mode):

$$B(\psi(2s) \to K^{*0}\overline{K}^0 + c.c.) = (8.4 \pm 2.9) \times 10^{-5}.$$

   This result, combined with the PDG average of $B(J/\psi \to K^{*0}\overline{K}^0 + c.c.) = (4.2 \pm 0.4) \times 10^{-3}$ yields the ratio of branching fractions

$$Q_{K^{*0}K^0} = 0.020 \pm 0.007.$$

3. There have been a number of theoretical attempts to explain the VP suppression puzzle [8-11], for example the Brodsky-Lepage-Tuan model, the Chaichian-Tornqvist model, and the Pinsky model. However, none of these can explain the BES results.

4. The $\psi(2s)$ decays to $2(\pi^+\pi^-)\pi^0$ and $\pi^+\pi^-K^+K^-$ final states have been studied from fully reconstructed events. The branching fractions of ωf_2, ρa_2 and $K^{*0}\overline{K}_2^{*0} + c.c.$, vector-tensor final states, are measured in $\psi(2s)$ decays for the first time.

$$\begin{aligned} B(\psi(2s) \to \rho a_2) &= (31 \pm 19) \times 10^{-5}, \\ B(\psi(2s) \to \omega f_2) &< 15 \times 10^{-5}, \\ B(\psi(2s) \to K^{*0}\overline{K}_2^{*0} + c.c.) &< 18 \times 10^{-5}. \end{aligned}$$

   Using the PDG values of branching fractions of J/ψ decays to corresponding final states, we obtained the ratios of branching fractions:

$$Q_{\rho a_2} = 0.028 \pm 0.017, \quad Q_{\omega f_2} < 0.035, \quad Q_{K^{*0}K_2^{*0}} < 0.028,$$

   much lower than the PQCD expectation. This changes the long-held view that the anomaly in charmonium hadronic decays is restricted to vector-pseudoscalar final states. Now the puzzle extends to the VT decay!

5. The discovery of an anomaly in VT decays is theoretically even more puzzling than that for VP decays. The strongly suppressed vector- pseudoscalar decays, i.e. $\rho\pi$, $K^{*\pm}K^{\mp}$ and $K^{*0}\overline{K}^0 + c.c.$, are not allowed by the PQCD expectation that total hadron helicity is conserved (HHC) in high-momentum-transfer exclusive processes [9]. A recent analysis [12] has shown that the vector-tensor decays, i,e, ωf_2, ρa_2 and $K^{*0}\overline{K}_2^{*0} + c.c.$, are allowed by HHC. Hence their suppression poses new challenges to the theory.

Table 1. Experimental Ratios of VP and VT modes

	Decay Mode	B($\psi(2s)$) (10^{-5})	B(J/ψ) (10^{-3})	Q (%)
VP	$\rho\pi$	< 2.9	12.8 ± 1.0	< 0.23
	$K^{*\pm}K^{\mp}$	< 3.2	5.0 ± 0.4	< 0.64
	$K^{*0}\overline{K}^0 + c.c.$	8.4 ± 2.9	4.2 ± 0.4	2.0 ± 0.7
VT	ωf_2	< 15	4.3 ± 0.6	< 3.5
	ρa_2	31 ± 19	10.9 ± 2.2	2.8 ± 1.7
	$K^{*0}\overline{K}_2^{*0} + c.c.$	< 18	6.7 ± 2.6	< 2.8

note : (1) Upper limits are at 90% confidence level.
(2) J/ψ data are from PDG.
(3) $\psi(2s)$ data are from this experiment.

3.2.2 J/ψ and $\psi(2s)$ decays to strange-axialvector plus pseudoscalar mesons

Since the strange members of the two $^3P_1$ and $^1P_1$ octets, called the K_A and K_B, respectively, do not have definite C-parity, the observed physical states are mixtures of the K_A and K_B quark states. These are identified with the $K_1(1270)$ and the $K_1(1400)$ meson states:

$$\begin{aligned} K_1(1270) &= cos\theta K_B + sin\theta K_A \\ K_1(1400) &= cos\theta K_A - sin\theta K_B, \end{aligned}$$

where the mixing angle is near $\theta = 45^\circ$ [13]. To the extent that flavor-SU(3) is a good symmetry, the amplitude for two body decays to conjugate mesons in the same pair of octets should be equal. Thus, since the $J/\psi(\psi') \to a_1\pi$ decays are forbidden by G-parity, the $J/\psi(\psi') \to K_A\overline{K}$ decays are disallowed and one expects relatively pure $K_B\overline{K}$ final states in J/ψ and ψ' decays. In that case, since

$$K_B = cos\theta K_1(1270) - sin\theta K_1(1400),$$

with $\theta \simeq 45^\circ$, there should be roughly equal amounts of $K_1(1270)$ and $K_1(1400)$.

Since there are no PDG entries for either the J/ψ or ψ' decays to $K_1\overline{K}$, using a sample of 3.6 million $\psi\prime$ events, we search for J/ψ and $\psi(2s) \to K_1^+K^-$ decays where the K_1 decays via $K_1^+ \to K^+\pi^+\pi^-$:

$$\begin{aligned} K_1^+(1270) &\to K^+\rho^0 \to K^+\pi^+\pi^-, \\ K_1^+(1270) &\to K^{*0}\pi^+ \to K^+\pi^+\pi^-, \\ K_1^+(1400) &\to K^{*0}\pi^+ \to K^+\pi^+\pi^-. \end{aligned}$$

The J/ψ sample is produced by $\psi(2s) \to \pi^+\pi^-J/\psi$ decay.

The preliminary results are listed on Table 2. The $K_1(1270)\overline{K}$ channel is the first observation of an exclusive $\psi(2s)$ hadronic decay channel that is enhanced relative to the J/ψ in the context of the 15% rule. In addition, contrary to the flavor-SU(3) expectation of equal amounts of $K_1(1270)$ and $K_1(1400)$, a flavor-SU(3)-violating $K_1(1270) - K_1(1400)$ asymmetry is observed, and this asymmetry shows an opposite character for the J/ψ and $\psi(2s)$. This can not be accommodated by adjustments of the singlet-triplet mixing angle.

Table 2. Branching fractions of $J/\psi, \psi' \to K_1^+ K^-$ decays. (10^{-4})

	$K_1(1270)\overline{K}$	$K_1(1400)\overline{K}$
$\psi(2s)$	$7.6 \pm 0.9 \pm 1.5$	<2.7
J/ψ	<18	$50 \pm 6 \pm 11$

note : Upper limits are at 90% confidence level.

3.2.3 Branching fractions of $\psi(2s)$ decays to baryon pairs

The branching fractions for $\psi(2s) \to B_i\overline{B}_i$, where $B_i = p, \Lambda, \Sigma^0, \Xi^-, \Delta^{++}, \Sigma^{*-}, \Xi^{*0}$ and Ω^-, have been measured using BES with a sample of 3.6 million produced $\psi(2s)$ events. The preliminary results of the branching fractions are listed on Table 3, together with their ratios of branching fractions, using the PDG values of branching fractions of J/ψ decays to corresponding final states. They are in reasonable agreement with PQCD expectations.

In the context of flavor SU(3), a pure $c\overline{c}$ state is a flavor singlet and, in the limit of SU(3) flavor symmetry, the phase-space-corrected reduced branching fractions to any baryon-antibaryon pair, $\mid M_i \mid^2$,

$$\mid M_i \mid^2 = \frac{B(\psi(2s) \to B_i\overline{B_i})}{\pi p^*/\sqrt{s}}$$

(p^* is the momentum of the baryon in the $\psi(2s)$ rest frame), should be the same for every baryon,B_i in the same multiplet. Deviations from this rule would indicate a non- $c\overline{c}$ component of the charmonium wave function. The reduced branching fractions for $J/\psi \to B\overline{B}$ decays are shown in Table 4. The SU(3) relation works reasonably well, although there may be some preference for the $p\overline{p}$ mode. This relation has not been tested for the $\psi(2s)$, where the only relevant branching fraction that has been measured is $\psi(2s) \to p\overline{p}$, and that with rather poor precision [14].

The reduced branching fractions derived from our measurements for octet and decuplet baryons are indicated in Table 4. The results show a trend to smaller values for the higher masses, showing some deviation from expectations based on flavor SU(3) symmetry. Higher precision measurements both for the J/ψ and $\psi(2s)$ and the study of explicitly SU(3)-violating octet-decuplet modes, such as $\Sigma\overline{\Sigma^*}$ and $\Xi\overline{\Xi^*}$, might clarify this problem.

Table 3. Experimental Ratios of $B\overline{B}$ modes

Decay Mode	B($\psi(2s)$) (10^{-5})	B(J/ψ) (10^{-3})	Q (%)
$p\overline{p}$	27.3 ± 3.9	2.14 ± 0.10	12.8 ± 1.9
$\Lambda\overline{\Lambda}$	21.1 ± 3.5	1.35 ± 0.14	15.6 ± 3.1
$\Sigma^0\overline{\Sigma}^0$	9.4 ± 4.8	1.3 ± 0.2	7.2 ± 3.9
$\Delta^{++}\overline{\Delta}^{--}$	8.9 ± 2.6	1.10 ± 0.29	8.1 ± 3.2
$\Xi^-\overline{\Xi}^+$	8.3 ± 3.0	0.9 ± 0.2	9.2 ± 3.9
$\Sigma^{*-}\overline{\Sigma}^{*+}$	5.6 ± 2.7	1.03 ± 0.13	5.4 ± 2.7
$\Xi^{*0}\overline{\Xi}^{*0}$	< 7.5		
$\Omega^-\overline{\Omega}^+$	< 8.3		

Table 4. Reduced branching fractions $\mid M_i \mid^2$ for $J/\psi, \psi(2s) \to B_i\overline{B}_i$

	$p\overline{p}$	$\Lambda\overline{\Lambda}$	$\Sigma^0\overline{\Sigma}^0$	$\Delta^{++}\overline{\Delta}^{--}$	$\Xi^-\overline{\Xi}^+$	$\Sigma^{*-}\overline{\Sigma}^{*+}$
$\mid M_i \mid^2_{J/\psi}$ (10^{-4})	17.1 ± 0.8	12.4 ± 1.3	12.6 ± 1.7		10.9 ± 2.4	
$\mid M_i \mid^2_{\psi'}$ (10^{-4})	2.02 ± 0.29	1.69 ± 0.28	0.78 ± 0.40	0.76 ± 0.22	0.76 ± 0.27	0.54 ± 0.26

4 The measurements of χ_c decay widths

The charmonium p-wave triplet states χ_{cJ} ($J = 0, 1, 2$) were found soon after the J/ψ and $\psi(2s)$ discovery in 1970's, and most of their decay parameters were measured before 1980. Recently, the E760 gas-jet experiment in the Fermilab $\overline{p}$ accumulator ring [15] reported precision measurements of the total widths and $p\overline{p}$ partial widths for χ_{c1} and χ_{c2}, but not for χ_{c0}. The PDG value of χ_{c0} decay width, $\Gamma_{\chi c0} = 13.5 \pm 3.3 \pm 4.2 MeV$, is derived from two apparently discrepant Crystal Ball results [16]: 13-21 Mev from $\psi(2s) \to \gamma X$ study and $8.8 \pm 1.3 \pm 1.5 MeV$ from $\psi(2s) \to \gamma\pi^0\pi^0$.

Using the full BES $\psi(2s)$ event sample, we subject $\gamma\pi^+\pi^-$ and γK^+K^- candidate events to a four-constraint kinematic fit. The resulting $\pi^+\pi^-$ and K^+K^- invariant mass spectra show clear peaks corresponding to χ_{c0} and χ_{c2}, respectively. Since parity conservation forbids χ_{c1} and $\eta_c(2s)$ decays to these final states, there is no distortion of the χ_{c0} and χ_{c2} spectra due to contaminations from these resonances.

Nevertheless, there exist some cross contamination between the $\pi^+\pi^-$ and K^+K^- channels for both states. Theory and experiments have shown [17] that χ_{cJ} is generated via pure a E1 transition. Moreover, χ_{cJ} decays to pseudoscalar meson pairs has only one independent helicity amplitude. A Monte Carlo simulation done with an event generator that incorporates these facts is used to determine the detection efficiencies for both channels and the probabilities for cross contamination betweem them. Our experimental mass resolution is calibrated by fitting the χ_{c2} to a convolution of a gaussian reslolution function and a Breit-Wigner resonance line with the PDG value for the χ_{c2} total width, which has been precisely determined by the E760 experiment. In this way we can infer the mass resolution at χ_{c0} mass region that only relies on Monte Carlo simulations to indciate how the resolution changes from the χ_{c2}

to the χ_{c0}. After this correction, fits to the $\chi_{c0} \to \pi^+\pi^-$ and K^+K^- invariant mass spectra yield the following results:

$$\Gamma_{\chi_{c0}} = 15.0 \pm^{3.2}_{2.8} \, MeV,$$

where the error includes both statistical and systematic uncertainties. This result is in agreement with the world average value, but with higher precision. It agrees with Kwong's theoretical prediction (14.8 ± 1.9 MeV) [18], while it has large discrepancy with the calculation by G.T.Bodwin (4.8 ± 0.7 MeV) [19].

We have also obtained the partial widths of χ_{c0}, χ_{c2} decays to $\pi^+\pi^-$, K^+K^- and $p\overline{p}$ listed in Table 5. It can be seen that the BES measurements for these modes are more precise than PDG values. For partial widths of $\chi_{c0} \to \pi^+\pi^-, K^+K^-$, BES measurements deviate from PDG values significantly, while for other partial widths they coincide within one standard deviation. From the branching fractions listed in Table 5, we obtained following ratios:

$$\frac{B(\chi_{c0} \to \pi^+\pi^-)}{B(\chi_{c0} \to K^+K^-)} = 1.24 \pm 0.13, \quad \frac{B(\chi_{c2} \to \pi^+\pi^-)}{B(\chi_{c2} \to K^+K^-)} = 2.95 \pm 1.18,$$

$$\frac{B(\chi_{c0} \to \pi^+\pi^-)}{B(\chi_{c2} \to \pi^+\pi^-)} = 2.81 \pm 0.63, \quad \frac{B(\chi_{c0} \to K^+K^-)}{B(\chi_{c2} \to K^+K^-)} = 6.6 \pm 2.7.$$

Contrary to the results listed in the PDG tables, there appears to be some discrepancy ($\sim 2\sigma$) between the $\chi_{c2} \to \pi^+\pi^-$, and K^+K^- branching ratios.

Table 5. Partial widths for χ_{c0}, χ_{c2} decays to $\pi^+\pi^-$, K^+K^- and $p\overline{p}$ (10^{-4})

		$\pi^+\pi^-$	K^+K^-	$p\overline{p}$
χ_{c0}	BES	42.7 ± 6.4	34.4 ± 5.1	1.45 ± 0.50
	PDG	75 ± 21	71 ± 24	< 9.0
χ_{c2}	BES	15.2 ± 3.4	5.2 ± 2.1	0.96 ± 0.54
	PDG	19 ± 10	15 ± 11	1.00 ± 0.10

5 Summary

With the 3.6M $\psi(2s)$ event sample, BES is able to study its decay properties with improved precision and to extend the investigation to J/ψ and χ_c. Significant improvements have been reached in many decay channels measurements.

1. The branching fraction of $\psi(2s) \to \tau^+\tau^-$ has been determined for the first time to be $(3.5 \pm 0.5 \pm 0.6) \times 10^{-3}$. This value is in agreement with $e - \mu - \tau$ universality.

2. Severe suppression is observed in $\psi(2s)$ decays into vector plus pseudoscalar mesons, $\rho\pi$, $K^{*\pm}\overline{K}^{\mp}$, and $K^{*0}\overline{K}^0 + c.c.$.

3. Sgnificant suppression is also seen in $\psi(2s)$ decays into the vector plus tensor meson final states ωf_2, ρa_2 and $K^{*0}\overline{K}_2^{*0} + c.c.$.

4. Existing theoretical models can not explain these VP, VT suppressions.

5. For the strange AP final states, the $K_1(1270)\overline{K}$ channel is the first observation of an exclusive $\psi(2s)$ hadronic decay channel that is enhanced relative to the J/ψ in the context of the 15% rule. A flavor-SU(3)-violating $K_1(1270) - K_1(1400)$ asymmetry is observed and has an opposite character for the J/ψ and $\psi(2s)$.

6. The 15% rule is observed for the $\psi(2s)$ decays to baryon-antibaryon pairs.

7. The total decay width for χ_{c0} and the patial decay widths of $\pi^+\pi^-$, K^+K^- and $p\overline{p}$ for χ_{c0} and χ_{c2} have been measured with improved accuracies.

The present situation regarding hadronic decays of charmonium states contains many mysteries that challenge both theoretical and experimental physicists.

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