Search for $B^0 \rightarrow \pi^0 \pi^0$ decay

CLEO Collaboration

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Abstract

We have searched for the charmless hadronic decay of $B^0$ mesons into two neutral pions. Using 9.13 fb$^{-1}$ taken at the $\Upsilon(4S)$ with the CLEO detector, we obtain an improved upper limit for the branching fraction $\mathcal{B}(B^0 \rightarrow \pi^0 \pi^0) < 5.7 \times 10^{-6}$ at the 90% confidence level.
D. M. Asner, A. Eppich, T. S. Hill, R. J. Morrison, R. A. Briere, G. P. Chen, T. Ferguson, H. Vogel, A. Gritsan, J. P. Alexander, R. Baker, C. Bebek, B. E. Berger, K. Berkelman, F. Blanc, V. Boisvert, D. G. Cassel, P. S. Drell, J. E. Duboscq, K. M. Ecklund, R. Ehrlich, P. Gaigalas, L. Gibbons, B. Gittelman, S. W. Gray, D. L. Hartill, B. K. Heltsley, P. I. Hopman, L. Hsu, C. D. Jones, J. Kandaswamy, D. L. Kreiniche, M. Lohner, A. Magerkurth, T. O. Meyer, N. B. Mistry, E. Nordberg, M. Palmer, J. R. Patterson, D. Peterson, D. Riley, A. Romano, J. G. Thayer, D. Urner, B. Valant-Spaight, G. Viehhauser, A. Warburton, P. Avery, C. Prescott, A. I. Rubiera, H. Stoeck, J. Yelton, G. Brandenburger, E. A. Ershov, D. Y.-J. Kim, R. Wilson, T. Bergfeld, B. I. Eisenstein, J. Ernst, G. E. Gladding, G. D. Gollin, R. M. Hans, E. Johnson, I. Karliner, M. A. Marsh, C. Plager, C. Sedlack, M. Selen, J. J. Thaler, J. Williams, K. W. Edwards, R. Janicek, P. M. Patel, A. J. Sadoff, R. Ammar, A. Bean, D. Besson, X. Zhao, S. Anderson, V. V. Frolov, Y. Kubota, S. J. Lee, J. O’Neill, R. Poling, T. Riehle, A. Smith, C. J. Stepaniak, J. Urheim, S. Ahmed, M. S. Alam, S. B. Athar, L. Jian, L. Ling, M. Saleem, S. Timm, F. Wappler, A. Anastassov, E. Eckhart, K. K. Gan, C. Gwon, T. Hart, K. Honscheid, D. Hufnagel, H. Kagan, R. Kass, T. K. Pedlar, H. Schwartboff, J. B. Thayer, E. von Toerne, M. M. Zoeller, S. J. Richichi, H. Severini, P. Skubic, A. Undrus, V. Savinov, S. Chen, J. Fast, J. W. Hinson, J. Lee, D. H. Miller, E. I. Shibata, I. P. J. Shipsey, V. Pavlunin, D. Cronin-Hennessy, A. L. Lyon, E. H. Thorndike, T. E. Coan, V. Fadeyev, Y. S. Gao, Y. Maravin, I. Narinsky, R. Stroynowski, J. Ye, T. Wlodk, M. Artuso, C. Boulahouache, K. Bukin, E. Dambasuren, G. Majumder, R. Mountain, S. Schulz, T. Skwarnicki, S. Stone, J.C. Wang, A. Wolf, J. Wu, S. Kopp, M. Kostin, A. H. Mahmoud, S. E. Csorna, I. Danko, K. W. McLean, Z. Xu, R. Godang, G. Bonvicini, D. Cinabro, M. Dubrovin, S. McGee, G. Zhou, A. Bornheim, E. Lipeles, S. P. Pappas, M. Schmidtler, A. Shapiro, W. M. Sun, A. J. Weinstein, D. E. Jaffe, R. Mahapatra, G. Masek, H. P. Paar.

1University of California, Santa Barbara, California 93106
2Carnegie Mellon University, Pittsburgh, Pennsylvania 15213
3University of Colorado, Boulder, Colorado 80309-0390
4Cornell University, Ithaca, New York 14853
5University of Florida, Gainesville, Florida 32611
6Harvard University, Cambridge, Massachusetts 02138
7University of Illinois, Urbana-Champaign, Illinois 61801
8Carleton University, Ottawa, Ontario, Canada K1S 5B6 and the Institute of Particle Physics, Canada
9McGill University, Montréal, Québec, Canada H3A 2T8 and the Institute of Particle Physics, Canada
10Ithaca College, Ithaca, New York 14850
11University of Kansas, Lawrence, Kansas 66045
12University of Minnesota, Minneapolis, Minnesota 55455
13State University of New York at Albany, Albany, New York 12222
Ohio State University, Columbus, Ohio 43210
University of Oklahoma, Norman, Oklahoma 73019
University of Pittsburgh, Pittsburgh, Pennsylvania 15260
Purdue University, West Lafayette, Indiana 47907
University of Rochester, Rochester, New York 14627
Southern Methodist University, Dallas, Texas 75275
Syracuse University, Syracuse, New York 13244
University of Texas, Austin, Texas 78712
University of Texas - Pan American, Edinburg, Texas 78539
Vanderbilt University, Nashville, Tennessee 37235
Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061
Wayne State University, Detroit, Michigan 48202
California Institute of Technology, Pasadena, California 91125
University of California, San Diego, La Jolla, California 92093
CP violation in the neutral kaon system was observed long ago [1], and evidence of CP violation in B decays is beginning to be seen [2]. In the standard model, CP violation arises naturally from a single complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [3]. Observation of the time-dependent CP-violating asymmetry in the decay $B^0 \rightarrow \pi^+\pi^−$ (charge-conjugate modes are implied throughout this Letter) would, in principle, give a measurement of the sum of the CKM phases $\beta \equiv \arg(V_{td}^*)$ and $\gamma \equiv \arg(V_{ub}^*)$. However, difficulties arise from the fact that the tree and penguin contributions to the $B^0 \rightarrow \pi^+\pi^−$ decay enter with similar amplitude and unknown relative phase. It is known already from the large ratio of branching fractions $\mathcal{B}(B \rightarrow K^+\pi^-)/\mathcal{B}(B \rightarrow \pi^+\pi^-)$ that the penguin contribution is large [4]. The tree and penguin contributions can (in principle) be separated by performing an isospin analysis on the related $B \rightarrow \pi\pi$ modes [4]. Although the decay mode $B^0 \rightarrow \pi^+\pi^−$ has been observed and there is some indication for the mode $B^+ \rightarrow \pi^+\pi^0$ [5], the $B^0 \rightarrow \pi^0\pi^0$ decay mode has not been seen yet. Theoretical calculations offer possible values for the branching fraction $\mathcal{B}(B^0 \rightarrow \pi^0\pi^0)$ ranging from $10^{-8}$ to $10^{-5}$ [6].

In this Letter, we present a new limit on the $B^0 \rightarrow \pi^0\pi^0$ branching fraction based on data taken with the CLEO II detector at the Cornell Electron Storage Ring (CESR). The data consist of 9.13 fb$^{-1}$ taken at the $\Upsilon(4S)$, corresponding to $9.67 \times 10^6$ $B\bar{B}$ pairs [7] and 4.35 fb$^{-1}$ taken below the $B\bar{B}$ threshold, used for background studies. The new result supersedes the result from a previous publication [8], which was obtained with one third of the present statistics.

CLEO II is a general purpose detector, described in detail elsewhere [9]. Most relevant for the present analysis are the tracking system and the electromagnetic calorimeter. Momentum and specific ionization ($dE/dx$) of charged tracks are measured in cylindrical drift chambers in a 1.5 T solenoidal magnetic field. In a second configuration of the detector, CLEO II.V, the innermost tracking chamber was replaced by a 3-layer, double-sided silicon vertex detector, and the gas in the main drift chamber was changed from argon-ethane to a helium-propane mixture. These modifications improved both the charged particle momentum resolution and the $dE/dx$ resolution. Photons are detected using a high resolution crystal CsI(Tl) electromagnetic calorimeter, composed of 7800-CsI(Tl) crystals covering 96% of the solid angle. Approximately two thirds of the data used in the present analysis was taken with the CLEO II.V detector.

Photon candidates are defined as isolated showers with energy greater than 30 MeV in the central region of the calorimeter ($|\cos \theta| < 0.71$, where $\theta$ is the polar angle relative to the beam axis), and with energy greater than 50 MeV elsewhere. Neutral pions are formed from pairs of isolated photons with invariant mass within $2.5\sigma$ of the $\pi^0$ mass ($\sigma \approx 9$ MeV/$c^2$ for a $2.7$ GeV/$c$ $\pi^0$). We require at least one of the two photons forming a $\pi^0$ candidate to be in the central region of the calorimeter. The energies of the selected photons are then kinematically fitted with the mass constrained to the $\pi^0$ mass.

The $B$ decay candidates are selected using a beam-constrained $B$ mass $M = \sqrt{E_b^2 - p_B^2}$, where $E_b$ is the beam energy and $p_B$ is the $B$ candidate momentum, and an energy difference $\Delta E = E_1 + E_2 - E_{beam}$, where $E_1$ and $E_2$ are the energies of the two neutral

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1We assume equal branching fractions for $\Upsilon(4S) \rightarrow B^0\bar{B}^0$ and $B^+B^-$. 

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pions. The resolution in $M$ is about $3.4\,\text{MeV}/c^2$, due to equal contributions from the beam energy spread and the $\pi^0$ energy resolution. The resolution on $\Delta E$ is approximately $60\,\text{MeV}$ and is slightly asymmetric because of energy loss out of the back of the CsI crystals. Using events containing at least three charged tracks, we select $B$ candidates with $M$ in the range $5.2-5.3\,\text{GeV}/c^2$ and $|\Delta E| < 400\,\text{MeV}$. The fiducial region in $M$ and $\Delta E$ includes the signal region and a substantial sideband used for background normalization.

The main background arises from $e^+e^- \rightarrow q\bar{q}$ (where $q = u, d, s, c$). Such events typically exhibit a two-jet structure and can produce high momentum back-to-back particles (tracks and/or showers) in the fiducial region. To reduce contamination from these events, we calculate the angle $\theta_S$ between the sphericity axis [10] of the candidate showers and the sphericity axis of the rest of the event. The distribution of $\cos \theta_S$ is strongly peaked at $\pm 1$ for $q\bar{q}$ events, due to their two-jet structure, and is nearly flat for $B\bar{B}$ events. We require $|\cos \theta_S| < 0.8$ which eliminates 85% of the $q\bar{q}$ background. Using a detailed GEANT-based Monte Carlo simulation [11] we determined the overall $B^0 \rightarrow \pi^0\pi^0$ signal detection efficiency $E = 28.8\%$, dominated by geometric acceptance. Additional discrimination between signal and $q\bar{q}$ background (continuum) is obtained from event shape information used in a Fisher discriminant ($F$) technique as described in detail in Ref. [12]. The Fisher discriminant is used in the maximum-likelihood fit described below.

A total of 1134 $B^0 \rightarrow \pi^0\pi^0$ candidates are selected with the requirements described above. Figure 1 shows the $\Delta E$ versus $M$ distribution of all the selected events, and the individual distributions of $M$, $\Delta E$ and $F$, with restrictions on the other two variables to emphasize the signal region.

![Figure 1](image)

**FIG. 1.** Distributions of the selected events. a) $\Delta E$ versus $M$ for all selected events (only $|\cos \theta_S| < 0.8$ restriction is applied). The solid lines show the $2\sigma$ boundaries. b) $M$ distribution after $2\sigma$ requirements on $\Delta E$ and $F < 0.6$. c) $\Delta E$ distribution after $2\sigma$ requirements on $M$ and $F < 0.6$. d) $F$ after $2\sigma$ requirements on $\Delta E$ and $M$. The dotted line shows the position of the cut on $F$ for the other two variables. In plots b), c) and d), the solid line shows the result of the fit for signal and background, and the dashed line shows the contribution of the background alone.

Monte Carlo simulation was also used to study backgrounds from $b \rightarrow c$ and other $b \rightarrow u$
and $b \to s$ decays. More than 40 decay modes of the $B$ meson into final states containing energetic $\pi^0$s and/or photons were considered. Only the $B^+ \to \rho^+\pi^0$ decay channel was found to give a non-negligible contribution to the selection of $B^0 \to \pi^0\pi^0$ signal events. The three-body final state $\pi^+\pi^0\pi^0$ can be misidentified as a two-body $\pi^0\pi^0$ signal candidate when the charged pion from the asymmetric decay of the polarized $\rho^+$ has sufficiently low momentum and the $\pi^0$ energies are poorly measured. The best separation between this background and signal is obtained in the $\Delta E$ distribution. The $B^+ \to \rho^+\pi^0$ background is accounted for in the maximum-likelihood fit as described below.

To extract the signal yield, we perform an unbinned maximum-likelihood fit using the variables $M$, $\Delta E$, and $\mathcal{F}$ for each candidate event. The likelihood of an event is parameterized by the sum of probabilities of signal, $q\bar{q}$ background, and $B^+ \to \rho^+\pi^0$ background hypotheses, with relative weights determined by maximizing the likelihood function $\mathcal{L}$. The probability of a particular hypothesis is calculated as the product of the probability density functions (PDFs) for each of the input variables. Further details about the likelihood fit can be found in Ref. [12]. The PDFs for signal and $B^+ \to \rho^+\pi^0$ are determined from high-statistics Monte Carlo samples. The PDFs for continuum are obtained from the data taken below the $B\bar{B}$ threshold.

Monte Carlo experiments are generated to test the fitting procedure, and to produce frequentist confidence intervals as defined in Ref. [1]. We generate Monte Carlo samples containing the same number of events as the real data sample. Continuum events are generated according to the continuum PDFs, neglecting the small correlation between the fit variables. According to a given branching fraction $\mathcal{B}(B^0 \to \pi^0\pi^0)$, we include signal events randomly selected from our large $B^0 \to \pi^0\pi^0$ Monte Carlo simulated sample. We also include Monte Carlo simulated $B^+ \to \rho^+\pi^0$ events. We generate 1000 samples for several values of $\mathcal{B}(B^0 \to \pi^0\pi^0)$ and $\mathcal{B}(B^+ \to \rho^+\pi^0)$ in the range $0 - 10 \times 10^{-6}$ and $0 - 42 \times 10^{-6}$, respectively. We apply the fitting procedure to every sample individually and determine the signal yield distribution for each value of $\mathcal{B}(B^0 \to \pi^0\pi^0)$ and $\mathcal{B}(B^+ \to \rho^+\pi^0)$. In the samples containing $B^+ \to \rho^+\pi^0$ events, we find a small increase of the signal yield proportional to $\mathcal{B}(B^+ \to \rho^+\pi^0)$. At the 90% confidence level (C.L.) upper limit $\mathcal{B}(B^+ \to \rho^+\pi^0) < 42 \times 10^{-6}$ [13], the contribution to the signal yield is 0.3 event. We include this maximal contribution as a one-sided systematic uncertainty in the result. The Monte Carlo experiments show that once the $B^+ \to \rho^+\pi^0$ background is accounted for, the average yield for any value of $\mathcal{B}(B^0 \to \pi^0\pi^0)$ is equal to the expected yield for this branching fraction, excluding thus any significant bias from the fitting method. An estimation of the statistical sensitivity of the measurement is given by the width of the yield distributions, and is measured to be about $\pm 5$ events.

Figure 2 shows the 68%, 90%, 95%, and 99% frequentist confidence intervals (statistical only) built from the signal yield distributions obtained with $\mathcal{B}(B^+ \to \rho^+\pi^0) = 0$ and following the method described in Ref. [14].

Figure 3 shows the result of the likelihood fit as a plot of $\chi^2 - \chi^2_{\text{min}} = -2 \ln \mathcal{L}/\mathcal{L}_{\text{max}}$. The maximum likelihood $\mathcal{L}_{\text{max}}$ is found for a signal yield $N_S = 6.2^{+4.8}_{-3.7}$ events, with a statistical significance of 2.0 $\sigma$. We define the statistical significance to be $n\sigma$ if the value of $-2\ln \mathcal{L}$ increases by $n^2$ when the signal yield $N_S$ is constrained to be zero. The measured yield for $B^+ \to \rho^+\pi^0$ is $N_{\rho\pi} = -11 \pm 9$ events, consistent with the upper limit for that mode [13].

This yield should, however, not be used to calculate a new value of the upper limit for
FIG. 2. Frequentist confidence intervals for the branching fraction $B(B^0 \to \pi^0\pi^0)$ versus signal yield $N_S$, as determined from Monte Carlo experiments. No systematic effects are included. The vertical line indicates the likelihood fit result for $N_S$.

$B(B^+ \to \rho^+\pi^0)$, as the $\pi^0\pi^0$ analysis described here is deliberately designed to minimize sensitivity to the $B^+ \to \rho^+\pi^0$ mode. We also checked that, due to the small correlation between signal and background, the signal yield is reduced by only 0.2 event when the background yield is constrained to be positive. Given the measured value of $N_S$, we use Figure 2 to determine the frequentist confidence interval for $B(B^0 \to \pi^0\pi^0)$. We obtain the 90% C.L. interval $0.3 \times 10^{-6} < B(B^0 \to \pi^0\pi^0) < 5.2 \times 10^{-6}$. This interval is statistical only, and does not include systematic uncertainties.

For the treatment of systematic uncertainties, we separate them into two categories. First, we estimate a systematic uncertainty on the fitted signal yield by varying the PDFs used in the fit within their uncertainties, and we add in quadrature the previously described systematic uncertainty due to the possible residual contamination from $B^+ \to \rho^+\pi^0$ events. We also consider a possible mismodeling of the $e^+e^- \to \tau^+\tau^-$ contribution in the PDFs for continuum, and we assign a systematic uncertainty of ±0.7 event based on a high-statistics Monte Carlo simulation study. We obtain the total systematic uncertainty of 2.0 events on the signal yield $N_S$. Secondly, we estimate an uncertainty on the signal detection efficiency $E$, to account for uncertainties related to $\pi^0$ finding efficiency, maximum-likelihood fit efficiency, luminosity, Monte Carlo statistics, and the $|\cos\theta_S|$ requirement. The efficiency with its uncertainty is $E = (28.8 \pm 2.0)\%$.

We derive the central value of the branching fraction $B(B^0 \to \pi^0\pi^0) = (2.2^{+1.7+0.7}_{-1.3-0.7}) \times 10^{-6}$, where the first uncertainty is statistical and the second is systematic. We also calculate the 90% C.L. upper limit yield by integrating the likelihood function.
FIG. 3. Likelihood function $-2 \ln \mathcal{L}/\mathcal{L}_{\text{max}}$ versus $B^0 \to \pi^0\pi^0$ signal yield.

$$\frac{\int_0^{N_{UL}} \mathcal{L}_{\text{max}}(N) \, dN}{\int_0^\infty \mathcal{L}_{\text{max}}(N) \, dN} = 0.90,$$

where $\mathcal{L}_{\text{max}}$ is the maximum $\mathcal{L}$ at fixed $N$ to conservatively account for possible correlations among the free parameters in the fit. We obtain the upper limit $N_S < 13.7$ events at 90% C.L. (statistical). We then calculate the corresponding upper limit of the branching fraction, add one standard deviation of the systematic uncertainty, and obtain the branching fraction 90% C.L. upper limit $\mathcal{B}(B^0 \to \pi^0\pi^0) < 5.7 \times 10^{-6}$.

In summary, using the full CLEO II and CLEO II.V data set, we have obtained an improved upper limit on the branching fraction of the $B^0 \to \pi^0\pi^0$ decay mode. We see no indication for a signal and we set a new 90% C.L. upper limit $\mathcal{B}(B^0 \to \pi^0\pi^0) < 5.7 \times 10^{-6}$. This limit is in the range of the theoretical predictions and constrains some of them.

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