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Authors
Aad, G
Abbott, B
Abdallah, J
et al.

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Observation of a New $\chi_b$ State in Radiative Transitions to $Y(1S)$ and $Y(2S)$ at ATLAS

G. Aad et al.* (ATLAS Collaboration)

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The $\chi_b(nP)$ quarkonium states are produced in proton-proton collisions at the Large Hadron Collider at $\sqrt{s} = 7$ TeV and recorded by the ATLAS detector. Using a data sample corresponding to an integrated luminosity of 4.4 fb$^{-1}$, these states are reconstructed through their radiative decays to $Y(1S,2S)$ with $Y \rightarrow \mu^+\mu^-$. In addition to the mass peaks corresponding to the decay modes $\chi_b(1P,2P) \rightarrow Y(1S)\gamma$, a new structure centered at a mass of 10.530 $\pm$ 0.005(stat) $\pm$ 0.009(syst) GeV is also observed, in both the $Y(1S)\gamma$ and $Y(2S)\gamma$ decay modes. This structure is interpreted as the $\chi_b(3P)$ system.

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Measurements of the properties of heavy quark-antiquark bound states, or quarkonia, provide a unique insight into the nature of quantum chromodynamics close to the strong decay threshold. For the $b\bar{b}$ system, the quarkonium states with parallel quark spins ($s = 1$) include the $S$-wave $Y$ and the $P$-wave $\chi_b$ states, where the latter each comprise a closely spaced triplet of $J = 0, 1, 2$ spin states: $\chi_{b0}$, $\chi_{b1}$, and $\chi_{b2}$. The $\chi_b(1P)$ and $\chi_b(2P)$, with spin-weighted mass barycenters of 9.90 and 10.26 GeV, respectively, can be readily produced in the radiative decays of $Y(2S)$ and $Y(3S)$ and have been studied experimentally [1].

In this Letter, $\chi_b$ quarkonium states are reconstructed with the ATLAS detector through the radiative decay modes $\chi_b(nP) \rightarrow Y(1S)\gamma$ and $\chi_b(nP) \rightarrow Y(2S)\gamma$, in which $Y(1S,2S) \rightarrow \mu^+\mu^-$ and the photon is reconstructed either through conversion to $e^+e^-$ or by direct calorimetric measurement. Previous experiments have measured the $\chi_b(1P)$ and $\chi_b(2P)$ through these decay modes [2]. The $\chi_b(3P)$ state has not previously been observed. It is predicted to have an average mass of approximately 10.52 GeV, with hyperfine mass splitting between the triplet states of 10–20 MeV [3,4].

The ATLAS detector [5] is a general-purpose particle physics detector with a forward-backward symmetric cylindrical geometry and near 4$\pi$ coverage in solid angle. The inner tracking detector (ID) consists of a silicon pixel detector, a silicon microstrip detector, and a transition radiation tracker. The ID is surrounded by a thin superconducting solenoid providing a 2 T magnetic field and by high-granularity liquid-argon sampling electromagnetic calorimeters. An iron-scintillator tile calorimeter provides hadronic coverage in the central rapidity range. The end cap and forward regions are instrumented with liquid-argon calorimeters for both electromagnetic and hadronic measurements. The muon spectrometer surrounds the calorimeters and consists of a system of precision tracking chambers and detectors for triggering, inside a toroidal magnetic field.

The data sample used for this measurement was recorded by the ATLAS experiment during the 2011 LHC proton-proton collision run at a center-of-mass energy $\sqrt{s} = 7$ TeV. The integrated luminosity of the data sample, which includes only data-taking periods where all relevant detector subsystems were operational, is 4.4 fb$^{-1}$. A set of muon triggers designed to select events containing muon pairs or single high transverse momentum muons was used to collect the data sample.

In this analysis, each muon candidate must satisfy standard muon quality requirements [6]. It must have a track, reconstructed in the muon spectrometer, combined with a track reconstructed in the ID with transverse momentum $p_T > 4$ GeV and pseudorapidity $|\eta| < 2.3$. The dimuon selection requires a pair of oppositely charged muons, which are fitted to a common vertex. A very loose vertex quality requirement [$\chi^2$ per degree of freedom (d.o.f.) $< 20$] is used and no mass or momentum constraints are applied to the fit. The dimuon candidate is also required to have $p_T > 12$ GeV and rapidity $|y| < 2.0$. The invariant mass distribution, $m_{\mu\mu}$, of dimuon candidates is shown in Fig. 1. Those candidates with masses in the ranges $9.25 < m_{\mu\mu} < 9.65$ GeV and $9.80 < m_{\mu\mu} < 10.10$ GeV are selected as $Y(1S) \rightarrow \mu^+\mu^-$ and $Y(2S) \rightarrow \mu^+\mu^-$ candidates, respectively. The asymmetric mass window (evident from Fig. 1) for $Y(2S)$ candidates is chosen in order to reduce contamination from the $Y(3S)$ peak and continuum background contributions.

The reconstruction of photons in ATLAS is described in Ref. [7]. Further details related to this particular analysis are described below.

Converted photons are reconstructed from two oppositely charged ID tracks intersecting at a conversion vertex, with the opening angle between the two tracks at this vertex constrained to be zero. For tracks with signals in
the transition radiation tracker, the transition radiation should be consistent with an electron hypothesis. In order to be reliably reconstructed, each conversion electron track must have a minimum transverse momentum of 500 MeV. It is also required to have at least four silicon detector hits and not to be associated to either of the two muon candidates. To reduce background contamination, the conversion candidate vertex is required to be at least 40 mm from the beam axis and have a vertex $\chi^2$ probability of greater than 0.01. The converted photon impact parameter with respect to the dimuon vertex is required to be less than 2 mm.

Electromagnetic calorimeter energy deposits not matched to any track are classified as unconverted photons. This analysis uses the “loose” photon selection described in Ref. [7], with a minimum photon transverse energy of 2.5 GeV. The loose photon selection includes a limit on the fraction of the energy deposit in the hadronic calorimeter as well as a requirement that the transverse width of the shower be consistent with the narrow shape expected for an electromagnetic shower.

To check that an unconverted photon originates from the same vertex as the $Y$, and to improve the mass resolution of the reconstructed $\chi_b^{+}$, the polar angle of the photon is corrected using the procedure described in Ref. [8]. The corrected polar angle is determined using the measurement of the photon direction from the longitudinal segmentation of the calorimeter and the constraint from the dimuon vertex position. Photons incompatible with having originated from the dimuon vertex are rejected by means of a loose cut on the fit result ($\chi^2$ per d.o.f. <200).

The converted (unconverted) photon candidates are required to be within $|\eta| < 2.30$ (2.37). Unconverted photons must also be outside the transition region between the barrel and the end cap calorimeters, $1.37 < |\eta| < 1.52$.

The $\chi_b$ candidates are formed by associating a reconstructed $Y \rightarrow \mu^+ \mu^-$ candidate with a reconstructed photon. The invariant mass difference $\Delta m = m(\mu^+ \mu^- \gamma) - m(\mu^+ \mu^-)$ is calculated to minimize the effect of $Y \rightarrow \mu^+ \mu^-$ mass resolution. In order to compare the $\Delta m$ distributions of both $\chi_b(nP) \rightarrow Y(1S)\gamma$ and $\chi_b(nP) \rightarrow Y(2S)\gamma$ decays, the variable $\tilde{m}_k = \Delta m + \sigma_{Y(kS)}$ is defined, where $m_{Y(kS)}$ are the world average masses [9] of the $Y(kS)$ states. Requirements of $p_T(\mu^+ \mu^-) > 20$ GeV and $p_T(\mu^+ \mu^-) > 12$ GeV are applied to $Y$ candidates with unconverted and converted photon candidates, respectively. These thresholds are

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**FIG. 1 (color online).** The invariant mass of selected dimuon candidates. The shaded regions A and B show the selections for $Y(1S)$ and $Y(2S)$ candidates, respectively.

**FIG. 2 (color online).** (a) The mass distribution of $\chi_b \rightarrow Y(1S)\gamma$ candidates for unconverted photons reconstructed from energy deposits in the electromagnetic calorimeter ($x_{\ell k}^2/d.o.f. = 0.85$). (b) The mass distributions of $\chi_b \rightarrow Y(kS)\gamma$ ($k = 1, 2$) candidates formed using photons which have converted and been reconstructed in the ID ($x_{\ell k}^2/d.o.f. = 1.3$). Data are shown before the correction for the energy loss from the photon conversion electrons due to bremsstrahlung and other processes. The data for decays of $\chi_b \rightarrow Y(1S)\gamma$ and $\chi_b \rightarrow Y(2S)\gamma$ are plotted using circles and triangles, respectively. Solid lines represent the total fit result for each mass window. The dashed lines represent the background components only.
chosen in order to optimize signal significance in the $\chi_b(1P, 2P)$ peaks.

Figure 2(a) shows the $m_1$ distribution for unconverted photons and Fig. 2(b) shows the $m_1$ and $m_2$ distributions for converted photons. In addition to the expected peaks for $\chi_b(1P, 2P) \rightarrow Y(1S, 2S)\gamma$, structures are observed at an invariant mass of approximately 10.5 GeV. These additional structures are interpreted as the radiative decays of the previously unobserved $\chi_b(3P)$ states, $\chi_b(3P) \rightarrow Y(1S)\gamma$ and $\chi_b(3P) \rightarrow Y(2S)\gamma$.

Separate fits are performed to the $m_k$ distributions of the selected $\mu^+\mu^-\gamma$ candidates reconstructed from converted and unconverted photons to extract mass information from the observed $\chi_b(3P)$ signals. The higher threshold for unconverted photons (2.5 GeV, versus 1 GeV for converted photons) prevents the reconstruction of the soft photons from $\chi_b(2P, 3P)$ decays into $Y(2S)$.

An unbinned extended maximum likelihood fit is performed to the $m_1 = \Delta m + m_{Y(1S)}$ distribution of the selected unconverted $\mu^+\mu^-\gamma$ candidates. The three peaks in the distribution are each modeled by a Gaussian probability density function (PDF) with an independent normalization parameter $N_n$, mean value $m_n$, and width parameter $\sigma_n$. The background distribution is parametrized by the PDF $N_B\exp\left[A\Delta m + B\Delta m^{-2}\right]$ where $N_B$, $A$, and $B$ are all free parameters. The three mean values $m_{n=1,2,3}$ determined by the fit are shown in Table I. The mean value $m_3$ is an estimate of the mass barycenter of the observed $\chi_b(3P)$ signal.

Likewise, the $m_1 = \Delta m + m_{Y(1S)}$ and $m_2 = \Delta m + m_{Y(2S)}$ distributions for the sample of $\mu^+\mu^-\gamma$ candidates reconstructed from converted photons are fitted using an unbinned extended maximum likelihood method. A simultaneous fit is performed on the $m_1$ and $m_2$ distributions for the $\chi_b(nP) \rightarrow Y(1S)\gamma$ (for $n = 1, 2, 3$) and $\chi_b(nP) \rightarrow Y(2S)\gamma$ (for $n = 2, 3$ only) signals, with the distributions modeled by three signal components (two of which are shared between the $Y(1S)$ and $Y(2S)$ distributions) and two background distributions.

In the $\Delta m$ distribution for the converted photon candidates the typical mass resolution is found to be in the range 16–20 MeV, of similar magnitude to the hyperfine splittings, motivating the need for multiple signal components for each of the $\chi_b(nP)$ peaks. For $n = 1, 2$, the radiative branching fractions of the $J = 0$ states are suppressed with respect to the $J = 1, 2$ states [9] and therefore a $J = 0$ component is not included in the fit. Similar behavior is assumed for the $n = 3$ case. Each of the three peaks ($n = 1, 2, 3$) is therefore parametrized by a doublet of Crystal Ball (CB) [10] functions (corresponding to $J = 1, 2$ states) with resolution $\sigma$ and radiative tail parameters common to all peaks. For $n = 1$ and $n = 2$, the peak mass values and hyperfine splittings are fixed to the world averages [9] for the respective $\chi_b$ states (see Table I). For $n = 3$, the hyperfine mass splitting is fixed to the theoretically predicted value of 12 MeV [4], while the average mass is left as a free parameter. The unknown relative normalization of the $J = 1$ and $J = 2$ CB peaks is taken to be equal and treated as a systematic uncertainty (for all doublets) for the baseline fit.

In order to take into account energy loss from the photon conversion electrons due to bremsstrahlung and other processes, the measured values of $\Delta m$ in the $m_1$ and $m_2$ distributions are scaled by a common parameter $\lambda = 0.961 \pm 0.003$, which determines the energy scale and is derived from the fit to the $\chi_b(1P, 2P)$ signals. The background components of the $\Delta m$ distributions for the $Y(1S)\gamma$ and $Y(2S)\gamma$ final states are each modeled by the PDF $N_B^0(\Delta m - q_{k}^0)^{A_k}\exp\left[B_k(\Delta m - q_{k}^0)\right]$ for $\Delta m > q_{k}^0$, and zero otherwise, where $N_{B_k}^0$, $q_{k}^0$, $A_k$, and $B_k$ ($k = 1, 2$) are all free parameters. The mean value $m_n$ determined by the fit is shown in Table I.

In the fit using unconverted photons, the signal is refitted using an alternative (two Gaussians) model for each of the three $\chi_b$ states, resulting in a negligible change in the peak positions. Alternative fits to the background are also used, either including constraints on the $\Delta m$ distribution using dimuon pairs from the low-mass ($8.0 \text{ GeV} < m_{\mu\mu} < 8.8 \text{ GeV}$) sideband or different background PDFs. The systematic uncertainty on the $\chi_b(3P)$ mass barycenter from the modeling of the background distribution is determined to be $\pm 21 \text{ MeV}$. The systematic uncertainty associated with the unconverted photon energy scale is estimated to be $\pm 2\%$ on the $\Delta m$ position, corresponding to a systematic uncertainty on $m_3$ of $\pm 22 \text{ MeV}$. The uncertainties due to background modeling and photon energy scale comprise the dominant sources of systematic uncertainty.

For the fit using converted photons, alternative signal and background models are compared, and various

<table>
<thead>
<tr>
<th>State</th>
<th>Model predictions [3,4] [MeV]</th>
<th>Unconverted photons</th>
<th>Converted photons</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi_b(1P)$</td>
<td>9900</td>
<td>9910 ± 6(stat) ± 11(syst)</td>
<td>Fixed to $\chi_{b1} = 9892.78$ and $\chi_{b2} = 9912.21$ [9]</td>
</tr>
<tr>
<td>$\chi_b(2P)$</td>
<td>10260</td>
<td>10246 ± 5(stat) ± 18(syst)</td>
<td>Fixed to $\chi_{b1} = 10255.46$ and $\chi_{b2} = 10268.65$ [9]</td>
</tr>
<tr>
<td>$\chi_b(3P)$</td>
<td>10525</td>
<td>10541 ± 11(stat) ± 30(syst)</td>
<td>10530 ± 5(stat) ± 9(syst)</td>
</tr>
</tbody>
</table>

TABLE I. The fitted mass of the $\chi_b(nP)$ signals for both converted and unconverted photons. The systematic uncertainty on the mass of candidates reconstructed with unconverted photons is determined in the same way for all three states. Also included are theoretical predictions [3,4] for the spin-averaged masses of the $\chi_b$ states.
constraints in the fit model are also released. The unknown relative normalizations of the $J = 1$ and $J = 2$ CB peaks are varied both coherently and incoherently between the $1P, 2P$, and $3P$ doublets by $\pm 0.25$, resulting in a maximum variation in $m_3$ of $\pm 5$ MeV. Smaller variations are obtained if the common value of the relative normalization is allowed to be determined freely by the fit to the three doublets. Background modeling variations, decoupled fits to the $m_1$ and $m_2$ distributions, and individually released constraints on the mass position of the $n = 1, 2$ doublets each result in deviations of the order of $\pm 5$ MeV or smaller. Furthermore, if the constraints on the masses of the $n = 1, 2$ peaks are released, the values obtained from the fit are consistent with expectations [9], within statistical errors and uncertainty in the relative contributions from $J = 1$ and $J = 2$ states. The effect of symmetrizing the $Y(2S)$ mass window is studied and found to have a negligible effect on the fitted $\chi_b$ masses while increasing background contamination. The resulting shifts in $m_3$ for these independent variations are added in quadrature to provide an estimate of the systematic uncertainty.

The $\chi_b(3P)$ signal significance is assessed from $\log(L_{\text{max}} / L_0)$, where $L_{\text{max}}$ and $L_0$ are the likelihood values from the nominal fit and from a fit with no $\chi_b(3P)$ signal included, respectively. The fit is repeated with each of the systematic variations in the model, as discussed above, and the likelihood ratio reevaluated. The significance of the $\chi_b(3P)$ signal is found to be in excess of 6 standard deviations in each of the unconverted and converted photon selections independently.

The mass barycenter for the $\chi_b(3P)$ signal, determined from the fit using unconverted photon candidates is

$$m_3 = 10.541 \pm 0.011(\text{stat}) \pm 0.030(\text{syst}) \text{ GeV.}$$

The mass barycenter for the $\chi_b(3P)$ signal, determined from the fit using converted photon candidates is

$$m_3 = 10.530 \pm 0.005(\text{stat}) \pm 0.009(\text{syst}) \text{ GeV.}$$

The measured mass barycenters of the $\chi_b(1P)$, $\chi_b(2P)$, and $\chi_b(3P)$ systems are summarized in Table I. The results of the converted and unconverted photon analyses for the $\chi_b(3P)$ are found to be compatible. Given the substantially smaller systematic uncertainties in the conversion measurement, the final mass determination for $m_3$ is quoted solely on the basis of this analysis.

In conclusion, the production of the heavy quarkonium states $\chi_b(nP)$ in proton-proton collisions at $\sqrt{s} = 7$ TeV is observed through the reconstruction of the radiative decay modes of $\chi_b(nP) \to Y(1S, 2S)\gamma$. Mass peaks corresponding to $\chi_b(1P, 2P)$ decays are observed, together with additional structures at higher mass, which are consistent with theoretical predictions for $\chi_b(3P) \to Y(1S)\gamma$ and $\chi_b(3P) \to Y(2S)\gamma$. These observations are interpreted as the $\chi_b(3P)$ multiplet, the mass barycenter of which is measured to be $10.530 \pm 0.005(\text{stat}) \pm 0.009(\text{syst}) \text{ GeV.}$

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(ATLAS Collaboration)

1 University at Albany, Albany, New York, USA
2 Department of Physics, University of Alberta, Edmonton AB, Canada
3 Department of Physics, Ankara University, Ankara, Turkey
4 Department of Physics, Ankara University, Ankara, Turkey
5 Department of Physics, Antwerpen University, Antwerp, Belgium
6 Department of Physics, University of Arizona, Tucson, Arizona, USA
7 Department of Physics, The University of Texas at Arlington, Arlington, Texas, USA
8 Department of Physics, University of Athens, Athens, Greece
9 Physik Department, National Technical University of Athens, Zografou, Greece
10 Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
11 Institut de Física d’Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona and ICREA, Barcelona, Spain
12a Institute of Physics, University of Belgrade, Belgrade, Serbia
12b Vinca Institute of Nuclear Sciences, Belgrade, Serbia
13 Department for Physics and Technology, University of Bergen, Bergen, Norway
14 Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, California, USA
15 Department of Physics, Humboldt University, Berlin, Germany
16 Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
17 School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
18a Department of Physics, Bogazici University, Istanbul, Turkey
18b Division of Physics, Dogus University, Istanbul, Turkey
19c Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey


152001-13
163c Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
166 Department of Physics, University of Illinois, Urbana, Illinois, USA
165 Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
169 Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain
168 Department of Physics, University of British Columbia, Vancouver BC, Canada
167 Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada
164 Department of Physics, University of Illinois, Urbana, Illinois, USA
170 Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
171 Department of Physics, University of Wisconsin, Madison, Wisconsin, USA
172 Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
173 Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
174 Department of Physics, Yale University, New Haven, Connecticut, USA
176 Domaine scientifique de la Doua, Centre de Calcul CNRS/IN2P3, Villeurbanne Cedex, France

aDeceased.
bAlso at Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa, Portugal.
cAlso at Faculdade de Ciencias and CFNUL, Universidade de Lisboa, Lisboa, Portugal.
dAlso at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.
eAlso at TRIUMF, Vancouver BC, Canada.
fAlso at Department of Physics, California State University, Fresno CA, USA.
gAlso at Novosibirsk State University, Novosibirsk, Russia.
hAlso at Fermilab, Batavia IL, USA.
iAlso at Department of Physics, University of Coimbra, Coimbra, Portugal.
jAlso at Università di Napoli Parthenope, Napoli, Italy.
kAlso at Institute of Particle Physics (IPP), Canada.
lAlso at Department of Physics, Middle East Technical University, Ankara, Turkey.
mAlso at Louisiana Tech University, Ruston LA, USA.
nAlso at Department of Physics and Astronomy, University College London, London, United Kingdom.
oAlso at Group of Particle Physics, University of Montreal, Montreal QC, Canada.
pAlso at Department of Physics, University of Cape Town, Cape Town, South Africa.
qAlso at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
rAlso at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
sAlso at Manhattan College, New York NY, USA.
tAlso at School of Physics, Shandong University, Shandong, China.
uAlso at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.
vAlso at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China.
wAlso at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.
xAlso at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat a l’Energie Atomique), Gif-sur-Yvette, France.
yAlso at Section de Physique, Université de Genève, Geneva, Switzerland.
zAlso at Departamento de Fisica, Universidade de Minho, Braga, Portugal.
aa Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, USA.
bb Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
cc Also at California Institute of Technology, Pasadena CA, USA.

dd Also at LAL, Univ. Paris-Sud and CNRS/IN2P3, Orsay, France.

dd Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom.
e Also at Department of Physics, Oxford University, Oxford, United Kingdom.
ffe Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
gh Also at Department of Physics, The University of Michigan, Ann Arbor MI, USA.
ii Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France.