Observation of an Excited $B_c^{±}$ Meson State with the ATLAS Detector

G. Aad et al.*

(ATLAS Collaboration)

(Received 3 July 2014; published 21 November 2014)

A search for excited states of the $B_c^{±}$ meson is performed using 4.9 fb$^{-1}$ of 7 TeV and 19.2 fb$^{-1}$ of 8 TeV $pp$ collision data collected by the ATLAS experiment at the LHC. A new state is observed through its hadronic transition to the ground state, with the latter detected in the decay $B_c^{±} \rightarrow J/\psi\pi^±$. The state appears in the $m(B_c^{±}\pi^±) - m(B_c^0) - 2m(\pi^±)$ mass difference distribution with a significance of 5.2 standard deviations. The mass of the observed state is 6842 $\pm$ 5 MeV, where the first error is statistical and the second is systematic. The mass and decay of this state are consistent with expectations for the second $S$-wave state of the $B_c^{±}$ meson, $B_c^{±}(2S)$.

DOI: 10.1103/PhysRevLett.113.212004

PACS numbers: 14.40.Nd

The $B_c^{±}$ meson was first observed by the CDF experiment in the semileptonic decay mode [1], and its hadronic decay mode was observed later by both the CDF [2] and the D0 [3] experiments. The $B_c^{±}$ meson has also been observed by the LHCb experiment in various decay modes [4]. Excited states of the $B_c^{±}$ meson have not previously been observed. The spectrum and properties of the $B_c^{±}$ family are predicted by nonrelativistic potential models, perturbative QCD, and lattice calculations [5]. Measurements of the ground and excited states through fully reconstructed channels will provide tests of the predictions of these models and ultimately the opportunity to extract information on the strong interaction potential.

The second $S$-wave state, $B_c^{±}(2S)$, is predicted to have a mass in the range 6835–6917 MeV [5]. The next $S$-wave state, $B_c^{±}(3S)$, is predicted to have a mass above the threshold for decay into a $BD$ meson pair. Both the 1S and 2S states have pseudoscalar ($0^−$) and vector (1$^−$) spin states that are predicted to differ in mass by about 20–50 MeV. Transitions between the spin states occur through soft photon radiation that escapes identification in ATLAS; the spin states cannot be separated by this analysis.

This Letter presents the observation of a new state whose mass is consistent with predictions for the $B_c^{±}(2S)$, the second $S$-wave state of the $B_c^{±}$ meson. The $B_c^{±}(2S)$ state is reconstructed in the decay to the $B_c^0$ meson and two oppositely charged pions, with the $B_c^0$ reconstructed through its decay to $J/\psi\pi^±$, $J/\psi \rightarrow \mu^+\mu^-$. The ATLAS Collaboration at the Large Hadron Collider (LHC) uses a general-purpose particle detector [6] consisting of several subsystems including the inner detector (ID), the electromagnetic and hadronic calorimeters, and the muon spectrometer (MS). Muon reconstruction at ATLAS makes use of both the ID and the MS.

Muons pass through the calorimeters and reach the MS if their momentum is above approximately 3 GeV. The inner detector features a three-component tracking system, consisting of two silicon-based detectors, the pixel detector and the microstrip semiconductor tracker (SCT), and the transition radiation tracker (TRT). ID tracks are reconstructed if their transverse momentum $p_{T}$ [7] is greater than 400 MeV and the magnitude of their pseudorapidity $|\eta|$ is less than 2.5. Muon candidates are formed from a standalone MS track that is matched to an ID track [8]. In this analysis the MS is only used to identify muons, while their momentum is measured using the ID information only.

The trigger system [9] comprises three levels: the hardware-based Level-1 trigger and the High-Level Triggers (HLT), consisting of the Level-2 trigger and the Event Filter (EF). The Level-1 trigger uses resistive plate chambers (RPC) and thin gap chambers (TGC) to trigger muons in the pseudorapidity ranges of $|\eta| < 1.05$ and $1.05 < |\eta| < 2.5$, respectively. One or more regions of interest identified by the Level-1 muon trigger seed the HLT muon online reconstruction algorithms, where the responses from both the ID and the MS are combined. For this analysis the HLT selection for the $J/\psi$ requires two muons, respectively, $\mu_1$ and $\mu_2$, originating at a common vertex, with the invariant mass of the muon pair lying between 2.5 and 4.3 GeV. The individual muon $p_{T}$ thresholds are $p_{T}(\mu_1) > 6$ GeV and $p_{T}(\mu_2) > 4$ GeV.

This study uses $pp$ collision data collected in the years 2011 ($\sqrt{s} = 7$ TeV) and 2012 ($\sqrt{s} = 8$ TeV) by the ATLAS experiment. The data sets correspond to an integrated luminosity of 4.9 and 19.2 fb$^{-1}$, respectively. The luminosity estimate has an uncertainty of 1.8% in 2011 [10] and 2.8% in 2012.

To improve the resolution, peaks are sought in the distribution of the variable $Q = m(B_c^0 \pi\pi) - m(B_c^0) - 2m(\pi\pi)$, where $m(B_c^0)$ is the offline reconstructed invariant
mass of the $B^\pm_c$ candidate, $m(B^\pm_c \pi)$ is the invariant mass of the $B^\pm_c$ candidate combined with two charged pion candidates, and $m(\pi^\pm)$ is the charged pion mass [11]. The $B^\pm_c$ candidates are reconstructed through the decay $B^\pm_c \rightarrow J/\psi(\mu^+\mu^-)\pi^\pm$. Since hadronic decays of excited $B$-meson states have no observable displacement from the $pp$ interaction point, these candidates are then combined with two charged pion candidates, both originating at the corresponding $pp$ interaction point. The mass difference ($Q$) distribution is formed and analyzed in the range 0–700 MeV.

The $B^\pm_c$ selection criteria for the events are optimized separately for 7 and 8 TeV data using the corresponding Monte Carlo (MC) samples, produced in the ATLAS simulation framework [12,13]. Differences between the 7 and 8 TeV selection criteria are due to the higher number of signal events and $B$ refers to the number of background MC events scaled according to the production cross section. The production cross sections are taken from the MC generators’ predictions. The optimization has been carried out separately for the two different data sets.

The $B^\pm_c$ candidates are reconstructed by fitting two muon tracks from the $J/\psi$ candidate together with a pion candidate track to a common vertex. The invariant mass of the two muons is constrained to the world average of $m(J/\psi)$. The yields per unit of integrated luminosity, and the central values of the dimuon invariant mass distributions, are verified to be consistent within each data set.

A significant part of the combinatorial background consists of real $J/\psi$ candidates combined with candidate pions that are not associated with a $B^\pm_c \rightarrow J/\psi \pi^\pm$ decay. This background is reduced by imposing a lower cut on $d_0/\sigma(d_0)$: $d_0$ here represents the projection of the pion track impact parameter relative to the primary vertex onto the transverse plane, and $\sigma(d_0)$ is the track-by-track uncertainty on $d_0$. Pion candidates are required to have $d_0/\sigma(d_0) > 5$ for 7 TeV data and $> 4.5$ for 8 TeV data. In 7 TeV data the PV is defined as the collision vertex with the highest summed scalar $p_T$ of its constituent tracks. In 8 TeV data—the data collected with higher pileup—the PV is identified as the vertex closest in three dimensions to the reconstructed decay vertex of the $B^\pm_c$ candidate. All reconstructed $B^\pm_c$ candidates are also required to satisfy the following selection criteria:

(i) The $J/\psi\pi$ vertex fit $\chi^2/NDOF < 2$ for 7 TeV and $< 1.5$ for 8 TeV data. (ii) The $p_T$ of the $B^\pm_c$ candidate must be above 15 GeV for 7 TeV and above 18 GeV for 8 TeV data.

Figure 1 shows the invariant mass distributions for the $B^\pm_c$ candidates for 7 TeV data and 8 TeV data in the mass range 5620–6820 MeV. Both distributions are fitted separately using an extended unbinned maximum likelihood fit, with a Gaussian function modeling the signal and an exponential modeling the background shape. The various
A TLAS
A TLAS

An additional selection requirement is applied to the 

B

of the 

B

requirements. The three tracks from the secondary vertex 

mππ = 6282 ± 8 MeV

Nπ = 100 ± 23

σπ = 49 ± 12 MeV

and the two tracks from the primary vertex are refitted 

simultaneously with the following constraints given by the 

\[ m_{\gamma} = 6277 ± 6 MeV \]

\[ N_{\gamma} = 227 ± 25 \]

\[ \sigma_{\gamma} = 50 ± 8 MeV \]

FIG. 1 (color online). Invariant mass distributions of the 

reconstructed 

B

candidates in 7 TeV data (top) and in 8 TeV data (bottom). The data are represented by the 

points with error bars (statistical only). The solid line is the 

projection of the results of the unbinned maximum likelihood fit 

to all candidates in the mass range 5620–6820 MeV. The dashed 

line is the projection of the background component of the same fit.

decay topology: the refitted triplet of the 

B

tracks and the 

pair of PV pion tracks must intersect in two separate 

B

and 

B

(2S) vertices. The invariant mass of the refitted 

muon tracks is constrained to the 

J/ψ world average mass, and the combined momentum of the refitted 

B

tracks must point to the 

B

(2S) vertex. When multiple 

B

(2S) 

candidates are found in the same event, the one with the 

best \( \chi^2 \) value returned by the fitter is kept as an excited state candidate. Wrong-charge combinations (\( B^+ π^− π^− \) and \( B^− π^+ π^− \)) are kept separately for comparison with the combinatorial background shape in the right-charge combinations (oppositely charged pion pairs).

Figure 2 shows the mass difference distribution 

\( m(B^+ π^− π^−) − m(B^−) − 2m(π) \) for the right-charge combinations 

\( B^+ π^+ π^− \) as well as the wrong-charge combinations.

A structure is observed in the mass difference distribution. In order to characterize it, an unbinned maximum likelihood fit to the right-charge combinations is performed. The fit includes a third-order polynomial to model the background and a Gaussian function for the structure. The background shape resulting from the fit is verified to be consistent with the wrong-charge combinations (which are not used to constrain the model in the right-charge fit) by fitting the same shape to them, with the normalization as the only free parameter. Alternative models for the signal and the background parametrizations are studied as sources of systematic uncertainty. A Breit-Wigner contribution was tested in convolution with the Gaussian function and was found to be negligible, implying that the natural width of the structure is small relative to the detector resolution. The resulting fit parameters (with statistical uncertainties only), as well as the distributions of the wrong-charge (\( B^± π^± π^± \), \( B^± π^− π^− \)) combinations are shown in Fig. 2. The wrong-charge combinations, are normalized to the same yield as the right-charge background.

The relative \( B^±(2S)/B^± \) yield ratio is verified to be statistically consistent between the 7 and 8 TeV data.

The fit finds the peak at a mass difference (\( \Delta Q \)) value of 

288.2 ± 5.1 MeV in the 7 TeV data and 288.4 ± 4.8 MeV in the 8 TeV data. The fit yields 22 ± 6 signal events in the 

7 TeV data and 35 ± 13 events in the 8 TeV data. The Gaussian width of the structure is found to be 18.2 ± 3.8 MeV in the 7 TeV data and 17.6 ± 4.0 MeV in the 8 TeV data. All uncertainties mentioned in this paragraph do not include systematic uncertainties.

There are two dominant sources of systematic uncertainty on the position of the peak. One comes from the

<table>
<thead>
<tr>
<th>Data</th>
<th>Signal events</th>
<th>Peak mean [MeV]</th>
<th>Peak width [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 TeV</td>
<td>100 ± 23</td>
<td>6282 ± 8</td>
<td>49 ± 12</td>
</tr>
<tr>
<td>8 TeV</td>
<td>227 ± 25</td>
<td>6277 ± 6</td>
<td>50 ± 8</td>
</tr>
</tbody>
</table>

Table I. The results of the unbinned maximum likelihood fits of the invariant mass distribution of the \( B^± \) candidates. Systematic uncertainties are not included.
The mass of the $B_c^-$ ground state candidate and is largely canceled in the mass difference distribution. The other involves systematic uncertainties in the fit of the mass difference distribution itself. The uncertainty on the mass of the $B_c^-$ (2S) candidate is dominated by the fitting procedure and estimated below to be about 3.6 MeV. The contribution from the uncertainty on the pion momentum scale to the $B_c^-$ mass is 1.2 MeV. The residual uncertainty from the $B_c^-$ candidate mass in the mass difference distribution, $\delta m_{B_c^-(2S)} = \delta m_{B_c^-} \times (m_{B_c^-}/m_{B_c^-(2S)})$, where the $\delta m_{B_c^-}$ is the world average uncertainty on the $B_c^-$ mass [11], is about 1.7 MeV. The systematic uncertainty on the mass difference introduced by the fitting procedure is estimated by (i) varying the background model. An exponential threshold function $f(Q) \sim Q^a e^{-bQ}$, where $a$ and $b$ are free parameters) and second- and fourth-order polynomials were considered as alternatives, resulting in a 3.4 MeV systematic uncertainty; (ii) varying the fit mass range from 0–700 to 0–1500 MeV, results in a 1.2 MeV contribution to the systematic uncertainty; (iii) using different models for the signal. A single Breit-Wigner function, a Breit-Wigner function convolved with a Gaussian function, and a double Gaussian function were considered. This results in a negligible systematic uncertainty, compared to the above two.

In each case the largest difference between any of the variations mentioned and the default fit model is used as the systematic uncertainty. The values are calculated as the weighted mean of the 7 and 8 TeV mass values.

An additional systematic uncertainty of 2 MeV is obtained from the study of the mass bias in the selection of the candidate with the best $\chi^2$ of the vertex fit.

The various sources of systematic uncertainty are treated as uncorrelated. The total averaged systematic uncertainty propagated to the mass value of the new structure is approximately 4.1 MeV.

The significance of the new structure is evaluated with pseudoexperiments. A large number of background-only mass difference distributions are generated. Parameters of the generation are taken from the fit with their uncertainties to account for systematic effects. The background shape is scaled to the observed number of events. The mean mass value of the signal contribution is left free to vary within the theoretically motivated range (6835–6917 MeV) to evaluate the “look-elsewhere effect” [19]. The significance is calculated as the fraction of the pseudoexperiments in which the difference of the logarithms of fit likelihoods $\Delta \ln L$ with and without signal is larger than in the data. In terms of standard deviations the significance of the observation is 3.7$\sigma$ in the 7 TeV data and 4.5$\sigma$ in the 8 TeV data. For the combined 7 and 8 TeV data set the total significance of the observation is found to be 5.2$\sigma$. The local significance of the observation, obtained by fixing the mean value of the signal component, is 5.4$\sigma$.

In conclusion, the distribution of the mass difference $Q = m(B_{c^-}^+\pi^-) - m(B_{c^-}^-) - 2m(\pi^\pm)$ for events with the $B_c^-$ meson reconstructed in its decay to $J/\psi\pi^\pm$ has been investigated in $pp$ collisions at the LHC using the ATLAS detector. The analysis is based on an integrated luminosity of 4.9 (19.2) fb$^{-1}$ of $pp$ collisions at a center-of-mass energy of 7 (8) TeV. A new state is observed at $Q = 288.3 \pm 3.5 \pm 4.1$ MeV (calculated as the error weighted mean of the 7 and 8 TeV mass values) corresponding to a mass of $6842 \pm 4 \pm 5$ MeV, where the first error is statistical and the second is systematic. The significance of the observation is 5.2$\sigma$ with the look elsewhere effect taken into account, and the local significance is 5.4$\sigma$. Within the uncertainties, the mass of the resonance corresponding to the observed structure is consistent with the predicted mass of the $B_c^-(2S)$ state.

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions, without whom ATLAS could not be operated efficiently.
We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DCAF, DAFNE and Lundbeck Foundation, Denmark; EPLANET, ERC and NSRF, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNSF, Georgia; BMBF, DFG, HGF, MPG and AvH Foundation, Germany; GSRT and NSRF, Greece; ISF, MINERVA, GIF, I-CORE and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; BRF and RCN, Norway; MNiSW and NCN, Poland; GRICES and FCT, Portugal; MEYS, Czech Republic; AVH Foundation, Germany; GSRT and NSRF, Greece; ISF, MINERVA, GIF, I-CORE and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; BRF and RCN, Norway; MNiSW and NCN, Poland; GRICES and FCT, Portugal; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; SRC and Wallenberg Foundation, Sweden; SERB, SNSF and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme Trust, United Kingdom; DOE and NSF, USA. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular, from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK), and BNL (USA) and in the Tier-2 facilities worldwide.

[7] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the z axis along the beam line. The x axis points from the IP to the center of the LHC ring, and the y axis points upward. Polar coordinates (r, ϕ) are used in the transverse (x, y) plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as η = − ln tan θ/2.
Department of Physics, University of Cape Town, Cape Town, South Africa

146a School of Physics, University of the Witwatersrand, Johannesburg, South Africa

146b Department of Physics, Stockholm University, Sweden

147a The Oskar Klein Centre, Stockholm, Sweden

148 Physics Department, Royal Institute of Technology, Stockholm, Sweden

149 Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook, New York, USA

150a Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom

150b School of Physics, University of Sydney, Sydney, Australia

151 Institute of Physics, Academia Sinica, Taipei, Taiwan

152 Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava, Slovak Republic

153 Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic

154 Department of Physics, University of Johannesburg, Johannesburg, South Africa

155 Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada

156 Ray and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel

157 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece

158 Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel

159 International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan

160a Department of Physics, University of Toronto, Toronto, Ontario, Canada

160b TRIUMF, Vancouver, British Columbia, Canada

161 Department of Physics and Astronomy, University of British Columbia, Vancouver, British Columbia, Canada

162 Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan

163 Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia

164 Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA

165a INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy

165b ICTP, Trieste, Italy

166 Department of Physics, University of Uppsala, Uppsala, Sweden

167 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-CNFM), University of Valencia and CSIC, Valencia, Spain

168 Department of Physics, University of Wisconsin, Madison, Wisconsin, USA

169 Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada

170 Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel

171 Department of Physics, University of Wisconsin, Madison, Wisconsin, USA

172 Faculty für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany

173 Department of Physics, Yale University, New Haven, Connecticut, USA

174 Waseda University, Tokyo, Japan

175 Fachbereich Physik, Bergische Universität Wuppertal, Wuppertal, Germany

176 Yerevan Physics Institute, Yerevan, Armenia

177 Yerevan Institute of Physics, Yerevan, Armenia

178 Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France

\*Deceased.

1 A also at Department of Physics, King’s College London, London, United Kingdom.

2 Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.

3 Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.

4 Also at TRIUMF, Vancouver BC, Canada.

5 Also at Department of Physics, California State University, Fresno, CA, USA.

6 Also at Tomsk State University, Tomsk, Russia.

7 Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.

8 Also at Università di Napoli Parthenope, Napoli, Italy.

9 Also at Institute of Particle Physics (IPP), Canada.

10 Also at Department of Physics, Saint Petersburg State Polytechnical University, Saint Petersburg, Russia.
Also at Chinese University of Hong Kong, China.

Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.

Also at Louisiana Tech University, Ruston, LA, USA.

Also at Institut Catala de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.

Also at Department of Physics, The University of Texas at Austin, Austin, TX, USA.

Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.

Also at CERN, Geneva, Switzerland.

Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan.

Also at Manhattan College, New York, NY, USA.

Also at Novosibirsk State University, Novosibirsk, Russia.

Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.

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

Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.

Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France.

Also at School of Physical Sciences, National Institute of Science Education and Research, Bhubaneswar, India.

Also at Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy.

Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.

Also at Section de Physique, Université de Genève, Geneva, Switzerland.

Also at International School for Advanced Studies (SISSA), Trieste, Italy.

Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, USA.

Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China.

Also at Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia.

Also at Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia.

Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.

Also at Department of Physics, Oxford University, Oxford, United Kingdom.

Also at Department of Physics, Nanjing University, Jiangsu, China.

Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.

Also at Department of Physics, The University of Michigan, Ann Arbor, MI, USA.

Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa.

Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia.