Evidence for Charged B Meson Decays to $a_1^{\pm}(1260)\pi^0$ and $a_1^0(1260)\pi^{\pm}$

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We present measurements of the branching fractions for the decays $B^{\pm} \to a_1^{\pm}(1260)\pi^0$ and $B^{\pm} \to a_1^0(1260)\pi^{\pm}$ from a data sample of 232×10^6 $B\bar{B}$ pairs produced in e^+e^- annihilation through the $\Upsilon(4S)$ resonance. We measure the branching fraction $\mathcal{B}(B^{\pm} \to a_1^{\pm}(1260)\pi^0) \times \mathcal{B}(a_1^{\pm}(1260) \to \pi^-\pi^+\pi^{\pm}) = (13.2 \pm 2.7 \pm 2.1) \times 10^{-6}$ with a significance of 4.2σ, and the branching fraction $\mathcal{B}(B^{\pm} \to a_1^0(1260)\pi^{\pm}) \times \mathcal{B}(a_1^0(1260) \to \pi^-\pi^+\pi^0) = (20.4 \pm 4.7 \pm 3.4) \times 10^{-6}$ with a significance of 3.8σ, where the first error quoted is statistical and the second is systematic.

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The rare decays of B mesons to two-body final states with an $a_1(1260)$ and a $\pi^\pm$, π^0, $K^\pm$, or K^0_S are important processes for testing theoretical factorization model predictions for branching fractions, branching fraction ratios, and CP-violation parameters. The measurements can be combined with assumptions about SU(3) symmetries to form upper bounds on $\Delta\alpha = | \alpha - \alpha_{\rm eff} |$, where α is the weak interaction phase $\alpha \equiv \arg[-V_{\rm td}V^*_{\rm tb}/V_{\rm ud}V^*_{\rm ub}]$ of the Unitarity Triangle [1] and $\alpha_{\rm eff}$ is the measured phase. The difference $\Delta\alpha$ is a measurement of the poorly known strength of the penguin amplitudes in the decay and can be used to improve our understanding of the CP-violating mechanism.

The rare decays $B^\pm \to a_1^\pm(1260)\pi^0$ and $B^\pm \to a_1^0(1260)\pi^\pm$ are expected to be dominated by $b \to u\bar{u}d$ contributions. The branching fraction for $B^0 \to a_1^\pm\pi^\mp$ has been measured to be $(33.2 \pm 3.8 \pm 3.0) \times 10^{-6}$ [2], and this agrees well with the calculation of Bauer, Stech, and Wirbel [3] within the framework of naive factorization and assuming $|V_{\rm ub}/V_{\rm cb}| = 0.08$. A more recent analysis using naive factorization and measured form factors predicts branching fractions in the range $(5\text{–}11) \times 10^{-6}$ and $(4\text{–}9) \times 10^{-6}$ for $B^\pm \to a_1^\pm\pi^0$ and $B^\pm \to a_1^0\pi^\pm$, respectively [4]. Previous measurements have placed 90% confidence level upper limits of 1.7×10^{-3} and 9×10^{-4} on the branching fractions for $B^\pm \to a_1^\pm\pi^0$ and $B^\pm \to a_1^0\pi^\pm$, respectively [5], and recently the *BABAR* collaboration reported the first measurements of the CP-violating asymmetries in the decay $B^0 \to a_1^\pm\pi^\mp$ [6].

We present measurements of the branching fractions for the two charmless B meson decays $B^\pm \to a_1^\pm\pi^0$ and $B^\pm \to a_1^0\pi^\pm$ where the final state contains one neutral and three charged pions. The $a_1 \to 3\pi$ decay proceeds mainly through the intermediate states $(\pi\pi)_\rho\pi$ and $(\pi\pi)_\sigma\pi$ [7]. We do not distinguish between the dominant P-wave $(\pi\pi)_\rho$ and the S-wave $(\pi\pi)_\sigma$ in the channel $\pi^+\pi^-$. Possible background contributions from $B \to a_2(1320)\pi$ are investigated. Charge conjugate modes are implied throughout this Letter.

The data were collected with the *BABAR* detector [8] at the PEP-II asymmetric e^+e^- collider. An integrated luminosity of 211 fb^{-1}, corresponding to 232×10^6 $B\bar{B}$ pairs, was recorded at the $\Upsilon(4S)$ resonance ("on-resonance") at a center-of-mass (c.m.) energy $\sqrt{s} = 10.58$ GeV. An additional 20 fb^{-1} were taken about 40 MeV below this energy ("off-resonance") for the study of the continuum background in which a charm or lighter quark pair is produced.

Charged particles are detected and their momenta measured by the combination of a silicon vertex tracker, consisting of five layers of double-sided silicon detectors, and a 40-layer central drift chamber, both operating in the 1.5-T magnetic field of a solenoid. The tracking system covers 92% of the solid angle in the c.m. frame. Charged-particle identification (PID) is provided by the average energy loss (dE/dx) in the tracking devices and by an internally reflecting ring-imaging Cherenkov detector. A K/π separation of better than 4 standard deviations (σ) is achieved for momenta below 3 GeV/c, decreasing to 2.5σ at the highest momenta in the B decay final states.

The off-resonance data together with the Monte Carlo (MC) simulations of the signal decay modes, continuum, $B\bar{B}$ backgrounds, and detector response [9] are used to establish the event selection criteria and reconstruction efficiency. The MC signal events are simulated as B^+ decays to $a_1\pi$ with $a_1 \to \rho\pi$. The a_1 and a_2 line shapes are generated with EVTGEN [10], where we use mass and width parameters from Refs. [2,7].

Two photons with a minimum energy of 30 MeV (100 MeV for $B^+ \to a_1^0\pi^+$) and an invariant mass of $120 < m_{\gamma\gamma} < 150$ MeV/c^2 are used to reconstruct the π^0. The intermediate dipion states ($\pi^+\pi^-$) or ($\pi^+\pi^0$) are required to have an invariant mass of $0.46 < m_{\pi\pi} < 1.1$ GeV/c^2. We impose PID requirements to cleanly identify the charged pions and to suppress contamination from a_1K. We require the invariant mass reconstructed for candidate $a_1^+ \to \pi^-\pi^+\pi^+$ and $a_1^0 \to \pi^-\pi^+\pi^0$ decays to be $0.8 < m_{a_1} < 1.8$ GeV/c^2.

A B meson candidate is characterized kinematically by the energy-substituted mass $m_{\rm ES} = \sqrt{(s/2 + \mathbf{p}_0 \cdot \mathbf{p}_B)^2/E_0^2 - \mathbf{p}_B^2}$ and energy difference $\Delta E = E_B^* - \sqrt{s}/2$, where the subscripts 0 and B refer to the initial $\Upsilon(4S)$ and to the B candidate in the lab frame, respectively, and the asterisk denotes the $\Upsilon(4S)$ frame. The resolutions in $m_{\rm ES}$ and in ΔE are about 3.0 MeV/c^2 and 20 MeV, respectively. Candidates are required to have $5.25 \le m_{\rm ES} \le 5.29$ GeV/c^2 and $|\Delta E| \le 0.2$ GeV. To reduce fake B meson candidates we require a B vertex χ^2 probability >0.01. The absolute value of the cosine of the angle between the direction of the π meson from $a_1 \to \rho\pi$ with respect to the flight direction of the B in the a_1 meson rest frame is required to be less than 0.85 to suppress misreconstructed candidates. The distribution of this variable is flat for signal and peaks near ±1 for misreconstructed candidates.

To reject continuum background, we use the angle θ_T between the thrust axis of the B candidate's decay products and that of the rest of the tracks and neutral clusters in the event, calculated in the c.m. frame. The distribution of $\cos\theta_T$ is sharply peaked near ±1 for combinations drawn from jetlike $q\bar{q}$ pairs and is nearly uniform for the isotropic B meson decays; we require $|\cos\theta_T| < 0.65$.

The decay mode $B \to a_2\pi$ can also give background contributions. It is suppressed by using the angular variable $\mathcal{A}$, defined as the cosine of the angle between the normal to the plane of the 3π resonance and the flight direction of the bachelor pion evaluated in the 3π resonance rest frame. Since the a_1 and a_2 have spins of 1 and 2, respectively, the distributions of $\mathcal{A}$ for these two resonances differ. We require $|\mathcal{A}| < 0.6$, which reduces the a_2 background by more than a factor of 2 in both decay channels.

After all the above selections, we have on average 1.20 and 1.56 candidates per event in events where there is at least one candidate, for $B^+ \to a_1^+ \pi^0$ and $B^+ \to a_1^0 \pi^+$, respectively, and we select the B candidate with the $(\pi\pi)$ mass nearest to the nominal ρ mass [7]. From the simulation, we find that this algorithm selects the correct-combination candidate in $B^+ \to a_1^+ \pi^0$ and $B^+ \to a_1^0 \pi^+$ in 65% and 55% of events containing multiple candidates, respectively.

We use an unbinned maximum-likelihood fit using five variables to extract the background and signal yields of $B^+ \to a_1^+ \pi^0$ and $B^+ \to a_1^0 \pi^+$. We describe the B decay kinematics with the two variables ΔE and $m_{\rm ES}$. We also include the invariant mass of the 3π system (m_{a_1}), the variable $\mathcal{A}$ and a Fisher discriminant $\mathcal{F}$. This discriminant combines four variables: the angles with respect to the beam axis of the B momentum and B thrust axis in the c.m. frame, and the zeroth and second angular moments of the energy flow around the B thrust axis [2].

The extended likelihood function is

$$\mathcal{L} = \frac{1}{N!} \exp\left(-\sum_j n_j\right) \prod_{i=1}^{N} \left[\sum_j n_j \mathcal{P}_j(\vec{x}_i; \vec{\alpha}_j)\right], \qquad (1)$$

where n_j is the yield of events for hypothesis j (signal, a_2, $B\bar{B}$ charmless, $B\bar{B}$ charm, or continuum) and N is the number of events in the sample. The probabilities $\mathcal{P}_j$ are products of probability density functions (PDF) for each of the independent variables $\vec{x}_i = \{m_{\rm ES}, \Delta E, m_{a_1}, \mathcal{F}, \mathcal{A}\}$ evaluated for each event i. The $\vec{\alpha}_j$ are the parameters of the distributions in $\vec{x}_i$. By minimizing the quantity $-\ln\mathcal{L}$ in two separate fits, we determine the yields for $B^+ \to a_1^+ \pi^0$ and $B^+ \to a_1^0 \pi^+$.

To take into account the relatively large number of misreconstructed signal events, the signal is separated into two components, representing the correctly reconstructed (true) and the self-cross-feed (SCF) candidates, with proportions fixed in the fit for each mode. SCF occurs when a track from an $a_1^+ \pi^0$ or $a_1^0 \pi^+$ is exchanged with a track from the rest of the event. The fraction of SCF, determined from MC, is 35% and 44% for $B^+ \to a_1^+ \pi^0$ and $B^+ \to a_1^0 \pi^+$, respectively.

In addition to the a_2, there are three main categories of backgrounds: $B\bar{B}$ charmless, $B\bar{B}$ charm, and continuum. $B\bar{B}$ backgrounds are studied using MC simulations of $B^0\bar{B}^0$ and B^+B^- decays, using a large sample equivalent to $\sim$0.8 ab^{-1}. There are 17 $B\bar{B}$ charmless decays for $B^+ \to a_1^+ \pi^0$ and 20 for $B^+ \to a_1^0 \pi^+$ that contribute as background. Those decays with similar distributions are grouped to form 13 and 10 hypotheses, respectively, and are included in the fit with a fixed yield as determined from MC. The total $B\bar{B}$ charmless yields are 368 ± 92 and 755 ± 164 for $B^+ \to a_1^+ \pi^0$ and $B^+ \to a_1^0 \pi^+$, respectively. These are dominated by $B \to \rho\rho$, $B \to a_1\rho$, and the other $B \to a_1\pi$ mode under study. The $B\bar{B}$ charm backgrounds are included as a single hypothesis, with the normalization of the $B\bar{B}$ charm yield as a free parameter. Continuum events come from light quark production. We establish the functional forms and parameter values of the PDFs for $B\bar{B}$ charm and $B\bar{B}$ charmless backgrounds from MC simulations. For continuum, we use off-resonance data for the Fisher, on-resonance data with $|\Delta E| > 0.1$ GeV for $m_{\rm ES}$, and on-resonance data with $5.25 < m_{\rm ES} < 5.27$ GeV$/c^2$ for the other variables.

We model the distributions using appropriate functions. The $\mathcal{A}$ distributions are modeled with polynomials. For the true signal component, the remaining distributions are fitted using modified Gaussians [11], and a relativistic Breit-Wigner line shape with a mass-dependent width [12], as necessary. The SCF component and the a_2 have similar shapes to the true signal but have broader or more asymmetric distributions and shifted means. The $B\bar{B}$ backgrounds and continuum distributions are modeled with modified Gaussians, polynomials, nonparametric functions [13], and, for $m_{\rm ES}$, a phase-space-motivated empirical function [14]. The PDF variables are assumed to be independent except for $B^+ \to a_1^0 \pi^+$, where a two-dimensional nonparametric PDF [13] in m_{a_1} and ΔE accounts for observed correlations in the MC for both true signal events and SCF.

In the fit there are six free parameters: four yields (signal, continuum, a_2, and $B\bar{B}$ charm background), and two continuum background parameters (ΔE polynomial coefficient and $m_{\rm ES}$ shape coefficient ξ [14]).

For $B^+ \to a_1^+ \pi^0$, there are 24 608 events in the data sample. We measure the raw signal yield to be 459 ± 78 events with a reconstruction efficiency of $12.5\% \pm 0.1\%$, corrected for differences in tracking and neutral particle reconstruction between data and MC. The yield of the decay $B^+ \to a_2^+ \pi^0$ is 28 ± 65 events. For $B^+ \to a_1^0 \pi^+$, there are 33 375 events in the data sample, and we measure the raw signal yield to be 382 ± 79 events with a corrected reconstruction efficiency of $7.2\% \pm 0.1\%$. The yield of the decay $B^+ \to a_2^0 \pi^+$ is 107 ± 65 events.

We confirm our fitting procedure by generating and fitting MC samples containing signal and background populations using the yields as found from data. We identify a signal yield bias for $B^+ \to a_1^+ \pi^0$ and $B^+ \to a_1^0 \pi^+$ of $16.8\% \pm 0.1\%$ and $10.9\% \pm 0.1\%$, respectively. We fit for the branching fractions taking into account the fitted signal yield, the yield bias, the corrected reconstruction efficiency, daughter branching fractions, and the number of produced B mesons, assuming equal production rates of $B^0\bar{B}^0$ and B^+B^- pairs. The statistical significance is taken as the square root of the difference between the value of

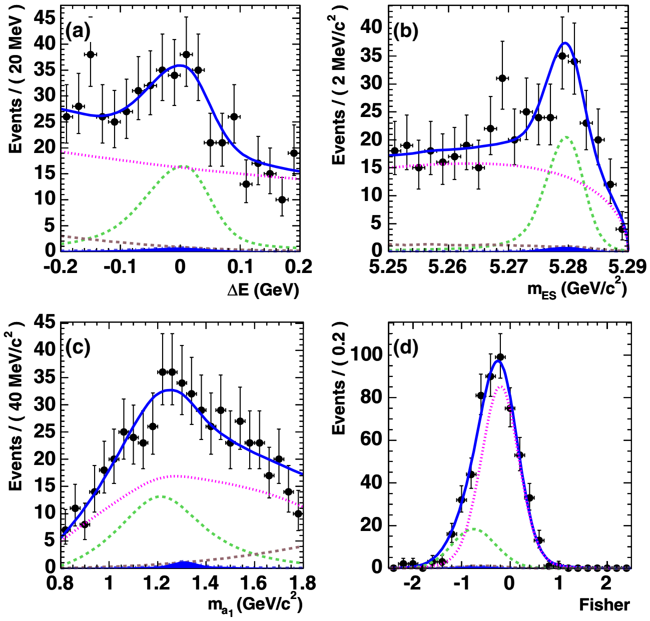

FIG. 1 (color online). Projections of (a) ΔE, (b) $m_{\rm ES}$, (c) m_{a_1}, and (d) $\mathcal{F}$ for $B^+ \to a_1^+\pi^0$. Points represent on-resonance data, dashed lines the signal, dotted lines the continuum, dash-dotted lines the $B\bar{B}$ charm background, the filled region the a_2 background, and solid lines the full fit function. These plots are made with a requirement on the signal likelihood to enhance the signal, and thus do not show all events in the data sample.

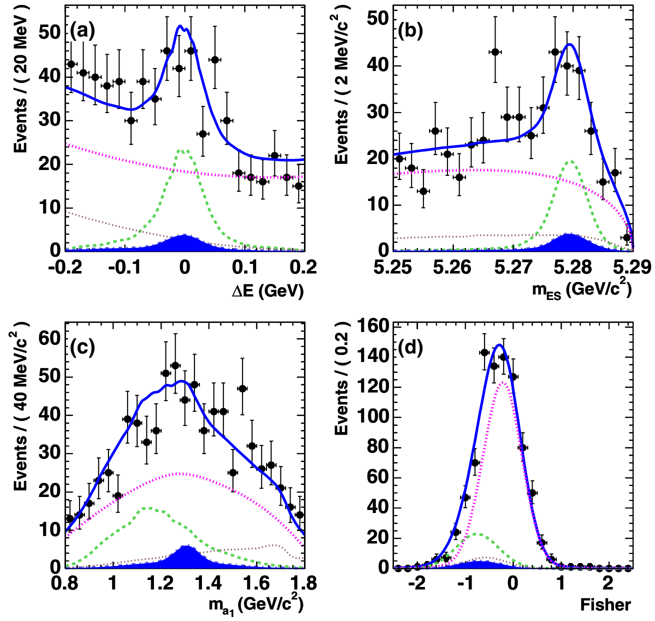

FIG. 2 (color online). Projections of (a) ΔE, (b) $m_{\rm ES}$, (c) m_{a_1}, and (d) $\mathcal{F}$ for $B^+ \to a_1^0\pi^+$, using the same criteria and line styles as Fig. 1.

$-2\ln\mathcal{L}$ for zero signal and the value at its minimum. We measure the branching fraction $\mathcal{B}(B^+ \to a_1^+\pi^0) \times \mathcal{B}(a_1^+ \to \pi^-\pi^+\pi^+) = (13.2 \pm 2.7) \times 10^{-6}$ with a statistical significance of 5.3σ and the branching fraction $\mathcal{B}(B^+ \to a_1^0\pi^+) \times \mathcal{B}(a_1^0 \to \pi^-\pi^+\pi^0) = (20.4 \pm 4.7) \times 10^{-6}$ with a statistical significance of 4.7σ, where the errors are statistical.

Figures 1 and 2 show the ΔE, $m_{\rm ES}$, m_{a_1}, and $\mathcal{F}$ projections for $B^+ \to a_1^+\pi^0$ and $B^+ \to a_1^0\pi^+$ made by selecting events with a signal likelihood (computed without the variable shown in the figure) exceeding a threshold that optimizes the expected sensitivity.

The systematic errors are summarized in Table I. We determine the sensitivity to the parameters of the signal and background PDF components by varying these within their uncertainties. The effect of varying the mass and width of the a_1 by the errors as reported in Ref. [2] is included in the PDF parameters' variation systematic. The uncertainty in the fit bias correction is taken as half of the fit bias correction. The effect of possible interference between a_2 and a_1 is estimated by adding the a_2 and a_1 amplitudes together with a varying phase difference and using half the maximum change in yield as an uncertainty. The uncertainty in SCF is investigated by varying the SCF fraction. We also perform a separate fit treating the SCF as an independent background component. The fitted branching fraction is compatible with the nominal fit within the increased statistical uncertainty, but the statistical significance is reduced to 3.5σ and 3.0σ for $B^+ \to a_1^+\pi^0$ and $B^+ \to a_1^0\pi^+$, respectively. A systematic uncertainty of 1.6% is estimated for the difference in reconstruction efficiency in the decay modes through the dominant P-wave $(\pi\pi)_\rho$ and the S-wave $(\pi\pi)_\sigma$. An error is assigned for the uncertainty in the fixed charmless $B\bar{B}$ background yields and possible interference effects by varying the individual components by the reported error on the branching fractions [7]. The systematic errors for the flight direc-

TABLE I. Summary of systematic errors for the $a_1^+\pi^0$ and $a_1^0\pi^+$ branching fraction measurements.

Systematic	$a_1^+\pi^0$	$a_1^0\pi^+$
PDF Parameter Variation	8.6%	8.8%
Fit Bias	8.4%	5.5%
$a_1 - a_2$ Interference	6.6%	7.4%
SCF Variation	4.4%	8.2%
Tracking Efficiency	3.9%	3.9%
π^0 Efficiency	3.0%	3.0%
Flight Direction Criteria	2.0%	2.0%
P-wave and S-wave Reconstruction	1.6%	···
Charmless $B\bar{B}$ Background	1.4%	3.1%
Number of $B\bar{B}$ Pairs	1.1%	1.1%
$\cos\theta_T$ Selection Criteria	1.1%	1.8%
Track Multiplicity	1.0%	1.0%
$\rho\pi\pi$, 4π Cross Feed	0.9%	0.5%
a_1K Cross Feed	···	0.4%
Total	16%	16%

tion criteria, number of $B\bar{B}$ pairs, $\cos\theta_T$ selection criteria, track multiplicity, potential backgrounds from $\rho\pi\pi$ and 4π, and a_1K cross feed are small. The total systematic error for both modes is 16%. The significance of the branching fractions, combining both statistical and systematic errors, is 4.2σ for $B^+ \to a_1^+\pi^0$ and 3.8σ for $B^+ \to a_1^0\pi^+$.

In conclusion, we have measured the branching fractions $\mathcal{B}(B^\pm \to a_1^\pm(1260)\pi^0) \times \mathcal{B}(a_1^\pm(1260) \to \pi^-\pi^+\pi^\pm) = (13.2 \pm 2.7 \pm 2.1) \times 10^{-6}$ and $\mathcal{B}(B^\pm \to a_1^0(1260)\pi^\pm) \times \mathcal{B}(a_1^0(1260) \to \pi^-\pi^+\pi^0) = (20.4 \pm 4.7 \pm 3.4) \times 10^{-6}$. Neglecting isoscalar contributions to the two-pion state, we assume $\mathcal{B}(a_1^\pm(1260) \to \pi^-\pi^+\pi^\pm)$ is equal to $\mathcal{B}(a_1^\pm(1260) \to \pi^\pm\pi^0\pi^0)$ and $\mathcal{B}(a_1^\pm(1260) \to (3\pi)^\pm)$ is equal to 100% [7], resulting in $\mathcal{B}(B^\pm \to a_1^\pm(1260)\pi^0) = (26.4 \pm 5.4 \pm 4.1) \times 10^{-6}$. We measure $\mathcal{B}(B^\pm \to a_1^0(1260)\pi^\pm) = (20.4 \pm 4.7 \pm 3.4) \times 10^{-6}$, assuming $\mathcal{B}(a_1^0(1260) \to \pi^-\pi^+\pi^0)$ is equal to 100%. The first errors quoted are statistical and the second are systematic. The signals are seen with significances of 4.2σ and 3.8σ, respectively, and are in agreement with factorization model predictions [3].

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