

DEUTSCHES ELEKTRONEN – SYNCHROTRON

DESY 91-076
SLAC-PUB-5449
July 1991



Search for D^0 and B^0 Decays into $\pi^0\pi^0$

CRYSTAL BALL Collaboration

ISSN 0418-9833

NOTKESTRASSE 85 · D-2000 HAMBURG 52

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We have searched for the decay modes $D^0 \rightarrow \pi^0 \pi^0$ and $B^0 \rightarrow \pi^0 \pi^0$ using data taken with the Crystal Ball detector at DORIS II. No evidence for these Cabibbo- and colour-suppressed decays was found, and 90% confidence level upper limits of $BR(D^0 \rightarrow \pi^0 \pi^0) < 3.8 \times 10^{-3}$ and $BR(B^0 \rightarrow \pi^0 \pi^0) < 4.6 \times 10^{-4}$ are given.

Search for D^0 and B^0 decays into $\pi^0 \pi^0$

The Crystal Ball Collaboration

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^{f)} Supported by the U.S. Department of Energy, contract No. DE-AC03-81ER40050
^{g)} and by the National Science Foundation, grant No. PHY78-22980
^{h)} Supported by the U.S. Department of Energy, contract No. DE-AC02-76ER03066
ⁱ⁾ Supported by the U.S. Department of Energy, contract No. DE-AC02-76ER03066
^{j)} Supported by the German Bundesministerium für Forschung und Technologie, contract No. 054 ER 12P
^{k)} Supported by the German Bundesministerium für Forschung und Technologie, contract No. 054 HH 11P(7)
^{l)} Supported by the U.S. Department of Energy, contract No. DE-AC02-76ER03064
^{m)} Supported by FOM-NWO
ⁿ⁾ Supported by the U.S. Department of Energy, contract No. DE-AC02-76ER03072
^{o)} and by the National Science Foundation, grant No. PHY82-08761
^{p)} Supported by the U.S. Department of Energy, contract No. DE-AC03-76SF00326
^{q)} and by the National Science Foundation, grant No. PHY80-07788
^{r)} Supported by the U.S. Department of Energy, contract No. DE-AC03-76SF00515
^{s)} Supported by the German Bundesministerium für Forschung und Technologie, contract No. 054 WU 11P(1)

Introduction

The decays of the lowest-lying mesons containing charm or bottom quarks, the D and B mesons, are mediated by the weak interaction. Studies of these decays are essential for testing the standard model and determining its quark mixing parameters [1]. A full understanding of the weak decays of these heavy mesons requires a detailed study of their exclusive decays. For most two-body decays satisfactory agreement of theoretical calculations [2] with experimental results is achieved, but some problems remain for the Cabibbo-suppressed channels. The ratio of Cabibbo-suppressed D^0 decays $\Gamma(D^0 \rightarrow K^+K^-)/\Gamma(D^0 \rightarrow \pi^+\pi^-)$ should be between 1 and 1.4 [2], while the experimental value is about 3 [3]. This difference could be due to SU(3) breaking and/or final-state interactions. A measurement of the decay $D^0 \rightarrow \pi^0\pi^0$ should help to determine which of these mechanisms is responsible [4].

Also of interest are B decays to non-charmed and non-strange states. To lowest order they depend on the Kobayashi-Maskawa matrix element $|V_{ub}|$ [1]. However, even with $|V_{ub}| = 0$, inelastic final-state-interactions can generate a non-zero amplitude for $B^0 \rightarrow \pi^+\pi^0$ and $B^0 \rightarrow \pi^+\pi^-$ [5]. This is not possible for $B^0 \rightarrow \pi^+\pi^0$. The knowledge of these three rates would thus help to elucidate the role of final-state interactions.

In this letter we present a search for the Cabibbo-suppressed decay modes $D^0 \rightarrow \pi^0\pi^0$ and $B^0 \rightarrow \pi^0\pi^0$ in data collected with the Crystal Ball detector from 1982 to 1986 at the e^+e^- storage ring DORIS II at DESY. The data sample for the D^0 study corresponds to an integrated luminosity \mathcal{L} of $(248 \pm 6) \text{ pb}^{-1}$ obtained on the $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(4S)$ resonances and in the nearby continua, the error on the luminosity is dominated by systematics [6]. For the B^0 study only the data taken on $\Upsilon(4S)$ are used. All events considered in the analysis passed the hadronic event-selection criteria described in Ref. [6].

The Crystal Ball detector [6, 7] is well-suited to detect π^0 mesons [8]. It consists of a spherical array of 672 NaI(Tl) crystals which cover 93% of the solid angle. Endcap arrays of NaI(Tl) crystals extend the solid angle coverage to 98%. The measured energy resolution for electromagnetically showering particles is $\sigma_E/E = (2.7 \pm 0.2)\%/\sqrt{E/\text{GeV}}$ and the polar angle resolution is between 1° and 3°, depending on the photon energy. The charged particles are detected by a set of four cylindrical double layers of proportional tubes surrounding the beam pipe (only three double layers for the first 1/4 of the data).

Given the granularity of the Crystal Ball calorimeter, π^0 mesons with an energy above about 500 MeV appear as one energy cluster since the showers from the two decay photons merge. An energy cluster is defined as a contiguous region of crystals where each crystal has more than 10 MeV of deposited energy E_i . Reconstruction of the high-energy π^0 's is based on the shape of the energy deposition. This is determined by the second moment S of the lateral energy distribution of the cluster [9], defined as

$$S = \frac{1}{E_c} \sum_i E_i (\bar{n}_i - \bar{c})^2 \quad (1)$$

where E_c is the sum of energies of crystals in the cluster, \bar{n}_i is the unit vector pointing from the interaction point to the center of the i^{th} crystal and \bar{c} is the vector pointing to the center of gravity of the cluster, $\bar{c} = (1/E_c) \sum_i \bar{n}_i E_i$. An energy-dependent cut on S (discussed below) is used to separate the wider π^0 showers from those due to single photons. The momentum vector of each π^0 is taken to be parallel to \bar{c} , and its energy is E_c corrected for lateral and longitudinal shower leakage, non-central hits and a small non-linearity [10].

Search for the decay $D^0 \rightarrow \pi^0\pi^0$

To search for the decay mode $D^0 \rightarrow \pi^0\pi^0$ we look for events in the hadronic event sample with merged π^0 's. As a merged π^0 candidate we accept any energy deposition without a correlated charged track, having an energy greater than 750 MeV and a polar angle θ with respect to the beam direction satisfying $|\cos\theta| < 0.85$. Fig. 1 shows the distribution of S vs. cluster energy for data and for Monte Carlo events (see below). As π^0 's we select energy depositions inside the polygon. Events with at least two merged π^0 's are accepted. For each $\pi^0\pi^0$ combination in the event the invariant mass is calculated.

To reduce combinatorial background two additional cuts are applied. We accept only D^0 candidates with $x_p > 0.5$, where $x_p = p(D^0)/\sqrt{E_{\text{beam}}^2 - m_{D^0}^2}$, E_{beam} is the beam energy, m_{D^0} is the nominal D^0 mass and $p(D^0)$ is the momentum of the $\pi^0\pi^0$ system. Accidental $\pi^0\pi^0$ combinations peak strongly at low values of x_p (Fig. 2), while D^0 's from continuum production have a hard fragmentation function [11, 12]. The second cut is on the distribution of $\cos\alpha$, where α is the angle between the π^0 direction in the D^0 rest frame and the D^0 direction in the laboratory frame, which should be isotropic. Because the distribution of random $\pi^0\pi^0$ combinations tends to peak at small forward and backward angles we require $|\cos\alpha| < 0.6$. The invariant mass spectrum for D^0 candidates is presented in Fig. 3. The distribution shows no signal in the D^0 mass region.

The efficiency of our D^0 reconstruction is estimated from Monte Carlo studies. The LUND 6.3 program version [13] is used to simulate the process $e^+e^- \rightarrow c\bar{c} \rightarrow D^0 + \text{anything}$, where one D^0 decays always into $\pi^0\pi^0$. The Peterson fragmentation function (with an ϵ parameter of 0.24), which well describes the D^0 data of Ref. [12], is used to generate the D^0 momentum distribution. The generated events are passed through a complete detector simulation, which uses the EGS3 program [14] for electrons and photons and the improved GHEISHA 6 program [15] for hadrons. The Monte Carlo events are then reconstructed with our standard software and subjected to the same cuts as the data. The $\pi^0\pi^0$ mass spectrum is fitted to obtain the number of reconstructed D^0 mesons. Divided by the number of generated $D^0 \rightarrow \pi^0\pi^0$ decays, this gives an efficiency of $\epsilon(D^0 \rightarrow \pi^0\pi^0) = (7.6 \pm 0.5 \pm 0.7)\%$, where the first error is statistical and the second is the systematic error, dominated by variations in the fit parameters.

To search for a possible D^0 signal we fit the spectrum shown in Fig. 3 with a Gaussian peak of width and mean fixed to the values obtained from the Monte Carlo simulation and a second order polynomial for the background. Including a third order polynomial results in a coefficient comparable with zero. This yields the number of detected D^0 events $N_{D^0} = (0 \pm 50)$. A systematic error has been derived from a variation in the Gaussian width and mean within their errors and a change in the fit range. We find changes of 11 events. This systematic error is combined quadratically with the statistical one. We convert this result to a 90% confidence level (CL) upper limit on the product of the D^0 production cross-section and the branching ratio

$$\sigma_{D^0} \times BR(D^0 \rightarrow \pi^0\pi^0) = \frac{N_{D^0}}{\epsilon(D^0 \rightarrow \pi^0\pi^0) \mathcal{L}} \quad (2)$$

This is accomplished [16] by numerically integrating the likelihood function for that quantity taking into account the errors in the efficiency, number of D^0 's and the luminosity. We get

$$\sigma_{D^0} \times BR(D^0 \rightarrow \pi^0\pi^0) < 4.5 \text{ pb}. \quad (3)$$

To extract from this an upper limit on $BR(D^0 \rightarrow \pi^0 \pi^0)$, we assume that half of all produced D mesons are D^0 's and estimate the continuum D^0 production cross-section as

$$\sigma_{D^0} \cong (4/10) \times \bar{\sigma}_{tot}(c^+ c^- \rightarrow \text{hadrons}), \quad (4)$$

where $\bar{\sigma}_{tot}$ is the luminosity-averaged continuum hadronic cross-section for our data sample. We use also the fact that all D^0 's resulting from decays of B mesons produced at the $\Upsilon(4S)$ resonance are eliminated by the cut on x_p because their momentum distribution is much softer as was shown in Ref. [12]. With those assumptions we get

$$BR(D^0 \rightarrow \pi^0 \pi^0) < 3.8 \times 10^{-3}. \quad (5)$$

This result is consistent with values obtained by the Crystal Ball at SPEAR [17]. $BR(D^0 \rightarrow \pi^0 \pi^0) < 3.0 \times 10^{-3}$, and by CLEO [3] $BR(D^0 \rightarrow \pi^0 \pi^0) < 4.6 \times 10^{-3}$. Several groups [3, 18, 19, 20] have observed the decay $D^0 \rightarrow \pi^+ \pi^-$. The most recent result obtained by CLEO [3] is $BR(D^0 \rightarrow \pi^+ \pi^-) = (2.1 \pm 0.3 \pm 0.2 \pm 0.3) \times 10^{-3}$, where the third error is due to the uncertainty in the $D^0 \rightarrow K^+ K^-$ branching ratio. This value is consistent with theoretical predictions [2]. The branching ratio to $\pi^0 \pi^0$ is predicted to be ten times smaller [3].

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

We search for the exclusive channel $B^0 \rightarrow \pi^0 \pi^0$ in the hadronic event sample taken on the $\Upsilon(4S)$ resonance, which corresponds to a luminosity of 76 pb^{-1} . The number of observed $B\bar{B}$ events $N_{B\bar{B}}$ is found by comparing the observed hadronic cross-section in the $\Upsilon(4S)$ data with that in 18.5 pb^{-1} of data taken in the nearby continuum. Assuming that charged and neutral B mesons are produced with equal probability, we find for the number of observed neutral B mesons $N_{B^0} = N_{B\bar{B}} = (60260 \pm 1100)$ [6]. The efficiency of our hadronic selection for $B\bar{B}$ events was also shown in Ref. [6] to be $\epsilon_{had} = (92.0 \pm 0.5 \pm 0.9)\%$.

In order to suppress continuum hadron production compared to resonance production and to reduce background due to $\pi^+ \pi^-$ pairs we require the event multiplicity (the number of local maxima of energy depositions in the calorimeter) to be larger than five. We select events with two high energy π^0 's ($2.2 - 3.0 \text{ GeV}$) with an opening angle of $\cos \beta < -0.98$. They have to be observed as neutral clusters with the second moment S consistent with a π^0 [9]. Only one event from the $\Upsilon(4S)$ sample survives this selection. It has a cluster multiplicity of six and a $\pi^0 \pi^0$ invariant mass of $5314 \text{ MeV}/c^2$. This one event corresponds to a 90% CL upper limit of 3.9 events.

To determine the efficiency of the selection of a $\pi^0 \pi^0$ pair we simulate $\Upsilon(4S)$ decay to $B\bar{B}$ pairs, where one B^0 meson always decays into a $\pi^0 \pi^0$ pair [13]. This gives an efficiency of $\epsilon(B^0 \rightarrow \pi^0 \pi^0) = (13.6 \pm 0.4 \pm 0.3)\%$. A 90% CL upper limit on the branching ratio is then calculated by numerical integrating the likelihood function for the quantity

$$BR(B^0 \rightarrow \pi^0 \pi^0) < \frac{N_{\pi^0 \pi^0} / \epsilon(B^0 \rightarrow \pi^0 \pi^0)}{N_{B^0} / \epsilon_{had}}, \quad (6)$$

taking into account the errors on the efficiencies and on the number of B^0 mesons N_{B^0} [16]. This yields the upper limit for the branching ratio of

$$BR(B^0 \rightarrow \pi^0 \pi^0) < 4.6 \times 10^{-4} \text{ at } 90\% \text{ CL}. \quad (7)$$

For comparison, the CLEO [21] and ARGUS [22] collaborations searched for the B^0 decay mode into $\pi^+ \pi^-$ and have set upper limits (90% CL) of $BR(B^0 \rightarrow \pi^+ \pi^-)$ of 0.9×10^{-4} and 1.3×10^{-4} , respectively, assuming that 43% (50%, respectively) of $\Upsilon(4S)$ decays are $B^0 \bar{B}^0$.

In conclusion, we have searched for the Cabibbo-suppressed decay modes of D^0 and B^0 mesons into $\pi^+ \pi^-$. We find no evidence for these final states and set an upper limit at 90% CL of 3.8×10^{-3} for $BR(D^0 \rightarrow \pi^0 \pi^0)$ and 4.6×10^{-4} for $BR(B^0 \rightarrow \pi^0 \pi^0)$.

Acknowledgements

We would like to thank the DESY and SLAC directorates for their support. This experiment would not have been possible without the dedication of the DORIS-machine group as well as the experimental support groups at DESY. Those of us from abroad wish to thank the DESY laboratory for the hospitality extended to us while working at DESY.

Z.J., T.L., B.Muryn, and G.N. thank DESY for financial support. D.W. acknowledges support from the National Science Foundation. E.D.B., R.H., and K.S. have benefited from financial support from the Humboldt Foundation. K.Königsmanacknowledges support from the Heisenberg Foundation.

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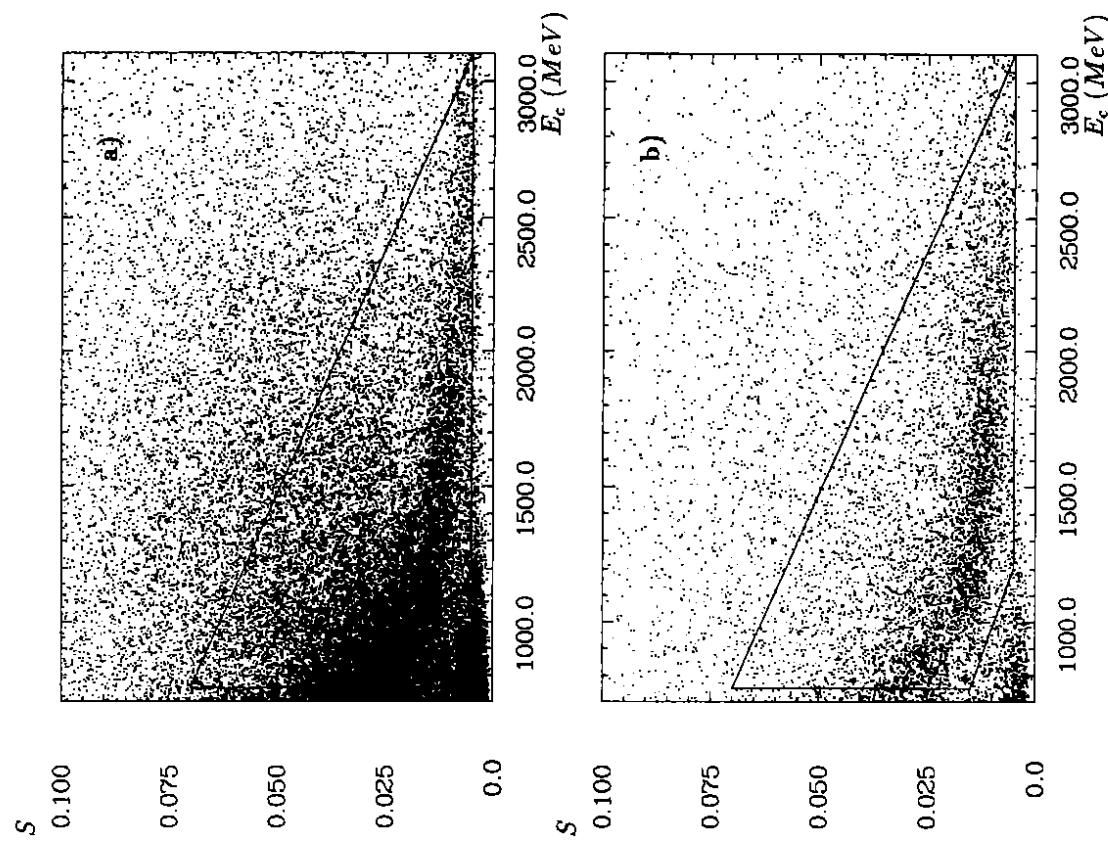


Figure 1: The distribution of the second moment S vs cluster energy E_c for data (a) and Monte Carlo (b). The accepted merged π^0 candidates lie inside the polygon.

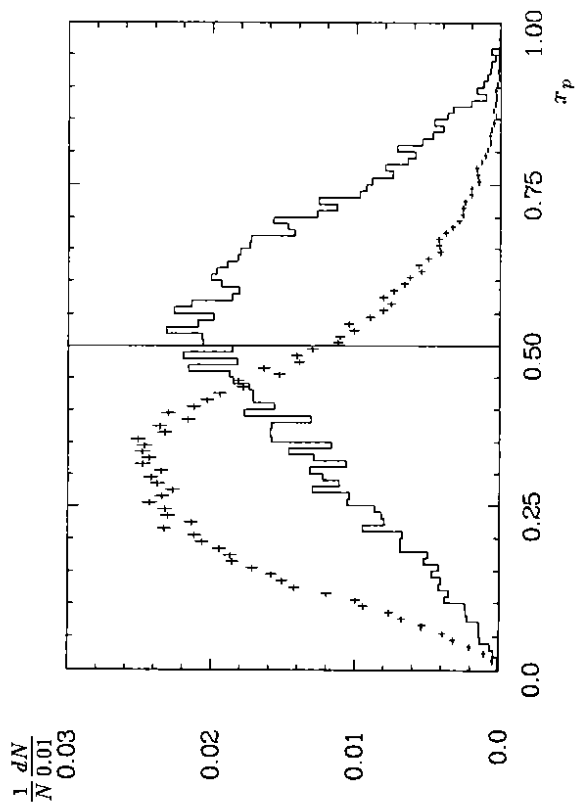


Figure 2: The n_p distribution for data (crosses) and Monte Carlo (solid line). Accepted events are to the right of the solid line.

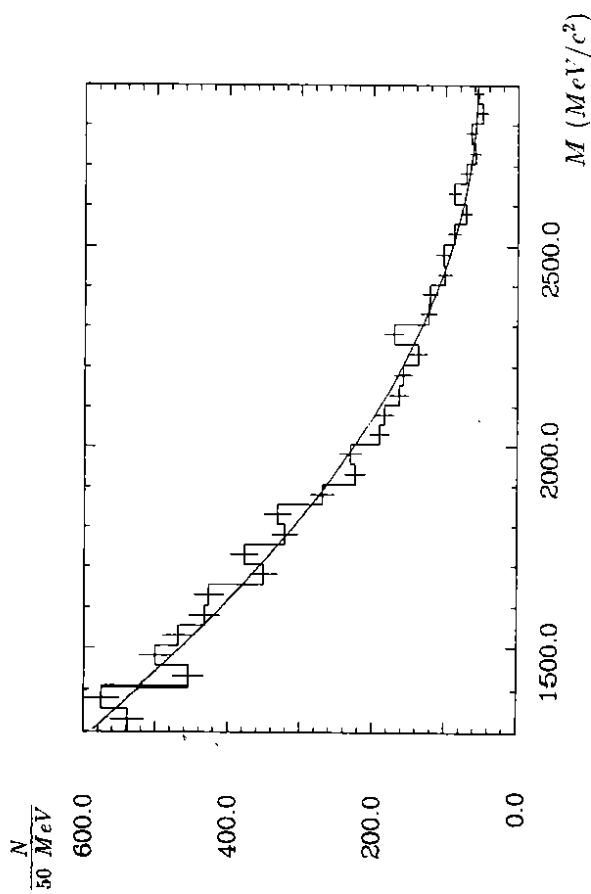


Figure 3: The distribution of the $\pi^0\pi^0$ invariant mass for D^0 candidates. The solid line shows a fit to the distribution with a Gaussian and polynomial background.