Search for the $Z_1(4050)^+$ and $Z_2(4250)^+$ states in $B^0 \to \chi_{c1}K^-\pi^+$ and $B^+ \to \chi_{c1}K^0_S\pi^+$

J. P. Lees, V. Poireau, and V. Tisserand
Laboratoire d’Annecy-le-Vieux de Physique des Particules (LAPP),
Université de Savoie, CNRS/IN2P3, F-74941 Annecy-Le-Vieux, France

J. Garra Tico and E. Grauges
Universitat de Barcelona, Facultat de Física, Departament ECM, E-08028 Barcelona, Spain

M. Martinelli$^{ab}$, D. A. Milanes$^a$, A. Palano$^{ab}$, and M. Pappagallo$^{ab}$
INFN Sezione di Bari$^a$; Dipartimento di Fisica, Università di Bari$^b$, I-70126 Bari, Italy

G. Eigen and B. Stugu
University of Bergen, Institute of Physics, N-5007 Bergen, Norway

D. N. Brown, L. T. Kerth, Yu. G. Kolomensky, and G. Lynch
Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA

H. Koch and T. Schroeder
Ruhr Universität Bochum, Institut für Experimentalphysik 1, D-44780 Bochum, Germany

D. J. Asgeirsson, C. Hearty, T. S. Mattison, and J. A. McKenna
University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z1

A. Khan
Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom

V. E. Blinov, A. R. Buzykaev, V. P. Druzhinin, V. B. Golubev, E. A. Kravchenko, A. P. Onuchin, S. I. Serednyakov, Yu. I. Skovpen, E. P. Solodov, K. Yu. Todyshev, and A. N. Yushkov
Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia

M. Bondioli, D. Kirkby, A. J. Lankford, M. Mandelkern, and D. P. Stoker
University of California at Irvine, Irvine, California 92697, USA

H. Atmacan, J. W. Gary, F. Liu, O. Long, and G. M. Vitug
University of California at Riverside, Riverside, California 92521, USA

C. Campagnari, T. M. Hong, D. Kovalskyi, J. D. Richman, and C. A. West
University of California at Santa Barbara, Santa Barbara, California 93106, USA

A. M. Eisner, J. Kroseberg, W. S. Lockman, A. J. Martinez, T. Schalk, B. A. Schumm, and A. Seiden
University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, California 95064, USA

C. H. Cheng, D. A. Doll, B. Echenard, K. T. Flood, D. G. Hitlin, P. Ongmongkolkul, F. C. Porter, and A. Y. Rakitin
California Institute of Technology, Pasadena, California 91125, USA

R. Andreassen, Z. Huard, B. T. Meadows, M. D. Sokoloff, and L. Sun
University of Cincinnati, Cincinnati, Ohio 45221, USA

P. C. Bloom, W. T. Ford, A. Gaz, M. Nagel, U. Nauenberg, J. G. Smith, and S. R. Wagner
University of Colorado, Boulder, Colorado 80309, USA

R. Ayad and W. H. Toki
Colorado State University, Fort Collins, Colorado 80523, USA

B. Spaan
Technische Universität Dortmund, Fakultät Physik, D-44221 Dortmund, Germany
We search for the $Z_1(4050)^+$ and $Z_2(4250)^+$ states, reported by the Belle Collaboration, decaying to $\chi_{c1}\pi^+$ in the decays $B^0 \rightarrow \chi_{c1}K^-\pi^+$ and $B^+ \rightarrow \chi_{c1}K^+\pi^+$ where $\chi_{c1} \rightarrow J/\psi\gamma$. The data were collected with the BaBar detector at the SLAC PEP-II asymmetric-energy $e^+e^-$ collider operating at center-of-mass energy 10.58 GeV, and correspond to an integrated luminosity of $429 \text{ fb}^{-1}$. In this analysis, we model the background-subtracted, efficiency-corrected $\chi_{c1}\pi^+$ mass distribution using the $K\pi$ mass distribution and the corresponding normalized $K\pi$ Legendre polynomial moments, and then test the need for the inclusion of resonant structures in the description of the $\chi_{c1}\pi^+$ mass distribution. No evidence is found for the $Z_1(4050)^+$ and $Z_2(4250)^+$ resonances, and 90% confidence level upper limits on the branching fractions are reported for the corresponding $B$-meson decay modes.

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I. INTRODUCTION

The Belle Collaboration has reported the observation of two resonance-like structures in the study of $B^0 \rightarrow \chi_{c1}K^-\pi^+$. These are labeled as $Z_1(4050)^+$ and $Z_2(4250)^+$, both decaying to $\chi_{c1}\pi^+$ [1]. The Belle Collaboration also reported the observation of a resonance-like structure, $Z(4430)^+ \rightarrow \psi(2S)\pi^+$ in the analysis of $B \rightarrow \psi(2S)K\pi$ [2, 3]. These claims have generated a great deal of interest [4]. Such states must have a minimum quark content $c\bar{c}u\bar{d}$, and thus would represent an unequivocal manifestation of four-quark meson states.

The BaBar Collaboration did not see the $Z(4430)^+$ in an analysis of the decay $B \rightarrow \psi(2S)K\pi$ [5]. Points of discussion are:

- The method of making slices of a three-body $B$ decay Dalitz plot can produce peaks which may be due to interference effects, not resonances.
- The angular structure of the $B \rightarrow \psi(2S)K\pi$ decay is rather complex and cannot be described adequately by only the two variables used in a simple Dalitz plot analysis.

In the BaBar analysis [5], the $B \rightarrow J/\psi K\pi$ decay does not show evidence for resonances neither in $J/\psi\pi$ nor in $J/\psi K$ systems. All resonance activity seems confined to the $K\pi$ system. It is also observed that the angular distributions, expressed in terms of the $K\pi$ Legendre polynomial moments, show strong similarities between $B \rightarrow \psi(2S)K\pi$ and $B \rightarrow J/\psi K\pi$ decays. Therefore, the angular information provided by the $B \rightarrow J/\psi K\pi$ decay can be used to describe the $B \rightarrow \psi(2S)K\pi$ decay. It is also observed that a localized structure in the $\psi(2S)\pi$ mass spectrum would yield high angular momentum Legendre polynomial moments in the $K\pi$ system. Therefore, a good description of the $\psi(2S)\pi$ data using only $K\pi$ mo-
ments up to \(L = 5\) also suggests the absence of narrow resonant structure in the \(\psi(2S)\)π system.

In this paper, we examine \(B \to \chi_{c1} K \pi\) decays following an analysis procedure similar to that used in Ref. \([3]\). In contrast to the analysis of Ref \([1]\), we model the background-subtracted, efficiency-corrected \(\chi_{c1}\pi^\pm\) mass distribution using the \(K\pi\) mass distribution and the corresponding normalized \(K\pi\) Legendre polynomial moments, and then test the need for the inclusion of resonant structures in the description of the \(\chi_{c1}\pi^\pm\) mass distribution.

This paper is organized as follows. A short description of the \(\text{BaBar}\) experiment is given in Sec. II, and the data selection is described in Sec. III. Section IV shows the data, while Sec. V and Sec. VI are devoted to the calculation of the efficiency and the extraction of branching fraction values, respectively. In Sec. VII we describe the fits to the \(K\pi\) mass spectra, and in Sec. VIII we show the Legendre polynomial moments. In Sec. IX we report the description of the \(\chi_{c1}\pi^\pm\) mass spectra, while Sec. X is devoted to the calculation of limits on the production of the \(\chi_{c1}\pi^\pm\) mass distribution.

II. THE \(\text{BaBar}\) EXPERIMENT

This analysis is based on a data sample of 429 fb\(^{-1}\) recorded at the \(\Upsilon(4S)\) resonance by the \(\text{BaBar}\) detector at the PEP-II asymmetric-energy \(e^+e^-\) storage rings. The \(\text{BaBar}\) detector is described in detail elsewhere \([2]\). Charged particles are detected and their momenta measured with a combination of a cylindrical drift chamber (DCH) and a silicon vertex tracker (SVT), both operating within the 1.5 T magnetic field of a superconducting solenoid. Information from a ring-imaging Cherenkov detector is combined with specific ionization measurements from the SVT and DCH to identify charged kaon and pion candidates. Photon energy and position are measured with a CsI(Tl) electromagnetic calorimeter (EMC), which is also used to identify electrons. The return yoke of the superconducting coil is instrumented with resistive plate chambers for the identification of muons. For the later part of the experiment the barrel-region chambers were replaced by limited streamer tubes \([3]\).

III. DATA SELECTION

We reconstruct events in the decay modes \([9]\):

\[
\begin{align*}
B^0 & \rightarrow \chi_{c1} K^- \pi^+, \\
B^+ & \rightarrow \chi_{c1} K^0 \pi^+,
\end{align*}
\]

where \(\chi_{c1} \rightarrow J/\psi \gamma\), and \(J/\psi \rightarrow \mu^+\mu^-\) or \(J/\psi \rightarrow e^+e^-\).

For each candidate, we first reconstruct the \(J/\psi\) by geometrically constraining an identified \(e^+e^-\) or \(\mu^+\mu^-\) pair of tracks to a common vertex point and requiring a \(\chi^2\) fit probability greater than 0.1\%. For \(J/\psi \rightarrow e^+e^-\) we introduce bremsstrahlung energy-loss recovery. If an electron-associated photon cluster is found in the EMC, its three-momentum vector is incorporated into the calculation of \(m(e^+e^-)\) \([10]\). The fit to the \(J/\psi\) candidates includes the constraint to the nominal \(J/\psi\) mass value \([2]\).

A \(K^0\) candidate is formed by geometrically constraining a pair of oppositely charged tracks to a common vertex (\(\chi^2\) fit probability greater than 0.1\%). For the two tracks the pion mass is assumed without particle-identification requirements. The \(K^0\) fit includes the constraint to the nominal mass value.

The \(J/\psi\), \(K^\pm\), and \(\pi^\pm\) candidates forming a \(B\) meson decay candidate are geometrically constrained to a common vertex and a \(\chi^2\) fit probability greater than 0.1\% is required. Particle identification is applied to both \(K\) and \(\pi\) candidates. The \(K^0\) flight length with respect to the \(B^+\) vertex must be greater than 0.2 cm.

A study of the scatter diagram \(E_{\gamma}\) vs. \(m(J/\psi\gamma)\) (not shown) reveals that no \(\chi_{c1}\) signal is kinematically possible for \(E_{\gamma}\ < 190\) MeV. Therefore, we consider only photons with a laboratory energy above this value. We select the \(\chi_{c1}\) signal within \(\pm 2\sigma_{\chi_{c1}}\) of the \(\chi_{c1}\) mass, where \(\sigma_{\chi_{c1}}\) and the \(\chi_{c1}\) mass are obtained from fits to the \(J/\psi\gamma\) mass spectra using a Gaussian function for the signal and a 2nd-order polynomial for the background, separated by \(B\) and \(J/\psi\) decay mode. The values of \(\sigma_{\chi_{c1}}\) range from 14.6 MeV/c\(^2\) to 17.6 MeV/c\(^2\).

We further define \(B\) meson decay candidates using the energy difference \(\Delta E \equiv E_B^* - \sqrt{s}/2\) in the center-of-mass (c.m.) frame and the beam-energy-substituted mass defined as \(m_{ES} \equiv \sqrt{(s/2 + \vec{p}_B/E_i)^2 - \vec{p}_B^2}\), where \((E_i, \vec{p}_i)\) is the initial state \(e^+e^-\) four-momentum vector in the laboratory frame and \(\sqrt{s}\) is the c.m. energy. In the above expressions \(E_B^*\) is the \(B\) meson candidate energy in the c.m. frame, and \(\vec{p}_B\) is its laboratory frame momentum. The \(B\) decay signal events are selected within \(\pm 2\sigma m_{ES}\) of the fitted central value, where the \(\sigma m_{ES}\) values are listed in Table I and are determined by fits of a Gaussian function plus an ARGUS function \([11]\) to the data.

The resulting \(\Delta E\) distributions have been fitted with a linear background function and a signal Gaussian function whose width values \((\sigma_{\Delta E})\) are also listed in Table I. Further background rejection is performed by selecting events within \(\pm 2\sigma \Delta E\) of zero. Table I also gives the values of event yield and purity, where the Purity is defined as \(\text{Signal}/(\text{Signal}+\text{Background})\). The \(\Delta E\) distributions shown in Fig. I have been summed over the \(J/\psi\rightarrow \mu^+\mu^-\) and \(J/\psi\rightarrow e^+e^-\) decay modes. Clear signals of the \(B\) decay modes (1) and (2) can be seen. We obtain 1863 candidates for \(B^0 \rightarrow \chi_{c1} K^-\pi^+\) decays with 78\% purity, and 628 \(B^+ \rightarrow \chi_{c1} K^0\pi^+\) events with 79\% purity. A study of the \(\Delta E\) and \(J/\psi\gamma\) spectra in the sideband regions does not show any \(B\) or \(\chi_{c1}\) signal respectively. We conclude that the observed background is consistent with being entirely of combinatorial origin.

The resulting \(J/\psi\gamma\) invariant mass distributions for
channels (1) and (2) are shown in Fig. 2.

In order to estimate the background contribution in the signal region, we define $\Delta E$ sideband regions in the intervals $(7 - 9) \sigma_{\Delta E}$ on both sides of zero. We obtain a “background-subtracted” distribution of events by subtracting the corresponding distribution for $\Delta E$ sideband events from that of events in the signal region.

### IV. DALITZ PLOTS

The Dalitz plots for $B^0 \rightarrow \chi_{c1} K^- \pi^+$ events in the signal and sideband regions are shown in Fig. 3. The shaded area defines the Dalitz plot boundary; it is obtained from a simple phase space Monte Carlo (MC) simulation of $B$ decays, smeared by the experimental resolution. For the sidebands, events can lie outside the boundary. We observe a vertical band due to the presence of the $K^+(892)^0$ resonance and a weaker band due to the $K^0_s(1430)^0$ resonance. We do not observe significant accumulation of events in any horizontal band.

The Dalitz plots for $B^+ \rightarrow \chi_{c1}K^0\pi^+$ candidates in the signal and sideband regions are shown in Fig. 4 and show features similar to those in Fig. 2.

### V. EFFICIENCY

To compute the efficiency, signal MC events (full-MC) for the different channels have been generated using a detailed detector simulation where $B$ mesons decay uniformly in phase space. They are reconstructed and analyzed in the same way as real events. We express the efficiency as a function of $m(K\pi)$ and $\cos \theta$, the normalized dot-product between the $K\pi$ momentum, both in the $K\pi$ laboratory frame and the latter to a $m_{ES}$-mass range. However these losses do not affect the regions of the reported $Z$ resonances. Using these fitted functions we obtain efficiency-corrected distributions by weighting each event by the inverse of the efficiency as a function of $m(K\pi)$, $\cos \theta$, $\Delta m_{ES}$ and $\Delta \theta$. The efficiency for the different channels have been generated using a detailed detector simulation where $B$ mesons decay uniformly in phase space. They are reconstructed and analyzed in the same way as real events. We express the efficiency as a function of $m(K\pi)$ and $\cos \theta$, the normalized dot-product between the $K\pi$ momentum, both in the $K\pi$ laboratory frame and the latter to a $m_{ES}$-mass range. However these losses do not affect the regions of the reported $Z$ resonances.

### VI. BRANCHING FRACTIONS

We measure the branching fractions for $B^0 \rightarrow \chi_{c1}K^-\pi^+$ and $B^+ \rightarrow \chi_{c1}K^0\pi^+$ relative to $B^0 \rightarrow J/\psi K^+\pi^-$ and $B^+ \rightarrow J/\psi K^0\pi^+$, respectively. In this way several systematic uncertainties, (namely uncertainties on the number of $B\bar{B}$ mesons, particle identification, tracking efficiency, data-MC differences, secondary branching fractions) cancel.

![FIG. 1: Distributions of $\Delta E$ for (a) $B^0 \rightarrow \chi_{c1}K^-\pi^+$ and (b) $B^+ \rightarrow \chi_{c1}K^0\pi^+$ summed over the $J/\psi$ decay modes; the $\chi_{c1}$ and $m_{ES}$ selection criteria have been applied. The shaded areas indicate the signal regions.](image)

![FIG. 2: The $J/\psi\gamma$ mass distribution for (a) $B^0 \rightarrow \chi_{c1}K^-\pi^+$ and (b) $B^+ \rightarrow \chi_{c1}K^0\pi^+$ candidates, summed over the $J/\psi$ decay modes; the $m_{ES}$ and $\Delta E$ selection criteria have been applied. The shaded areas indicate the signal regions.](image)
TABLE I: Resolution parameter values from fits to the $\Delta E$ and $m_{ES}$ distributions.

| Channel | $\sigma_{\Delta E}$ (MeV) | $\sigma_{m_{ES}}$ (MeV/$c^2$) | events | Purity % |
|---------|----------------|----------------|--------|---------|
| $B^0 \rightarrow \chi_{c1} K^- \pi^+$ | $6.96 \pm 0.34$ | $2.60 \pm 0.10$ | 980 | 79.3 ± 1.3 |
| $B^0 \rightarrow \chi_{c1} K^- \pi^+$ | $7.81 \pm 0.43$ | $2.77 \pm 0.12$ | 883 | 77.1 ± 1.4 |
| $B^+ \rightarrow \chi_{c1} K^0 \pi^+$ | $6.65 \pm 0.55$ | $2.65 \pm 0.27$ | 299 | 81.7 ± 2.2 |
| $B^+ \rightarrow \chi_{c1} K^0 \pi^+$ | $7.52 \pm 0.70$ | $2.65 \pm 0.18$ | 329 | 77.5 ± 2.3 |

FIG. 3: Dalitz plot for $B^0 \rightarrow \chi_{c1} K^- \pi^+$ in (a) the signal region and (b) the $\Delta E$ sidebands. The shaded area defines the Dalitz plot boundary.

To obtain the yields, for each $B$ decay mode we perform new fits to the $\Delta E$ distributions using the full-MC lineshape for the signal and a linear background. The background-subtracted data are then integrated between $\pm 2.0 \sigma_{\Delta E}$. The correction for efficiency is obtained as described in Sec. V. A similar procedure is applied to the $B^0 \rightarrow J/\psi K^- \pi^+$ and $B^+ \rightarrow J/\psi K^0 \pi^+$ data.

The branching fraction for $\chi_{c1} \rightarrow J/\psi \gamma$ from Ref. [2] is $0.344 \pm 0.015$. Using this value, we obtain the following branching fraction ratios:

$$\frac{B(B^0 \rightarrow \chi_{c1} K^- \pi^+)}{B(B^0 \rightarrow J/\psi K^- \pi^+)} = 0.474 \pm 0.013 \pm 0.026,$$

and

$$\frac{B(B^+ \rightarrow \chi_{c1} K^0 \pi^+)}{B(B^+ \rightarrow J/\psi K^0 \pi^+)} = 0.501 \pm 0.024 \pm 0.028.$$

Systematic uncertainties are summarized in Table II and have been evaluated as follows:

1. We obtain the uncertainty on the background subtraction by modifying the model used to fit the $\Delta E$ distributions. The signal was alternatively described by the sum of two Gaussian functions and the background was parametrized by a 2nd-order polynomial.

2. We compute the uncertainty on the efficiency by making use of the binned efficiency on the $(m(K\pi), \cos \theta)$ plane. In each cell we randomize the generated and reconstructed yields according to Poisson distributions. Deviations from the fitted efficiencies give the uncertainty on this quantity.

3. We vary the bin size for the binned efficiency calculation.

4. We include a systematic error due to the uncertainty on the $\chi_{c1} \rightarrow J/\psi \gamma$ branching fraction [2].

5. We assign a 1.8 % uncertainty to the $\gamma$ reconstruction efficiency.

6. We modify the $\Delta E$ and $m_{ES}$ selection criteria and assign systematic uncertainties based on the variation of the extracted branching fractions.

We note that the systematic uncertainties are dominated by the uncertainty on the $\chi_{c1} \rightarrow J/\psi \gamma$ branching fraction.

The branching fractions measured in Ref. [6] are:

$$B(B^0 \rightarrow J/\psi K^- \pi^+) = (1.079 \pm 0.011) \times 10^{-3},$$

$$B(B^+ \rightarrow J/\psi K^0 \pi^+) = (1.101 \pm 0.021) \times 10^{-3},$$

where the latter value has been corrected for $K^0_L$ and $K^0_S \rightarrow \pi^0 \pi^0$ decays [2].
FIG. 4: Dalitz plot for $B^+ \to \chi_{c1}^{0} K^+ \pi^+$ in (a) the signal region and (b) the $\Delta E$ sidebands. The shaded area defines the Dalitz plot boundary.

FIG. 5: Fitted efficiency on the $\cos \theta$ vs. $m(K\pi)$ plane for (a) $B^0 \to \chi_{c1}^{-} K^+ \pi^+$ and (b) $B^+ \to \chi_{c1}^{0} K^0 \pi^+$ summed over the $J/\psi$ decay modes.

TABLE II: Systematic uncertainties (%) for the $B \to \chi_{c1} K\pi$ relative branching fraction measurements.

| Contribution                  | $B^0 \to \chi_{c1}^{-} K^+ \pi^+$ | $B^+ \to \chi_{c1}^{0} K^+ \pi^+$ |
|-------------------------------|---------------------------------|---------------------------------|
| 1. Background subtraction     | 1.6                             | 1.0                             |
| 2. Efficiency                 | 1.5                             | 1.6                             |
| 3. Efficiency binning         | 1.1                             | 1.9                             |
| 4. $\chi_{c1}$ branching fraction | 4.4                           | 4.4                             |
| 5. $\gamma$ reconstruction    | 1.8                             | 1.8                             |
| 6. $\Delta E$ and $m_{ES}$ selections | 1.0                         | 1.0                             |
| Total (%)                     | 5.4                             | 5.5                             |

Multiplying the ratio in Eq. (4) by the $B^0 \to J/\psi K^- \pi^+$ branching fraction in Eq. (6) we obtain

$$\mathcal{B}(\overline{B}^0 \to \chi_{c1}^{-} K^+ \pi^+) = (3.83 \pm 0.10 \pm 0.39) \times 10^{-4}.$$ Mulyplying the ratio in Eq. (5) by the $B^+ \to J/\psi K^0 \pi^+$ branching fraction in Eq. (7) we obtain

$$\mathcal{B}(B^+ \to \chi_{c1}^{0} K^+ \pi^+) = (5.52 \pm 0.26 \pm 0.31) \times 10^{-4},$$

so that, after all corrections, the branching fractions corresponding to decay modes (1) and (2) are the same within uncertainties.

VII. FITS TO THE $K\pi$ MASS SPECTRA

We perform binned-$\chi^2$ fits to the background-subtracted and efficiency-corrected $K\pi$ mass spectra in terms of $S$, $P$, and $D$ wave amplitudes. The fitting func-
TABLE III: $S$, $P$, $D$ wave fractions (in %), and $\chi^2$/NDF (NDF = Number of Degrees of Freedom) from the fits to the $K\pi$ mass spectra in $B^0 \to \chi_{c1}K^-\pi^+$ and $B^+ \to \chi_{c1}K^+\pi^+$. The second $P$-wave entry in the two $\chi_{c1}$ channels corresponds to the fraction of $K^*(1680)$.

| Channel | $S$-wave $|f_S|$ | $P$-wave $|f_P|$ | $D$-wave $|f_D|$ | $\chi^2$/NDF |
|---------|-------------|-------------|-------------|-------------|
| $B^0 \to \chi_{c1}K^-\pi^+$ | $40.4 \pm 2.2$ | $37.9 \pm 1.3$ | $11.4 \pm 2.0$ | $58/54$ |
| | $10.3 \pm 1.5$ | | | |
| $B^+ \to \chi_{c1}K^+\pi^+$ | $42.4 \pm 3.5$ | $37.1 \pm 3.2$ | $10.1 \pm 3.1$ | $55/54$ |
| | $10.4 \pm 2.5$ | | | |

The above model gives a good description of the data for the $B \to J/\psi K\pi$ [2]. However, for $B \to \chi_{c1}K\pi$ the above resonances do not describe the high mass region of the $K\pi$ mass spectra well. A better fit is obtained by including an additional incoherent spin-1 $K^*(1680)$ [2] resonance contribution. The fit results are shown by the solid curves in Fig. 7 and the resulting intensity contributions are summarized in Table III. In Figs. 7(a) and 7(b) the contributions due to the $K^*(1680)$ amplitude are shown by the dashed curves. The $\chi_{c1}K\pi$ decay modes differ from the corresponding $J/\psi K\pi$ and $\psi(2S)K\pi$ decay modes in that the $S$-wave fraction is much larger in the former than in the latter. This was observed for the $K^*(892)$ region in a previous $\bar{B}B$ analysis [13].

VIII. THE $K\pi$ LEGENDRE POLYNOMIAL MOMENTS

We compute the efficiency-corrected Legendre polynomial moments $<Y_L^n>$ in each $K\pi$ mass interval by correcting for efficiency, as explained in Sec. V, and then weighting each event by the $Y_L^0(\cos \theta)$ functions. A similar procedure is performed for the $\Delta E$ sideband events, for which the distributions are subtracted from those in the signal region. We observe consistency between the $B^0$ and $B^+$ data. Therefore, in the following we combine the $B^0$ and $B^+$ distributions.

This yields the background-subtracted and efficiency-corrected $K\pi$ mass spectra for (a) $B^0 \to \chi_{c1}K^-\pi^+$ and (b) $B^+ \to \chi_{c1}K^+\pi^+$. The $K^*(1680)$ contribution is shown in each figure by the dashed curve.

In Figs. 8 we observe the presence of the spin-1 $K^*(890)$ in the $<Y_L^0>$ moment and $S$-$P$ interference in the $<Y_L^1>$ moment. We also observe evidence for the spin-2 $K_2^*(1430)$ resonance in the $<Y_L^0>$ moment. There are some similarities between the moments of Fig. 8 and those from $B \to J/\psi K\pi$ decays in Ref. [6]. However we also observe a significant structure around 1.7 GeV/$c^2$ in $<Y_L^0>$ which is absent in the $B \to J/\psi K\pi$ decays. We attribute this to the presence of the $K_1^*(1680)$ resonance produced in $B \to \chi_{c1}K\pi$ but absent in $B \to J/\psi K\pi$. The presence of scalar $Z$ resonances should show up especially in high $<Y_L^0>$ moments.

From the $<Y_L^0>$ we obtain the normalized moments

$$<Y_L^n> = \frac{<Y_L^0>}{n},$$

where $n$ is the number of events in the given $m(K\pi)$ mass interval.

![Fig. 7](image_url)
 IX. MONTE CARLO SIMULATIONS

We model $B \to \chi_{c1} K\pi$ using the resonant structure obtained from the analysis of the $K\pi$ mass spectra and $K\pi$ Legendre polynomial moments. For this purpose we generate a large number of MC events according to the following procedure.

- $B \to \chi_{c1} K\pi$ events are generated uniformly in phase space [12]. The $B$ mass is generated as a Gaussian lineshape with parameters obtained from a fit to the data.

- We weight each event by a factor $w_{m(K\pi)}$ derived from the resonant structure in the $K\pi$ system described in Sec. VII (Eq. (10)), and displayed in Table [III]

- We incorporate the measured $K\pi$ angular structure by giving weight $w_L$ to each event according to the expression:

$$w_L = \sum_{i=0}^{L_{\text{max}}} <Y_i^N> Y_i^0(\cos \theta).$$  \hspace{1cm} (13)

The moments correspond to the combined data from the decay modes of Eqs. (1) and (2). The $<Y_i^N>$ are evaluated for the $m(K\pi)$ value by linear interpolation between consecutive $m(K\pi)$ mass intervals.

- The total weight is thus:

$$w = w_{m(K\pi)} \cdot w_L$$  \hspace{1cm} (14)

The generated distributions, weighted by the total weight $w$, are then normalized to the number of data events obtained after background-subtraction and efficiency-correction.

We first test the method using as control sample the combined data from $B^0 \to J/\psi K^- \pi^+$ and $B^+ \to J/\psi K_S^0 \pi^+$, where no resonant structure is observed in the $J/\psi \pi$ mass distributions [8]. In this case we generate $B \to J/\psi K\pi$ events and use the $K\pi$ resonant structure and Legendre polynomial information from the same channels. We compare the MC simulation to the $J/\psi \pi^+$ mass projection from data in Fig. [I]. We obtain $\chi^2/NDF = 223, 162, 180/152$ for $L_{\text{max}} = 4, 5, 6$ respectively. We conclude that $L_{\text{max}} = 5$ gives the best description of the data.

We now perform a similar MC simulation for $B \to \chi_{c1} K\pi$ using moments from the same channels. We obtain $\chi^2/NDF = 53, 46, 49/58$ for $L_{\text{max}} = 4, 5, 6$ respectively. The result of the simulation with $L_{\text{max}} = 5$ is superimposed on the data in Fig. [II] and the corresponding $\chi^2/NDF$ is given in Table [IV]. The excellent description of the data indicates that the angular information from the $K\pi$ channel with $L_{\text{max}} = 5$ is able to account for the structures observed in the $\chi_{c1}$ projection. This indicates the absence of significant structure in the exotic $\chi_{c1}\pi^+$ channel.

We perform a MC simulation where, to the data from $B^0 \to \chi_{c1} K^- \pi^+$, we add an arbitrary fraction ($\approx 25\%$) of events which include a $Z_2(4250)^+$ resonance decaying to $\chi_{c1}\pi$. These $Z_2(4250)^+$ events are obtained from phase-space MC $B^0 \to \chi_{c1} K^- \pi^+$ events weighted by a simple table.
Breit-Wigner. We then compute Legendre polynomial moments for the total sample and use them to predict the $\chi_{c1}\pi$ mass distribution as described above. The $\chi_{c1}\pi$ mass spectrum for these events is shown in Fig. 10(a).

We obtain $\chi^2/\text{NDF} = 103, 91, 88/58$ for $L_{\text{max}} = 4, 5, 6$ respectively. Therefore, in the presence of a $Z_2(4250)^+$ resonance, it is not possible to obtain a good description of the $\chi_{c1}\pi$ mass distribution using $L_{\text{max}} = 5$. We then increase the value of $L_{\text{max}}$ and obtain a good description of this MC simulation with $L_{\text{max}} = 15$, as shown by the dashed curve in Fig. 11(a) ($\chi^2/\text{NDF} = 57/58$).

We next test a “mixed” simulation where we use $L_{\text{max}} = 3$ up to a $K\pi$ mass of 1.2 GeV/$c^2$ and $L_{\text{max}} = 4$ for the rest of the events. This choice is justified by the presence of spin 0 and 1 resonances mostly in the low $K\pi$ mass region, while the $K_2^*(1430)$ contributes for $m(K\pi) > 1.2$ GeV/$c^2$. This simulation gives a satisfactory description of the $B \to \chi_{c1}K\pi$ data with $\chi^2/\text{NDF} = 63/58$ but gives a bad description of the MC sample of Fig. 11(a), yielding $\chi^2/\text{NDF} = 140/58$.

We now fit the MC sample including a simple Breit-Wigner (with the width fixed to the simulated value) to describe the $Z_2(4250)^+$ (Fig. 11(b)). We obtain the solid curve, which has $\chi^2/\text{NDF} = 75/56$, a $Z_2(4250)^+$ mass consistent with the generated value, and a yield consistent with the generated one. The dashed curve represents the background model from the “mixed” simulation. The MC test therefore validates the use of this background model for a quantitative evaluation of the upper limits described in Sec. X.

The data-MC comparisons for the different simulations are summarized in Table IV.

### X. SEARCH FOR $Z_1(4050)^+$ AND $Z_2(4250)^+$

We have shown, in the previous sections, that in the absence of $Z$ resonances, the simulation with $L_{\text{max}} = 5$ gives a good description of the $B \to J/\psi K\pi$ and $B \to \chi_{c1}K\pi$ data. We now test the possible presence of the $Z_1(4050)^+$ and $Z_2(4250)^+$ resonances in $B \to \chi_{c1}K\pi$ decay. Therefore we adopt the minimum $L_{\text{max}}$ configuration (“mixed”) described in Sec. IX and investigate whether something else is needed by the data.

For this purpose we perform binned $\chi^2$ fits to the $\chi_{c1}\pi^+$ mass spectrum. In these fits the normalization of the background component is determined by the fit. We observe that this background model predicts an enhancement in the mass region of the $Z$ resonances. We then add, for the signal, relativistic spin-0 Breit-Wigner
functions with parameters fixed to the Belle values for the signals [1]. We compute statistical significance using the fitted fraction divided by its uncertainty.

We first perform fits to the total mass spectrum.

- Fit a) is shown in Fig. 12(a), and includes both $Z_1(4050)^+$ and $Z_2(4250)^+$ resonances.

In both cases the fits give fractional contributions consistent with zero for the $Z$ resonances.

We next fit the $\chi_{c1}\pi$ mass spectrum in the Dalitz plot region $1.0 \leq m^2(K\pi) < 1.75$ GeV$^2$/c$^4$ in order to make a direct comparison to the Belle results [1]. Figures 12(c), (d) show the $\chi_{c1}\pi$ mass spectrum for this mass region labeled as “window” in Table V where the Belle data show the maximum of the reported resonance activity. This sample accounts for 25% of our total data sample. Table V gives the corresponding $\chi^2$/NDF values for the MC simulations described in Sec. IX, in this mass window.

- Fit b) is shown in Fig. 12(b), and includes a single broad $Z(4150)^+$ resonance.

- Fit c) is shown in Fig. 12(c), and includes both $Z_1(4050)^+$ and $Z_2(4250)^+$ resonances.

- Fit d) is shown in Fig. 12(d), and includes a single broad $Z(4150)^+$ resonance.

In each case the fit gives a $Z$ resonance contribution consistent with zero.

The results of the fits are summarized in Table V, and in every case the yield significance does not exceed 2\sigma. Similar results are obtained when the resonance parameters are varied within their statistical errors.

We compute upper limits integrating the region of positive branching fraction values for a Gaussian function having the above mean and $\sigma$ values, and obtain the following 90% C.L. limits for the $Z_1(4050)^+$ and $Z_2(4250)^+$ resonances:

\[
\begin{align*}
B(\vec{B}^0 \to Z_1(4050)^+K^-) \times B(Z_1(4050)^+ \to \chi_{c1}\pi^+)(15) & < 1.8 \times 10^{-5}, \\
B(\vec{B}^0 \to Z_2(4250)^+K^-) \times B(Z_2(4250)^+ \to \chi_{c1}\pi^+)(16) & < 4.0 \times 10^{-5}, \\
B(\vec{B}^0 \to Z^+K^-) \times B(Z^+ \to \chi_{c1}\pi^+)(17) & < 4.7 \times 10^{-5}.
\end{align*}
\]

Systematic uncertainties related to the $Z$ parameters have been ignored since they give negligible contributions. The corresponding values for $B^+$ decay are $\approx 8\%$ larger (see Eqs. (8) and (9)).
Our measurements can be compared to the Belle results [1]:

\[ B(\mathcal{B}^0 \rightarrow Z_1(4050)^+ K^-) \times B(Z_1(4050)^+ \rightarrow \chi_{c1}\pi^+) = 3.0^{+1.5}_{-0.8} \times 10^{-5}, \]

\[ B(\mathcal{B}^0 \rightarrow Z_2(4250)^+ K^-) \times B(Z_2(4250)^+ \rightarrow \chi_{c1}\pi^+) = 4.0^{+2.3}_{-0.9} \times 10^{-5}, \]

\[ B(\mathcal{B}^0 \rightarrow \chi_{c1} K^- \pi^+) = (5.11 \pm 0.14 \pm 0.28) \times 10^{-4}, \]

\[ B(B^+ \rightarrow \chi_{c1} K^0 \pi^+) = (5.52 \pm 0.26 \pm 0.31) \times 10^{-4}. \]

Given the large uncertainties, these branching fraction values are compatible with our upper-limit estimates.

XI. CONCLUSIONS

We use 429 fb\(^{-1}\) of data from the \textit{BaBar} experiment at SLAC to search for the \(Z_1(4050)^+\) and \(Z_2(4250)^+\) states decaying to \(\chi_{c1}\pi^+\) in the decays \(\mathcal{B}^0 \rightarrow \chi_{c1} K^- \pi^+\) and \(B^+ \rightarrow \chi_{c1} K^0 \pi^+\), where \(\chi_{c1} \rightarrow J/\psi \gamma\).

We measure the following branching fractions for the decays \(\mathcal{B}^0 \rightarrow \chi_{c1} K^- \pi^+\) and \(B^+ \rightarrow \chi_{c1} K^0 \pi^+\):

\[ B(\mathcal{B}^0 \rightarrow \chi_{c1} K^- \pi^+) = (5.11 \pm 0.14 \pm 0.28) \times 10^{-4}, \]

and

\[ B(B^+ \rightarrow \chi_{c1} K^0 \pi^+) = (5.52 \pm 0.26 \pm 0.31) \times 10^{-4}. \]
In our search for the $Z$ states, we first attempt to describe the data assuming that all resonant activity is concentrated in the $K\pi$ system. We use the decay $B \to J/\psi K\pi$ as a control sample, since no resonant structure has been observed in the $J/\psi \pi$ mass spectrum. In this case a good description of the data is obtained by a MC simulation which makes use of the known resonant structure in the $K\pi$ mass spectrum together with a Legendre-polynomial description of the angular structure as a function of $K\pi$ mass.

The same procedure is then applied to our data on the decays $B \to \chi_{c1} K\pi$ and a good description of the $\chi_{c1}\pi$ mass distribution is obtained. This indicates that no significant resonant structure is present in the $\chi_{c1}\pi$ mass spectrum, as observed for the $J/\psi \pi$ mass distribution [6]. We also observe that this background model predicts an enhancement in the mass region of the $Z$ resonances. We then report 90% C.L. upper limits on possible $B^0 \to Z^+ K^-$ decays.

In conclusion, we find that it is possible to obtain a good description of our data without the need for additional resonances in the $\chi_{c1}\pi$ system.

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