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Observation of B^0 Meson Decay to $a_1^+(1260)\,\pi^-$

The *BABAR* Collaboration

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Abstract

We present a preliminary measurement of the branching fraction of the B meson decay $B^0 \to a_1^+(1260)\,\pi^-$ with $a_1^+(1260) \to \pi^+\pi^+\pi^-$. The data were recorded with the *BABAR* detector at the SLAC B factory PEP-II and correspond to 124×10^6 $B\overline{B}$ pairs produced in e^+e^- annihilation through the $\Upsilon(4S)$ resonance. We find the branching fraction $\mathcal{B}(B^0 \to a_1^+(1260)\,\pi^-)= (42.6 \pm 4.2 \pm 4.1) \times 10^{-6}$. The fitted values of the $a_1(1260)$ parameters are $m_{a_1} = 1.19 \pm 0.02$ GeV/c^2 and $\Gamma_{a_1} = 312 \pm 55$ MeV/c^2.

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1 INTRODUCTION

We report on the preliminary measurement of the branching fraction $B^0 \to a_1^+(1260)\pi^-$ with $a_1^+(1260) \to \pi^+\pi^+\pi^-$ [1] . The $a_1(1260) \to 3\pi$ decay proceeds mainly through the intermediate states $(\pi\pi)_\rho\pi$ and $(\pi\pi)_\sigma\pi$.

The study of this decay mode is complicated by open questions on the parameters of the $a_1(1260)$ meson. There are large discrepancies between these parameters when comparing results from analyses involving hadronic interactions [2] and τ decays [3]. Therefore, it is important to verify the theoretical prediction of the branching fraction for this decay mode and have new measurements of the $a_1(1260)$ parameters. It is also important to note that the $B^0 \to a_1^+(1260)\pi^-$ channel can be used to measure the Cabibbo-Kobayashi-Maskawa angle α of the Unitarity triangle [4].

There has been no experimental observation of this decay mode. An upper limit of 49×10^{-5} at the 90% C.L. has been set by CLEO [5] for the branching fraction of $B^0 \to a_1^+(1260)\pi^-$, while the DELPHI [6] collaboration has set the 90% C.L. upper limit of 28×10^{-5} for the branching fraction of $B^0 \to 4\pi$.

Below we present the details of the analysis for the measurement of the branching fraction for $B^0 \to a_1^+(1260)\pi^- \to 4\pi$. Presently, we do not distinguish between the final states $(\pi\pi)_\rho\pi$ and $(\pi\pi)_\sigma\pi$. Such an analysis would require a study of the angular distributions of the decay products. Background contributions from B^0 decays to $a_2(1320)\pi$ and $\pi(1300)\pi$ were assumed to be negligible.

2 THE *BABAR* DETECTOR AND DATASET

The results presented in this paper are based on data collected in 1999–2003 with the *BABAR* detector [7] at the PEP-II asymmetric e^+e^- collider [8] located at the Stanford Linear Accelerator Center. An integrated luminosity of 112 fb^{-1}, corresponding to 124 million $B\overline{B}$ pairs, was recorded at the $\Upsilon(4S)$ resonance ("on-resonance", center-of-mass energy $\sqrt{s} = 10.58$ GeV). An additional 12 fb^{-1} were taken about 40 MeV below this energy ("off-resonance") for the study of continuum background in which a light or charm quark pair is produced instead of an $\Upsilon(4S)$.

The asymmetric beam configuration in the laboratory frame provides a boost of $\beta\gamma = 0.56$ to the $\Upsilon(4S)$. Charged particles are detected and their momenta measured by the combination of a silicon vertex tracker (SVT), 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 CM frame.

Charged-particle identification (PID) is provided by the average energy loss ($\mathrm{d}E/\mathrm{d}x$) in the tracking devices and by an internally reflecting ring-imaging Cherenkov detector (DIRC) covering the central region. A K/π separation of better than four standard deviations (σ) is achieved for momenta below 3 GeV/c, decreasing to 2.5 σ at the highest momenta in the B decay final states. Photons and electrons are detected by a CsI(Tl) electromagnetic calorimeter (EMC). The EMC provides good energy and angular resolutions for detection of photons in the range from 30 MeV to 4 GeV. The energy and angular resolutions are 3% and 4 mrad , respectively , for a 1 GeV photon.

The flux return for the solenoid is composed of multiple layers of iron and resistive plate chambers for the identification of muons and long-lived neutral hadrons.

3 ANALYSIS METHOD

Monte Carlo (MC) simulations [9] of the signal decay modes and of continuum and $B\overline{B}$ backgrounds are used to establish the event selection criteria. We select $a_1^+(1260)$ candidates with the following requirement on the invariant mass in GeV/c^2 : $0.6 < m_{a_1(1260)} < 1.8$. The intermediate dipion state is reconstructed with an invariant mass between 0.46 and 1.1 GeV/c^2.

We make several particle identification requirements to ensure the identity of the signal pions. For the bachelor charged track we require an associated DIRC Cherenkov angle between $-2\,\sigma$ and $+5\,\sigma$ from the expected value for a pion.

A B meson candidate is characterized kinematically by the energy-substituted mass $m_{\rm ES} = \sqrt{(\frac{1}{2}s + \mathbf{p}_0 \cdot \mathbf{p}_B)^2/E_0^2 - \mathbf{p}_B^2}$ and energy difference $\Delta E = E_B^* - \frac{1}{2}\sqrt{s}$, where the subscripts 0 and B refer to the initial $\Upsilon(4S)$ and to the B candidate in the lab-frame, respectively, and the asterisk denotes the $\Upsilon(4S)$ frame. We require $|\Delta E| \leq 0.2$ GeV and $5.25 \leq m_{\rm ES} \leq 5.29$ GeV/c^2. The momentum of $a_1^+(1260)$ in the center-of-mass frame is required to be between 2.3 and 2.7 GeV/c. To reduce fake B meson candidates we require $\mathrm{p}(\chi^2) > 0.01$ for the B vertex fit. The angular variable $\mathcal{H}_{a_1}$ (cosine of the angle between the direction of the π meson 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 combinatorics.

To reject continuum background, we make use of 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 sideband data. We use Monte Carlo simulations of $B^0\overline{B}^0$ and B^+B^- decays to look for $B\overline{B}$ backgrounds, which can come from both charmless and charm decays. We find that the decay mode $B^0 \to D^-\pi^+$, with $D^- \to K^+\pi^-\pi^-$ and $D^- \to K^0_S\pi^-$, is the only significant background, and is included in the maximum likelihood fit.

We use an unbinned, multivariate maximum-likelihood fit to extract the signal yield for $B^0 \to a_1^+(1260)\pi^-$. The likelihood function incorporates four uncorrelated variables. We describe the B decay kinematics with two variables: ΔE and $m_{\rm ES}$, as mentioned above. We also include m_{a_1} and a Fisher discriminant $\mathcal{F}$ which describes the energy flow in the event. 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 axis, and the zeroth and second angular moments $L_{0,2}$ of the energy flow around the B thrust axis. The moments are defined by

$$L_j = \sum_i p_i \times |\cos\theta_i|^j\,, \qquad (1)$$

where θ_i is the angle with respect to the B thrust axis of track or neutral cluster i, p_i is its momentum, and the sum excludes tracks and clusters used to build the B candidate.

Since the correlations between the observables in the selected data are small, we take the probability density function (PDF) for each event to be a product of the PDFs for the separate observables. The product PDF for event i and hypothesis j, where j can be signal, continuum background or $B\overline{B}$ background, is given by

$$\mathcal{P}_j^i = \mathcal{P}_j(m_{\rm ES}) \cdot \mathcal{P}_j(\Delta E) \cdot \mathcal{P}_j(\mathcal{F}) \cdot \mathcal{P}_j(m_{a_1}). \qquad (2)$$

There is the possibility that a track from a signal event is exchanged with a track from the rest of the event. We call these events "self-cross-feed" (SCF) events. The fraction of SCF events with respect to the total number of signal events, f_{SCF}, is found to be 0.31 from Monte Carlo studies. The likelihood function for the event i is defined as :

$$\mathcal{L}^i = n_{sig}(1 - f_{SCF})\mathcal{P}^i_{sig} + n_{sig}f_{SCF}\mathcal{P}^i_{SCF} + n_{q\bar{q}}\mathcal{P}^i_{q\bar{q}} + n_{B\bar{B}1}\mathcal{P}^i_{B\bar{B}1} + n_{B\bar{B}2}\mathcal{P}^i_{B\bar{B}2}\,, \tag{3}$$

where n_{sig} is the number of signal events, $n_{q\bar{q}}$ the number of continuum background events, $n_{B\bar{B}1}$ the number of $B\overline{B}$ background events $D^-\pi^+$ with $K^+\pi^-\pi^-$ and $n_{B\bar{B}2}$ the number of $B\overline{B}$ background events $D^-\pi^+$ with $K^0_S\pi^-$. The extended likelihood function for all events is :

$$\mathcal{L} = \frac{\exp\left(-\sum_j n_j\right)}{N!}\prod_i^N \sum_j n_j\mathcal{P}^i_j\,, \tag{4}$$

where n_j is the yield of events of hypothesis j found by the fitter, and N is the number of events in the sample. The first factor takes into account the Poisson fluctuations in the total number of events.

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 data from sidebands in $m_{\rm ES}$ or ΔE. We allow the signal m_{a_1} PDF parameters and several background PDF parameters to float in the final fit.

The distribution of m_{a_1} in signal events is parameterized as a relativistic Breit-Wigner. The $m_{\rm ES}$ and ΔE distributions for signal are parameterized as double Gaussian functions. Slowly varying distributions are parameterized by linear functions. The combinatoric background in $m_{\rm ES}$ is described by a phase-space-motivated empirical function [10]. We model the $\mathcal{F}$ distribution using a Gaussian function with different widths above and below the mean.

Possible differences between Monte Carlo simulation and on-resonance data are investigated using the control sample $B \to \pi^- D^0, D^0 \to K^-\pi^+\pi^0$, which has a similar topology to the signal mode.

4 SYSTEMATIC STUDIES

Most of the systematic errors on the yields that arise from uncertainties in the values of the PDF parameters have already been incorporated into the overall statistical error, since they are floated in the fit. We determine the sensitivity to the other parameters of the signal PDF components by varying these within their uncertainties. The results are shown in the first row of Table 1. This is the only systematic error on the fit yield; the other systematics apply to either the efficiency or the number of $B\overline{B}$ pairs in the data sample.

The uncertainty in our knowledge of the efficiency is found to be $0.8N_t\%$, where N_t is the number of signal tracks. We estimate the uncertainty in the number of $B\overline{B}$ pairs to be 1.1%. The fitting algorithm introduces a systematic bias of 3.1%, which was found from fits to simulated samples with varying background populations. Published world averages [11] provide the B daughter branching fraction uncertainties. The systematic error from $a_1(1260)K$ cross-feed background is estimated to be 5%, while the systematic error due to SCF is found to be 3%. A systematic error of 1% is assigned to potential contributions from $B \to 4\pi$ and $B \to \rho\pi\pi$. Finally, we account for systematic effects in $\cos\theta_{\rm T}$ (1%) and in the PID requirement (0.5%) on the prompt charged track. The values for each of these contributions are given in Table 1.

Table 1: Estimates of the systematic errors (in percent).

Quantity	$a_1^+\pi^-$
Fit yield	6.3
Fit eff/bias	1.7
Track multiplicity	1.0
Tracking eff/qual	3.2
Number $B\overline{B}$	1.1
SCF	3
a_1K cross-feed	5
$B \rightarrow 4\pi$,$\rho\pi\pi$	1.0
MC statistics	1.0
$\cos\theta_{\rm T}$	1.0
Total	9.6

5 RESULTS

By generating (from the PDFs) and fitting simulated samples of signal and background, we verify that our fitting procedure is working properly. We find that the minimum $\ln\mathcal{L}$ value for the on-resonance data lies well within the $\ln\mathcal{L}$ distribution from these simulated samples.

The efficiency is obtained from the fraction of signal MC events passing the selection criteria, adjusted for any bias in the likelihood fit. This bias is determined from fits to simulated samples, each equal in size to the data and containing a known number of signal MC events combined with events generated from the background PDFs. We find a fit bias of 0.97.

Table 2: Final fit results.

Fit quantity	$a_1^+(1260)\,\pi^-$
Fit sample size	
On-resonance	32500
Off-resonance	2680
Signal yield	
On-res data	$472.3^{+46.8}_{-45.9}$
Off-res data	$6.2^{+10.8}_{-8.4}$
Selection ϵ (%)	19.4
Track corr.	0.953
Fit-bias	0.967
$\prod \mathcal{B}_i$ (%)	50
Stat. sign. (σ)	13.8
$\mathcal{B}(\times 10^{-6})$	$42.6 \pm 4.2 \pm 4.1$

In Table 2 we show the results of the fits for on- and off-resonance data. We also show the fitted signal yield, the efficiency (ϵ), the daughter branching fraction product ($\prod \mathcal{B}_i$), the statistical significance, and the central value of the branching fraction. The statistical error on the number of events is taken to be the change in the central value when the quantity $-2\ln\mathcal{L}$ changes by one unit. The statistical significance is taken as the square root of the difference between the value of $-2\ln\mathcal{L}$ for zero signal and the value at its minimum.

In Fig. 1 we show the $m_{\rm ES}$, ΔE, m_{a_1}, and m_ρ 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.

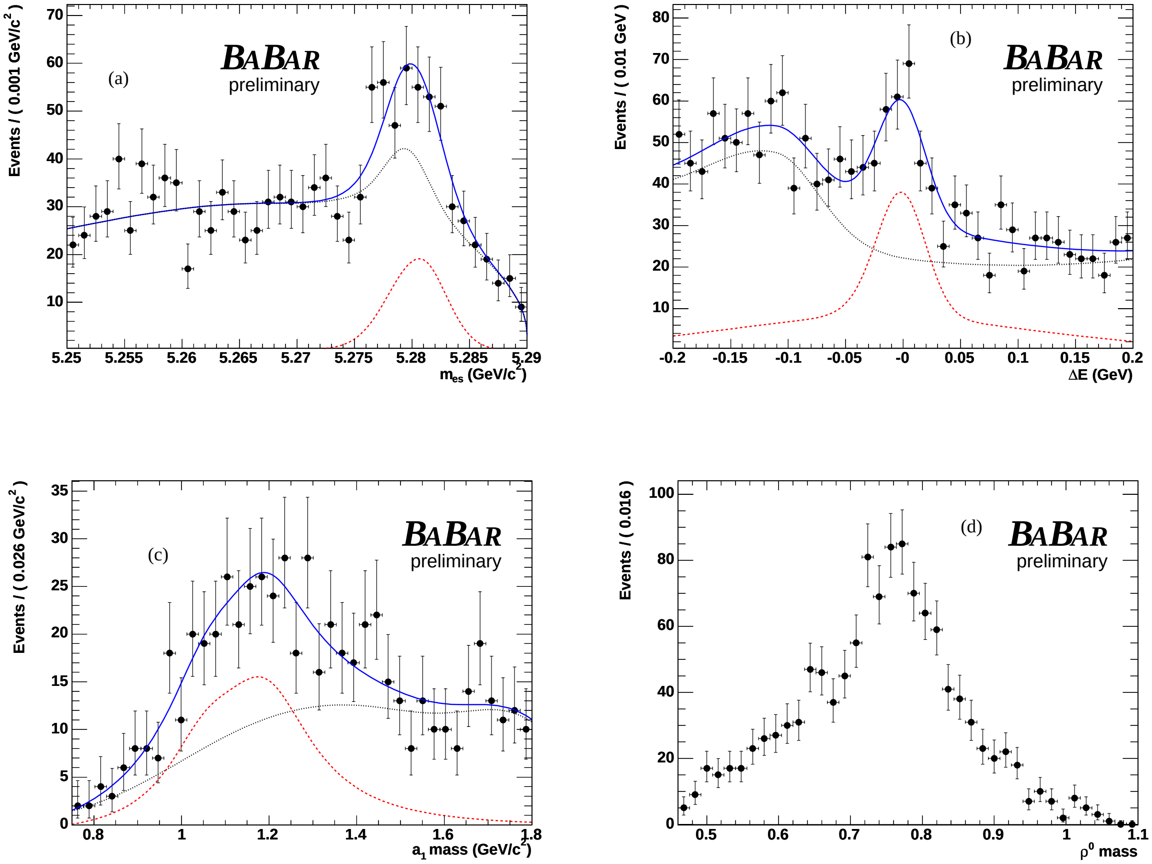

Figure 1: Projections of $m_{\rm ES}$ (a), ΔE (b), m_{a_1} (c), and ρ^0 mass (d). Points with errors represent data, dotted lines the continuum and $B\overline{B}$ backgrounds, solid curves the full fit functions, and dashed curves the signal. These plots are made with a cut on the signal likelihood and thus do not show all events in the data sample.

The fitted values of the $a_1(1260)$ parameters are $m_{a_1} = 1.19\pm0.02$ GeV/c^2 and $\Gamma_{a_1} = 312\pm55$ MeV/c^2 .

6 SUMMARY

We have obtained a preliminary measurement of the branching fraction for B^0 meson decays to $a_1^+(1260)\,\pi^-$ with $a_1(1260) \rightarrow 3\pi$. The measured branching fraction is:

$$\mathcal{B}(B^0 \rightarrow a_1^+(1260)\,\pi^-) = (42.6 \pm 4.2 \pm 4.1) \times 10^{-6}, \tag{5}$$

where the first uncertainty is statistical and the second uncertainty is systematic. The fitted values of the $a_1(1260)$ parameters are $m_{a_1} = 1.19 \pm 0.02$ GeV/c^2 and $\Gamma_{a_1} = 312 \pm 55$ MeV/c^2. These values are closer to those found in hadronic production of $a_1(1260)$ meson.

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[1] We use a particle name to denote either member of a charge conjugate pair.

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