Search for a light CP-odd Higgs boson and low-mass dark matter at the Belle experiment

I. S. Seong, 18 S. E. Vahsen, 18 I. Adachi, 19, 16 H. Aihara, 87 S. Al Said, 81, 38 D. M. Asner, 4 V. Aulchenko, 5, 68 T. Aushev, 9, 66 R. Ayad, 81 V. Babu, 82 A. M. Bakich, 80 V. Bansal, 70 P. Behera, 27 V. Bhardwaj, 23 B. Bhuyan, 25 T. Bilka, 6 J. Biswal, 34 A. Bobrov, 5, 68 G. Bonvicini, 91 A. Bozek, 64 M. Bračko, 50, 34 T. E. Broader, 18 L. Cao, 35 D. Červenkov, 6 P. Chang, 63 V. Chekelián, 51 A. Chen, 61 B. G. Cheon, 17 K. Chilikin, 45 K. Cho, 39 Y. Choi, 79 S. Choudhury, 26 D. Cinabro, 91 S. Cunliffe, 9 N. Dash, 24 S. Di Carlo, 43 J. Dingfelder, 3 T. V. Dong, 19, 16 S. Eidelman, 5, 68, 45 D. Epifanov, 5, 68 J. E. Fast, 70 A. Frey, 15 B. G. Fulsom, 70 R. Garg, 71 V. Gaur, 90 N. Gabyshev, 5, 68 A. Garmash, 5, 68 M. Gelb, 95 A. Giri, 26 P. Goldenzweig, 35 B. Golob, 46, 34 E. Guido, 32 J. Haba, 19, 16 K. Hayasaka, 66 H. Hayashii, 60 M. T. Hedges, 18 T. Higuchi, 36 W.-S. Hou, 63 C.-L. Hsu, 80 K. Huang, 63 T. Iijima, 58, 57 K. Inami, 57 G. Inguglia, 9 A. Ishikawa, 85 R. Itoh, 19, 16 M. Iwasaki, 69 Y. Iwasaki, 9 W. Jacobs, 28 H. B. Jeon, 42 S. Jia, 2, 7, 87 D. Joffe, 37 K. K. Joo, 7 T. Julius, 52 A. B. Kaliyar, 27 G. Karyan, 9 T. Kawasaki, 94 H. Kichimi, 19 C. Kiesling, 51 D. Y. Kim, 77 J. B. Kim, 40 K. T. Kim, 40 S. H. Kim, 17 K. Kinoshita, 8, P. Kodys, 6, S. Korpar, 59, 34 D. Kotchetkov, 18 P. Križan, 46, 34 R. Kroeger, 53 P. Krokovny, 5, 68 T. Kuhr, 47 T. Kumita, 89 A. Kuzmin, 5, 68 Y. -J. Kwon, 93 J. S. Lange, 13 I. S. Lee, 17 S. C. Lee, 52 L. K. Li, 29 Y. B. Li, 72 L. Li Gioi, 51 J. Libby, 27 D. Liventsev, 90, 19 M. Lubej, 34 T. Luo, 12 C. MacQueen, 52 M. Masuda, 86 T. Matsuda, 54 M. Merola, 31, 59 K. Miyabayashi, 60 H. Miyata, 66 R. Mizuk, 45, 55, 56 G. B. Mohanty, 82 T. Morii, 57 R. Mussa, 32 E. Nakano, 69 M. Nakao, 19, 16 T. Nanut, 34 K. J. Nath, 25 M. Nayak, 91, 19 M. Niyama, 41 N. K. Nisar, 73 S. Nishida, 19, 16 K. Nishimura, 18 S. Ogawa, 84 H. Ono, 65, 66 W. Ostrowicz, 64 P. Pakhlov, 45, 55 G. Pakhlova, 45, 56 B. Pal, 9 H. Park, 12 T. K. Pedlar, 48 R. Pestotnik, 34 L. E. Piilonen, 80 E. Prencipe, 21 M. Ritter, 47 A. Rostomyan, 9 G. Russo, 31 Y. Sakai, 19, 16 M. Salehi, 49, 47 S. Sandilya, 8 L. Santelj, 19 T. Sanuki, 85 V. Savinov, 73 O. Schneider, 44 G. Schnell, 1, 22 J. Schneler, 18 C. Schwanda, 30 Y. Seino, 66 K. Senyo, 92 O. Seon, 57 M. E. Sevior, 52 C. P. Shen, 2 T.-A. Shibata, 88 J.-G. Shiu, 63 F. Simon, 51, 83 E. Solovieva, 45, 56 S. Stanič, 67 M. Starić, 34 M. Sumihama, 14 T. Sumiyoshi, 89 W. Sutchiel, 35 M. Takizawa, 76, 20, 74 K. Tanida, 33 F. Tchetchova, 52 K. Trabelsi, 19, 16 M. Uchida, 88 T. Uglow, 45, 56 Y. Unno, 17 S. Uno, 19, 16 Y. Usov, 5, 68 C. Van Hulse, 1 R. Van Tonder, 35 G. Varner, 18 A. Vinokurova, 5, 68 A. Vossen, 10 B. Wang, 8 C. H. Wang, 62 P. Wang, 29 M. Watanabe, 66 S. Watanuki, 85 E. Widmann, 78 E. Won, 40 H. Yamamoto, 85 H. Ye, 9 J. Yelton, 11 C. Z. Yuan, 29 Y. Yusa, 66 S. Zakharov, 45, 56 Z. P. Zhang, 75 V. Zhilich, 5, 68 V. Zhukova, 45, 55 V. Zhulanov, 5, 68 and A. Zupanc 46, 34

(The Belle Collaboration)

1 University of the Basque Country UPV/EHU, 48080 Bilbao
2 Beihang University, Beijing 100191
3 University of Bonn, 53115 Bonn
4 Brookhaven National Laboratory, Upton, New York 11973
5 Budker Institute of Nuclear Physics SB RAS, Novosibirsk 630090
6 Faculty of Mathematics and Physics, Charles University, 121 16 Prague
7 Chonnam National University, Kwangju 660-701
8 University of Cincinnati, Cincinnati, Ohio 45221
9 Deutsches Elektronen-Synchrotron, 22607 Hamburg
10 Duke University, Durham, North Carolina 27708
11 University of Florida, Gainesville, Florida 32611
12 Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) and Institute of Modern Physics, Fudan University, Shanghai 200443
13 Justus-Liebig-Universität Giessen, 35392 Giessen
14 Gifu University, Gifu 501-1193
15 II. Physikalisches Institut, Georg-August-Universität Göttingen, 37073 Göttingen
16 SOKENDAI (The Graduate University for Advanced Studies), Hayama 240-0193
17 Hanyang University, Seoul 133-791
18 University of Hawaii, Honolulu, Hawaii 96822
19 High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801
20 J-PARC Branch, KEK Theory Center, High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801
21 Forschungszentrum Jülich, 52425 Jülich
22 IKERBASQUE, Basque Foundation for Science, 48013 Bilbao
Indian Institute of Science Education and Research Mohali, SAS Nagar, 140306
Indian Institute of Technology Bhubaneswar, Satya Nagar 751007
Indian Institute of Technology Guwahati, Assam 781039
Indian Institute of Technology Hyderabad, Telangana 502285
Indian Institute of Technology Madras, Chennai 600036
Indian University, Bloomington, Indiana 47408
Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049
Institute of High Energy Physics, Vienna 1050
INFN - Sezione di Napoli, 80126 Napoli
INFN - Sezione di Torino, 10125 Torino
Advanced Science Research Center, Japan Atomic Energy Agency, Naka 319-1195
J. Stefan Institute, 1000 Ljubljana
Institute for Experimentelle Teilchenphysik, Karlsruher Institut für Technologie, 76131 Karlsruhe
Kavli Institute for the Physics and Mathematics of the Universe (WPI), University of Tokyo, Kashiwa 277-8583
Department of Physics, King Abdulaziz University, Jeddah 21589
Korea Institute of Science and Technology Information, Daegu 305-806
Korea University, Seoul 136-713
Kyungpook National University, Daegu 702-701
LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay
École Polytechnique Fédérale de Lausanne (EPFL), Lausanne 1015
P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow 119991
Faculty of Mathematics and Physics, University of Ljubljana, 1000 Ljubljana
Ludwig Maximilians University, 80539 Munich
Luther College, Decorah, Iowa 52101
University of Malaya, 50603 Kuala Lumpur
University of Maribor, 2000 Maribor
Maz-Planck-Institut für Physik, 80805 München
School of Physics, University of Melbourne, Victoria 3010
University of Mississippi, University, Mississippi 38677
University of Miyazaki, Miyazaki 889-2192
Moscow Physical Engineering Institute, Moscow 115409
Moscow Institute of Physics and Technology, Moscow Region 141700
Graduate School of Science, Nagoya University, Nagoya 464-8602
Kobayashi-Maskawa Institute, Nagoya University, Nagoya 464-8602
Università di Napoli Federico II, 80055 Napoli
Nara Women's University, Nara 630-8506
National Central University, Chung-li 32054
National United University, Miaoli 36003
Department of Physics, National Taiwan University, Taipei 10617
H. Niewodniczanski Institute of Nuclear Physics, Krakow 31-342
Nippon Dental University, Niigata 951-8580
Niigata University, Niigata 950-2181
University of Nova Gorica, 5000 Nova Gorica
Novosibirsk State University, Novosibirsk 630090
Osaka City University, Osaka 558-8585
Pacific Northwest National Laboratory, Richland, Washington 99352
Panjab University, Chandigarh 160014
Peking University, Beijing 100871
University of Pittsburgh, Pittsburgh, Pennsylvania 15260
Theoretical Research Division, Nishina Center, RIKEN, Saitama 351-0198
University of Science and Technology of China, Hefei 230026
Showa Pharmaceutical University, Tokyo 194-8543
Soongsil University, Seoul 156-743
Stefan Meyer Institute for Subatomic Physics, Vienna 1090
Sungkyunkwan University, Suwon 440-746
School of Physics, University of Sydney, New South Wales 2006
Department of Physics, Faculty of Science, University of Tabuk, Tabuk 71451
Tata Institute of Fundamental Research, Mumbai 400005
Excellence Cluster Universe, Technische Universität München, 85748 Garching
Toho University, Funabashi 274-8510
Department of Physics, Tohoku University, Sendai 980-8578
We report on the first Belle search for a light CP-odd Higgs boson, $A^0$, that decays into low mass dark matter, $\chi$, in final states with a single photon and missing energy. We search for events produced via the dipion transition $\Upsilon(2S) \rightarrow \gamma \pi^+ \pi^-$, followed by the on-shell process $\Upsilon(1S) \rightarrow \gamma A^0$ with $A^0 \rightarrow \chi \chi$; or by the off-shell process $\Upsilon(1S) \rightarrow \gamma \chi \chi$. Utilizing a data sample of $157.3\times10^6 \Upsilon(2S)$ decays, we find no evidence for a signal. We set limits on the branching fractions of such processes in the mass ranges $M_{A^0} < 8.97$ GeV/$c^2$ and $M_\chi < 4.44$ GeV/$c^2$. We then use the limits on the off-shell process to set competitive limits on WIMP-nucleon scattering in the WIMP mass range below 5 GeV/$c^2$.

PACS numbers: 13.25.Gv, 14.80.Da, 95.35.+d

Identifying the nature of dark matter (DM) is a long-standing yet unsolved problem in astronomy and particle physics. DM may consist of weakly interacting massive particles (WIMPs), which are postulated in popular extensions of the standard model (SM) [1]. Numerous experiments aim to directly detect WIMPs, but no clear evidence has emerged to date. WIMPs are generally expected to have masses in the $100$ GeV/$c^2$ to $1$ TeV/$c^2$ range, but there are also scenarios with DM particle masses below $100$ GeV/$c^2$ [2–4]. Such low mass DM particles, $\chi$, can be produced in interactions of SM particles through the exchange of a CP-odd Higgs boson $A^0$ [4–5], which is part of the Next-to-Minimal Supersymmetric Model (NMSSM) [6]. Searches for low mass DM particles from $\Upsilon$ decays at collider experiments have been discussed in Refs. [7] [8]. A typical collider detector would be insensitive to DM particles in the final state without additional constraints. However, at a B factory, such invisible decays can still be measured by utilizing the dipion transition $\Upsilon(2S) \rightarrow \pi^+ \pi^- \Upsilon(1S)$, which enables us to tag $\Upsilon(1S)$ mesons without reconstructing them. Since the mass of the $A^0$ is unknown, we consider two processes: the on-shell process $\Upsilon(1S) \rightarrow \gamma A^0$ with $A^0 \rightarrow \chi \chi$; and the off-shell process $\Upsilon(1S) \rightarrow \gamma \chi \chi$. The SM process $\Upsilon(1S) \rightarrow \gamma \nu \bar{\nu}$ has the same final state as the signal, but is predicted to have a branching fraction (BF) $B(\Upsilon(1S) \rightarrow \gamma \nu \bar{\nu})$ of the order of $10^{-9}$ [3], which is three orders of magnitude below our experimental sensitivity. The most stringent existing upper limits on the processes considered here were set by the BaBar experiment: $B(\Upsilon(1S) \rightarrow \gamma A^0) \times B(A^0 \rightarrow \chi \chi) < (1.9 - 37)\times10^{-6}$ for $M_{A^0} < 9.0$ GeV/$c^2$ and $B(\Upsilon(1S) \rightarrow \gamma \chi \chi) < (0.5 - 24)\times10^{-5}$ for $M_\chi < 4.5$ GeV/$c^2$ [9], both at 90% confidence level (C.L.).

This analysis uses a data sample with an integrated luminosity of $24.9$ $fb^{-1}$, corresponding to $(157.3 \pm 3.6)\times10^6 \Upsilon(2S)$ decays [10], collected with the Belle detector [11] at the KEKB $e^+e^-$ asymmetric-energy collider [12]. We generate one million Monte Carlo (MC) simulated events for each of the on-shell and the off-shell processes, the on-shell process with 20 different values of the $A^0$ mass, $M_{A^0}$, and the off-shell process with 10 different values of the $\chi$ mass, $M_\chi$. The $A^0$ in the on-shell process is assumed to have zero spin while the off-shell process is modeled with a phase space distribution. In this paper, we do not assume a specific model for the $A^0$ and $\chi$. The $\Upsilon(2S) \rightarrow \pi^+ \pi^- \Upsilon(1S)$ transition is simulated using the EvtGen model to describe the decays of a vector particle to a vector particle and two pions [13].

Both signal processes produce only three detectable particles: two charged pions, which have low transverse momentum; and a photon that deposits energy in the electromagnetic calorimeter (ECL). The small number of charged tracks and their low momenta are difficult to trigger on, thus the main level-1 (L1) triggers used are related to the ECL. Instead of using all possible L1 triggers in this analysis, we only use the two highest-efficiency L1 triggers, which require the total deposited energy in the ECL to be larger than 1.0 GeV with a cosmic ray veto applied and larger than 3.0 GeV without the veto. This choice reduces the systematic uncertainty on the L1 trigger efficiency. The signal trigger efficiency is a function of photon energy. In the energy region from 0.5 to 5 GeV, our L1 trigger requirements reduce the signal efficiency by less than 15%. In the energy region below 0.5 GeV, the efficiency is greatly reduced, but even when using all available triggers, the efficiency is below 3%. Therefore, we avoid the regions of lowest trigger efficiency by restricting our search to the range $M_{A^0} < 8.97$ GeV/$c^2$ and $M_\chi < 4.44$ GeV/$c^2$.

We require exactly two oppositely charged tracks originating from the interaction point (IP) with impact parameters within $\pm 4.0$ cm along the beam axis and 2.0 cm in the transverse plane. These two charged tracks...
are identified as pions by requiring the likelihood ratio
$\mathcal{L}_\pi / (\mathcal{L}_\pi + \mathcal{L}_K)$, where $\mathcal{L}_\pi$ and $\mathcal{L}_K$ are the likelihood
with a pion and kaon hypothesis, respectively. The like-
lihood uses information from the central drift chamber
(CDC), time-of-flight scintillation (TOF) counters, and
aerogel Cherenkov counters (ACC), and the ratio is re-
quired to be larger than 0.6. To suppress contamination
from electrons, we further require an electron identifica-
tion, which is a similar likelihood ratio derived mainly
from ECL information, to be less than 0.1. We estimate
from MC that 90% of signal candidate events contain a
pair of correctly reconstructed pions. Fake pions origi-
nate from muons (< 6.4% of tracks), electrons (< 3.8%),
and protons (< 0.2%). The tagged charged pion candi-
dates are mostly identified using CDC information only
due to the low transverse momenta of the tracks, hence
resulting in higher fake rates in comparison to those in
generic hadronic events triggered by Belle. The high-
est energy photon in the center-of-mass (CM) frame is
chosen as the photon candidate in each event. This pho-
ton is required to have energy in the $\Upsilon(1S)$ frame, $E_\gamma > 0.15 \text{ GeV}$, must lie in the polar angle range
$-0.63 < \cos(\theta) < 0.84$ of the ECL, must hit more than 2
calorimeter crystals, and have an energy-deposit ratio in
3×3 over 5×5 crystals around the shower center greater
than 0.9.

The invariant recoil mass of the dipion system is de-
ened as $M^2_{\text{recoil}} = s + M^2_{\pi\pi} - 2\sqrt{s} E^*\pi\pi$, where $\sqrt{s} = 10.02 \text{ GeV}/c^2$ is the $\Upsilon(2S)$ resonance energy, $M_{\pi\pi}$ is the
invariant mass of the dipion system, and $E^*\pi\pi$ is the
energy of the dipion system in the CM frame of the
$\Upsilon(2S)$. The recoil mass is required to be between
$9.450 \pm 0.005 \text{ GeV}$ and $9.475 \pm 0.005 \text{ GeV}$, which corresponds to the $\Upsilon(1S)$ mass [11]. The vertex of the two pions is re-
quired to be near the IP with $\chi^2/n.d.f. < 11$ from the
vertex-constrained fit, and an opening angle of the dip-
ion system in the $\Upsilon(1S)$ frame larger than 45°.

The angle between the candidate photon and each charged
track in the lab frame must satisfy $\cos(\theta_{\pi\gamma}) < 0.97$
to reject photons due to bremsstrahlung and final-state
radiation, while the azimuthal angle difference between
the dipion system and the candidate photon must satisfy
$\cos(\phi_{\pi\gamma} - \phi_\gamma) < 0.97$, to suppress QED background
processes, such as $e^+e^- \rightarrow \gamma \pi^+\pi^-$. Neutral hadrons may pass these selections, thus we also
require that the energy of the second-highest-energy
photon in the CM frame and the remaining energy in the
ECL both be less than 0.18 GeV. To suppress events
with a long-lived particle in the direction opposite to the
candidate photon, we define the absolute azimuthal angle
difference between a candidate photon and a candidate
long-lived particle as $|180° - \phi_\gamma - \phi_{\text{long}}|$, where the long-
lived $K_L$ candidate is in the direction opposite to the
photon. This absolute value of the angle difference is
required to be larger than 20°. This selection rejects
54% of $\Upsilon(1S) \rightarrow \gamma K_L K_L$, 98% of $\Upsilon(1S) \rightarrow \gamma f_2^*(1525)$,
and 95% of $\Upsilon(1S) \rightarrow \gamma f_2^*(1270)$ events.

The selection criteria described above are optimized
with the figure of merit $S/\sqrt{B}$, where $S$ and $B$ are the
numbers of signal and expected background events, re-
spectively, after applying all selections except the se-
lection being evaluated. The signal efficiency ranges from
0.001% to 14% for the on-shell signal and from 0.0007%
to 9.4% for the off-shell signal. The lowest efficiencies cor-
respond to the highest $M_A$ and $M_{\chi}$, respectively. The
efficiency drop is due to the reduced trigger efficiency for
low energy photons.

Irreducible background from the $\Upsilon(2S)$ resonance is
studied using a sample of $400 \times 10^6 \Upsilon(2S)$ inclusive MC
events, and categorized into three event types: tau-pair
production $\Upsilon(2S) \rightarrow \tau^+\tau^-$, leptonic decays $\Upsilon(1S) \rightarrow l^+l^-$, and hadronic decays $\Upsilon(1S) \rightarrow \gamma hh$. Taus can
decay to charged pions and a tau neutrino, thus the slow
candidates in such decays can pass the selection cri-
teria. Leptons $l$ and hadrons $h$ can escape the detector
along the beam pipe, so that we only tag the two charged
dips from the dipion transition and a photon. The lep-
tonic decay backgrounds do not produce a peak in the
$E_\gamma$ spectrum, but the hadronic decay backgrounds can
produce such a peak. Both types of backgrounds peak in
the $M_{\text{recoil}}$ distribution. The background contributions
from these backgrounds are predicted to be: $3.5 \pm 1.2$
events from $\Upsilon(2S) \rightarrow \tau^+\tau^-$ decays, $20.0 \pm 2.8$ events
from leptonic decays, and $1.2 \pm 0.7$ events from hadronic
decays. Continuum backgrounds are studied with an off-
resonance data set collected about 60 MeV below the
$\Upsilon(4S)$ resonance. This sample corresponds to an in-
tegrated luminosity of 40.41 fb$^{-1}$; we do not observe any
significant peaking backgrounds.

To search for a signal after the event selection, we use
the two observables $M_{\text{recoil}}$ and $E_\gamma$. We construct prob-
bility density functions (PDFs) for signal and for back-
ground from the $\Upsilon(2S)$ by using MC samples. Continuum
background PDFs are created from $M_{\text{recoil}}$ sideband reg-
ions in the $\Upsilon(2S)$ on-resonance data. The recoil mass for
the $\Upsilon(2S)$ on-resonance is described with a double-sided
Crystal Ball (CB) function [13], and continuum in the
recoil mass distribution is described with a second-order
Chebyshev polynomial. The bias in the $E_\gamma$ spectrum
from the trigger efficiency is accounted for by multi-
plying the $E_\gamma^*$ PDFs by a parameterization of the trigger
efficiency as a function of $E_\gamma^*$. The on-shell process $E_\gamma^*$ PDF is described with a CB
function, and the off-shell process is described with a cus-
to broad distribution function [16]. Each parameter of
the $E_\gamma^*$ PDF is extracted separately for the assumed val-
es of $M_A$ and $M_{\chi}$; these parameterized functions are
used to search for a peak in the $E_\gamma^*$ spectrum. An exponen-
tial function is used for leptonic decay backgrounds,
and a Gaussian function is used for hadronic decay back-
grounds. Continuum backgrounds are described with the
sum of an exponential function and a Gaussian function.
Tau-pair production from the $\Upsilon(2S)$ does not peak either in the recoil mass distribution nor in the photon energy spectrum; therefore, we combine $\Upsilon(2S) \to \tau^+\tau^-$ events and continuum backgrounds. The shape parameters of the recoil mass PDF are determined by using $\Upsilon(1S) \to \mu^+\mu^-$ data.

We perform an unbinned extended log-likelihood fit in the two-dimensional ($M_{\text{recoil}}, E_{\text{c}}^*$) space to estimate the yields of different event types. The fit is repeated for each possible signal mass value. We fix all shape parameters of the PDFs. Instead of floating three background yields, we combine the two $\Upsilon(1S)$ background PDFs as $P_{\Upsilon(1S)} \propto f_{\text{fit}} P_0 + (1 - f_{\text{fit}}) P_{hh}$, where $P_0$ and $P_{hh}$ are the PDFs of the leptonic and hadronic decay backgrounds and $f_{\text{fit}}$ is the fraction of leptonic decay backgrounds, respectively. We use a fixed value of $f_{\text{fit}} = 0.933 \pm 0.034$, obtained from the $\Upsilon(2S)$ inclusive MC sample. To maximize the likelihood function and obtain signal yields, we vary two background yields and one signal yield, $N_{\text{cont}}, N_{\Upsilon(1S)}$, and $N_{\text{sig}}$.

We search for a signal peak in the $E_{\text{c}}^*$ and the $M_{\text{recoil}}$ distributions, in the mass ranges $0 < M_{A^0} < 8.97 \text{ GeV}/c^2$ (on-shell process) and $0 < M_{A^0} < 4.44 \text{ GeV}/c^2$ (off-shell process) by repeating the extended log-likelihood fit for each value of $M_{A^0}$ or $M_{\chi}$. For the on-shell case, we scan the photon energy in 353 steps that correspond to half the photon energy resolution, and step size in the range from 25 MeV to 4.0 MeV. For the off-shell case, we use 45 $M_{\chi}$ scan points with a fixed step size of 100 MeV. If the likelihood fit finds $N_{\text{sig}} > 0$, we compute the signal significance $S = \sqrt{2 \ln(L_{\text{max}}/L_0)}$, where $- \ln L_{\text{max}}$ is the negative log-likelihood value at the minimum and $- \ln L_0$ is the minimum value for the background-only hypothesis. We perform the mass scans and observe the largest local significance. The largest local significance for the off-shell case is 1.4σ at $M_{\chi} = 4.2 \text{ GeV}/c^2$. We observe no statistically significant signal and compute an upper limit (UL) at 90% C.L. on the signal yield ($N_{\text{UL}}$) by integrating the likelihood function $\int_{N_{\text{UL}}}^{N_{\text{UL}}} L(N_{\text{sig}}) dN_{\text{sig}} = 0.9 \int_{0}^{\infty} L(N_{\text{sig}}) dN_{\text{sig}}$. The systematic uncertainty is accounted for in the limit calculation by convolving the likelihood with a Gaussian function, which has a width equal to the total systematic uncertainty. The upper limits (90% C.L.) on the BF of the on-shell and the off-shell signals are then given by $N_{\text{UL}}/(N_{\Upsilon(2S)} \times B(\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-) \times \epsilon)$, where $\epsilon$ is the signal efficiency.

Several sources of systematic uncertainties are included in the upper limits on the BF. For most scan points, the observed yield $N_{\text{sig}}$ is small, thus multiplicative signal uncertainties do not have a significant effect. The leading sources of systematic uncertainties are due to fit bias and PDF shape parameters. The systematic uncertainty due to the BF of the dipion transition is estimated to be 1.46% based on Ref. [14], and the uncertainty due to the number of $\Upsilon(2S)$ events is 2.3%. The uncertainty in the tracking efficiency for tracks with angles and momenta characteristic of signal events is about 1.4% per track. The photon reconstruction contributes an additional 3.0% uncertainty. Systematic uncertainties on the signal efficiency range from 0.2% to 0.7% at $M_{A^0} \leq 8.5 \text{ GeV}/c^2$ and from 0.7% to 30% at $8.5 < M_{A^0} < 8.97 \text{ GeV}/c^2$ for the on-shell signal; and from 0.3% to 0.8% at $M_{\chi} \leq 4.0 \text{ GeV}/c^2$ and from 0.8% to 38% at $4.0 < M_{\chi} < 4.44 \text{ GeV}/c^2$ for the off-shell signal. The uncertainty in the L1 trigger efficiency is estimated to be 13.5% by comparing the relative efficiency of the two L1 triggers in experiment against the same quantity in MC. A possible bias in the fit is checked for by using toy MC samples, for the same values of $M_{A^0}$ or $M_{\chi}$ used to generate the signal MC samples. For each signal mass, a toy MC is generated using the background and signal PDFs. The number of background events in the toy MC is obtained from the background-only fit to the $\Upsilon(2S)$ on-resonance data and it is generated following the Poisson distribution. The signal yield is varied from zero to 11 events. For each signal mass and each signal yield, we generate 1000 toy MC events. We observe a fit bias of 0.001 for the on-shell signal and observe a bias that...
depends on $M_\chi$ for the off-shell signal. The largest fit bias for the off-shell process, 3.6 events, occurs at $M_\chi \approx 3.5$ GeV/$c^2$, which corresponds to a photon energy range $1 < E_\gamma^* < 2$ GeV. In this range, the leptonic decay background influences the measured signal yield. Therefore, we assign a systematic uncertainty due to fit bias that varies with $M_\chi$ for the off-shell signal, and assign a 0.001 event systematic uncertainty for the on-shell signal. Systematic uncertainties due to the PDF shapes are estimated by refitting with the shape parameters and the predicted $f_\mu$ varied within their uncertainties. The continuum shape in the recoil mass distribution is also refit with a first-order Chebyshev polynomial function. We repeat the likelihood scan for each variation of this kind, and add in quadrature all of the resulting variations in the fitted yield at that signal mass. The largest systematic uncertainty of shape parameters is 2.5 and 2.8 events for the on-shell and the off-shell signal, respectively. We quote fit variation uncertainties depending on $M_{A^0}$ and $M_\chi$.

The estimated systematic uncertainty is included in the likelihood and we obtain the 90% C.L. upper limits on $B(\Upsilon(1S) \rightarrow \gamma A^0) \times B(A^0 \rightarrow \chi\chi)$ and $B(\Upsilon(1S) \rightarrow \gamma\chi\chi)$ shown in Fig. 2. For the on-shell process, we achieve slightly better sensitivity in the low mass region than the BaBar result, and comparable or worse sensitivity in the high mass region. This low sensitivity is due to the lower trigger efficiency of Belle in that mass region. For the off-shell process, we achieve better limits than BaBar for all masses. Our limits are dominated by statistical uncertainties. The limit on the BF of the off-shell process can be converted into a WIMP-nucleon scattering cross section limit by using the procedure in Ref. [17]. The off-shell process generated in this analysis corresponds to the S1 operator in Ref. [17], and we set new spin-independent (SI) WIMP-nucleon cross section limits, shown in Fig. 3. We place one set of limits assuming that the WIMP couples to all quarks, and another set of limits assuming it couples to $b$-quarks only. These limits extend down into the interesting low-mass WIMP region unreachable by currently running direct detection experiments. It should be noted that these limits are valid regardless of whether the CP-odd light Higgs exists, but they do assume the existence of some new spin-zero boson, because the S1 operator is used to set the limit.

To conclude, we have performed the first Belle search for the on-shell process, $\Upsilon(1S) \rightarrow \gamma A^0$ with $A^0 \rightarrow \chi\chi$, and the off-shell process, $\Upsilon(1S) \rightarrow \gamma\chi\chi$, and have set upper limits on the branching fractions at 90% C.L. in the mass ranges $0 < M_{A^0} < 8.97$ GeV/$c^2$ and $0 < M_\chi < 4.44$ GeV/$c^2$. Our results improve on the existing limits from BaBar, mainly for the off-shell case. We have used the Belle branching fraction limit on the off-shell process to set new limits on the SI WIMP-nucleon scattering cross section. We uniquely constrain the low mass dark matter region where direct detection experiments do not yet have sensitivity, under the general assumption that a new spin-zero boson exists. We expect that this work can be extended significantly in the near future by using data from the Belle II experiment, which is currently being commissioned [29], and by searching for WIMPs assuming other contact operators, as discussed in Ref. [17].

We thank the KEKB group for excellent operation of the accelerator; the KEK cryogenics group for efficient solenoid operations; and the KEK computer group, the NII, and PNNL/EMSL for valuable computing and SINET5 network support. We acknowledge support from MEXT, JSPS and Nagoya’s TLPRC (Japan); ARC (Australia); FWF (Austria); NSFC and CCEPP (China); MSMT (Czechia); CZF, DFG, EXC153, and VS (Germany); DST (India); INFN (Italy); MOE, MSIP, NRF, RSRI, FLRFAS project and GSDC of KISTI (Korea); MNISW and NCN (Poland); MSHE under contract 14.W03.31.0026 (Russia); ARRS (Slovenia); IKERBASQUE and MINECO (Spain); SNSF (Switzerland); MOE and MOST (Taiwan); and DOE and NSF (USA).
are also shown.

GeNT [26], DAMA/LIBRA [27], and CDMS II (Silicon) [28] are the upper limits obtained by assuming the WIMP couples to all quarks and only b-quarks, respectively. The 90% C.L. exclusion limits of LUX [18], CRESST II [19], SuperCDMS [20], and ATLAS [21,22] and CMS [23,24] are shown for reference; and the 90% C.L. signal regions of CRESST II [25], CoGeNT [26], DAMA/LIBRA [27], and CDMS II (Silicon) [28] are also shown.

FIG. 3. WIMP-nucleon spin-independent scattering cross-section limits at 90% C.L. The black solid and dashed curves are the upper limits obtained by assuming the WIMP couples to all quarks and only b-quarks, respectively. The 90% C.L. exclusion limits of LUX [18], CRESST II [19], SuperCDMS [20], and ATLAS [21,22] and CMS [23,24] are shown for reference; and the 90% C.L. signal regions of CRESST II [25], CoGeNT [26], DAMA/LIBRA [27], and CDMS II (Silicon) [28] are also shown.

[1] G. L. Kane and M. Shifman, The supersymmetric world: The beginning of the theory, Singapore, Singapore: World Scientific (2000) 271.

[2] D. B. Kaplan, Phys. Rev. Lett. 68, 741 (1992) doi:10.1103/PhysRevLett.68.741.

[3] D. E. Kaplan, M. A. Luty and K. M. Zurek, Phys. Rev. D 79, 115016 (2009) doi:10.1103/PhysRevD.79.115016 [arXiv:0901.4117 [hep-ph]].

[4] J. F. Gunion, D. Hooper and B. McElrath, Phys. Rev. D 73, 015011 (2006) doi:10.1103/PhysRevD.73.015011 [hep-ph/0509024].

[5] K. Petraki and R. R. Volkas, Int. J. Mod. Phys. A 28, 1330028 (2013) doi:10.1142/S0217751X13300287 [arXiv:1305.4939 [hep-ph]].

[6] U. Ellwanger, C. Hugonie and A. M. Teixeira, Phys. Rept. 496, 1 (2010) doi:10.1016/j.physrep.2010.07.001 [arXiv:0910.1785 [hep-ph]].

[7] P. Fayet, Phys. Rev. D 74, 054034 (2006) doi:10.1103/PhysRevD.74.054034 [hep-ph/0607318].

[8] G. K. Yeghiyan, Phys. Rev. D 80, 115019 (2009) doi:10.1103/PhysRevD.80.115019 [arXiv:0909.4919 [hep-ph]].

[9] P. del Amo Sanchez et al. [BaBar Collaboration], Phys. Rev. Lett. 107, 021804 (2011) doi:10.1103/PhysRevLett.107.021804 [arXiv:1007.4646 [hep-ex]].

[10] J. Brodzicka et al. [Belle Collaboration], PTEP 2012, 04D001 (2012) doi:10.1093/ptep/pts072 arXiv:1212.5342 [hep-ex].

[11] A. Abashian et al. (Belle Collab.), Nucl. Instr. and Meth. A 479, 117 (2002).

[12] T. Abe et al., Prog. Theor. Exp. Phys. 2013, 03A001 (2013).

[13] D. J. Lange, Nucl. Instrum. Meth. A 462, 152 (2001).

[14] C. Patrignani et al. [Particle Data Group], Chin. Phys. C 100001 (2016) doi:10.1088/1674-1137/40/10/100001.

[15] M. J. Oreglia, Ph.D. Thesis, report SLAC-R-236 (1980), Appendix D.

[16] I. Seong, Ph.D Thesis, report KEK-BF-BELLE (2017).

[17] N. Fernandez, I. Seong and P. Stengel, Phys. Rev. D 93, 054023 (2016) doi:10.1103/PhysRevD.93.054023 [arXiv:1511.03728 [hep-ph]].

[18] D. S. Akribis et al. [LUX Collaboration], Phys. Rev. Lett. 118, 021303 (2017) doi:10.1103/PhysRevLett.118.021303 [arXiv:1608.07468 [astro-ph.CO]].

[19] G. Angloher et al. [CRESST Collaboration], Eur. Phys. J. C 76, 25 (2016) doi:10.1140/epjc/s10052-016-3877-3 [arXiv:1509.01515 [astro-ph.CO]].

[20] R. Agnese et al. [SuperCDMS Collaboration], Phys. Rev. Lett. 112, 241302 (2014) doi:10.1103/PhysRevLett.112.241302 [arXiv:1402.7137 [hep-ex]].

[21] G. Aad et al. [ATLAS Collaboration], Phys. Rev. D 91, 012008 (2015) Erratum: [Phys. Rev. D 92, 059903 (2015)] doi:10.1103/PhysRevD.92.059903, 10.1103/PhysRevD.91.012008 [arXiv:1411.1559 [hep-ex]].

[22] G. Aad et al. [ATLAS Collaboration], Eur. Phys. J. C 75, 299 (2015) Erratum: [Eur. Phys. J. C 75, no. 9, 408 (2015)] doi:10.1140/epjc/s10052-015-3517-3, 10.1140/epjc/s10052-015-3639-7 [arXiv:1502.01518 [hep-ex]].

[23] V. Khachatryan et al. [CMS Collaboration], Phys. Lett. B 755, 102 (2016) doi:10.1016/j.physletb.2016.01.057 [arXiv:1410.8812 [hep-ex]].

[24] V. Khachatryan et al. [CMS Collaboration], Eur. Phys. J. C 75, 235 (2015) doi:10.1140/epjc/s10052-015-3451-4 [arXiv:1408.3583 [hep-ex]].

[25] G. Angloher et al., Eur. Phys. J. C 72, 1971 (2012) doi:10.1140/epjc/s10052-012-1971-8 [arXiv:1109.0702 [astro-ph.CO]].

[26] C. E. Aalseth et al., arXiv:1401.6234 [astro-ph.CO].

[27] C. Savage, G. Gelmini, P. Gondolo and K. Freese, JCAP 0904, 010 (2009) doi:10.1088/1475-7516/2009/04/010 arXiv:0908.3607 [astro-ph].

[28] R. Agnese et al. [CDMS Collaboration], Phys. Rev. Lett. 111, 251301 (2013) doi:10.1103/PhysRevLett.111.251301 [arXiv:1304.4279 [hep-ex]].

[29] P. M. Lewis et al., doi:10.1016/j.nima.2018.05.071 arXiv:1802.01366 [physics.ins-det]].