Evidence for $B^+ \to J/\psi p\overline{\Lambda}$ and Search for $B^0 \to J/\psi p\overline{p}$

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We have performed a search for the decays $B^+ \to J/\psi p\overline{\Lambda}$ and $B^0 \to J/\psi p\overline{p}$ in a data set of $(88.9 \pm 1.0) \times 10^6$ $\Upsilon(4S)$ decays collected by the BABAR experiment at the PEP-II e^+e^- storage ring at the Stanford Linear Accelerator Center. Four charged B candidates have been observed with an expected background of 0.21 ± 0.14 events. The corresponding branching fraction is $(12^{+9}_{-6}) \times 10^{-6}$, where statistical and systematic uncertainties have been combined. The result can be interpreted as a 90% confidence level (C.L.) upper limit of 26×10^{-6}. We also find one B^0 candidate, with an expected background of 0.64 ± 0.17 events, implying a 90% C.L. upper limit of 1.9×10^{-6}.

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Studies of the inclusive production of charmonium mesons in B decays at the $\Upsilon(4S)$ resonance have been published by CLEO [1] and BABAR [2], and preliminary results have been presented by Belle [3]. One of the interesting features observed by all three collaborations is an excess of J/ψ mesons at low momentum in the e^+e^- center-of-mass frame, p_{CM}, when compared to distributions predicted by nonrelativistic QCD (NRQCD) calculations [4]. Figure 1 (from Ref. [2]) shows p_{CM} for J/ψ mesons produced in B decay after subtraction of the component due to the decay of heavier charmonium states. The excess below 0.8 GeV/c corresponds to a branching fraction of approximately 6×10^{-4}, 8% of the total direct J/ψ production.

Possible sources of the excess include an intrinsic charm component of the B [6] or the production of an $s\bar{d}g$ hybrid [7] in conjunction with a J/ψ. Another possibility [8] is that the excess is from decays of the form $B \to J/\psi$ *baryon antibaryon*. The rate of these decays could be enhanced by the intermediate production of an exotic state allowed by QCD but not yet observed, including nuclear-bound quarkonium (a $c\bar{c}$ pair bound to a nucleon), baryonium (a baryon-antibaryon bound state), or a pentaquark (a baryon containing five quarks). If such resonances were narrow, the other particle in the decay would be monoenergetic in the B rest frame. Note that the J/ψ spectrum in Fig. 1 would not directly display such narrow distributions because it is measured in the e^+e^- center-of-mass frame. The difference between p_{CM} and p^*, the J/ψ momentum in the B rest frame, has an rms of 0.12 GeV/c due to the motion of the B.

This Letter presents searches for the decays $B^+ \to J/\psi p \overline{\Lambda}$ and $B^0 \to J/\psi p \overline{p}$ in a sample of 81.9 fb^{-1} collected by the BABAR detector. Note that the latter decay is Cabibbo suppressed relative to the former. Charge conjugation is implied throughout.

BABAR operates at the PEP-II e^+e^- storage ring, which collides 9.0 GeV electrons on 3.1 GeV positrons to create a center-of-mass system with energy 10.58 GeV moving along the z axis with a Lorentz boost of $\beta\gamma = 0.55$. $\Upsilon(4S)$ production makes up approximately 23% of the total hadronic cross section.

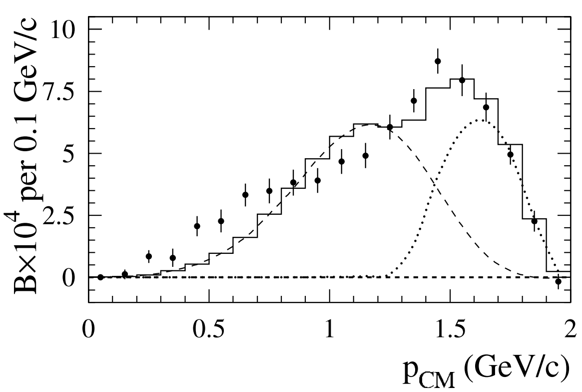

FIG. 1. Center-of-mass momentum of J/ψ mesons produced directly in B decays (points) [2]. The histogram is the sum of the color-octet component from a recent NRQCD calculation [4] (dashed line), which includes multibody final states, and the color-singlet $J/\psi K^{(*)}$ component from simulation [5] (dotted line). Normalizations of the curves have been constrained to fit the data.

The BABAR detector is described in detail in Ref. [9]. The trajectories of charged particles are reconstructed and their momenta measured with two detector systems located in a 1.5-T solenoidal magnetic field: a five-layer, double-sided silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH). The tracking fiducial volume covers the polar angular region $0.41 < \theta < 2.54$ rad, which is 86% of the solid angle in the center-of-mass frame. The transverse momentum resolution is 0.49% at 0.3 GeV/c and 0.59% at 1 GeV/c.

The energies deposited by charged tracks and photons are measured by a CsI(Tl) calorimeter (EMC) in the fiducial volume $0.41 < \theta < 2.41$ rad (84% of the center-of-mass solid angle) with energy resolution at 1 GeV of 2.6%. Muons are detected in the IFR, a multilayer device of resistive plate chambers located in the flux return of the solenoid. The DIRC, a Cherenkov radiation detector, is used to identify charged particles.

We select B candidates of interest in a $B\overline{B}$-enriched sample. Events in the sample are required to have visible energy E greater than 4.5 GeV and a ratio of the second to the zeroth Fox-Wolfram moment [10], R_2, less than 0.5. Both E and R_2 are calculated from tracks and neutral energy deposits in the respective fiducial volumes noted above. The same tracks are used to construct a primary event vertex, which is required to be located within 6 cm of the beam spot in z and within 0.5 cm of the beam line. The beam spot rms size is approximately 0.9 cm in z, 120 μm horizontally, and 5.6 μm vertically.

There must be at least three tracks in the fiducial volume satisfying the following quality criteria: they must have transverse momentum greater than 0.1 GeV/c, momentum less than 10 GeV/c, at least 12 hits in the DCH, and approach within 10 cm of the beam spot in z and within 1.5 cm of the beam line. Studies with simulated data indicate that these criteria are satisfied by 96% of generic $B\overline{B}$ events.

$B^+ \to J/\psi p \overline{\Lambda}$ candidates are formed by combining J/ψ, proton, and $\overline{\Lambda}$ candidates. J/ψ candidates must have mass in the range 2.950–3.130 GeV/c^2 if reconstructed in the e^+e^- final state or 3.060–3.130 GeV/c^2 in $\mu^+\mu^-$.

One of the two electrons from the J/ψ must satisfy the following ("tight") requirements. It must have an energy deposit in the EMC between 89% and 120% of its momentum, a Cherenkov angle in the DIRC within 3σ of expectation for an electron, a lateral moment of the energy deposit [11], LAT, between 0.1 and 0.6, an A_{42} Zernike moment [12] less than 0.11, and an energy loss in the DCH consistent with expectation. Less stringent ("loose") requirements are imposed in the selection of the second electron: we require an energy deposit in the EMC of at least 65% of its momentum and place a less restrictive requirement on DCH energy, with no requirements on LAT or A_{42}. Whenever possible, photons radiated by an electron traversing material prior to the DCH

(0.04 r.l. at normal incidence) are combined with the track [2].

At 1.5 GeV/c, a typical lepton momentum, the tighter criteria have an efficiency of 91% with a pion misidentification probability of 0.13%. The looser criteria give 98% efficiency with 3% pion misidentification.

Muon candidates must deposit less than 0.5 GeV in the EMC (2.3 times the minimum-ionizing peak) and have a pattern of hits in the IFR consistent with the trajectory of a muon. The total amount of material penetrated must be greater than 2 interaction lengths and must be within 2 interaction lengths of the value expected for a muon. The muon identification efficiency at 1.5 GeV/c is 77% with a pion misidentification probability of 11%.

Proton candidates are selected with a likelihood method that uses the energy deposited in the SVT and the DCH, and the Cherenkov angle and number of photons observed in the DIRC. They are also required to fail the tight electron identification criteria. At a typical momentum of 300 MeV/c, the selection efficiency is greater than 98% with a kaon misidentification probability less than 1%.

The $\overline{\Lambda}$ is reconstructed from a proton, which must satisfy the above criteria, and an oppositely charged track, assumed to be a pion. It must have mass between 1.10 and 1.14 GeV/c^2 and a vertex that is separated from the J/ψ vertex by at least 2 mm. The angle between the $\overline{\Lambda}$ momentum and the vector from the J/ψ vertex to the $\overline{\Lambda}$ vertex must be less than 90° in the laboratory frame.

Geometrical vertex fits are performed on the resulting B^+ candidates, of which approximately 68% are rejected by a requirement on the quality of the fit.

$B^0 \to J/\psi p\overline{p}$ candidates are formed from J/ψ candidates and an oppositely charged pair of proton candidates. Approximately 83% of resulting candidates fail a requirement on the quality of a vertex fit.

We use two nearly independent kinematic variables [9] to categorize B candidates: the difference between the reconstructed and expected energy of the B candidate in the e^+e^-center-of-mass frame, $\Delta E = (q_\Upsilon q_B - s/2)/\sqrt{s}$, and the beam-energy substituted mass, $m_{\rm ES} = \sqrt{(0.5s + \vec{p}_B \cdot \vec{p}_\Upsilon)^2/E_\Upsilon^2 - p_B^2}$. The four-momentum of the e^+e^- initial state, obtained from the beam momenta, is $q_\Upsilon = (E_\Upsilon, \vec{p}_\Upsilon)$, and $s \equiv |q_\Upsilon|^2$. The four-momentum of the reconstructed B candidate, $q_B = (E_B, \vec{p}_B)$, is found by summing the four-momenta of the three daughters, with daughter masses constrained to accepted values [13].

The "analysis window" (AW) is defined by $5.2 < m_{\rm ES} < 5.3$ GeV/c^2 and $-0.10 < \Delta E < 0.25$ GeV (B^+ candidates) and $-0.25 < \Delta E < 0.25$ GeV (B^0 candidates). The ΔE range is smaller for the charged candidates due to a kinematic cutoff in the $B^+ \to J/\psi p\overline{\Lambda}$ decay. Only candidates in the AW are considered in the analysis. Approximately 15% of B^+ events and 1.5% of B^0 events contain more than one candidate, in which case we select the one with the lowest $|\Delta E|$.

For signal events, $\langle \Delta E \rangle \approx 0$ and $\langle m_{\rm ES} \rangle \approx M_B$. We define a signal ellipse by $[(m_{\rm ES} - M_B)/\sigma_m]^2 + [\Delta E/\sigma_E]^2 < S^2$, where the resolutions σ_m and σ_E are estimated from simulated data to be 3.1 MeV/c^2 and 6.5 MeV, respectively, for $B^+ \to J/\psi p\overline{\Lambda}$, and 2.7 MeV/$c^2$ and 5.5 MeV for $B^0 \to J/\psi p\overline{p}$. $S = 2.4$ for $B^+ \to J/\psi p\overline{\Lambda}$ and $S = 2.2$ for $B^0 \to J/\psi p\overline{p}$.

The selection criteria for charged and neutral B candidates, including the values for S, have been chosen to minimize the 90% C.L. upper limit expected in the absence of real signal, based on simulated signal and background events. Approximately 90% of the background events satisfying the criteria are combinatorial $B\overline{B}$, in which tracks from the decays of both B mesons are used to form the candidate. The rest are continuum (non-$B\overline{B}$) events. Both components are distributed throughout the AW, and neither peaks in the signal of either ΔE or $m_{\rm ES}$.

We use simulated $B^+ \to J/\psi p\overline{\Lambda}$ and $B^0 \to J/\psi p\overline{p}$ events to measure the selection efficiency. The simulation does not include exotic QCD bound states. We study the accuracy of the simulation of the detector response by comparing data and simulated background events in samples similar to the final selection. We compare the number of J/ψ mesons reconstructed in $B^0 \to J/\psi p\overline{p}$ candidates in which only one proton satisfies the identification criteria, and we compare the number of $\overline{\Lambda}$ baryons reconstructed in $B^+ \to J/\psi p\overline{\Lambda}$ candidates in which the proton daughter of the B^+ is required to fail the criteria. Based on these studies, we apply multiplicative corrections to the efficiency of 0.97 ± 0.06 for J/ψ reconstruction and 0.86 ± 0.14 for $\overline{\Lambda}$ reconstruction. We also compare the distributions of the χ^2 of the B vertex for candidates satisfying all other criteria and obtain corrections of 0.98 ± 0.02 for $B^+ \to J/\psi p\overline{\Lambda}$ and 0.90 ± 0.10 for $B^0 \to J/\psi p\overline{p}$.

The efficiency for $B^+ \to J/\psi p\overline{\Lambda}$, with the J/ψ decaying to e^+e^- or $\mu^+\mu^-$ and $\overline{\Lambda}$ decaying to $\overline{p}\pi^+$, is 0.049 ± 0.009. The 18% fractional uncertainty includes 16% from $\overline{\Lambda}$ reconstruction, 6% from the J/ψ, 3% from statistical uncertainty in the simulation, 2% from the χ^2 correction, and 1% uncertainty on proton reconstruction efficiency. Approximately 25% of signal events satisfying all other criteria are reconstructed outside the signal ellipse.

The efficiency for $B^0 \to J/\psi p\overline{p}$ with the J/ψ decaying to e^+e^- or $\mu^+\mu^-$ is 0.184 ± 0.024. The 13% uncertainty includes 6% from J/ψ reconstruction, 2% for statistical uncertainty in the simulation, 11% for the χ^2 correction, and 3% for proton reconstruction.

We use world average values [13] for $\mathcal{B}(J/\psi \to e^+e^-)$, $\mathcal{B}(J/\psi \to \mu^+\mu^-)$, and $\mathcal{B}(\Lambda \to p\pi^-)$.

We estimate the mean expected background in the signal ellipse (μ_B) from the number N_A elsewhere in the AW: $\mu_B = fN_A$. We obtain f, the proportionality constant, from a larger sample in which only one proton satisfies the proton identification criteria. We perform a Kolmogorov test [14] to verify that the distribution of candidates in the ΔE-m_{ES} plane is similar to the standard selection. Comparing the regions outside the ellipse, the test gives a probability of 0.52 for $B^+ \to J/\psi p\overline{\Lambda}$ and 0.36 for $B^0 \to J/\psi p\overline{p}$. We obtain $f = 0.0054 \pm 0.0035$ (B^+) and $f = 0.0051 \pm 0.0013$ (B^0). The uncertainties are largely statistical, but include a component (16% for B^+ and 2% for B^0) due to differences in the number of events with multiple candidates.

For $B^+ \to J/\psi p\overline{\Lambda}$, $N_A = 39$, implying an expected background of 0.21 ± 0.14 events. We observe four candidates in the signal ellipse (Fig. 2). The probability of observing ≥ 4 candidates when expecting 0.21 ± 0.14 is 2.5×10^{-4}. Three of the four are positively charged. Two of the four J/ψ mesons decay to e^+e^- and two to $\mu^+\mu^-$.

To interpret this result as a B^+ branching fraction $\mathcal{B}$, we undertake a Bayesian analysis with a uniform prior above zero. We define the likelihood for $\mathcal{B}$ as the probability of observing exactly four events, including uncertainties on the expected background, signal efficiency, secondary branching fractions, and number of $\Upsilon(4S)$ decays, $(88.9 \pm 1.0) \times 10^6$. We assume the branching fractions $\mathcal{B}[\Upsilon(4S) \to B^+B^-] = \mathcal{B}[\Upsilon(4S) \to B^0\overline{B}^0] = 0.5$.

The central value for $\mathcal{B}$ is the peak of the likelihood function. We obtain "$\pm 1\sigma$" uncertainties from a confidence interval that encloses 68.3% of the area of the likelihood function, selected such that the likelihoods for all values of $\mathcal{B}$ in the interval are larger than the likelihoods outside. The result is $\mathcal{B}(B^+ \to J/\psi p\overline{\Lambda}) = (11.6^{+8.5}_{-5.6}) \times 10^{-6}$. We similarly obtain a 90% C.L. upper limit of 26×10^{-6}.

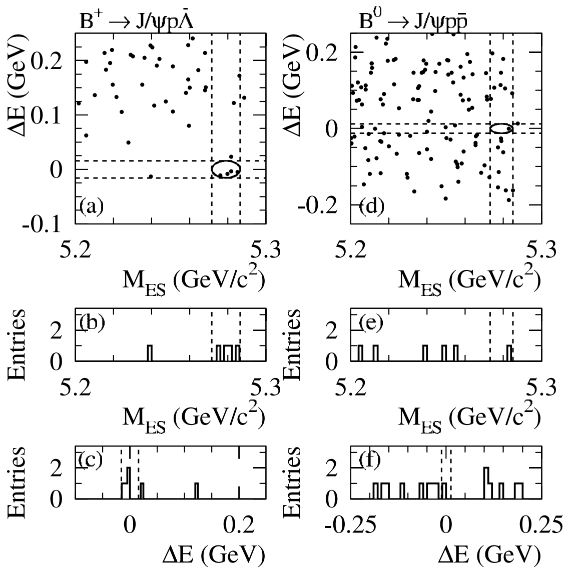

FIG. 2. (a) Distribution of $B^+ \to J/\psi p\overline{\Lambda}$ candidates in the ΔE-m_{ES} plane, with the signal ellipse and its projection in each dimension (dashed lines). Histogram of candidates within marked bands in (b) m_{ES} and (c) ΔE. Plots (d)–(f) Similar quantities for $B^0 \to J/\psi p\overline{p}$.

If we consider only the statistical uncertainty, the result would be $\mathcal{B}(B^+ \to J/\psi p\overline{\Lambda}) = (11.6^{+7.4}_{-5.3}) \times 10^{-6}$. Subtracting these uncertainties in quadrature would indicate contributions from systematic errors of 4.2×10^{-6} and 1.8×10^{-6} on the upper and lower sides, respectively. The systematic error arises almost entirely from the uncertainty on the signal efficiency.

The creation of a narrow QCD exotic bound state as an intermediate resonance in the B^+ decay would be reflected as a narrow p^* distribution of the other decay daughter. We do not observe any significant clustering in the p^* distributions of the J/ψ, proton, or $\overline{\Lambda}$ daughters of the four B^+ candidates (Fig. 3). The resolution in p^* is $\sigma \sim 20$ MeV/c.

For $B^0 \to J/\psi p\overline{p}$, there are 126 events outside the signal ellipse, indicating an expected background of 0.64 ± 0.17 events, and one event in the ellipse. Following the procedure described for $B^+ \to J/\psi p\overline{\Lambda}$, and again assuming a uniform prior above 0, we obtain $\mathcal{B}(B^0 \to J/\psi p\overline{p}) < 1.9 \times 10^{-6}$ (90% C.L.). This limit is dominated by statistical uncertainty.

In summary, we observe four $B^+ \to J/\psi p\overline{\Lambda}$ candidates in a data set of $(88.9 \pm 1.0) \times 10^6$ $\Upsilon(4S)$ decays. The probability of the expected charged B background, 0.21 ± 0.14 events, producing ≥ 4 events is 2.5×10^{-4}. The branching fraction is $(12^{+9}_{-6}) \times 10^{-6}$, where the uncertainty includes both statistical and systematic components. This result can be interpreted as a 90% C.L. upper limit of 26×10^{-6}.

We observe one $B^0 \to J/\psi p\overline{p}$ candidate with an expected background of 0.64 ± 0.17, and determine a 90% C.L. upper limit of 1.9×10^{-6} on the branching fraction.

Neither final state makes a significant contribution to the observed excess of J/ψ mesons in inclusive B decay. The momentum distributions of the B^+ daughters do not provide evidence for QCD exotic particles produced as narrow intermediate states.

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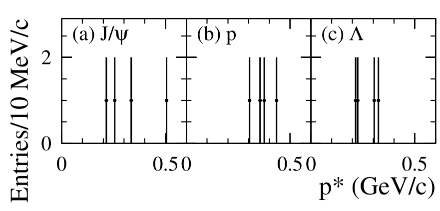

FIG. 3. Momentum in the B^+ rest frame of the (a) J/ψ, (b) proton, and (c) $\overline{\Lambda}$ daughters of the four $B^+ \to J/\psi p\overline{\Lambda}$ candidates.

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