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Observation and polarization measurement of $B^0 \rightarrow a_1(1260)^+ a_1(1260)^-$ decay

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We present measurements of the branching fraction $\mathcal{B}$ and longitudinal polarization fraction f_L for $B^0 \to a_1(1260)^+ a_1(1260)^-$ decays, with $a_1(1260)^\pm \to \pi^-\pi^+\pi^\pm$. The data sample, collected with the *BABAR* detector at the SLAC National Accelerator Laboratory, represents 465×10^6 produced $B\bar{B}$ pairs. We measure $\mathcal{B}(B^0 \to a_1(1260)^+ a_1(1260)^-) \times [\mathcal{B}(a_1(1260)^+ \to \pi^-\pi^+\pi^+)]^2 = (11.8 \pm 2.6 \pm 1.6) \times 10^{-6}$ and $f_L = 0.31 \pm 0.22 \pm 0.10$, where the first uncertainty is statistical and the second systematic. The decay mode is measured with a significance of 5.0 standard deviations including systematic uncertainties.

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Charmless B decays to final states involving two axial-vector mesons (AA) have received considerable theoretical attention in the last few years [1–3]. The branching fractions of several $B \to AA$ decay modes have been calculated using the QCD factorization [2] and the naive factorization [3] approaches. Theoretical predictions for the branching fraction of the $B^0 \to a_1(1260)^+ a_1(1260)^-$ decay mode vary between 37.4×10^{-6} [2] and 6.4×10^{-6} [3]. Branching fractions at this level should be observable with the *BABAR* data sample, which can be used to discriminate between the predictions. The only available experimental information on this B decay mode is the branching fraction upper limit of 2.8×10^{-3} at 90% confidence level measured by CLEO [4].

The study of the decay polarization in the charmless B decays to vector vector (VV), vector axial-vector (VA), and AA mesons provides information on the underlying helicity structure of the decay mechanism [2]. The measured value of the longitudinal polarization fraction $f_L \sim 0.5$ in penguin-dominated $B \to \phi K^*$ decays [5] is in contrast with naive standard model (SM) calculations predicting a dominant longitudinal polarization ($f_L \sim 1$) [6]. The naive SM expectation is confirmed in the tree-dominated $B \to \rho\rho$ [7] and $B^+ \to \omega\rho^+$ [8] decays. A value of $f_L \sim 1$ is found in vector-tensor $B \to \phi K_2^*(1430)$ decays [9], while $f_L \sim 0.5$ is found in $B \to \omega K_2^*(1430)$ decays [8]. The small value of f_L observed in $B \to \phi K^*$ decays has stimulated theoretical effort, such as the introduction of nonfactorizable terms and penguin-annihilation amplitudes [10]. Other explanations invoke new physics [11].

There are no experimental measurements of f_L in $B \to AA$ decays. The predicted value of the f_L in $B^0 \to a_1^+ a_1^-$ [12] is 0.64 [2].

We present the first measurements of the branching fraction and polarization in $B^0 \to a_1^+ a_1^-$ decays, with $a_1^+ \to \pi^-\pi^+\pi^+$ [13]. We do not separate the P-wave $(\pi\pi)_\rho$ and the S-wave $(\pi\pi)_\sigma$ components in the $a_1 \to 3\pi$ decay; a systematic uncertainty is estimated due to the difference in the selection efficiencies [14]. Because of the limited number of signal events expected in the data sample, we do not perform a full angular analysis. Using helicity formalism, and after integration over the azimuthal angle between the decay planes of the two a_1 mesons, the predicted angular distribution $d\Gamma/d\cos\theta$ is

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta} \propto f_L(1-\cos^2\theta) + \frac{1}{2} f_T(1+\cos^2\theta), \qquad (1)$$

where $f_T = 1 - f_L$ and θ is the angle between the normal to the decay plane of the three pions of one a_1 and the flight direction of the other a_1, both calculated in the rest frame of the first a_1.

The results presented here are based on data collected with the *BABAR* detector [15] at the PEP-II asymmetric-energy e^+e^- collider [16] located at the SLAC National Accelerator Laboratory. The analysis uses an integrated luminosity of 423.0 fb^{-1}, corresponding to $(465 \pm 5) \times 10^6$ $B\bar{B}$ pairs, recorded at the $\Upsilon(4S)$ resonance at a center-of-mass energy of $\sqrt{s} = 10.58$ GeV. An additional 43.9 fb^{-1}, taken about 40 MeV below this energy (off-resonance data), is used for the study of the $q\bar{q}$ continuum background ($e^+e^- \to q\bar{q}$, with $q = u, d, s, c$).

Charged particles are detected, and their momenta measured, by a combination of a vertex tracker consisting of five layers of double-sided silicon microstrip detectors, and a 40-layer central drift chamber, both operating in 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. We identify photons and electrons using a CsI(Tl) electromagnetic calorimeter. Further charged-particle identification is provided by the specific energy loss (dE/dx) in the tracking devices and by an internally reflecting ring-imaging Cherenkov detector covering the central region. A K/π separation of better than 4 standard deviations is achieved for momenta below 3 GeV/c, decreasing to 2.5σ at the highest momenta in the B decay final states. A more detailed description of the reconstruction of charged tracks in *BABAR* can be found elsewhere [17].

Monte Carlo (MC) simulations of the signal decay mode, continuum, $B\bar{B}$ backgrounds, and detector response [18] are used to establish the event selection criteria. The MC signal events are simulated as B^0 decays to $a_1^+ a_1^-$ with

$a_1 \to \rho(770)\pi$. The a_1 meson parameters in the simulation are mass $m_0 = 1230\ \mathrm{MeV}/c^2$ and width $\Gamma_0 = 400\ \mathrm{MeV}/c^2$ [19,20].

We reconstruct the decay of a_1^+ into three charged pions. Two pion candidates are combined to form a ρ^0 candidate. Candidates with an invariant mass between 0.51 and $1.10\ \mathrm{GeV}/c^2$ are combined with a third pion to form an a_1 candidate. The a_1 candidate is required to have a mass between 0.87 and $1.75\ \mathrm{GeV}/c^2$. We impose several particle identification requirements to ensure the identity of the signal pions. We also require the χ^2 probability of the B vertex fit to be greater than 0.01 and the number of charged tracks in the event to be greater or equal to seven.

A B meson candidate is kinematically characterized by the energy-substituted mass $m_{\mathrm{ES}} \equiv \sqrt{(s/2 + \mathbf{p}_0 \cdot \mathbf{p}_B)^2/E_0^2 - \mathbf{p}_B^2}$ and energy difference $\Delta E \equiv E_B^* - \sqrt{s}/2$, where the subscripts 0 and B refer to the initial $\Upsilon(4S)$ and the B candidate in the laboratory frame, respectively, and the asterisk denotes the $\Upsilon(4S)$ frame. The resolutions in m_{ES} and ΔE are about $3.0\ \mathrm{MeV}/c^2$ and 20 MeV, respectively. We require candidates to satisfy $5.27 \le m_{\mathrm{ES}} \le 5.29\ \mathrm{GeV}/c^2$ and $-90 < \Delta E < 70$ MeV.

Background arises primarily from random track combinations in continuum events. We reduce this background by using the angle θ_T between the thrust axis of the B candidate and the thrust axis of the rest of the event, evaluated in the $\Upsilon(4S)$ rest frame. The distribution of $|\cos\theta_T|$ is sharply peaked near 1 for combinations drawn from jetlike continuum events and is nearly uniform for $B\bar{B}$ events; for this reason, we require $|\cos\theta_T| < 0.65$.

Background can also arise from $B\bar{B}$ events, especially events containing a charmed meson (these are mostly events with five pions and a misidentified kaon in the final state). The charmed background includes peaking modes, with structures in m_{ES} and ΔE that mimic signal events, and nonpeaking "generic" modes. To suppress the charm background, we reconstruct D and D^* mesons. Events are vetoed if they contain D or D^* candidates with reconstructed masses within $20\ \mathrm{MeV}/c^2$ (window size of about $\pm 2\sigma$) of the nominal charmed meson masses [19].

The mean number of B candidates per event is 2.9. If an event has multiple B candidates, we select the candidate with the highest B vertex χ^2 probability. From MC simulation, we find that this algorithm selects the correct candidate 90% of the time in signal events while inducing negligible bias.

Using MC simulation of signal events with longitudinal (transverse) polarization, signal events are divided in two categories: correctly reconstructed signal (CR), where all candidate particles come from the correct signal B^0, and self-cross feed (SCF) signal, where candidate particles are exchanged with a rest of the event particle. The fraction of SCF candidates is $31.8 \pm 3.2(19.4 \pm 1.9)\%$.

We determine the number of signal events (the signal yield) from an unbinned extended maximum-likelihood fit. The seven input observables are ΔE, m_{ES}, a Fisher discriminant $\mathcal{F}$ [17], the two a_1 masses, and the two $\mathcal{H} = |\cos\theta|$. The Fisher discriminant $\mathcal{F}$ combines four variables calculated in the $\Upsilon(4S)$ frame: the absolute values of the cosines of the angles with respect to the beam axis of the B momentum and the thrust axis of the B decay products, and the zeroth and second angular Legendre moments $L_{0,2}$ of the momentum flow about the B thrust axis. The Legendre moments are defined by $L_k = \sum_m p_m |\cos\theta_m|^k$, where θ_m is the angle with respect to the B thrust axis of a track or neutral cluster m, p_m is its momentum, and the sum includes the rest of the event particles only.

There are five hypotheses in the likelihood model: signal, continuum, and three $B\bar{B}$ components, which take into account charmless, generic charm, and peaking charm backgrounds. The likelihood function is

$$\mathcal{L} = e^{-(\sum_{j=1}^{5} n_j)} \prod_{i=1}^{N} \left[\sum_{j=1}^{5} n_j \mathcal{P}_j(\mathbf{x}_i) \right], \tag{2}$$

where N is the number of input events, n_j is the number of events for hypothesis j, and $\mathcal{P}_j(\mathbf{x}_i)$ is the corresponding probability density function (PDF), evaluated with the observables $\mathbf{x}_i$ of the ith event. Since correlations among the observables are small ($< 10\%$), we take each $\mathcal{P}$ as the product of the PDFs for the separate variables.

The signal includes both CR and SCF signal components with the SCF fraction fixed in the fit to the value estimated from MC simulation. Both CR and SCF signals are used to measure the branching fraction and polarization. The PDF of the signal takes the form

$$\begin{aligned} P_{\mathrm{sig}} = {} & f_L(1 - g_L^{\mathrm{SCF}})\mathcal{P}_{\mathrm{CR},L} + f_L g_L^{\mathrm{SCF}} \mathcal{P}_{\mathrm{SCF},L} \\ & + f_T(1 - g_T^{\mathrm{SCF}})\mathcal{P}_{\mathrm{CR},T} + f_T g_T^{\mathrm{SCF}} \mathcal{P}_{\mathrm{SCF},T}, \end{aligned} \tag{3}$$

where g_L^{SCF} (g_T^{SCF}) is the fraction of SCF in longitudinal (transverse) polarized signal events and $\mathcal{P}_{\mathrm{CR},L}$, $\mathcal{P}_{\mathrm{SCF},L}$ ($\mathcal{P}_{\mathrm{CR},T}$, $\mathcal{P}_{\mathrm{SCF},T}$) are the signal PDFs of CR and SCF signal components for longitudinal (transverse) polarization.

We determine the PDF parameters from Monte Carlo simulation for the signal and $B\bar{B}$ backgrounds and from off-resonance data for the continuum background.

We parametrize m_{ES} and ΔE using a Gaussian function with exponential tails [21] for the CR signal and charmless components, and using polynomials for all other components, except for the m_{ES} distribution for continuum events which is described by the ARGUS empirical phase space function [22] $x\sqrt{1 - x^2}\exp[-\xi(1 - x^2)]$, where $x \equiv 2m_{\mathrm{ES}}/\sqrt{s}$ and ξ is a parameter. The a_1 mass is described by a relativistic Breit-Wigner function for the CR signal component, an asymmetric Gaussian plus a linear polynomial for the SCF signal component, and polynomials for the remaining components. The Fisher variable is parametrized with an asymmetric Gaussian plus a linear polynomial in all cases. The $\mathcal{H}$ variables are parametrized with a Gaussian plus a linear polynomial for the charm peaking component and with a polynomial in all other cases. The parameters left free in the fit are the signal, continuum, and three $B\bar{B}$ component yields, and f_L. We also float some of the parameters of the continuum PDFs: the three parameters of the asymmetric Gaussian part of $\mathcal{F}$, and one parameter each for the $\mathcal{H}$, the a_1 masses, and ΔE.

Large data samples of B decays to charmed final states ($B^0 \to D^{*-} a_1^+$), which have similar topology to the signal, are used to verify the simulated resolutions in m_{ES} and ΔE. Where the data samples reveal differences from the Monte Carlo, we shift or scale the resolution function used in the likelihood fits. Any bias in the fit, which arises mainly from neglecting the small correlations among the discriminating observables, is determined from a large set of simulated experiments for which the continuum background is generated from the PDFs, and into which we have embedded the expected number of $B\bar{B}$ background, signal, and SCF events chosen randomly from fully simulated Monte Carlo samples.

The fit results are presented in Table I. The detection efficiencies are calculated as the ratio of the number of signal MC events passing all the cuts to the total number generated. We compute the branching fraction by subtracting the fit bias from the measured yield, and dividing the result by the number of produced $B\bar{B}$ pairs times the product of the daughter branching fractions and the detection efficiency. We assume that the branching fractions of the $\Upsilon(4S)$ to B^+B^- and $B^0\bar{B}^0$ are each 50%. The branching fraction and f_L are corrected for the slightly different reconstruction efficiencies in longitudinal and transversal polarizations. The statistical uncertainty on the signal yield is taken as the change in the central value when the quantity $-2\ln\mathcal{L}$ increases by one unit from its minimum value. The significance is 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. In this calculation we have taken into account the fact that the floating f_L parameter is not defined in the zero signal hypothesis.

TABLE I. Fitted signal yield and yield bias (in events), bias on f_L, detection efficiencies ϵ_L and ϵ_T for events with longitudinal and transversal polarization, respectively, significance S (including systematic uncertainties), measured branching fraction $\mathcal{B}$, and fraction of longitudinal polarization f_L with statistical and systematic uncertainties.

Signal yield	545 ± 118
Signal yield bias	+14
f_L bias	−0.06
ϵ_L (%)	9.0
ϵ_T (%)	10.0
S (σ)	5.0
$\mathcal{B}$ ($\times 10^{-6}$)	11.8 ± 2.6 ± 1.6
f_L	0.31 ± 0.22 ± 0.10

Figure 1 shows the projections of m_{ES}, ΔE, the a_1 invariant mass, $\mathcal{F}$, and $\mathcal{H}$ for a subset of the data for which the ratio of the signal likelihood to the total likelihood (computed without using the variable plotted) exceeds a threshold that optimizes the sensitivity.

A systematic uncertainty of 38 events on the signal yield due to the PDF parametrization is estimated by varying the signal PDF parameters within their uncertainties, obtained through comparison of MC and data in control samples. The uncertainty from the fit bias (7 events) is taken as half the correction itself. Uncertainty from lack of knowledge of the a_1 meson parameters is 31 events. We vary the SCF fractions by their uncertainties and estimate a systematic uncertainty of 12 events. A systematic uncertainty of 19 events from possible contamination by $B^0 \to a_1(1260)^+ a_2(1320)^-$ background events is estimated with simulated MC experiments. The uncertainty due to cross feed between the signal and nonresonant backgrounds, evaluated with MC events, is 10 events. Uncertainties of 1.4% and 3.6% are associated with the track efficiency and particle identification, respectively. Differences between data and simulation for the $\cos\theta_T$ variable lead to a systematic uncertainty of 2.5%. Assuming that 20% of a_1 decays proceed through the S-wave $(\pi\pi)_\sigma$ channel [19], we estimate a systematic uncertainty of 6.8% from the difference in reconstruction efficiency between the P-wave $(\pi\pi)_\rho$ and S-wave components. The uncertainty in the total number of $B\bar{B}$ pairs in the data sample is 1.1%. The total systematic uncertainty, obtained by adding the individual terms in quadrature, is 12.9%.

The main systematic uncertainties on f_L arise from the fit bias (0.03), the variation of PDF parameters (0.08), the a_1 parametrization (0.04), and the nonresonant background (0.02).

In conclusion, we have measured the branching fraction $\mathcal{B}(B^0 \to a_1^+ a_1^-) \times [\mathcal{B}(a_1^+ \to (3\pi)^+)]^2 = (11.8 \pm 2.6 \pm 1.6) \times 10^{-6}$ and the fraction of longitudinal polarization $f_L = 0.31 \pm 0.22 \pm 0.10$. Assuming that $\mathcal{B}(a_1^+ \to \pi^-\pi^+\pi^+)$ is equal to $\mathcal{B}(a_1^+ \to \pi^+\pi^0\pi^0)$, and that $\mathcal{B}(a_1^+ \to (3\pi)^+)$ is equal to 100% [19], we obtain $\mathcal{B}(B^0 \to a_1^+ a_1^-) = (47.3 \pm 10.5 \pm 6.3) \times 10^{-6}$. The decay mode is observed with a significance of 5.0σ including systematic uncertainties. The measured branching fraction and longitudinal polarization are in general agreement with the theoretical expectations in [2], while they disfavor those in [3].

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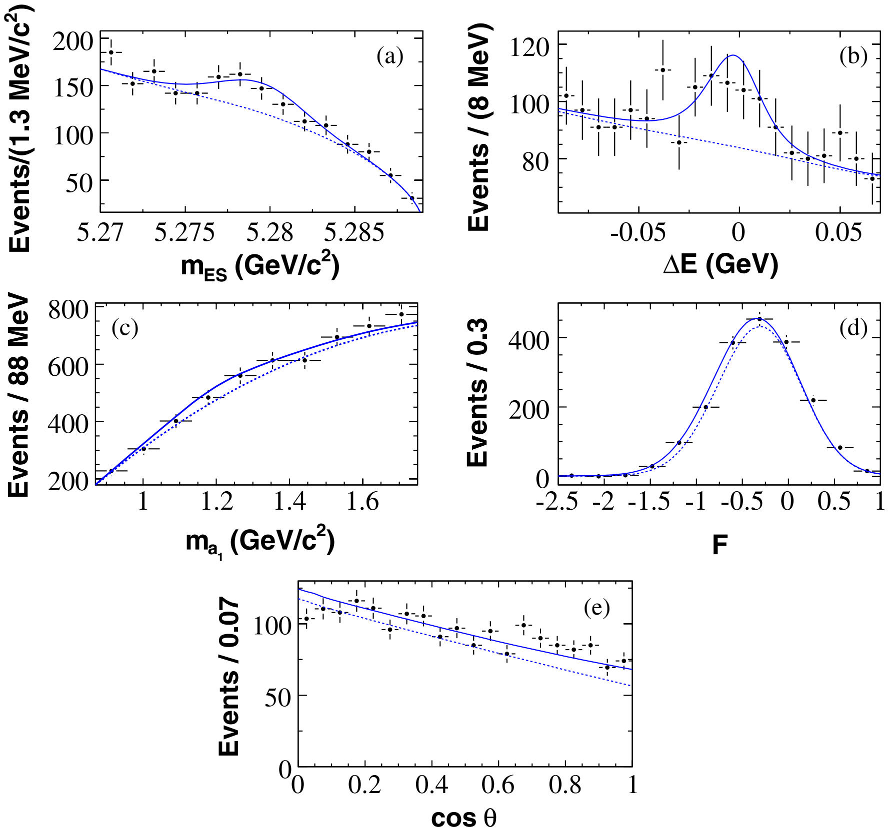

FIG. 1 (color online). Projections of (a) m_{ES}, (b) ΔE, (c) a_1 invariant mass (average of $m_{a_1^+}$ and $m_{a_1^-}$ is shown), (d) $\mathcal{F}$, and (e) $\mathcal{H} = |\cos\theta|$ (average of $|\cos\theta_{a_1^+}|$ and $|\cos\theta_{a_1^-}|$ is shown). Points with error bars (statistical only) represent the data, the solid line the full fit function, and the dashed line the background component. These plots are made with a requirement on the signal likelihood that selects 25%–40% of the signal and 2%–5% of the background.

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$$f(x) = \exp\left(\frac{-(x-\mu)^2}{2\sigma_{L,R}^2 + \alpha_{L,R}(x-\mu)^2}\right),$$

where μ is the peak position of the distribution, $\sigma_{L,R}$ are the left and right widths, and $\alpha_{L,R}$ are the left and right tail parameters.

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