Measurement of the photon polarization in $\Lambda_b^0 \rightarrow \Lambda \gamma$ decays

LHCb collaboration†

Abstract

The photon polarization in $b \rightarrow s \gamma$ transitions is measured for the first time in radiative $b$-baryon decays exploiting the unique spin structure of $\Lambda_b^0 \rightarrow \Lambda \gamma$ decays. A data sample corresponding to an integrated luminosity of 6 fb$^{-1}$ collected by the LHCb experiment in $pp$ collisions at a center-of-mass energy of 13 TeV is used. The photon polarization is measured to be $\alpha_\gamma = 0.82^{+0.17+0.04}_{-0.26-0.13}$, where the first uncertainty is statistical and the second systematic. This result is in agreement with the Standard Model prediction and previous measurements in $b$-meson decays. Charge-parity breaking effects are studied for the first time in this observable and found to be consistent with $CP$ symmetry.

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Rare decays of hadrons containing $b$-quarks mediated by flavor-changing neutral currents (FCNC) are suppressed in the Standard Model (SM) since they occur only at higher order in the perturbative expansion. They are sensitive to physics beyond the SM (BSM) which can give additional contributions and alter the decay properties. Radiative decays of the type $b \to s\gamma$ are FCNC, mediated by electroweak-loop transitions which produce a final state photon. In the SM, due to the chirality of the electroweak interaction, the emitted photons are polarized. The photon polarization is defined as the normalized difference between the number of left-handed ($\gamma_L$) and right-handed ($\gamma_R$) photons produced in radiative decays,

$$\alpha_\gamma \equiv \gamma_L - \gamma_R \over \gamma_L + \gamma_R,$$

with photons emitted in $b$ decays being predominantly left-handed. Right-handed contributions arise only due to chirality flips in the outgoing $s$-quark line of the Feynman diagram, which are suppressed by the ratio of the $s$ and $b$ quark masses. At leading order in the SM, the photon polarization is predicted to be $\alpha_\gamma = (1 - |r|^2)/(1 + |r|^2)$, with $|r| \approx m_s/m_b^{1/3}$. Effects arising at next-to-leading order are estimated to be at the percent level [2]. Therefore, a larger right-handed polarization, which would lower the value of $\alpha_\gamma$, could be a clear indication of BSM physics [1,4].

The photon polarization in $b \to s\gamma$ transitions has been indirectly probed by the BaBar, Belle and LHCb experiments through the measurement of mixing-induced charge-parity ($CP$) asymmetries in $B^0$ and $B^0_s$ decays [5–7] and through the angular analysis of $B^0 \to K^{*0}e^+e^-$ decays at very low dielectron mass [8], with the latter providing the strongest constraints on right-handed currents. Radiative decays of $b$ baryons offer a unique opportunity for a direct measurement of the photon polarization due to the nonzero spin of the initial- and final-state particles [9]. The $\Lambda_b^0 \to \Lambda\gamma$ decay is of special interest due to the weak decay of the $\Lambda$ baryon, which probes the helicity structure of the $b \to s\gamma$ transition through the measurement of the $\Lambda$ helicity [2,10]. The $\Lambda_b^0 \to \Lambda\gamma$ decay was first observed in data recorded by LHCb during 2016 [11]. The photon-polarization sensitivity using this decay was estimated in Ref. [12].

The angular distribution of $\Lambda_b^0 \to \Lambda\gamma$ decays, where the $\Lambda$ baryon decays into a proton and a pion, is given by the differential width [3]

$$\frac{d\Gamma}{d(\cos \theta_p)} \propto 1 - \alpha_\Lambda \alpha_A \cos \theta_p,$$

where $\alpha_A$ is the $\Lambda$ weak decay parameter, which describes the interference between the parity-violating s-wave and parity-conserving p-wave of the $\Lambda \to p\pi^-$ decay [13], and $\theta_p$ is the angle between the proton momentum and the negative $\Lambda_b^0$ momentum in the $\Lambda$ rest frame. The photon direction is integrated over in this study since the distribution in this variable is flat for unpolarized $\Lambda_b^0$ baryons, as produced at the LHC [14,15].

Contrary to $b$ decays, photons produced in $\bar{b}$ decays are expected to be predominantly right-handed in the SM, resulting in a photon polarization of $\alpha_\gamma = -1$. A discrepancy in the absolute value of the photon polarization in $b$ and $\bar{b}$ decays would be a hint of $CP$ asymmetry in these transitions. In the SM, $CP$ asymmetries in $b \to s\gamma$ decays are estimated to be less than $O(1\%)$ [2]. However, new $CP$-violating BSM contributions can

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1 The inclusion of charge-conjugate processes is implied throughout, except in the discussion of asymmetries.
produce asymmetries of $O(10\%)$ \[^2\]. Experimentally, the strongest constraint on direct CP violation in $b \rightarrow s\gamma$ transitions is from $B^0 \rightarrow K^{\ast 0}\gamma$ decays \[^{16}\]. Measurements of angular asymmetries and CP-conjugated decay branching ratios can separate the CP-odd and CP-even components of both the SM and opposite chirality contributions to the $A_b^0 \rightarrow \Lambda\gamma$ decay rate \[^{2}\].

This Letter reports the first measurement of the photon polarization in $A_b^0 \rightarrow \Lambda\gamma$ decays, with $\Lambda \rightarrow p\pi^-$, using a data sample corresponding to an integrated luminosity of 6 fb\(^{-1}\) collected by the LHCb experiment in proton-proton (pp) collisions at a center-of-mass energy of 13 TeV during 2015–2018. Additionally, the first study of CP angular asymmetries in $b \rightarrow s\gamma$ decays is performed.

The LHCb detector \[^{17,18}\] 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 elements that are relevant for this analysis are: a silicon-strip vertex detector surrounding the pp interaction region that allows $c$ and $b$ hadrons to be identified from their characteristically long flight distance; a tracking system that provides a measurement of the momentum of charged particles; two ring-imaging Cherenkov detectors that are able to discriminate between different species of charged hadrons; a calorimeter system consisting of scintillating-pad and preshower detectors, an electromagnetic calorimeter (ECAL) and a hadronic calorimeter, that enables the reconstruction and identification of photons, electrons and hadrons; and a muon system composed of alternating layers of iron and multiwire proportional chambers.

Charged and neutral clusters in the ECAL are separated by extrapolating reconstructed tracks to the ECAL; photons and neutral pions are distinguished by their cluster shape and energy distribution. For decays with high-energy photons in the final state, e.g. $A_b^0 \rightarrow \Lambda\gamma$, a mass resolution around 100 MeV is achieved\[^{19,20}\], dominated by the photon energy resolution. The online event selection is performed by a trigger \[^{21}\], consisting of a hardware stage followed by a software stage which fully reconstructs the event. The hardware trigger requires events to have an ECAL cluster with an energy component transverse to the beam, $E_T$, above a threshold varying between 2.1 – 3.0 GeV. The software trigger first requires at least one charged particle to have transverse momentum $p_T > 1$ GeV and to be inconsistent with originating from any primary pp collision vertex (PV). Subsequently, $\Lambda$ candidates are formed from two tracks significantly displaced from any PV, and combined with a high-$E_T$ photon to identify decays consistent with the signal mode. In the offline selection, trigger signals are associated with reconstructed particles and only events where the trigger was activated by the decay products of the signal candidate are kept.

Simulated events are used to model the effects of the detector geometry and the selection requirements. In the simulation, pp collisions are generated using PYTHIA \[^{22}\] with a specific LHCb configuration \[^{23}\]. Decays of unstable particles are described by EVTGEN \[^{24}\], in which final-state radiation is generated using PHOTOS \[^{25}\]. The interaction of the generated particles with the detector, and its response, are implemented using the GEANT4 toolkit \[^{26}\] as described in Ref. \[^{27}\]. The signal sample is generated with unpolarized $A_b^0$ decays and only a left-handed photon contribution. The simulation is validated using the $A_b^0 \rightarrow pK^-J/\psi$ and $A_b^0 \rightarrow AJ/\psi$, with $J/\psi \rightarrow \mu^+\mu^-$, control modes in data. The $A_b^0 \rightarrow pK^-J/\psi$ mode is selected according to Ref. \[^{28}\], while the $A_b^0 \rightarrow
A J/ψ mode is selected with the strategy described for the signal mode below. The \( \Lambda_0^b \) momentum distribution of all simulated samples with \( \Lambda_0^b \) decays is corrected to data in two-dimensional intervals of \( \Lambda_0^b \) transverse momentum and pseudorapidity, \( p_T(\Lambda_0^b) \) and \( \eta(\Lambda_0^b) \), using \( \Lambda_0^b \rightarrow pK^-J/\psi \) background-subtracted data and simulated candidates.

Offline signal candidates are reconstructed from the combination of a \( \Lambda \) baryon and a high-energy photon candidate. Opposite-charge good-quality track pairs, well separated from any PV, are combined to form \( \Lambda \) candidates, where one track is consistent with the proton hypothesis and the other with the pion hypothesis. Proton and pion candidates are required to have \( p_T \) larger than 800 MeV and 300 MeV, respectively. The \( \Lambda \) candidate must form a good-quality vertex that is well separated from the nearest PV and have a mass in the range 1110–1122 MeV. Only \( \Lambda \) candidates that decay in the central part of the vertex detector (\( z < 270 \) mm) and have a \( p_T \) larger than 1 GeV are retained for further study. Photons, reconstructed from clusters in the ECAL, must have \( E_T > 3 \) GeV and be inconsistent with the extrapolation of reconstructed tracks to the ECAL. Since the \( \Lambda_0^b \) decay vertex cannot be reconstructed in this mode, the photon is assumed to originate from the pp interaction region. The sum of the \( \Lambda p_T \) and the photon \( E_T \) must be larger than 5 GeV. The \( \Lambda_0^b \) candidate must have a transverse momentum above 4 GeV and a mass within 900 MeV of the known \( \Lambda_0^b \) mass \([29]\). The distance of closest approach between the \( \Lambda_0^b \) and \( \Lambda \) trajectories is required to be small; the \( \Lambda_0^b \) trajectory is assumed to originate from the PV closest to the \( \Lambda \) trajectory.

A boosted decision tree (BDT) \([30]\), implementing the XGBoost algorithm \([31]\), used within the Scikit-learn library \([32]\), separates signal from combinatorial background, which is formed by combinations of a real \( \Lambda \) baryon with a random photon. The BDT classifier is trained on a signal sample of \( \Lambda_0^b \rightarrow \Lambda \gamma \) simulated events and a background sample from data candidates with a mass larger than 6.1 GeV. The same variables of Ref. \([11]\), with the addition of the photon pseudorapidity, are used as input for the classifier. To maximize sensitivity to the photon polarization, the BDT threshold is selected to reject 99\% of background and retain around 50\% of signal candidates.

The mass distribution of the selected candidates is shown in Fig. 1. A fit to this mass distribution is used to determine the signal and background yields. The \( \Lambda_0^b \rightarrow \Lambda \gamma \) signal component is modeled with a Crystal Ball \([33]\) probability density function (PDF), with power-law tails above and below the \( \Lambda_0^b \) mass. The tail parameters and the width of the signal peak are fixed to values determined from simulation while the mean is allowed to vary freely in the fit to data. A comprehensive set of background contributions is investigated but only two are found to be significant \([11]\). The dominant contribution is from combinatorial background which is modeled by an exponential PDF with a freely varying slope. A small contamination from \( \Lambda_0^b \rightarrow \Lambda \eta \) decays with \( \eta \rightarrow \gamma \gamma \), where one of the photons is not reconstructed, is also expected and is described with the shape determined from simulation. The signal and combinatorial background yields vary freely in the fit to data, while the yield of \( \Lambda_0^b \rightarrow \Lambda \eta \) is constrained to its expected value, obtained from its measured branching fraction \([29]\) and reconstruction and selection efficiencies determined from simulation.

The signal and background yields are obtained from an extended unbinned maximum likelihood fit to data, as shown in Fig. 1 (left). In the signal region, \([5387.1, 5852.1]\) MeV, the signal yield is 440 \( \pm 40 \), with 1460 \( \pm 23 \) and 10 \( \pm 4 \) combinatorial and \( \Lambda_0^b \rightarrow \Lambda \eta \) decays, respectively.

The photon polarization is measured with an unbinned maximum likelihood fit to the
Figure 1: Distribution of (left) mass, $m(p\pi\gamma)$, and (right) $\cos \theta_p$ for $\Lambda_0^b \to \Lambda\gamma$ candidates. The latter shows the subset of candidates in the signal region $m(p\pi\gamma) \in [5387.1, 5852.1]$ MeV, delimited by dashed vertical lines in the former. The results of the fits are overlaid as well as the individual contributions.

$\cos \theta_p$ distribution for events in the signal region, as shown in Fig. 1 (right). The signal is described by the PDF in Eq. (2) multiplied by an acceptance function, which accounts for the effect of the detector geometry, reconstruction and selection requirements. The photon polarization parameter, $\alpha_\gamma$, is allowed to vary freely in the fit to data, whereas the physical boundary $[-1, 1]$ on this parameter is imposed later using the Feldman-Cousins technique [34]. The $\Lambda$ weak decay parameter, $\alpha_A$, is fixed to the average of the values measured by BESIII in $\Lambda$ and $\bar{\Lambda}$ decays, $\alpha_A = 0.754 \pm 0.004$ [35]. The shape of the acceptance in $\cos \theta_p$ is determined from simulation and is parametrized as a fourth order polynomial. It is dominated by the impact parameter and transverse momentum requirements on the proton and the pion. The correct description of the acceptance in simulation is validated using $\Lambda_0^b \to \Lambda J/\psi$ decays, which are reconstructed without using information from the $J/\psi$ vertex. This decay mode, with higher yield and purity than that of the signal mode, has the same final-state hadrons. The combinatorial and $\Lambda_0^b \to \Lambda\eta$ components are described together by a fourth-order polynomial, with the coefficients determined from a fit to the candidates in the $\Lambda_0^b$ mass control region $[4719.6, 5382.1] \cup [5857.1, 6519.6]$ MeV. The values of these coefficients are found to be consistent for candidates below and above the signal region. The ratio between signal and background decays is constrained by the yields obtained from the mass fit. The fit stability is validated with pseudoexperiments and the results were only examined after all analysis procedures had been finalized in order to avoid experimenter’s bias. The result of the fit to data candidates is $\alpha_\gamma = 0.82 \pm 0.23$, where the uncertainty is obtained from the Hessian matrix.

The data are separated into $\Lambda_0^b \to \Lambda\gamma$ and $\bar{\Lambda}_0^b \to \bar{\Lambda}\gamma$ by the charge of the final-state pion and potential $CP$ breaking effects on the photon polarization are studied. The photon polarization values in $\Lambda_0^b \to \Lambda\gamma$ and $\bar{\Lambda}_0^b \to \bar{\Lambda}\gamma$ decays, denoted as $\alpha^-_\gamma$ and $\alpha^+_\gamma$, are expected to have the same absolute value with opposite sign in the absence of $CP$ violation. Both values are measured independently for $\Lambda_0^b$ and $\bar{\Lambda}_0^b$ decays following the same strategy as described for the combined sample. The shape of the mass distribution for $\Lambda_0^b$ and $\bar{\Lambda}_0^b$ decays is studied in simulation and is compatible, for both signal and $\Lambda_0^b \to \Lambda\eta$ decays,
therefore the shape from the combined sample is used in the fit of the two data sets. In the
signal region, $233 \pm 32 \Lambda_0^b \rightarrow \Lambda \gamma$ and $210 \pm 30 \Lambda_0^b \rightarrow \Lambda \gamma$ decays are found. These yields are
affected by production and detection asymmetries \([36]\) and cannot be directly interpreted
as a measurement of CP-violation effects. The $\Lambda$ and $\bar{\Lambda}$ weak-decay parameters measured
by BESIII \([35]\), $\alpha^-_{\Lambda} = 0.750 \pm 0.009 \pm 0.004$ and $\alpha^+_{\bar{\Lambda}} = -0.758 \pm 0.010 \pm 0.007$, are used in
the angular fit for $\Lambda_0^b \rightarrow \Lambda \gamma$ and $\Lambda_0^b \rightarrow \bar{\Lambda} \gamma$, respectively. Due to the limited sample size,
the acceptance and background shapes are taken from the combined sample. The fit to
data candidates yields $\alpha^-_{\gamma} = 1.26 \pm 0.42$ and $\alpha^+_{\gamma} = -0.55 \pm 0.32$, where the uncertainty is statistical only. The results of the angular fits are shown in Fig. 2. The measured value
of $\alpha^-_{\gamma}$ is found to be affected by a $5\%$ bias and a $13\%$ over-coverage driven by boundary
effects in this observable.

Systematic uncertainties associated with the determination of the signal and back-
ground yields in the mass fit, the modeling of the background shape and signal acceptance
and the finite precision on the external parameter $\alpha_A$ are evaluated. These uncertainties
are determined by fitting pseudosamples, generated by an alternative model, with the
default model. The limited data size from the mass control region used to determine the
background angular shape dominates this uncertainty and is evaluated by varying the
background shape parameters. The systematic uncertainty of the background parameteriza-
tion is evaluated using a third and fifth degree polynomial. The acceptance uncertainty
is evaluated by considering the limited size of the simulation, using alternative fifth and
third degree parametrizations, and removing the $\Lambda_0^b$ kinematic corrections. The mass
fit uncertainty is determined with pseudoexperiments using an alternative model with a
variable signal width. Finally, the limited precision of the $\Lambda$ decay parameter introduces a
small systematic uncertainty. The photon polarization, with all systematic uncertainties
included, is $\alpha_{\gamma} = 0.82 \pm 0.23 \pm 0.13$.

For the CP asymmetry measurement, the uncertainties described above are $100\%$
correlated and sum to $0.13$ and $0.11$ for $\alpha^-_{\gamma}$ and $\alpha^+_{\gamma}$, respectively. Additional uncertainties arise from potential differences in the background shape and signal acceptance between
$\Lambda_0^b$ and $\Lambda_0^b$ decays. Fits are performed with the default combined model to pseudosamples
generated with alternative models obtained independently for $\Lambda_0^b$ and $\Lambda_0^b$ candidates, to
estimate this effect. These uncertainties are uncorrelated and are $0.15$ and $0.12$ for $\alpha^-_{\gamma}$.
Confidence intervals on the photon polarization are set within the physical limits of $[-1, 1]$, see Eq. 1, using the Feldman-Cousins technique, the fit result, and the relation between the true and measured values obtained from pseudoexperiments, including both statistical and systematic uncertainties. The photon polarization in $A^0_b \rightarrow A\gamma$ decays is found to be

$$\alpha_\gamma = 0.82^{+0.17}_{-0.26} \text{ (stat.)}^{+0.04}_{-0.13} \text{ (syst.)},$$

which is compatible with the SM prediction. This result excludes two regions allowed by previous measurements for the Wilson coefficients of the effective Hamiltonian of the $b \rightarrow s\gamma$ transition (see the Supplemental material to this Letter for details).

The Feldman-Cousins technique is also applied to the photon polarization measurements in $A^0_b \rightarrow A\gamma$ and $\bar{A}^0_b \rightarrow \bar{A}\gamma$ decays, which are found to be

$$\alpha_\gamma^- > 0.56 \pm 0.44 \text{ at } 90\% \text{ (95\%) CL},$$

$$\alpha_\gamma^+ = -0.56^{+0.36}_{-0.33} \text{ (stat.)}^{+0.16}_{-0.09} \text{ (syst.)},$$

consistent with $CP$ symmetry.

To summarize, the photon polarization in $b \rightarrow s\gamma$ transitions has been measured for the first time in $b$-baryon decays exploiting the decay chain $A^0_b \rightarrow A\gamma$, $A \rightarrow p\pi^-$, which enables the determination of this observable from the angular distribution of the $\Lambda$ decay products. The $\alpha_\gamma$ result is compatible with the SM prediction at the level of one standard deviation and provides new constraints that are compatible with previous measurements of the photon polarization in $b$-meson decays [7,8]. Additionally, $CP$-breaking effects on this observable are studied for the first time and the results are compatible with $CP$ symmetry. These results can be used to place constraints on the real and imaginary contributions of right-handed currents in BSM models. The precision of the results is dominated by the statistical uncertainty; furthermore, the dominant systematic uncertainty, due to the angular shape of the background, can be reduced with more data. Consequently, future data that will be collected by the LHCb experiment during the next decade will enable significant improvements of these results.

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1 Supplemental material for PRL

The measurement of $\alpha_{\gamma}$ in this paper is used to place constraints on the electromagnetic dipole Wilson coefficients of the effective Hamiltonian of the $b \to s\gamma$ transition, namely $C_7^{(\text{eff})}$ and $C_7'^{(\text{eff})}$. The leading order expression of $\alpha_{\gamma}$ in terms of Wilson coefficients is used within the flavio package \cite{37} to this end. This enables the experimental exclusion of two solutions with large real values of $C_7^{(\text{eff})}$ and $C_7'^{(\text{eff})}$ which, although phenomenologically unfavored, were experimentally allowed by all the previous measurements, as shown in Fig. 4 (top).

![Graphs showing profile of negative log likelihood vs $\alpha_{\gamma}$ for $b \to s\gamma$ transition](image)

Figure 3: Profile of the negative log likelihood along the (top) combined, (bottom-left) $\Lambda_b^0 \to \Lambda\gamma$ and (bottom-right) $\bar{\Lambda}_b^0 \to \bar{\Lambda}\gamma$ photon polarization values ($\alpha_{\gamma}$, $\alpha_{-\gamma}$ and $\alpha_{+\gamma}$, respectively).
Figure 4: Constraints at the 1σ level on the new physics contributions to the (top) left- and right-handed Wilson coefficients, $C_{7}^{\text{(eff)}}$ and $C'_{7}^{\text{(eff)}}$, and on the (bottom) real and imaginary parts of $C'_{7}^{\text{(eff)}}$. In the latter, the $C_{7}^{\text{(eff)}}$ coefficient is fixed to its SM value. The measurements of the inclusive branching fraction, $B(\bar{B} \to X_{s}\gamma)$, and the $B^{0} \to K_{S}^{0}\pi^{0}\gamma$ mixing-induced CP asymmetry by the Belle and BaBar experiments [5,6] are shown in blue and yellow, respectively, the $B_{s}^{0} \to \phi\gamma$ and $B^{0} \to K^{*0}e^{+}e^{-}$ measurements by the LHCb experiment [7,8] in purple and red, respectively, and the $\alpha_{\gamma}$ measurement presented in this paper in green. The global fit is shown in dashed red (green) lines including (excluding) this measurement.
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f Università di Ferrara, Ferrara, Italy
g Università di Firenze, Firenze, Italy
h Università di Genova, Genova, Italy
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j Università di Milano Bicocca, Milano, Italy
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l Università di Padova, Padova, Italy
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n Università di Pisa, Pisa, Italy
o Università della Basilicata, Potenza, Italy
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u Novosibirsk State University, Novosibirsk, Russia
v Deceased