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Observation of $B^+ \rightarrow a_1^+(1260)\,K^0$ and $B^0 \rightarrow a_1^-(1260)\,K^+$

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We present branching fraction measurements of the decays $B^+ \to a_1^+(1260) K^0$ and $B^0 \to a_1^-(1260) K^+$ with $a_1^\pm(1260) \to \pi^\mp \pi^\pm \pi^\pm$. The data sample corresponds to 383×10^6 $B\overline{B}$ pairs produced in e^+e^- annihilation through the $\Upsilon(4S)$ resonance. We measure the products of the branching fractions $\mathcal{B}(B^+ \to a_1^+(1260) K^0) \mathcal{B}(a_1^+(1260) \to \pi^-\pi^+\pi^+) = (17.4 \pm 2.5 \pm 2.2) \times 10^{-6}$ and $\mathcal{B}(B^0 \to a_1^-(1260) K^+) \mathcal{B}(a_1^-(1260) \to \pi^+\pi^-\pi^-) = (8.2 \pm 1.5 \pm 1.2) \times 10^{-6}$. We also

measure the charge asymmetries $\mathcal{A}_{ch}(B^+ \rightarrow a_1^+(1260)\,K^0) = 0.12 \pm 0.11 \pm 0.02$ and $\mathcal{A}_{ch}(B^0 \rightarrow a_1^-(1260)\,K^+) = -0.16 \pm 0.12 \pm 0.01$. The first uncertainty quoted is statistical and the second is systematic.

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Recently the *BABAR* Collaboration has reported the measurement of the branching fraction [1] and time-dependent *CP*-violation parameters for the process $B^0 \rightarrow a_1^\pm(1260)\,\pi^\mp$ [2]. If this process were mediated by a single tree amplitude these measured parameters would enable a determination of the angle α of the unitary triangle of the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [3]. However, in the presence of a penguin amplitude with a different weak phase from the tree amplitude the measured angle, called $\alpha_{\rm eff}$, would differ from α [4]. An upper bound on the difference $\Delta\alpha = |\alpha - \alpha_{\rm eff}|$ can be calculated using SU(3) together with measurements of the *CP*-averaged decay rates for either the decays $B^+ \rightarrow a_1^+(1260)\,K^0$ or $B^0 \rightarrow a_1^-(1260)\,K^+$ and the decays $B \rightarrow K_1(1270)\,\pi$ and $B \rightarrow K_1(1400)\,\pi$ [5]. Knowing the value of this difference is important in calculating bounds on the angle α.

There are no experimental measurements of the branching fractions of the decays $B^+ \rightarrow a_1^+(1260)\,K^0$ and $B^0 \rightarrow a_1^-(1260)\,K^+$ to this date. Recent theoretical estimates of these branching fractions have been calculated assuming naive factorization for two different values of the mixing angle θ between the two strange P wave axial mesons [6]. The estimated branching fractions lie in the range $(16 - 52) \times 10^{-6}$ [7]. Comparison between theoretical predictions and measured quantities is useful to test the underlying theoretical hypotheses of factorization and $B \rightarrow a_1(1260)$ transition form factors.

We present measurements of the branching fraction for the decays $B^+ \rightarrow a_1^+(1260)\,K^0$ and $B^0 \rightarrow a_1^-(1260)\,K^+$ with $a_1^\pm(1260) \rightarrow \pi^\mp\pi^\pm\pi^\pm$ [8]. We also search for a direct *CP* violation by measuring the charge asymmetry $\mathcal{A}_{ch}$, defined as $(\Gamma^- - \Gamma^+)/(\Gamma^- + \Gamma^+)$, in the decay rates $\Gamma^\pm$ for a charged B meson, or Γ^+ ($B^0 \rightarrow a_1^-(1260)\,K^+$) and its charge conjugate for a neutral B meson.

The data were collected with the *BABAR* detector [9] at the PEP-II asymmetric energy e^+e^- collider [10]. An integrated luminosity of 347 fb^{-1}, corresponding to 382.9 ± 4.2 million $B\overline{B}$ pairs, was recorded at the $\Upsilon(4S)$ resonance (on-resonance, center-of-mass energy $\sqrt{s} = 10.58\,{\rm GeV}$). An additional 37 fb^{-1}, recorded about 40 MeV below the $\Upsilon(4S)$ resonance (off-resonance), is used for continuum background studies.

Charged particles are detected and their momenta measured by a combination of a silicon vertex tracker, consisting of five layers of double-sided silicon detectors, and a 40-layer central drift chamber, both operating inside the 1.5-T magnetic field of a superconducting solenoid. The tracking system covers 92% of the solid angle in the center-of-mass frame.

Photons and electrons are detected with a CsI(Tl) electromagnetic calorimeter. Charged-particle identification (PID) is provided by the average energy loss $({\rm d}E/{\rm d}x)$ measured in the tracking devices and by an internally reflecting ring-imaging Cherenkov detector (DIRC) covering the central region. A K/π separation of more than four standard deviations (σ) is achieved for momenta below 3 GeV/c, decreasing to 2.5 σ at the highest momenta of the B decay products.

Monte Carlo (MC) simulations of the signal decay modes, continuum, $B\overline{B}$ backgrounds and detector response [11] are used to establish the event selection criteria. Exclusive MC signal events are simulated as $B \rightarrow a_1(1260)K$ with $a_1(1260) \rightarrow \rho\pi$. For the $a_1(1260)$ meson parameters we take the mass $m_0 = 1230\,{\rm MeV}/c^2$ and $\Gamma_0 = 400\,{\rm MeV}/c^2$ [1, 12]. We account for the uncertainties of these resonance parameters in the determination of systematic uncertainties. The $a_1^+(1260) \rightarrow \pi^-\pi^+\pi^+$ decay proceeds mainly through the intermediate states $(\pi\pi)_\rho\pi$ and $(\pi\pi)_\sigma\pi$ [13]. No attempt is made to separate the contributions of the dominant P-wave $(\pi\pi)_\rho$ from the S-wave $(\pi\pi)_\sigma$ in the channel $\pi^+\pi^-$. A systematic uncertainty is estimated due to the difference in the selection efficiency.

We reconstruct the decay $a_1^+(1260) \rightarrow \pi^-\pi^+\pi^+$ with the following requirement on the invariant mass: $0.87 < m_{a_1} < 1.5$ GeV/c^2 for $B^0 \rightarrow a_1^-(1260)\,K^+$ and $0.87 < m_{a_1} < 1.8$ GeV/c^2 for $B^+ \rightarrow a_1^+(1260)\,K^0$. The different a_1 mass selections are motivated by charm background studies. The intermediate $\pi^+\pi^-$ state is reconstructed with an invariant mass between 0.51 and 1.1 GeV/c^2. Secondary $a_1(1260)$ daughter pions are rejected if their PID signatures satisfy requirements for being consistent with protons, electrons, or kaons. PID requirements ensure the identity of the primary charged kaon. Candidate $K_s^0 \rightarrow \pi^+\pi^-$ decays are formed from pairs of oppositely charged tracks with $0.486 < m_{\pi\pi} < 0.510$ GeV/c^2, having a decay vertex χ^2 probability greater than 0.001, and a reconstructed decay length larger than three times its uncertainty.

We reconstruct the B-meson candidate by combining an $a_1(1260)$ candidate and a charged or neutral kaon. 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 $\Delta E = E_B^* - \frac{1}{2}\sqrt{s}$, where the subscripts 0 and B refer to the $\Upsilon(4S)$ and the B candidate in the laboratory frame, respectively, and the asterisk denotes the $\Upsilon(4S)$ frame. The resolutions in $m_{\rm ES}$ and ΔE are about 3.0 MeV/c^2 and 20 MeV respectively. We require $|\Delta E| \leq 0.1$ GeV

and $5.25 \leq m_{\mathrm{ES}} \leq 5.29$ GeV/c^2. To reduce fake B-meson candidates we require a B vertex χ^2 probability larger than 0.01. The cosine of the angle between the direction of the π meson from $a_1(1260) \to \rho\pi$ with respect to the flight direction of the B in the $a_1(1260)$ meson rest frame is required to be between -0.85 and 0.85 to suppress combinatorial background. The distribution of this variable is flat for signal and peaks near ± 1 for this background.

To reject continuum background, we use the angle θ_T between the thrust axis of the B candidate and that of the rest of the tracks and neutral clusters in the event, calculated in the center-of-mass frame. The distribution of $\cos\theta_T$ is sharply peaked near ± 1 for combinations drawn from jet-like $q\bar{q}$ pairs and is nearly uniform for the isotropic B-meson decays; we require $|\cos\theta_T| < 0.65$. The remaining continuum background is modeled from off-resonance data.

We use MC simulations of $B^0\overline{B}^0$ and B^+B^- decays to study $B\overline{B}$ backgrounds, which can come from both charmless and charmed decays. The modes $B^0 \to a_2^-(1320)\,K^+$ and $B^+ \to a_2^+(1320)\,K^0$ decay to the same final states as the signal modes. We suppress these backgrounds with the angular variable $\mathcal{H}$, defined as cosine of the angle between the normal to the plane of the 3π resonance and the flight direction of the K meson evaluated in the 3π resonance rest frame. Since the $a_1(1260)$ and $a_2(1320)$ have spins of 1 and 2 respectively, the distributions of the variable $\mathcal{H}$ for these two resonances differ. We require $|\mathcal{H}| < 0.62$.

We have on average 1.3 candidates per event for both signal decay modes and we select the B candidate with the highest B vertex probability. From the MC simulation we find that the best candidate selection algorithm finds the correct-combination candidate in 92 % of both signal decay modes and that it induces negligible bias.

We use unbinned, multivariate maximum-likelihood (ML) fits to measure the yields of $B^+ \to a_1^+(1260)\,K^0$ and $B^0 \to a_1^-(1260)\,K^+$. The likelihood function incorporates five variables. We describe the B decay kinematics with the two above-mentioned variables ΔE and m_{ES}, as well as the invariant mass of the 3π system, a Fisher discriminant $\mathcal{F}$ and the variable $\mathcal{H}$. The Fisher discriminant combines four variables: the angles with respect to the beam axis in the $\Upsilon(4S)$ frame of the B momentum and B thrust axes and the zeroth and second angular moments $L_{0,2}$ with respect to the thrust axis of the B-candidate [14]. Since the correlation between the observables in the selected data and in MC signal events is small, we take the probability density function (PDF) for each event to be a product of the PDFs for the individual observables. Corrections for the effects of possible correlations are made on the basis of MC studies described later. The selected data samples besides the signal events contain continuum $q\bar{q}$ and $B\overline{B}$ combinatorial background.

The $B\overline{B}$ background has the following components in the likelihood: charmless, charm and $a_2^-(1320)\,K^+$. There are also three additional components: $f_0 K$, $\rho^0 K$ with their yields fixed to the value determined from the measured branching fractions [15], and the non-resonant $\rho^0\pi^+K$ with a yield fixed in the fit to the value expected using an assumed branching fraction of $(2.0\pm 2.0)\times 10^{-6}$. We account for the uncertainties of these branching fractions in the determination of the systematic uncertainties. A charged particle from a signal event may be exchanged with a charged particle from the rest of the event. These so-called self cross feed (SCF) events are considered background events. The charmless $B\overline{B}$ background has a dependence on the ML fit observables that is similar to that for SCF events, and thus the SCF events can be modeled as part of the charmless component.

The likelihood function is defined as

$$\mathcal{L} = \exp\Big(-\sum_k n_k\Big)\prod_{i=1}^{N}\sum_j n_j \times \qquad (1)$$
$$\mathcal{P}_k(m_{\mathrm{ES}}{}^i)\mathcal{P}_k(\Delta E^i)\mathcal{P}_k(\mathcal{F}^i)\mathcal{P}_k(m_{a_1}^i)\mathcal{P}_k(\mathcal{H}^i)\,,$$

where N is the total number of events in the fit sample, n_k is the yield fitted for the likelihood component k and $P_k(x^i)$ is the PDF for observable x in event i. We determine the PDFs for signal and $B\overline{B}$ backgrounds from MC distributions in each observable. For the continuum background we establish the functional forms and initial parameter values of the PDFs with off-resonance data. The PDF of the invariant mass of the $a_1(1260)$ meson in signal events is parameterized as a relativistic Breit-Wigner lineshape with a mass-dependent width which takes into account the effect of the mass-dependent ρ width [16]. We fix the $a_1(1260)$ meson parameters to the values found in the branching fraction measurement of $B^0 \to a_1^{\pm}\pi^{\mp}$[1]. The PDF of the invariant mass of the $a_2(1320)$ meson is parameterized by a relativistic Breit-Wigner distribution. The m_{ES} and ΔE distributions for signal are parameterized as double Gaussian functions. The ΔE distribution for continuum background is parameterized by a linear function. The m_{ES} distribution for the combinatorial background is described by an empirical function that accounts for threshold effects [17]. We model the Fisher distribution $\mathcal{F}$ using a Gaussian function with different widths above and below the mean. The $\mathcal{H}$ distributions are modeled using polynomials.

In the fit for the decay $B^0 \to a_1^-(1260)\,K^+$ $(B^+ \to a_1^+(1260)\,K^0)$ there are respectively fourteen (twelve) free parameters: five (five) yields and nine (seven) parameters affecting the shape of the combinatorial background. Table I lists the results of the fits. We measure the signal yield bias by generating and fitting MC simulated samples containing signal and background populations expected from data. The signal reconstruction efficiency is obtained from the fraction of correctly reconstructed signal MC events passing the

selection criteria. Branching fractions for each decay are computed by subtracting the fit bias from the measured yield, and dividing the result by the efficiency, the daughter branching fraction product, and the number of $B\overline{B}$ pairs produced. Equal production rates to $B^0\overline{B}^0$ and B^+B^- pairs are assumed. The significance is taken as the square root of the difference between the value of $-2\ln\mathcal{L}$ (with systematic uncertainties included) for zero signal and the value at its minimum.

TABLE I: Number of events N in the sample, fitted signal yield and measured bias (to be subtracted from the signal yield) in events (ev.), detection efficiency (ϵ), daughter branching fraction product $\prod\mathcal{B}_i$, significance (S) (systematic uncertainties included), the products of the branching fractions $\mathcal{B}(B^0 \to a_1^-(1260)\,K^+)\,\mathcal{B}(a_1^-(1260) \to \pi^+\pi^-\pi^-)$ and $\mathcal{B}(B^+ \to a_1^+(1260)\,K^0)\,\mathcal{B}(a_1^+(1260) \to \pi^-\pi^+\pi^+)$ respectively, and charge asymmetry with statistical and systematic error.

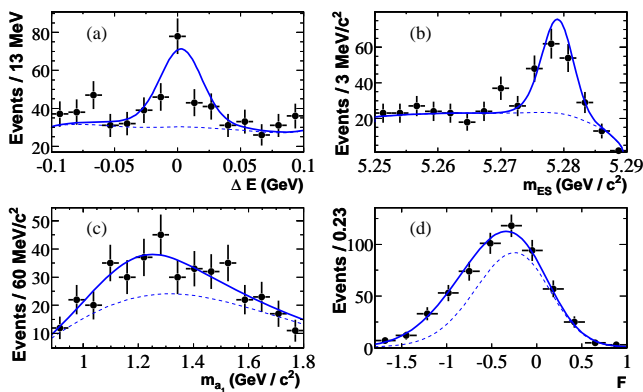| Parameter	$a_1^-(1260)\,K^+$	$a_1^+(1260)\,K^0$
N (ev.)	12196	9468
Signal yield (ev.)	272 ± 44	241 ± 32
Bias (ev.)	$+24$	$+18$
ϵ (%)	7.9	9.6
$\prod\mathcal{B}_i$ (%)	100.0	34.6
$S\,(\sigma)$	5.1	6.2
$\mathcal{B}(\times 10^{-6})$	$8.2 \pm 1.5 \pm 1.2$	$17.4 \pm 2.5 \pm 2.2$
$\mathcal{A}_{ch}$	$-0.16 \pm 0.12 \pm 0.01$	$0.12 \pm 0.11 \pm 0.02$

FIG. 1: Projections of a) ΔE, b) m_{ES}, c) m_{a_1}, and d) $\mathcal{F}$ for the $B^+ \to a_1^+(1260)\,K^0$ decay mode. Points represent on-resonance data, dashed lines the continuum and $B\overline{B}$ backgrounds, and solid lines the full fit function. These plots are made with a cut on the signal likelihood which includes $30\% - 40\%$ of the signal.

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In Figs. 1 and 2 we show the ΔE, m_{ES}, m_{a_1}, and $\mathcal{F}$ projections made by selecting events with a signal likelihood (computed without the variable shown in the figure) exceeding a threshold that optimizes the expected sensitivity.
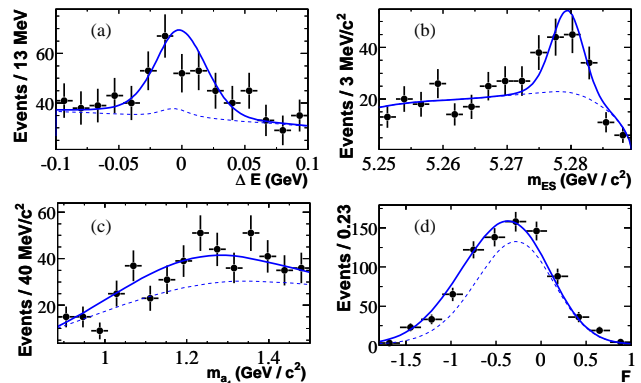

FIG. 2: Projections of a) ΔE, b) m_{ES}, c) m_{a_1}, and d) $\mathcal{F}$ for the $B^0 \to a_1^-(1260)\,K^+$ decay mode. Points represent data, dashed lines the continuum and $B\overline{B}$ backgrounds, and solid lines the full fit function. These plots are made with a cut on the signal likelihood which includes $30\% - 40\%$ of the signal.

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Most of the systematic errors on the signal yield arising from uncertainties in the values of the PDF parameters are already incorporated into the overall statistical error, since they are floated in the fit. The systematic error on the $B^0 \to a_1^-(1260)\,K^+$ ($B^+ \to a_1^+(1260)\,K^0$) fit yield is 28 (23) events, which is obtained by varying the PDF parameters within their uncertainties. We estimate the uncertainty arising from the number of $B\overline{B}$ pairs to be 1.1%. The uncertainty in the fit bias correction is 12 (9) events, taken as half of the fit bias correction. The uncertainty in the $a_1(1260)$ meson parameters is 12 (6) events. The systematic uncertainty assigned to the fixed yields in the fit is 3 (4) events. The systematic effect due to differences between data and MC for the $\cos\theta_{\mathrm{T}}$ selection is 1.8%. A systematic uncertainty of $2.0\,(2.5)\,\%$ is evaluated for the PID. The tracking efficiency contributes to the systematics with $1.8\,(1.3)\,\%$. A systematic uncertainty of $2.5\,\%$ is estimated for the difference in selection efficiency in the decay modes through the dominant P-wave $(\pi\pi)_\rho$ and the S-wave $(\pi\pi)_\sigma$. The contribution of interference between $a_2(1320)$ and $a_1(1260)$ is negligible. In fact, varying the $a_2(1320)K$ background with different selection criteria on the angular variable $\mathcal{H}$ gives no significant change to the efficiency-corrected signal yield of $a_1(1260)K$. We find also that the systematic effect due to different form factors in MC signal simulation is negligible. The total systematic error on the branching fraction of the charged (neutral) mode is 14% (13%).

The primary sources of systematic uncertainties in the charge asymmetry measurement are the track reconstruction or particle identification, the imperfect modelling of the interactions with material in the detector and the $B\overline{B}$ background. We study these systematic uncertainties with MC signal events, $q\bar{q}$ background in the data, and control samples. We assign a systematic uncertainty

of 0.02 (0.01) to the charge asymmetry of the charged (neutral) mode.

In summary, we have measured the branching fractions $\mathcal{B}(B^+ \to a_1^+(1260)\,K^0)\mathcal{B}(a_1^+(1260) \to \pi^-\pi^+\pi^+)$ = $(17.4 \pm 2.5 \pm 2.2) \times 10^{-6}$ and $\mathcal{B}(B^0 \to a_1^-(1260)\,K^+)$ $\mathcal{B}(a_1^-(1260) \to \pi^+\pi^-\pi^-)$ = $(8.2 \pm 1.5 \pm 1.2) \times 10^{-6}$. The charged (neutral) B decay mode is observed with a significance of 6.2 (5.1) standard deviations, which includes systematic uncertainties. We find no evidence for a direct CP-violating asymmetry in these decay modes. Assuming $\mathcal{B}(a_1^\pm(1260) \to \pi^\mp\pi^\pm\pi^\pm)$ is equal to $\mathcal{B}(a_1^\pm(1260) \to \pi^\pm\pi^0\pi^0)$, and that $\mathcal{B}(a_1^\pm(1260) \to (3\pi)^\pm)$ is equal to 100% [13], we obtain $\mathcal{B}(B^0 \to a_1^-(1260)K^+) = (16.3 \pm 2.9 \pm 2.3) \times 10^{-6}$ and $\mathcal{B}(B^+ \to a_1^+(1260)K^0) = (34.9 \pm 5.0 \pm 4.4) \times 10^{-6}$. These results are in reasonable agreement with the theoretical estimates.

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