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Observation of Photon Polarization in the $b \to s\gamma$ Transition

R. Aaij et al.*
(LHCb Collaboration)

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This Letter presents a study of the flavor-changing neutral current radiative $B^+ \to K^+\pi^-\pi^+\gamma$ decays performed using data collected in proton-proton collisions with the LHCb detector at 7 and 8 TeV center-of-mass energies. In this sample, corresponding to an integrated luminosity of $3\,\text{fb}^{-1}$, nearly $14,000$ signal events are reconstructed and selected, containing all possible intermediate resonances with a $K^+\pi^-\pi^+$ final state in the [1.1, 1.9] GeV/$c^2$ mass range. The distribution of the angle of the photon direction with respect to the plane defined by the final-state hadrons in their rest frame is studied in intervals of $K^+\pi^-\pi^+$ mass and the asymmetry between the number of signal events found on each side of the plane is obtained. The first direct observation of the photon polarization in the $b \to s\gamma$ transition is reported with a significance of $5.2\sigma$. The standard model (SM) predicts that the photon emitted from the electroweak penguin loop in $b \to s\gamma$ transitions is predominantly left-handed, since the recoiling $s$ quark that couples to a $W$ boson is left-handed. This implies maximal parity violation up to small corrections of the order $m_s/m_b$. While the measured inclusive $b \to s\gamma$ rate [1] agrees with the SM calculations, no direct evidence exists for a nonzero photon polarization in this type of decay. Several extensions of the SM [2], compatible with all current measurements, predict that the photon acquires a significant right-handed component, in particular, due to the exchange of a heavy fermion in the penguin loop [3].

This Letter presents a study of the radiative decay $B^+ \to K^+\pi^-\pi^+\gamma$, previously observed at the $B$ factories with a measured branching fraction of $(27.6 \pm 2.2) \times 10^{-6}$ [1,4,5]. The inclusion of charge-conjugate processes is implied throughout. Information about the photon polarization is obtained from the angular distribution of the photon direction with respect to the normal to the plane defined by the momenta of the three final-state hadrons in their center-of-mass frame. The shape of this distribution, including the up-down asymmetry between the number of events with the photon on either side of the plane, is determined. This investigation is conceptually similar to the historical experiment that discovered parity violation by measuring the up-down asymmetry of the direction of a particle emitted in a weak decay with respect to an axial vector [6]. In $B^+ \to K^+\pi^-\pi^+\gamma$ decays, the up-down asymmetry is proportional to the photon polarization $\lambda_\gamma$ [7,8] and therefore measuring a value different from zero corresponds to demonstrating that the photon is polarized.

The currently limited knowledge of the structure of the $K^+\pi^-\pi^+$ mass spectrum, which includes interfering kaon resonances, prevents the translation of a measured asymmetry into an actual value for $\lambda_\gamma$.

The differential $B^+ \to K^+\pi^-\pi^+\gamma$ decay rate can be described in terms of $\theta$, defined in the rest frame of the final state hadrons as the angle between the direction opposite to the photon momentum $\vec{p}_\gamma$ and the normal $\vec{n}_s \times \vec{p}_{\pi,\text{fast}}$ to the $K^+\pi^-\pi^+$ plane, where $\vec{p}_{\pi,\text{slow}}$ and $\vec{p}_{\pi,\text{fast}}$ correspond to the momenta of the lower and higher momentum pions, respectively. Following the notation and developments of Ref. [7], the differential decay rate of $B^+ \to K^+\pi^-\pi^+\gamma$ can be written as a fourth-order polynomial in $\cos \theta$:

$$\frac{d\Gamma}{dsds_1ds_2ds_3d\cos \theta} \propto \sum_{i=0,2,4} a_i(s,s_1,s_2,s_3)\cos^i \theta + \lambda_\gamma \sum_{j=1,3} a_j(s,s_1,s_2,s_3)\cos^j \theta,$$

where $s_{ij} = (p_i + p_j)^2$ and $s = (p_1 + p_2 + p_3)^2$, and $p_1$, $p_2$, and $p_3$ are the four-momenta of the $\pi^-$, $\pi^+$, and $K^+$ mesons, respectively. The functions $a_i$ depend on the resonances present in the $K^+\pi^-\pi^+$ mass range of interest and their interferences. The up-down asymmetry is defined as

$$A_{ud} \equiv \frac{\int_0^1 d\cos \theta \frac{d\Gamma}{d\cos \theta} d\cos \theta - \int_{-1}^0 d\cos \theta \frac{d\Gamma}{d\cos \theta} d\cos \theta}{\int_{-1}^1 d\cos \theta \frac{d\Gamma}{d\cos \theta} d\cos \theta},$$

which is proportional to $\lambda_\gamma$.

The LHCb detector [9] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing $b$ or $c$ quarks. The detector includes a high-precision tracking system consisting of a silicon-strip vertex detector surrounding the

*Full author list given at the end of the article.

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A boosted decision tree [16,17] is used to further improve the separation between signal and background. Its training is based on the following variables: the impact parameter $\chi^2$ of the $B^+$ meson and of each of the final state hadrons, defined as the difference between the $\chi^2$ of a primary vertex (PV) reconstructed with and without the considered particle; the cosine of the angle between the reconstructed $B^+$ momentum and the vector pointing from the PV to the $B^+$ decay vertex; the flight distance of the $B^+$ meson, and the $K^+\pi^-\pi^+$ vertex $\chi^2$.

The mass distribution of the selected $B^+ \rightarrow K^+\pi^-\pi^+\gamma$ signal is modeled with a double-tailed Crystal Ball [18] probability density function (PDF), with power-law tails above and below the $B$ mass. The four tail parameters are fixed from simulation; the width of the signal peak is fit separately for the 2011 and 2012 data to account for differences in calorimeter calibration. Combinatorial and partially reconstructed backgrounds are considered in the fit, the former modeled with an exponential PDF, the latter described using an ARGUS PDF [19] convolved with a Gaussian function with the same width as the signal to account for the photon energy resolution. The contribution to the partially reconstructed background from events with only one missing pion is considered separately.

The fit of the mass distribution of the selected $B^+ \rightarrow K^+\pi^-\pi^+\gamma$ candidates (Fig. 1) returns a total signal yield of 13876 $\pm$ 153 events, the largest sample recorded for this channel to date. Figure 2 shows the background-subtracted $K^+\pi^-\pi^+$ mass spectrum determined using the technique of Ref. [20], after constraining the $B$ mass to its nominal value. No peak other than that of the $K_1(1270)^+$ resonance can be clearly identified. Many kaon resonances, with various masses, spins, and angular momenta, are expected to contribute and interfere in the considered mass range [1].

The contributions from single resonances cannot be isolated because of the complicated structure of the

**FIG. 1** (color online). Mass distribution of the selected $B^+ \rightarrow K^+\pi^-\pi^+\gamma$ candidates. The blue solid curve shows the fit results as the sum of the following components: signal (red solid), combinatorial background (green dotted), missing pion background (black dashed), and other partially reconstructed backgrounds (purple dash-dotted).
The up-down asymmetry is thus studied inclusively in four intervals of $K^+\pi^-\pi^+$ mass. The $[1.4,1.6]$ GeV/$c^2$ interval, studied in Ref. [7], includes the $K_1(1400)^+$, $K_2^*(1430)^+$ and $K^*(1410)^+$ resonances with small contributions from the upper tail of the $K_1(1270)^+$. At the time of the writing of Ref. [7], the $K_1(1400)^+$ was believed to be the dominant $1^+$ resonance, so the $K_1(1270)^+$ was not considered. However, subsequent experimental results [21] demonstrated that the $K_1(1270)^+$ is more prominent than the $K_1(1400)^+$; hence, the $[1.1,1.3]$ GeV/$c^2$ interval is also studied here. The $[1.3,1.4]$ GeV/$c^2$ mass interval, which contains the overlap region between the two $K_1$ resonances, and the $[1.6,1.9]$ GeV/$c^2$ high mass interval, which includes spin-2 and spin-3 resonances, are also considered.

In each of the four $K^+\pi^-\pi^+$ mass intervals, a simultaneous fit to the $B$-candidate mass spectra in bins of the photon angle is performed in order to determine the background-subtracted angular distribution; the previously described PDF is used to model the mass spectrum in each bin, with all of the fit parameters being shared except for the yields. Since the sign of the photon polarization depends on the sign of the electric charge of the $B$ candidate, the angular variable $\cos \hat{\theta} \equiv \text{charge}(B) \cos \theta$ is used. The resulting background-subtracted $\cos \hat{\theta}$ distribution, corrected for the selection acceptance and normalized to the inverse of the bin width, is fit with a fourth-order polynomial function normalized to unit area,

$$f(\cos \hat{\theta}; c_0 = 0.5, c_1, c_2, c_3, c_4) = \sum_{i=0}^{4} c_i L_i(\cos \hat{\theta}), \quad (3)$$

where $L_i(x)$ is the Legendre polynomial of order $i$ and $c_i$ is the corresponding coefficient. Using Eqs. (1) and (3) the up-down asymmetry defined in Eq. (2) can be expressed as

$$A_{ud} = c_1 - \frac{3}{4} c_3. \quad (4)$$

As a cross-check, the up-down asymmetry in each mass interval is also determined with a counting method, rather than an angular fit, as well as considering separately the $B^+$ and $B^-$ candidates. All these checks yield compatible results.

The results obtained from a $\chi^2$ fit of the normalized binned angular distribution, performed taking into account the full covariance matrix of the bin contents and all of the systematic uncertainties, are summarized in Table I. These systematic uncertainties account for the effect of choosing a different fit model, the impact of the limited size of the simulated samples on the fixed parameters, and the possibility of some events migrating from a bin to its neighbor because of the detector resolution, which gives the dominant contribution. The systematic uncertainty associated with the fit model is determined by performing the mass fit using several alternative PDFs, while the other two are estimated with simulated pseudoexperiments. Such uncertainties, despite being of the same size as the statistical uncertainty, do not substantially affect the fit results since they are strongly correlated across all angular bins.

The fitted distributions in the four $K^+\pi^-\pi^+$ mass intervals of interest are shown in Fig. 3. In order to illustrate the effect of the up-down asymmetry, the results of another fit imposing $c_1 = c_3 = 0$, hence forbidding the terms that carry the $\lambda_{\gamma}$ dependence, are overlaid for comparison.

The combined significance of the observed up-down asymmetries is determined from a $\chi^2$ test where the null hypothesis is defined as $\lambda_{\gamma} = 0$, implying that the up-down asymmetry is expected to be zero in each mass interval. The corresponding $\chi^2$ distribution has 4 degrees of freedom, and the observed value corresponds to a $p$ value of $1.7 \times 10^{-7}$. This translates into a 5.2$\sigma$ significance for nonzero up-down asymmetry. Up-down asymmetries can be computed also for an alternative definition of the photon

<table>
<thead>
<tr>
<th>Mass Interval</th>
<th>$c_1$</th>
<th>$c_2$</th>
<th>$c_3$</th>
<th>$c_4$</th>
<th>$A_{ud}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>[1.1,1.3]</td>
<td>6.3 ± 1.7</td>
<td>5.4 ± 2.0</td>
<td>4.3 ± 1.9</td>
<td>−4.6 ± 1.8</td>
<td></td>
</tr>
<tr>
<td>[1.3,1.4]</td>
<td>31.6 ± 2.2</td>
<td>27.0 ± 2.6</td>
<td>43.1 ± 2.3</td>
<td>28.0 ± 2.3</td>
<td></td>
</tr>
<tr>
<td>[1.4,1.6]</td>
<td>−8.1 ± 2.6</td>
<td>2.0 ± 3.1</td>
<td>−5.2 ± 2.8</td>
<td>−0.6 ± 2.7</td>
<td></td>
</tr>
<tr>
<td>[1.6,1.9]</td>
<td>3.0 ± 3.0</td>
<td>6.8 ± 3.6</td>
<td>8.1 ± 3.1</td>
<td>−6.2 ± 3.2</td>
<td></td>
</tr>
<tr>
<td>$A_{ud}$</td>
<td>6.9 ± 1.7</td>
<td>4.9 ± 2.0</td>
<td>5.6 ± 1.8</td>
<td>−4.5 ± 1.9</td>
<td></td>
</tr>
</tbody>
</table>
determined in four intervals of interest in the distribution of the photon with respect to the plane defined signal events is observed. The shape of the angular distribution in each bin, as well as the values of the photon polarization, is measured for the first observation of a parity-violating photon polarization different from zero at the 5.2σ significance level in $b \to s\gamma$ transitions is reported. The shape of the photon angular distribution in each bin, as well as the values for the up-down asymmetry, may be used, if theoretical predictions become available, to determine for the first time a value for the photon polarization, and thus constrain the effects of physics beyond the SM in the $b \to s\gamma$ sector.

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42 Nikhef National Institute for Subatomic Physics and VU University Amsterdam, Amsterdam, The Netherlands
43 NSC Kharkiv Institute of Physics and Technology (NSC KIPT), Kharkiv, Ukraine
44 Institute for Nuclear Research of the National Academy of Sciences (KINR), Kyiv, Ukraine
45 University of Birmingham, Birmingham, United Kingdom
46 H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom
47 Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
48 Department of Physics, University of Warwick, Coventry, United Kingdom
49 STFC Rutherford Appleton Laboratory, Didcot, United Kingdom
50 School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
51 School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
52 Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
53 Imperial College London, London, United Kingdom
54 School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
55 Department of Physics, University of Oxford, Oxford, United Kingdom
56 Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
57 University of Cincinnati, Cincinnati, Ohio, USA
58 Syracuse University, Syracuse, New York, USA
59 Pontifícia Universidade Católica do Rio de Janeiro (PUC-Rio), Rio de Janeiro, Brazil
(aassociated with Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil)
60 Institut für Physik, Universität Rostock, Rostock, Germany
(aassociated with Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany)
61 National Research Centre Kurchatov Institute, Moscow, Russia
(aassociated with Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia)
62 Instituto de Fisica Corpuscular (IFIC), Universitat de Valencia-CSIC, Valencia, Spain
(aassociated with Universitat de Barcelona, Barcelona, Spain)
63 KVI—University of Groningen, Groningen, The Netherlands
(aassociated with Nikhef National Institute for Subatomic Physics, Amsterdam, The Netherlands)
64 Celal Bayar University, Manisa, Turkey
(aassociated with European Organization for Nuclear Research (CERN), Geneva, Switzerland)

Also at Università di Firenze, Firenze, Italy.
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Also at Università degli Studi di Milano, Milano, Italy.
Also at Università di Pisa, Pisa, Italy.
Also at Università di Urbino, Urbino, Italy.
Also at P.N. Lebedev Physical Institute, Russian Academy of Science (LPI RAS), Moscow, Russia.
Corresponding author: giovanni.veneziano@cern.ch