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

S. Villa, K. Abe, I. Adachi, H. Aihara, Y. Asano, T. Aushev, S. Bahinipati, A. M. Bakich, V. Balagura, E. Barberio, A. Bay, I. Bedny, K. Belous, U. Bitenc, I. Bizjak, A. Bondar, A. Bozek, M. Bračko, Y. Chao, Y. Choi, A. Clavikov, S. Cole, J. Daleno, M. Danilov, A. Drutskoy, S. Eidelman, N. Gabyshev, A. Garmash, Y. Gershon, G. Golkrho, B. Golob, J. Haba, T. Haraj, K. Hayasaka, M. Hazumi, L. Hinz, T. Hokue, Y. Hoshi, S. Hou, K. Ikado, A. Imoto, K. Inami, R. Itoh, M. Iwasaki, Y. Iwasaki, C. Jacoby, J. H. Kang, P. Kapusta, T. Kawasaki, H. R. Khan, H. Kichimi, S. K. Kim, S. M. Kim, K. Kinoshita, S. Korpar, P. Krokovny, R. Kulasiri, C. C. Kuo, A. Kuzmin, Y.-J. Kwon, G. Leder, T. Lesiak, S.-W. Lin, S. M. Kim, T. Lesiak, D. Mohapatra, Y. Hoshi, C. Jacoby, K. Trabelsi, G. Gokhroo, T. Okabe, M. Danilov, K. Abe, R. Pestotnik, L. E. Piilonen, Y. Sakai, N. Sato, N. Satoyama, T. Schietinger, O. Schneider, C. Schwanda, R. Seidl, K. Senyo, M. E. Sevior, M. Shapkin, H. Shibuya, A. Somov, N. Soni, R. Stamen, S. Stanič, M. Starić, T. Sumiyoshi, K. Tamaï, N. Tamura, M. Tanaka, G. N. Taylor, Y. Teramoto, X. C. Tian, K. Trabelsi, T. Tsukamoto, S. Uehara, T. Uglov, K. Ueno, S. Uno, P. Urquijo, G. Varner, K. E. Varvell, C. C. Wang, C. H. Wang, Y. Watanabe, L. M. Zhang, J. Ying, L. Zhang, Z. P. Zhang, M. Zhang, J. Z. Zhang, and D. Zürcher

The Belle Collaboration

1 Budker Institute of Nuclear Physics, Novosibirsk
2 Chonnam National University, Kwangju
3 University of Cincinnati, Cincinnati, Ohio 45221
4 University of Hawaii, Honolulu, Hawaii 96822
5 High Energy Accelerator Research Organization (KEK), Tsukuba
6 Institute of High Energy Physics, Chinese Academy of Sciences, Beijing
7 Institute of High Energy Physics, Vienna
8 Institute of High Energy Physics, Protvino
9 Institute for Theoretical and Experimental Physics, Moscow
10 J. Stefan Institute, Ljubljana
11 Kanagawa University, Yokohama
12 Korea University, Seoul
13 Swiss Federal Institute of Technology of Lausanne, EPFL, Lausanne
14 University of Ljubljana, Ljubljana
15 University of Maribor, Maribor
16 University of Melbourne, Victoria
17 Nagoya University, Nagoya
18 Nara Women’s University, Nara
19 National Central University, Chung-li
20 National United University, Miaoli
21 Department of Physics, National Taiwan University, Taipei
22 H. Niewodniczanski Institute of Nuclear Physics, Krakow
23 Niigata University, Niigata
24 Nova Gorica Polytechnic, Nova Gorica
25 Osaka City University, Osaka
26 Osaka University, Osaka
27 Panjab University, Chandigarh
28 Peking University, Beijing
29 Princeton University, Princeton, New Jersey 08544
30 RIKEN BNL Research Center, Upton, New York 11973
31 University of Science and Technology of China, Hefei
32 Seoul National University, Seoul
33 Shinshu University, Nagano
The rare decay $B^0 \to \gamma \gamma$ is searched for in 104 $fb^{-1}$ of data, corresponding to $111 \times 10^6$ $B\overline{B}$ pairs, collected with the Belle detector at the KEKB asymmetric-energy $e^+e^-$ collider. No evidence for the signal is found, and an upper limit of $6.2 \times 10^{-7}$ at 90% confidence level is set for the corresponding branching fraction.

PACS numbers: 13.20.He, 14.40.Nd

The channel $B^0 \to \gamma \gamma$ is a rare decay of the $B^0$ meson that is interesting both experimentally, for its remarkably clean signature, and theoretically, as a tool for constraining physics beyond the Standard Model (SM). The SM prediction for the $B^0 \to \gamma \gamma$ branching fraction (BF) is around $3 \times 10^{-8}$, and a possible Feynman diagram contributing to this channel is shown in Fig. 1. Sizable enhancements of the BF are predicted in many new physics models; a typical contribution arising from non-SM effects would follow from the replacement of the $W$ boson in Fig. 1 with another charged particle such as a charged Higgs boson. The $B^0 \to \gamma \gamma$ channel is also interesting because it allows the study of non-trivial QCD dynamics in $B$ decay, via a pure non-hadronic final state.

Experimental limits on the BF have been set by L3 and BaBar. The BaBar upper limit of $1.7 \times 10^{-6}$ at 90% confidence level (CL), obtained with 19.4 $fb^{-1}$ of data, is the most restrictive existing experimental constraint on this channel.

The present search for the $B^0 \to \gamma \gamma$ decay is based on a data sample of 104 $fb^{-1}$, which contains $111 \times 10^6$ $B\overline{B}$ pairs, collected with the Belle detector at the KEKB asymmetric-energy $e^+e^-$ (3.5 on 8 GeV) collider operating at the $\Upsilon(4S)$ resonance.

The Belle detector is a large-solid-angle magnetic spectrometer that consists of a 4-layer silicon vertex detector, a small-cell inner drift chamber, a 47-layer central drift chamber, an array of aerogel threshold Cerenkov counters, a barrel-like arrangement of time-of-flight scintillation counters, and an electromagnetic calorimeter comprised of CsI(Tl) crystals located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented to detect $K^0_L$ mesons and to identify muons. The detector is described in detail elsewhere.

The $B^0 \to \gamma \gamma$ events are characterized in the center-of-mass (CM) frame by two back-to-back highly energetic photons. Photons are selected from isolated clusters in the calorimeter that are not matched to charged tracks. We require a shower shape consistent with that of a photon: for each cluster, the ratio of the energy deposited in the array of the central $3 \times 3$ calorimeter cells to that of $5 \times 5$ cells is computed, and clusters with a ratio smaller than 0.95 are rejected.

In the Belle detector, a large background for this channel is due to the overlap of a hadronic event with energy deposits left in the calorimeter by previous QED interactions (mainly Bhabha scattering). Such composite events are completely removed using timing information for calorimeter clusters associated with the candidate photons. Only photons that are in time with the rest of the event are retained. The efficiency of this selection on signal events is larger than 99.5%. The cluster timing information is stored in the raw data, and is available in the reduced format used for analyses only for data processed after the summer of 2004, thus limiting the dataset available for this analysis to 104 $fb^{-1}$.

Rejection of $\pi^0$ and $\eta$ mesons is of primary importance in a search for a purely radiative rare decay of the $B^0$ meson. All pairs of photons with energy larger than 50 MeV are retained.

FIG. 1: A possible diagram contributing to $B^0 \to \gamma \gamma$ at the lowest order in the SM. The exchange of a charged Higgs boson instead of the $W$ boson could contribute to this process in some extensions of the SM.
corresponding to about two standard deviation intervals above and below the central values just mentioned.

The main background for the $B^0 \rightarrow \gamma \gamma$ channel is due to continuum events, mostly coming from light quark pair production and fragmentation ($u\bar{u}$, $d\bar{d}$, and $s\bar{s}$, $u\bar{d}$ for short). Two variables that display quite powerful separation between signal and continuum background are a Fisher discriminant based on modified Fox-Wolfram moments and the $B^0$ production angle with respect to the beam in the CM frame, $\cos \theta_B$. These variables are combined in a likelihood ratio, $LR$; signal and background distributions used to construct the $LR$ are extracted from Monte Carlo (MC) samples. In the continuum background, the two particles that are reconstructed as photons are more abundantly produced at low polar angle ($\theta^*$, measured in the CM frame), while the signal photons have a flat distribution in $\cos \theta^*$. Selection requirements on LR ($LR > 0.92$) and on the cosine of the polar angle of the most energetic photon in the event ($|\cos \theta^*| < 0.65$) are optimized by maximizing $N_{\text{sig}}/\sqrt{N_{\text{sig}} + N_{\text{bck}}}$, where $N_{\text{sig}}$ ($N_{\text{bck}}$) is the expected number of signal (background) events in the signal window. The expected numbers of events are computed for an integrated luminosity of 104 fb$^{-1}$ and assuming for the signal the BF predicted by the SM and for the background the prediction of the continuum MC. The above requirements reduce the continuum background in the signal window by a factor of 55, while retaining 31% of signal events.

The total selection efficiency for signal, evaluated using MC events, is 11.7%. In data, seven events lie in the signal window. They are shown in the $\Delta E$-$M_{bc}$ plane in Fig. 2, where the signal window is represented as a solid-border rectangle.

Exclusive backgrounds coming from rare $B$ decays have been studied by means of large MC samples and only two channels have been found to give non-negligible contributions within the signal window: $B^0 \rightarrow \pi^0 \pi^0$ and $B^0 \rightarrow \eta \pi^0$. Assuming the measured $B^0 \rightarrow \pi^0 \pi^0$ branching fraction, $\text{BF}(B^0 \rightarrow \pi^0 \pi^0) = 1.45 \pm 0.29 \times 10^{-6}$, and the existing limit on the $B^0 \rightarrow \eta \pi^0$ branching fraction, $\text{BF}(B^0 \rightarrow \eta \pi^0) < 2.5 \times 10^{-6}$ at 90% CL, 0.09 $B^0 \rightarrow \pi^0 \pi^0$ events and less than 0.06 $B^0 \rightarrow \eta \pi^0$ events at 90% CL are expected.

A two-dimensional extended unbinned maximum likelihood fit is performed on $\Delta E$ and $M_{bc}$ to extract the signal yield. The probability density functions (PDFs) for the signal are extracted from the MC simulation. The photon energy resolution in the simulation is corrected to match the resolution measured in a photon test beam. The signal PDFs are parametrized with a Crystal Ball lineshape function for $\Delta E$ and a double Gaussian for $M_{bc}$.

For the continuum background, a linear shape is assumed for $\Delta E$, with the slope free to float in the fit, and an ARGUS function for $M_{bc}$, with the slope parameter also free in the fit. The exclusive backgrounds enter the fit with the normalization described above. They are parametrized with a Gaussian PDF for $\Delta E$ and a double Gaussian for $M_{bc}$.

The fit has four free parameters: two slopes and the numbers of events of the continuum background and of the signal. It is performed within the $\Delta E$ range between $-0.7$ GeV and 0.6 GeV and with $M_{bc}$ greater than 5.2 GeV/c$^2$. The fit window is shown in Fig. 2 as a dashed rectangle. The projections of the fit result on $\Delta E$ (with $M_{bc}$ in its signal window) and on $M_{bc}$ (with $\Delta E$ in its signal window) are shown in Fig. 3 as solid curves; the continuum background is shown as dashed curves, the signal as the dark shaded regions, and the exclusive backgrounds as the light shaded regions.

The signal yield is measured to be $N_{\text{sig}} = 1.8^{+3.5}_{-2.7}$, cor...
responding to a limit on the BF of $6 \times 10^{-7}$ at $90\%$ CL, obtained by integration of the likelihood curve up to $90\%$ of its total area, and including only the statistical uncertainty.

Several possible sources of systematic uncertainty are considered. Uncertainties are included in the likelihood function as additional parameters and then integrated over their respective ranges by assuming Gaussian probability distributions. The largest contribution is due to the modelling of the signal shape, which depends on angular and energy resolutions of the calorimeter. Uncertainties on these quantities, evaluated by studying samples of Bhabha and $e^+ e^- \to \gamma \gamma$ events, have been propagated to the parameters of the signal PDFs and to the fit result. Other contributions are the uncertainties on the photon reconstruction efficiency, on event selection (LR and $\cos \theta^*$ requirements, $\pi^0$ and $\eta$ mesons rejection), on the number of $B \bar{B}$ events, on background shapes, and on the normalization of the exclusive backgrounds. The separate contributions are summarized in Table I as uncertainties on the signal yield.

TABLE I: Summary of the main systematic sources, expressed as uncertainties on the fit signal yield.

| Source                        | Syst. unc. on $N_{sig}$ |
|-------------------------------|-------------------------|
| Signal shape                  | 0.37                    |
| Photon rec. efficiency        | 0.09                    |
| LR and $\cos \theta^*$ req.  | 0.06                    |
| $\pi^0$ and $\eta$ vetoes     | 0.05                    |
| Number of $B \bar{B}$ events  | 0.03                    |
| Background shape and norm.    | 0.02                    |

Inclusion of systematic uncertainties results in the following upper limit on the BF:

$$BF(B^0 \to \gamma \gamma) < 6.2 \times 10^{-7} \text{ at } 90\% \text{ CL}.$$ 

In conclusion, a search for the decay $B^0 \to \gamma \gamma$ has been performed in $104 \text{ fb}^{-1}$ of data with the Belle detector. No evidence of a signal has been observed and a new upper limit has been set, corresponding to an improvement of the previous limit of about a factor of three.

We thank the KEKB group for the excellent operation of the accelerator, the KEK cryogenics group for the efficient operation of the solenoid, and the KEK computer group and the National Institute of Informatics for valuable computing and Super-SINET network support. We acknowledge support from the Ministry of Education, Culture, Sports, Science, and Technology of Japan and the Japan Society for the Promotion of Science; the Australian Research Council and the Australian Department of Education, Science and Training; the National Science Foundation of China and the Knowledge Innovation Program of Chinese Academy of Sciences; the German Ministry of Education and Research; the CNRS/IN2P3 and the Ministry of Education and Research of France, the Swiss National Science Foundation; the Ministry of Education, Science and Technology of the Republic of Slovenia; the Swiss National Science Foundation; the National Science Council and the Ministry of Education of Taiwan; and the U.S. Department of Energy.

[1] S.W. Bosch and G. Buchalla, JHEP 0208, 54 (2002) arXiv:hep-ph/0208202 and references therein.
[2] For a review see The Discovery Potential of a Super B Factory, Proceedings of the 2003 SLAC Workshops, SLAC-R-709, p. 60. See also: T.M. Aliev and G. Turan, Phys. Rev. D 48, 1176 (1993); G.G. Devidze and G.R. Jibuti, Phys. Lett. B 429, 48 (1998); G. Devidze, A. Liparteliani and Ulf-G. Meißner, Phys. Lett. B 634, 59 (2006).
[3] M. Acciarri et al. (L3 Collaboration), Phys. Lett. B 363, 137 (1995).
[4] B. Aubert et al. (BaBar Collaboration), Phys. Rev. Lett. 87, 241803 (2001).
[5] S. Kurokawa and E. Kikutani, Nucl. Instr. and Meth. A 499, 1 (2003), and other papers included in this volume.
[6] Y. Ushiroda (Belle SVD2 group), Nucl. Instr. and Meth. A 511, 6 (2003).
[7] A. Abashian et al. (Belle Collaboration), Nucl. Instr. and Meth. A 479, 117 (2002).
[8] S. Eidelman et al. (Particle Data Group), Phys. Lett. B 592, 1 (2004).
[9] The Fox-Wolfram moments were introduced in G. C. Fox and S. Wolfram, Phys. Rev. Lett. 41, 1581 (1978). The Fisher discriminant used by Belle, based on modified Fox-Wolfram moments, is described in K. Abe et al. (Belle et al.)
Collaboration), Phys. Rev. Lett. 87, 101801 (2001) and K. Abe et al. (Belle Collaboration), Phys. Lett. B 511, 151 (2001).

[10] E. Barberio et al. (Heavy Flavour Averaging Group), arXiv:hep-ex/0603003 and online update available at http://www.slac.stanford.edu/xorg/hfag.

[11] H. Ikeda et al., Nucl. Instr. and Meth. A 441, 401 (2000).

[12] J.E. Gaiser et al. (Crystal Ball Collaboration), Phys. Rev. D 34, 711 (1986).

[13] H. Albrecht et al. (ARGUS Collaboration), Phys. Lett. B 241, 278 (1990).