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Evidence for the decay X(3872) → ψ(2S)γ

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Abstract

Evidence for the decay mode X(3872) → ψ(2S)γ in $B^+ \to X(3872)K^+$ decays is found with a significance of 4.4 standard deviations. The analysis is based on a data sample of proton–proton collisions, corresponding to an integrated luminosity of 3 fb^{-1}, collected with the LHCb detector, at centre-of-mass energies of 7 and 8 TeV. The ratio of the branching fraction of the X(3872) → ψ(2S)γ decay to that of the X(3872) → J/ψγ decay is measured to be

$$\frac{\mathcal{B}(X(3872) \to \psi(2S)\gamma)}{\mathcal{B}(X(3872) \to J/\psi\gamma)} = 2.46 \pm 0.64 \pm 0.29,$$

where the first uncertainty is statistical and the second is systematic. The measured value does not support a pure $D\bar{D}^*$ molecular interpretation of the X(3872) state.

1. Introduction

The X(3872) state was discovered in 2003 by the Belle Collaboration [1]. Subsequently, it has been studied by several other experiments [2–6]. Several properties of the X(3872) state have been determined, including the precise value of its mass [5,7] and the dipion mass spectrum in the decay X(3872) → J/ψπ+π− [1,6,8]. Recently, its quantum numbers were determined to be $J^{PC} = 1^{++}$ by combination of the measurements performed by the CDF [9] and the LHCb [10] Collaborations.

Despite a large amount of experimental information, the nature of X(3872) state and other similar states is still uncertain [11,12]. In particular for the X(3872) state, interpretation as a $D\bar{D}^*$ molecule [13], tetraquark [14], $c\bar{c}g$ hybrid meson [15], vector glueball [16] or mixed state [17,18] are proposed. Radiative decays of the X(3872) provide a valuable opportunity to understand its

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nature. Studies of the decay modes $X(3872) \to J/\psi\gamma$ resulted in the determination of its C-parity [19,20]. Evidence for the $X(3872) \to \psi(2S)\gamma$ decay and the branching fraction ratio,

$$R_{\psi\gamma} \equiv \frac{\mathcal{B}(X(3872) \to \psi(2S)\gamma)}{\mathcal{B}(X(3872) \to J/\psi\gamma)} = 3.4 \pm 1.4,$$

were reported by the BaBar Collaboration [21]. In contrast, no significant signal was found for the $X(3872) \to \psi(2S)\gamma$ decay by the Belle Collaboration, therefore only an upper limit for $R_{\psi\gamma} < 2.1$ (at 90% confidence level) was reported [20]. The ratio $R_{\psi\gamma}$ is predicted to be in the range $(3\text{–}4) \times 10^{-3}$ for a $D\bar{D}^*$ molecule [22–24], 1.2–15 for a pure charmonium state [25–32] and 0.5–5 for a molecule-charmonium mixture [29,33].

In this paper, evidence for the decay $X(3872) \to \psi(2S)\gamma$ and a measurement of the ratio $R_{\psi\gamma}$ using $B^+ \to X(3872)K^+$ decays are presented.[1] The analysis is based on a data sample of proton–proton (pp) collisions, corresponding to an integrated luminosity of 1 fb^{-1} at a centre-of-mass energy of 7 TeV and 2 fb^{-1} at 8 TeV, collected with the LHCb detector.

2. Detector and software

The LHCb detector [34] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing b or c quarks. The detector includes a high-precision tracking system consisting of a silicon-strip vertex detector surrounding the pp interaction region, a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 Tm, and three stations of silicon-strip detectors and straw drift tubes placed downstream. The combined tracking system provides a momentum measurement with relative uncertainty that varies from 0.4% at 5 GeV/c to 0.6% at 100 GeV/c, and impact parameter resolution of 20 μm for tracks with high transverse momentum. Charged hadrons are identified using two ring-imaging Cherenkov detectors [35]. The calorimeter system consists of a scintillating pad detector (SPD) and a pre-shower system (PS), followed by electromagnetic (ECAL) and hadron calorimeters. The SPD and PS are designed to distinguish between signals from photons and electrons. Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers [36].

The trigger [37] consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage where a full event reconstruction is applied. This analysis uses events collected by triggers that select the $\mu^+\mu^-$ pair from J/ψ and $\psi(2S)$ decays with high efficiency. At the hardware stage either one or two muon candidates are required to trigger the event. For single muon triggers, the transverse momentum of the muon candidate, p_T, is required to be greater than 1.48 GeV/c. For dimuon candidates, the product of the p_T of the muon candidates is required to satisfy $\sqrt{p_T(\mu^+) \times p_T(\mu^-)} > 1.3$ GeV/c. At the subsequent software trigger stage, two muons are selected with an invariant mass larger than 2.5 GeV/c^2 and consistent with originating from a common vertex. The common vertex is required to be significantly displaced from the pp collision vertices by requiring the decay length significance to be greater than 3.

The analysis technique reported below has been validated using simulated events. The pp collisions are generated using PYTHIA [38] with a specific LHCb configuration described in Ref. [39]. Decays of hadronic particles are described by EVTGEN [40] in which final state radiation is generated using PHOTOS package [41]. The interaction of the generated particles with

[1] The inclusion of charged conjugate processes is implied throughout.

the detector and its response are implemented using the GEANT4 toolkit [42,43] as described in Ref. [44].

3. Event selection

Candidate $B^+ \to X(3872)K^+$ decays, followed by $X(3872) \to \psi\gamma$, where ψ denotes a J/ψ or $\psi(2S)$ meson, are reconstructed using the $\psi \to \mu^+\mu^-$ channel. The $\psi(2S) \to J/\psi\pi^+\pi^-$ decay mode is not used due to low reconstruction efficiency. Most selection criteria are common for the two channels, except where directly related to the photon kinematics, due to the difference in the energy release in these two channels. The selection criteria follow those used in Refs. [45–47].

The track quality of reconstructed charged particles is ensured by requiring that the χ^2 per degree of freedom, χ^2/ndf, is less than 3. Well-identified muons are selected by requiring that the difference in the logarithms of the muon hypothesis likelihood with respect to the pion hypothesis likelihood, $\Delta \log \mathcal{L}_{\mu/\pi}$ [48], is larger than zero. To select kaons, the corresponding difference in the logarithms of likelihoods of the kaon and pion hypotheses [35] is required to satisfy $\Delta \log \mathcal{L}_{K/\pi} > 0$.

To ensure that the muons and kaons do not originate from a pp interaction vertex, the impact parameter χ^2, defined as the difference between the χ^2 of a given PV formed with and without the considered track, is required to be When more than one PV is reconstructed, the smallest value of χ^2_{IP} is chosen.

Pairs of oppositely charged tracks identified as muons, each having $p_T > 0.55\ \text{GeV}/c$, are combined to form $\psi \to \mu^+\mu^-$ candidates. The fit of the common two-prong vertex is required to satisfy $\chi^2/\text{ndf} < 20$. The vertex is required to be well separated from the reconstructed PV by selecting candidates with decay length significance greater than 3. The invariant mass of the dimuon combination is required to be between 3.020 and 3.135 GeV/c^2 for the J/ψ candidates and between 3.597 and 3.730 GeV/c^2 for the $\psi(2S)$ candidates. The selected ψ candidates are required to match the dimuon candidates used to trigger the event.

Photons are reconstructed using the electromagnetic calorimeter and identified using a likelihood-based estimator, constructed from variables that rely on calorimeter and tracking information [49]. Candidate photon clusters must not be matched to the trajectory of a track extrapolated from the tracking system to the cluster position in the calorimeter. Further photon quality refinement is done using information from the PS and SPD detectors. The photon transverse momentum is required to be greater than 1 GeV/c or 0.6 GeV/c for the J/ψ or $\psi(2S)$ in the final state, respectively. To suppress the large combinatorial background from $\pi^0 \to \gamma\gamma$ decays, a pion veto is applied [46]. The photons that, when combined with another photon, form a $\pi^0 \to \gamma\gamma$ candidate with invariant mass within 25 MeV/c^2 of the π^0 mass, corresponding to ± 3 times the mass resolution [46,50], are not used in the reconstruction.

To form X(3872) candidates, the selected ψ candidates are combined with a reconstructed photon. To be considered as a X(3872) candidate, the $J/\psi\gamma$ or $\psi(2S)\gamma$ combination must have an invariant mass in the range 3.7–4.1 GeV/c^2 or 3.75–4.05 GeV/c^2, respectively, to account for the different available phase space.

The X(3872) candidates are combined with selected kaons to create B^+ meson candidates. The kaons are required to have transverse momentum larger than 0.8 GeV/c. The quality of the B^+ vertex is ensured by requiring the χ^2/ndf of the vertex fit to be less than 25/3. In addition, the decay time of the B^+ is required to be larger than 150 $\mu\text{m}/c$ to reduce the large combinatorial background from particles produced at the PV.

To improve the invariant mass resolution of the X(3872) candidate, a kinematic fit [51] is performed. In this fit, the invariant mass of the ψ candidate is constrained to its nominal value [52], the decay products of the B^+ candidate are required to originate from a common vertex, and the momentum vector of the B^+ candidate is required to point back to the PV. The χ^2/ndf for this fit is required to be less than 5. To improve the resolution on the B^+ candidate invariant mass, and reduce its correlation with the reconstructed X(3872) candidate mass, the B^+ mass is determined from a similar kinematic fit with an additional constraint applied to the mass of the X(3872) resonance [52]. The B^+ candidates are required to have invariant mass in the range 5.0–5.5 GeV/c^2. To reject possible contributions from $B^+ \to \psi K^+$ decays with an additional random soft photon, the invariant mass of the ψK^+ combination is required to be outside a ± 40 MeV/c^2 mass window around the known B^+ mass [52].

4. Signal yields

To determine the signal yield of the $B^+ \to X(3872)K^+$ decays followed by $X(3872) \to \psi\gamma$, an unbinned extended maximum likelihood two-dimensional fit in $\psi\gamma K^+$ and $\psi\gamma$ invariant masses is performed. The probability density function used in the fit consists of three components to describe the mass spectrum: signal, background from other B decays that peaks in the $\psi\gamma K^+$ and $\psi\gamma$ invariant mass distributions (henceforth called "peaking background") and pure combinatorial background.

The signal component is modelled as a product of a Gaussian function in the $\psi\gamma K^+$ invariant mass and a Crystal Ball function [53] in the $\psi\gamma$ invariant mass. The mass resolution and tail parameters of the Crystal Ball function are fixed to those determined from simulated signal events.

The peaking background is studied using simulation. The sources of the peaking background are different in the J/ψ and $\psi(2S)$ channels due to differences in the photon spectra and in the photon selection requirements in these two channels. The main source of the peaking background in the J/ψ channel is the partially reconstructed $B^+ \to J/\psi K^{*+}$ decays followed by $K^{*+} \to K^+\pi^0$ where one photon from the π^0 decay is not detected. In the $\psi(2S)$ channel the peaking background arises from partially reconstructed $B \to \psi(2S)K^+Y$ decays combined with a random photon, where B denotes a b hadron and Y denotes additional particles of the B decay, that escape detection. These background contributions are modelled in the fit using non-parametric kernel probability density functions [54], obtained from simulation of B decays to final states containing a J/ψ or $\psi(2S)$ meson.

Pure combinatorial background is modelled as the product of an exponential function of the $\psi\gamma K^+$ invariant mass and a second-order polynomial function of the $J/\psi\gamma$ invariant mass or a third-order polynomial function of the $\psi(2S)\gamma$ invariant mass. For the latter case, the polynomial function is constrained to account for the small available phase space, allowing only two polynomial degrees of freedom to vary in the fit.

The significance of the observed signal in the $\psi(2S)$ channel is determined by simulating a large number of background-only experiments, taking into account all uncertainties in the shape of the background distribution. The probability for the background to fluctuate to at least the number of observed events is found to be 1.2×10^{-5}, corresponding to a significance of 4.4 standard deviations for the $B^+ \to X(3872)K^+$ decay followed by $X(3872) \to \psi(2S)\gamma$.

The fit results for the position of the B^+ and X(3872) mass peaks, m_{B^+} and $m_{X(3872)}$, respectively, and the signal yields N_ψ are listed in Table 1. Projections of the fit on $\psi\gamma K^+$ and $\psi\gamma$ invariant masses are shown in Figs. 1 and 2 for the J/ψ and $\psi(2S)$ channels, respectively.

Table 1
Parameters of the signal functions of the fits to the two-dimensional mass distributions of the $B^+ \to X(3872)K^+$ decays followed by $X(3872) \to \psi\gamma$. Uncertainties are statistical only.

Parameter	Decay mode	
	$X(3872) \to J/\psi\gamma$	$X(3872) \to \psi(2S)\gamma$
m_{B^+} [MeV/c^2]	5277.7 ± 0.8	5281.9 ± 2.4
$m_{X(3872)}$ [MeV/c^2]	3873.4 ± 3.4	3869.5 ± 3.4
N_ψ	591 ± 48	36.4 ± 9.0

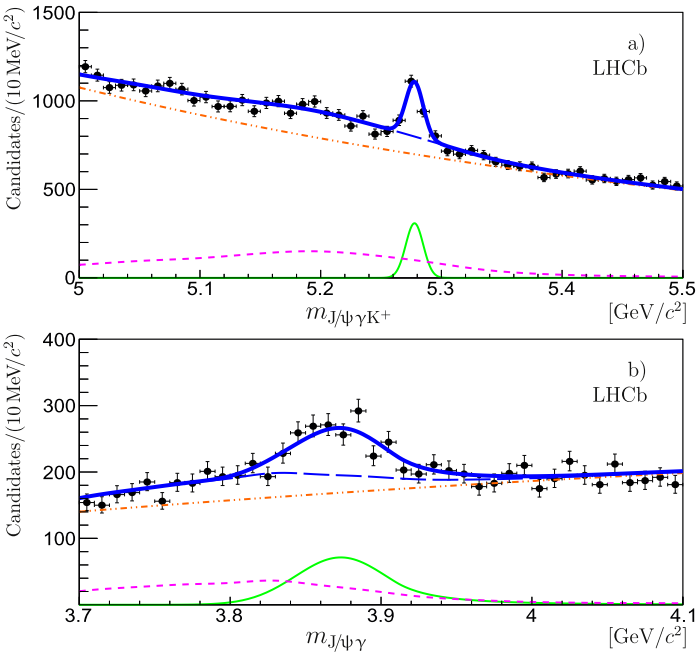

Fig. 1. a) Distribution of the $J/\psi\gamma K^+$ invariant mass with fit projection overlaid, restricted to those candidates with $J/\psi\gamma$ invariant mass within $\pm 3\sigma$ from the X(3872) peak position. b) Distribution of the $J/\psi\gamma$ invariant mass with fit projection overlaid, restricted to those candidates with $J/\psi\gamma K^+$ invariant mass within $\pm 3\sigma$ from the B^+ peak position. The total fit (thick solid blue) together with the signal (thin solid green) and background components (dash-dotted orange for the pure combinatorial, dashed magenta for the peaking component and long dashed blue for their sum) are shown. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

5. Efficiencies and systematic uncertainties

The ratio of the $X(3872) \to \psi(2S)\gamma$ and $X(3872) \to J/\psi\gamma$ branching fractions is calculated using the formula

$$R_{\psi\gamma} = \frac{N_{\psi(2S)}}{N_{J/\psi}} \times \frac{\varepsilon_{J/\psi}}{\varepsilon_{\psi(2S)}} \times \frac{\mathcal{B}(J/\psi \to \mu^+\mu^-)}{\mathcal{B}(\psi(2S) \to \mu^+\mu^-)}, \tag{1}$$

where $N_{J/\psi}$ and $N_{\psi(2S)}$ are the measured yields listed in Table 1, and $\varepsilon_{J/\psi}$ and $\varepsilon_{\psi(2S)}$ are the total efficiencies. For the ratio of the $\psi \to \mu^+\mu^-$ branching fractions, lepton universality is assumed and a ratio of dielectron branching fractions equal to 7.60 ± 0.18 [52] is used. The uncertainty is treated as a systematic uncertainty.

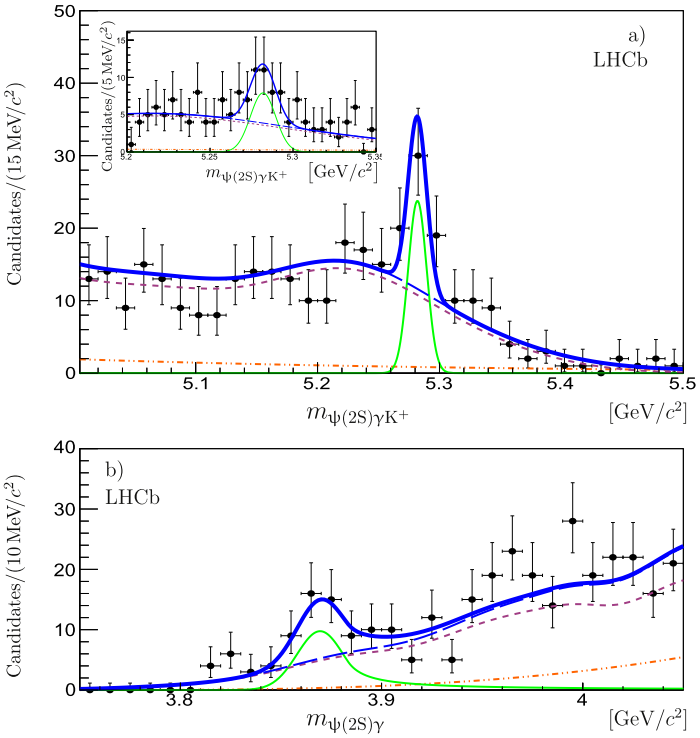

Fig. 2. a) Distribution of the $\psi(2S)\gamma K^+$ invariant mass with fit projection overlaid, restricted to those candidates with $\psi(2S)\gamma$ invariant mass within $\pm 3\sigma$ from the X(3872) peak position (the inset shows a zoom of the $\psi(2S)\gamma K^+$ mass region). b) Distribution of the $\psi(2S)\gamma$ invariant mass with fit projection overlaid, restricted to those candidates with $\psi(2S)\gamma K^+$ invariant mass within $\pm 3\sigma$ from the B^+ peak position. The total fit (thick solid blue) together with the signal (thin solid green) and background components (dash-dotted orange for the pure combinatorial, dashed magenta for the peaking component and long dashed blue for their sum) are shown. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The total efficiency is the product of the geometrical acceptance, the detection, reconstruction, selection and trigger efficiencies. The efficiencies are estimated using simulated events that have been corrected to reproduce the observed kinematics of B^+ mesons using the high-yield decay $B^+ \to \chi_{c1} K^+$ with $\chi_{c1} \to J/\psi\gamma$, which has a topology and kinematics similar to those of the decays under study. The ratio of the efficiencies is found to be $\varepsilon_{J/\psi}/\varepsilon_{\psi(2S)} = 5.25 \pm 0.04$, where the uncertainty is due to finite size of the simulated samples. The ratio of efficiencies is different from unity mainly because of the different photon spectra in the decays with J/ψ and $\psi(2S)$ in the final state.

Most sources of systematic uncertainty cancel in the ratio, in particular those related to the kaon, muon and ψ reconstruction and identification. The remaining systematic uncertainties are summarized in Table 2 and discussed in turn in the following.

Systematic uncertainties related to the signal yield determination are considered in four categories: signal, peaking background, combinatorial background and intervals used in the fit. For each category individual uncertainties are estimated using a number of alternative fit models. The maximum deviations from the baseline values of the yields are taken as individual systematic uncertainties, which are then added in quadrature. The systematic uncertainties on the event yields

Table 2
Relative systematic uncertainties on the ratio of branching fractions ($R_{\psi\gamma}$).

Source	Uncertainty [%]
$X(3872) \to J/\psi\gamma$ yield determination	6
$X(3872) \to \psi(2S)\gamma$ yield determination	7
Photon reconstruction	6
B^+ kinematics	3
Selection criteria	2
Trigger	1
$\mathcal{B}(J/\psi \to e^+e^-)/\mathcal{B}(\psi(2S) \to e^+e^-)$	2
Simulation sample size	1
Sum in quadrature	12

are dominated by uncertainties in the description of backgrounds and are 6% and 7% in the J/ψ and $\psi(2S)$ channels, respectively.

Another important source of systematic uncertainty arises from the potential disagreement between data and simulation in the estimation of efficiencies. This includes the photon reconstruction efficiency, the imperfect knowledge of B^+ kinematics and the description of the selection criteria efficiencies. The photon reconstruction efficiency is studied using a large sample of $B^+ \to J/\psi K^{*+}$ decays, followed by $K^{*+} \to K^+\pi^0$ and $\pi^0 \to \gamma\gamma$ decays. The relative yields of $B^+ \to J/\psi K^{*+}$ and $B^+ \to J/\psi K^+$ decays are compared in data and simulation. For photons with transverse momentum greater than 0.6 GeV/c, the agreement between data and simulation is within 6%, which is assigned as the systematic uncertainty due to the photon reconstruction.

The systematic uncertainty related to the knowledge of the B^+ production properties is estimated by comparing the ratio of efficiencies determined without making corrections to the B^+ transverse momentum and rapidity spectra to the default ratio of efficiencies determined after the corrections. The relative difference between the two methods is found to be 3% and is conservatively assigned as the systematic uncertainty from this source.

To study the uncertainty due to selection criteria, the high-yield decay $B^+ \to \chi_{c1}K^+$, followed by $\chi_{c1} \to J/\psi\gamma$, which has a similar topology to the decays studied in this analysis, is used. The selection criteria for the photon and kaon transverse momentum, the $\pi^0 \to \gamma\gamma$ veto and the χ^2/ndf of the kinematic fit are studied. The selection criteria are varied in ranges corresponding to as much as a 30% change in the signal yields and the ratios of the selection and reconstruction efficiencies are compared between data and simulation. The largest difference of 2% is assigned as the corresponding systematic uncertainty.

The systematic uncertainty related to the trigger efficiency is obtained by comparing the trigger efficiency ratios in data and simulation for the high yield decay modes $B^+ \to J/\psi K^+$ and $B^+ \to \psi(2S)K^+$, which have similar kinematics and the same trigger requirements as the channels under study in this analysis [55]. An agreement within 1% is found, which is assigned as the corresponding systematic uncertainty.

6. Results and summary

Using a sample of pp collisions at centre-of-mass energies of 7 and 8 TeV, corresponding to an integrated luminosity of 3 fb^{-1}, evidence for the decay $X(3872) \to \psi(2S)\gamma$ in $B^+ \to X(3872)K^+$ decays is found with a significance of 4.4 standard deviations. Its branching fraction, normalized to that of the $X(3872) \to J/\psi\gamma$ decay mode is measured to be

$$R_{\psi\gamma} = \frac{\mathcal{B}(X(3872) \to \psi(2S)\gamma)}{\mathcal{B}(X(3872) \to J/\psi\gamma)} = 2.46 \pm 0.64 \pm 0.29,$$

where the first uncertainty is statistical and the second is systematic. This result is compatible with, but more precise than, previous measurements [20,21]. The measured value of $R_{\psi\gamma}$ does not support a pure $D\bar{D}^*$ molecular interpretation [22–24] of the X(3872) state, whereas it agrees with expectations for a pure charmonium interpretation of the X(3872) state [25–32] and a molecular-charmonium mixture interpretations [29,33].

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