PROCEEDINGS OF SCIENCE

Search for the B-meson decay to four baryons $B \to pp\bar{p}\bar{p}$ at BABAR

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The B mesons are the lightest mesons which can weakly decay to several final states containing baryons. The measurement of the exclusive branching fractions of baryonic B decays, as well as studies on the dynamic of the decay, may allow better understanding of baryon production in B decays and, more generally, hadron fragmentation into baryons. We report about the search for the four-body baryonic decay $B^0 \to pp\bar{p}\bar{p}$, performed on the full dataset of about 471 million $B\bar{B}$ pairs collected with the BABAR detector, which operated at the asymmetric-energy e^+e^- collider PEP II, at SLAC National Accelerator Laboratory. No measurement is currently available for this decay channel.

XVII International Conference on Hadron Spectroscopy and Structure
25-29 September, 2017
University of Salamanca, Salamanca, Spain

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PoS(Hadron2017)083

1. Introduction

The inclusive branching fraction of B mesons decaying into final states with baryons and anti-baryons pairs is approximately 7% [1], while the sum of the measured exclusive baryonic decays of the B meson is less than 1% [2]. This discrepancy motivates further searches for yet unmeasured B-meson decays to baryons. The main open issues concern the observed hierarchy of the branching fractions, due to resonant subchannels, and the threshold enhancement effect, observed as a decay rate increasing at the baryon-antibaryon invariant mass threshold, a better understanding of which might provide advances in explaining the mechanism of hadronization into baryons. Previous studies at BABAR have searched for the purely baryonic four-body decay $\bar{B}^0 \to \Lambda_c^+ p\bar{p}\bar{p}$ [3], for which no signal events were observed. The upper limit on the branching fraction was computed to be 2.8×10^{-6} at 90% CL. From this result, we calculate the expected branching fraction $\mathscr{B}(B^0 \to pp\bar{p}\bar{p}$ [1]$) = 10^{-7}$, which would be consistent with a few number of signal events, given the available integrated luminosity at BABAR. Our estimate results from the application of two scaling factors, one due to the Cabibbo suppression for the $b \to u$ decay, and one for the enlargement of the phase space, due to the lower proton mass with respect to the Λ_c^+.

2. *BABAR* experiment and dataset

The dataset used for this analysis corresponds to 424 fb^{-1} of e^+e^- collisions at the centre-of-mass (CM) energy of the $\Upsilon(4S)$ resonance (on-peak data), $\sqrt{s} = 10.58$ GeV, collected with the BABAR detector, which is described in details elsewhere [4]. A tracking system composed of a five-layer double-sided silicon vertex tracker and a 40-layer multiwire drift chamber, both operating in the 1.5 T magnetic field of a superconducting solenoid, provides the precise measurement of charged-particle momenta. The particle identification algorithms (PID) for protons, kaons and pions exploit the information on the specific energy loss measured by the tracking devices and on the Cherenkov angle mesurement, provided by the internally reflecting, ring-imaging Cherenkov detector. Monte Carlo (MC) events corresponding to at least three times the data integrated luminosity are used for the signal efficiency evaluation and for the modeling of the signal and the background shape.

3. Analysis method

The event is reconstructed combining four oppositely charged tracks identified as protons and antiprotons and kinematically fitted to a common vertex, with a fit probability larger than 0.1%. Loose cuts are also applied to the kinematic variables $m_{\rm ES}= \sqrt{(E^*_{\rm beam})^2 - (\vec{p}_{\rm B}{}^*)^2}$ and $\Delta E= E^*_{\rm B} - E^*_{\rm beam}$ [5], related to the momentum $\vec{p}_{\rm B}{}^*$ and the reconstructed energy $E^*_{\rm B}$ of the B-candidate and to the beam energy $E^*_{\rm beam}$, in the CM reference frame ($m_{\rm ES}> 5.2$ GeV$/c^2$, $|\Delta E| < 0.2$ GeV). This search has been developed as a *blind* analysis, which means that all cuts are optimized without looking at the data in the region where the signal is expected, $5.27 < m_{\rm ES} < 5.29$ GeV$/c^2$. The PID efficiency for protons is excellent for this analysis ($> 99\%$) and mis-identification rates for wrongly assigning the proton identity to kaons and pions are lower than 1%. The background is mainly

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[1] the charge conjugate is always implied throughout the article

combinatoric due to real protons coming from continuum hadronization processes ($e^+e^- \to q\bar{q}$). After the preselection cuts, further background rejection is achieved by cutting on the output of a multivariate analysis method, the Boosted Decision Tree (BDT). The BDT classifier exploits the following input variables: ΔE, $\cos\theta^*_{\mathrm{B}}$, with θ^*_{B} being the flight polar angle of the B meson in the CM reference, and the event-shape variables $R_2, |\cos\theta_{\mathrm{TH}}|$. Respectively, R_2 consists in the ratio between the second and the zeroth Fox Wolfram moments [6] and θ_{TH} is the angle between the Thrust axis [7] of the rest of the event and that of the B candidate. These continuum-suppression variables are powerful in discriminating between the spherical shape of a signal event from $B\bar{B}$ decays and a jet-like $q\bar{q}$ event. The BDT output is a number in the range $(-1,1)$, peaking at 1 for signal events, while the response for background events generally provides negative values. The signal efficiency, computed on the signal MC sample as the ratio of the number of selected to generated events, is $\varepsilon = 0.207 \pm 0.005$. The associated uncertainty is systematic and takes into account the contributions from the PID and tracking efficiency, and from the BDT selection.

The signal yield is extracted from an unbinned extended maximum likelihood fit to the m_{ES} distribution of the selected events in the range $5.2 < m_{\mathrm{ES}} < 5.3$ GeV/c^2. The shape of the signal and the background components is fixed in the fit on the data to the results of the modeling study performed on both MC samples and on the data in the control region $m_{\mathrm{ES}} < 5.27$ GeV$/c^2$. The signal shape is described by a Gaussian, whose width and mean are estimated by fitting the m_{ES} distribution on the signal MC sample. For the combinatorial background shape, we use an empirical Argus function [8], which depends on two parameters, the Argus cutoff and the Argus shape. The first is completely determined by the kinematics, being the endpoint of the m_{ES} distribution. It is estimated as half of the total energy available in the centre-of-mass frame, $\sqrt{s}/2 = 5.289$ GeV$/c^2$. The Argus shape is evaluated in a fit to the m_{ES} distribution of the background MC samples. The only floating parameters in the signal extraction are the signal and the background yields.

4. Results and systematic uncertainties

The result from the fit to the on-peak data is reported in Figure 1. It provides a signal yield of $N_{\mathrm{sig}} = 10.4 \pm 4.3$ and the corresponding branching fraction is calculated with the formula:

$$\mathscr{B}(B^0 \to pp\bar{p}\bar{p}) = \frac{N_{\mathrm{sig}}}{\varepsilon \cdot 2N_{\mathrm{B^0\bar{B}^0}}} = \frac{N_{\mathrm{sig}}}{\varepsilon \cdot N_{\mathrm{B\bar{B}}}} = (1.1 \pm 0.5_{\mathrm{stat}} \pm 0.2_{\mathrm{sys}}) \times 10^{-7}, \tag{4.1}$$

where the experimental inputs are the signal yield N_{sig}, the signal efficiency ε and the number of B meson pairs $N_{\mathrm{B\bar{B}}}$. The number of neutral B mesons $N_{\mathrm{B^0\bar{B}^0}}$ is taken as half of the total number of B-meson pairs $N_{\mathrm{B\bar{B}}}$, assuming exactly the same branching fraction for $\Upsilon(4S) \to B^0\bar{B}^0$ and for $\Upsilon(4S) \to B^+B^-$. The 0.5 factor then eliminates due to the charge-conjugated decay, leading to the final formula in Equation 4.1.

We study the contributions to the systematic uncertainty on the branching fraction (Equation 4.1) arising from three sources: the number of B-meson pairs $N_{\mathrm{B\bar{B}}}$, the fit procedure and the signal efficiency. The systematic uncertainty on $N_{\mathrm{B\bar{B}}}$ is known to contribute as 1% [9]. For the fit procedure, the possible sources of systematic uncertainty are the choice of the functions for modeling the m_{ES} shape in the fit and the shape parameters estimate. The largest contribution comes from the uncertainty on the estimate of the Argus shape and it is evaluated in a pseudo-unblinding

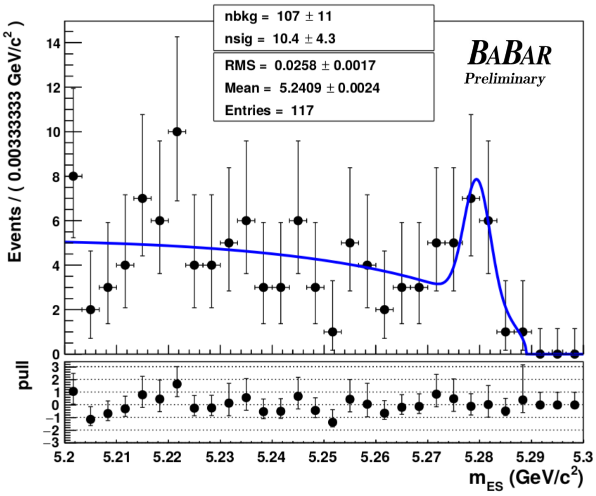

Figure 1: The preliminary result from the fit (blue line) to the on-peak data (black dots). The extracted signal yield $N_{\mathrm{sig}} = 10.4 \pm 4.3$ is reported in the box.

exercise on the full MC sample by simulating the signal yield extraction and letting the Argus shape vary within its uncertainty. The systematic contribution is conservately estimated from the maximum difference of the fitted signal yields and it is 14%. The contribution of the finite width of the endpoint distribution is evaluated as the difference between the number of fitted signal events by varying the fixed cutoff within its minimum and maximum values. This leads to a relative systematic uncertainty of 3% on the signal yield.

For the systematic uncertainty on the signal efficiency, different sources are taken into account: the MC statistics; the PID performance; the track finding efficiency; the BDT method; the decay model used for the generation of the signal MC sample. The finite size of the signal MC sample results in a relative systematic uncertainty of 0.24%. The PID performance contributes in two ways to the systematic uncertainty on the signal efficiency, with the PID efficiency and with the mis-identification probability rate for a given particle type. The latter is sensitive to the background composition and, if there is a large fraction of mis-identified events, its contribution becomes relevant. MC studies show that the number of mis-identified signal events is below 0.2%, resulting in a negligible contribution from the mis-identification rate. The contribution from the PID efficiency is evaluated by comparing the signal efficiency resulting from two configurations, with and without the correction applied to the MC PID efficiency to match the one observed in the data. This contribution gives a relative uncertainty on the efficiency of 0.86%.

The systematic uncertainty due to the track finding efficiency at BABAR [10] varies as a function of the particle momentum. Given a mean momentum of 1 GeV/c for the proton tracks coming from the signal MC simulation, this contribution is estimated to be 1%.

For the BDT method, its contribution is evaluated by means of a weighting technique. It consists in reweighting the input variable distributions of the BDT classifier on the background MC samples to match the shape observed in the data in the control region $m_{\mathrm{ES}} < 5.27$ GeV/c^2. The difference between the efficiency with and without the weighting procedure is assumed as systematic uncertainty and it results in a contribution of 2.2%.

Table 1: List of the contributions to the relative systematic uncertainty on the branching fraction.

Variable	Source	Relative systematic uncertainty
$N_{B\bar{B}}$	B counting	1%
N_{sig}	Argus shape estimate	14%
N_{sig}	Argus cutoff	3%
ε	MC statistics	0.24%
ε	PID efficiency	0.86%
ε	Track finding efficiency	1%
ε	BDT selection	2.2%
ε	decay model	14%
Total		20%

Finally, the systematic uncertainty related to the decay model used for the signal MC simulation is estimated using a weighting technique, based on the comparison of the momentum spectra of the decay products obtained with different decay models. The default signal MC simulation assumes a model for the decay products being flatly-distributed in the phase space. An alternative resonant model is also implemented. The contribution to the systematic uncertainty is estimated from the difference in the signal efficiency computed on two signal MC samples, generated with different decay models. It yields a systematic uncertainty of 14%. The summary of the relative systematic uncertainties on the branching fraction is given in Table 1. Combining them in quadrature, the final result is obtained:

$$\mathscr{B}(B^0 \to pp\bar{p}\bar{p}) = (1.1 \pm 0.5_{\text{stat}} \pm 0.2_{\text{sys}}) \times 10^{-7}. \tag{4.2}$$

5. Upper limit calculation

To obtain the statistical significance we repeat the fit with the background hypothesis only, and we calculate the difference between the likelihood logarithm from the two fits, $-2(\Delta \log L) = 9.97$, which corresponds to a significance of 3.16σ. The upper limit at 90% CL on the branching fraction is computed by integrating the likelihood as a function of N_{sig}, up to the value of N_{sig}^{UL} such that the equality $\int_0^{N_{\text{sig}}^{UL}} L(n_{\text{sig}})dn_{\text{sig}} = 0.90\int_0^{+\infty} L(n_{\text{sig}})dn_{\text{sig}}$ is verified. This calculation is based on the Bayesian approach, assuming a flat prior for $N_{\text{sig}} > 0$ and 0 otherwise, and it results in an upper limit on the signal yield of $N_{\text{sig}}^{UL} = 18$. Finally we compute the upper limit for the searched branching fraction to be $\mathscr{B}(B^0 \to pp\bar{p}\bar{p}) < 2 \times 10^{-7}$ at 90% CL. The preliminary result has been recently updated and confirmed after we ascertained the negligible impact of the potential contaminating modes $B \to p\bar{p}h^+h^-$, whose branching fraction measurement has been provided in a recent work by the LHCb collaboration [11]. The preparation of a paper on this analysis is on going and it is currently under the final review for submission.

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