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ABSTRACT

We present deep near-infrared spectroscopic observations of 13 luminous $z \simeq 7$ Lyman break galaxies (LBGs) ($M_{UV} \simeq -21$) and a $z \simeq 9.6$ lensed LBG candidate, MACS1149-JD1, using the LBT/LUCI spectrograph in the multi-object mode and long-slit mode, respectively. The $z \sim 7$ galaxies are selected in one of the Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey/WIDE survey observations, the UKIRT Infrared Deep Sky Survey Ultra Deep Survey field, and MACS1159-JD1 is selected from the Cluster Lensing And Supernova survey with Hubble survey observations. With ~ 4 – 5 hr integrations, the LBT spectra are sensitive to Ly α emission, with rest-frame equivalent width greater than $55 \text{ \AA}$ ($EW_0 > 55 \text{ \AA}$) at $z \sim 7$ and $90 \text{ \AA}$ ($EW_0 > 90 \text{ \AA}$) at $z \sim 9.5$. No Ly α emission is observed in any of the $z \simeq 7$ LBGs. After correcting the spectroscopic incompleteness, our measurements place an upper limit on the Ly α emission fraction of $X_{Ly\alpha}(EW_0 > 55 \text{ \AA}, z \simeq 7) < 9.8\%$ in luminous LBGs at $z \simeq 7$. This result is consistent with the lack of Ly α emission in $z > 7$ LBGs in previous studies. Together with other measurements of the Ly α emission fraction in LBGs at $z \simeq 7$, this study puts a strong constraint on the fraction of luminous $z \simeq 7$ LBGs with large EW Ly α , $X_{Ly\alpha}(EW_0 > 55 \text{ \AA}, z \simeq 7) = 2.6^{+3.2}_{-2.6}\%$. We estimate the expected Ly α emission fraction at $z \simeq 7$ by extrapolating the evolution of the fraction at low redshifts and find that the observed Ly α emission fraction is lower than the expected Ly α emission fraction at the 89% significance level, consistent with expectations if Ly α emission in $z \simeq 7$ LBGs has been suppressed by neutral hydrogen in the intergalactic medium or optically thick absorbers around the galaxies. We do not find any strong Ly α emission feature at the redshift range of $z \simeq 7.3$ – 9.7 in the MACS1159-JD1 spectrum, either. This is consistent with the conclusion that Ly α emission in the galaxy has been highly suppressed.

Key words: cosmology: observations – galaxies: evolution – galaxies: high-redshift

1. INTRODUCTION

In the past few years, the knowledge of galaxies at $z \geq 6.5$ has tremendously improved through large samples of galaxy candidates at $z \geq 6.5$ discovered using both the narrowband imaging method (Ly α emitters [LAEs]; e.g., Kashikawa et al. 2006; Hu et al. 2010; Ouchi et al. 2010; Clément et al. 2012; Krug et al. 2012) and Lyman break dropout method (Lyman break galaxies [LBGs]; e.g., Oesch et al. 2010; Bouwens et al. 2011; Yan et al. 2011; Finkelstein et al. 2012a; Ellis et al. 2013). Bright LBG candidates at $z > 7$ have been routinely discovered based on the dropout method in the Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey (CANDELS; Grogin et al. 2011; Koekemoer et al. 2011) and Cluster Lensing And Supernova survey with Hubble (CLASH; Postman et al. 2012) fields via deep imaging with the *Hubble Space Telescope* (HST) Wide Field Camera 3 (WFC3). With these galaxies, the luminosity functions (LFs) of LBGs up to $z \sim 10$ have been measured (e.g., Bouwens et al. 2012; Oesch et al. 2014), and the cosmic star formation

rate density and stellar mass density at early cosmic epochs have been determined (e.g., Coe et al. 2013; Ellis et al. 2013; Stark et al. 2013; Duncan et al. 2014; Salmon et al. 2015).

Over the past decade, observations of the cosmic microwave background (CMB) and high-redshift galaxies and quasars have provided new insight into the process of cosmic reionization. The CMB large-scale polarization results suggest that reionization is under way at $z \sim 11$ (e.g., Page et al. 2007). Deep spectra of quasars indicate that intergalactic hydrogen is in a highly ionized state at $z \lesssim 6$ (e.g., Fan et al. 2006; Mortlock et al. 2011). Spectroscopic observation of high- z LBG candidates not only enables us to confirm the redshifts and study their properties (e.g., Jones et al. 2012); it is also a powerful probe to study the cosmic reionization process in the early universe from $z \simeq 10$ to $z \simeq 6$.

Studying properties of galaxies $z > 6$, including Ly α LFs of LAEs (e.g., Kashikawa et al. 2011) and the Ly α occurrence frequency in LBGs (e.g., Stark et al. 2010), could help us to understand when the neutral hydrogen in the IGM was re-ionized. The diffuse H I in IGM resonantly scatters the Ly α photons emitted by galaxies, which significantly decreases the LAE number density (e.g., McQuinn et al. 2007; Dijkstra et al. 2011; Bolton & Haehnelt 2013; Jensen et al. 2013). The rapid evolution of the Ly α LF from $z \sim 5.7$ to 7 suggests that the fraction of neutral hydrogen of the IGM increases rapidly with increasing redshift (Kashikawa et al. 2006; Hu et al. 2010; Ouchi et al. 2010; Clément et al. 2012; Jiang et al. 2013). Another powerful tool to probe the cosmic reionization history

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is the evolution of the fraction of galaxies with strong Ly α emission. Spectroscopic follow-up observations of LBGs at $z > 4$ have shown that the Ly α fraction increases up to $z \simeq 6$ (e.g., Stark et al. 2010, 2011), and the fraction drops significantly at $z > 7$ (e.g., Hayes et al. 2011; Pentericci et al. 2011; Ono et al. 2012; Schenker et al. 2012, 2014; Treu et al. 2012; Bunker et al. 2013; Pentericci et al. 2014; Tilvi et al. 2014). By comparing the Ly α emission fraction with the cosmic reionization models (e.g., McQuinn et al. 2007; Dijkstra et al. 2011; Mesinger et al. 2015), it was found that the neutral hydrogen fraction of the IGM is 0.4–0.9 at $z \simeq 7$.

However, out of hundreds of LBG candidates at $z > 6.5$, there are only about 100 candidates with spectroscopic follow-up observations and about 10 LBGs at $z > 6.8$ that have been spectroscopically confirmed (e.g., Pentericci et al. 2011; Vanzella et al. 2011; Bradač et al. 2012; Ono et al. 2012; Schenker et al. 2012; Finkelstein et al. 2013; Schenker et al. 2014; Oesch et al. 2015). To increase the sample size of the $z \simeq 7$ LBGs with spectroscopic follow-up observations and probe the reionization process in the early universe, we present deep spectroscopic observations of a sample of 13 luminous $z \simeq 7$ LBGs in the UKIRT Infrared Deep Sky Survey (UKIDSS) Ultra Deep Survey (UDS). The aim of this study is to investigate the frequency of occurrence of Ly α emission in luminous star-forming galaxies at $z \simeq 7$. Furthermore, we will also present deep LBT/LUCI spectroscopic observations of a $z \simeq 9.6$ lensed galaxy candidate, MACS1149-JD1, discovered in the galaxy cluster MACS1149.

The paper is organized as follows: The spectroscopic observations and data reductions are described in Section 2. The results of the Ly α emission fraction in $z \simeq 7$ galaxies are present in Section 3. In Section 4, we summarize the main scientific results. Throughout this paper, we use the following cosmological parameters for the calculations: Hubble constant $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, dark matter density $\Omega_M = 0.30$, and dark energy density $\Omega_\Lambda = 0.70$ for a flat universe (e.g., Spergel et al. 2007). All the magnitudes are expressed in the AB magnitude system (Oke & Gunn 1983).

2. OBSERVATIONS AND DATA REDUCTION

2.1. $z \simeq 7$ LBG Candidates in the UDS Field

We carried out deep near-IR spectroscopic observations of a sample of $z \simeq 7$ LBG candidates using the LUCI-1 instrument (Ageorges et al. 2010), which is the first of the two near-IR imagers and spectrographs mounted on the $2 \times 8.4 \text{ m}$ Large Binocular Telescope (LBT; Hill et al. 2012). LUCI can provide near-IR multi-object spectroscopy over a field of view of $4' \times 4'$. The $z \simeq 7$ LBG candidates that we targeted in this campaign were selected by using the dropout selection method in the sub-region of the UKIDSS UDS (Lawrence et al. 2007) field observed by the CANDELS/Wide survey (Grogin et al. 2011; Koekemoer et al. 2011).

We designed two LBT/LUCI masks to observe as many $z \simeq 7$ LBG candidates as possible in the UDS field. Finally, 13 bright $z \simeq 7$ LBG candidates in the UDS were observed (Table 1). The galaxies were picked from the dropout catalog presented in Grazian et al. (2012). The J -band apparent total magnitudes (determined from the CANDELS F125W WFC3 imaging) are between 25.5 and 26.7. Using the photometric redshifts presented in Grazian et al. (2012), we estimated that the absolute UV magnitudes of our $z \simeq 7$ LBG sample lie in

Table 1
 $z \simeq 7$ LBG Candidates with LBT/LUCI Spectra in the UDS Field

ID	J mag	R.A. (J2000)	Decl. (J2000)
18797	26.16	02:17:08.06	−05:11:45.5
16669	26.48	02:17:06.97	−05:12:15.7
16119	26.30	02:17:00.89	−05:12:24.5
15482	26.00	02:17:00.89	−05:12:34.4
15399	25.43	02:16:56.13	−05:12:36.1
13796	26.04	02:17:28.20	−05:13:08.5
33684	26.70	02:17:47.14	−05:07:55.8
30492	25.79	02:17:57.61	−05:08:44.9
27601	25.86	02:17:47.50	−05:09:30.2
26120	26.21	02:17:46.52	−05:09:52.8
18932	26.17	02:17:55.88	−05:11:43.1
19136	26.25	02:17:52.10	−05:11:40.1
19390	26.10	02:17:44.20	−05:11:36.3

the range $-21.75 < M_{\text{UV}} < -20.25$, placing these galaxies in the most luminous subset covered by previous Ly α studies (e.g., Pentericci et al. 2011; Stark et al. 2011; Ono et al. 2012; Schenker et al. 2012, 2014).

We used slit widths of $1''.0$, and the typical slit length was chosen to be $8''.0$ to sample enough sky background for sky subtraction. We used the N1.25 camera and the second order of the 200 $H + K$ grating with a central wavelength of $1.1 \mu\text{m}$, providing a resolving power of $R \sim 1000$. The wavelength coverage is slightly different from object to object (depending on the position of the galaxy on the slit mask) but typically spans $0.95\text{--}1.35 \mu\text{m}$ (zJ band). The LUCI instrument has a relatively high throughput throughout the above wavelength range. Therefore, this setup enables us to detect Ly α emission in the redshift range between $z \simeq 6.8$ and $z \simeq 10.1$.

The observations were conducted on 2012 November 7 (UT) and 2012 December 11 and 12 (UT). The observing conditions were good with mostly clear sky and image quality of $0''.7\text{--}0''.9$ (Table 2). The total exposure times of the two masks were 270 and 315 minutes, respectively (Table 2). The observations were divided into 900 s integrations with small dithers between exposures.

We adopted and modified the LUCI long-slit data reduction pipeline (see details in Becker et al. 2009; Bian et al. 2010) to reduce the LUCI multi-slit data. The wavelength calibration was performed using atmospheric OH emission lines. We used traces of standard stars and sky lines to map the curvatures in the x and y directions of the detector. The trace of each slit was determined by a flat-field frame. We corrected the science frames with a master flat field, subtracted each science frame with a neighboring science frame, and used the Kelson (2003) sky subtraction method to subtract the sky residuals. The individual sky-subtracted exposures were subsequently co-added together to produce the final 2D spectral images. Flux calibration was performed using the standard stars (G1912b2 and FS13) observed just after the science exposures. To verify the flux calibration and monitor the variation in atmospheric transparency, we also considered the counts from stars with known infrared magnitudes in our slit mask alignment boxes. The two methods of flux calibration are consistent with each other within 30%. Frame-to-frame variance in the alignment star calibration is minimal, implying that the sky transparency was stable during the observations.

We used the following procedures to determine the limiting depth of the survey: (1) We used a $0''.8$ aperture to extract one-

Table 2
Observing Log

DATE (UT)	Target	Observing Condition	Exposure Time	Instrument Configuration
2012 April 19	MACS1149-JD1	Mostly clear, image quality $0''.7\text{--}1''.0$	10×900 s	Long-slit mode
2012 May 2	MACS1149-JD1	Mostly clear, image quality $0''.8$	2×900 s	Long-slit mode
2012 June 11	MACS1149-JD1	Clear, image quality $0''.6\text{--}0''.9$	4×900 s	Long-slit mode
2012 November 7	UDS-ID924315	Clear, image quality $0''.7\text{--}0''.9$	18×900 s	Multi-slit mode
2012 December 11, 12	UDS-ID933758	Clear, image quality $0''.8\text{--}0''.9$	21×900 s	Multi-slit mode

dimensional spectra from the sky-subtracted individual 2D spectral images; this aperture size is comparable to typical seeing conditions. We extracted the standard star spectrum with the same aperture for flux calibration. (2) We carried out flux and wavelength calibrations on each spectrum. (3) For a given wavelength, we assumed that the flux distribution from the individual frames follows a Gaussian distribution. Therefore, the standard deviation of the fluxes is the 1σ uncertainty for each exposure at that wavelength. The 1σ uncertainty of the stacked spectrum is $1/\sqrt{n-1}$ times the 1σ uncertainty of the spectrum from individual exposures, where n is the number of the individual exposure. With this approach, we calculated the flux density limit for each given wavelength and found that the median flux density limit in the wavelength coverage range was $f_\lambda = 4.6 \times 10^{-19} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1}$. (4) By assuming that the FWHM of the Ly α line is 500 km s^{-1} , we calculated the median 5σ flux limit, which is $(1.6 \pm 0.6) \times 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2}$. This flux limit is consistent with the LBT/LUCI flux limit found in Jiang et al. (2013) after scaling it with the total exposure time. Here we adopted the 5σ flux limits to calculate the Ly α detection completeness, because we want to keep consistency with previous works (Schenker et al. 2012) and make it easier to combine our results with those from other studies. In the analysis, we adopted the Ly α FWHM of 500 km s^{-1} . This value can be considered as an upper limit of Ly α FWHM in high- z galaxies (e.g., Kashikawa et al. 2011; Ono et al. 2012). If the FWHM is lower than our adopted value, the flux limit will be somewhat reduced.

Based on the estimated flux limits, we can calculate the 5σ rest-frame equivalent width (EW_0) detection limits as a function of wavelength for a given continuum magnitude. Figure 1 shows the 5σ EW_0 detection limit as a function of wavelength for a $J = 25.5$ galaxy (red solid line) and a $J = 26.5$ galaxy (blue solid line). For a $J = 26.0$ galaxy (roughly the median magnitude of the observed galaxy sample), we can detect Ly α emission with $\text{EW}_0 > 55 \text{ \AA}$ over 88% of the spectral window between 0.95 and $1.20 \mu\text{m}$, where Ly α emission is most likely to be located.

To make sure that we can identify the Ly α emission in the stacked 2D spectra, we also artificially placed two pairs of positive and negative mock 2D Ly α emission lines in the stacked 2D LUCI spectra. One pair is between sky emission lines, and the other pair is right on top of a strong sky emission line. The lines have EW_0 of $55 \text{ \AA}$ with continuum magnitude of $J = 26$. We adopted the Ly α line profile from the composite spectra of Ly α emitters at $z \simeq 6.5$ (Kashikawa et al. 2011) and convolved it with the image quality of $0''.8$ spatially. We can easily identify the lines located between the sky lines. However, it is difficult to distinguish between the Ly α emission line and the residual sky lines (Figure 2).

In this section, we have demonstrated that the flux limits of the deep LUCI spectra allow us to detect $J = 26.0$ galaxies at

Figure 1. 5σ EW_0 detection limits of a $J = 26.5$ galaxy (blue curve) and a $J = 25.5$ galaxy (red curve) as a function of wavelength. The purple horizontal line represents the $\text{EW}_0 = 55 \text{ \AA}$. The plot demonstrates that the LBT/LUCI survey is sensitive to the galaxy with $\text{EW}_0 > 55 \text{ \AA}$.

$z \sim 7$ with Ly α $\text{EW}_0 > 55 \text{ \AA}$, the region without strong OH emission.

2.2. MACS1149-JD1

We also carried out LBT/LUCI long-slit spectroscopic observations of MACS1149-JD1, a bright ($H_{160} = 25.7$) lensed LBG with a photometric redshift of $z \simeq 9.6$ discovered as part of the CLASH survey (Zheng et al. 2012). The LUCI data were taken on 2012 April 17, 2012 May 2, and 2012 June 11 using a $1''.0$ slit width (Table 2). The total exposure time is 240 minutes. The weather was mostly clear, and the image quality was $0''.6\text{--}1''.0$. A nearby bright star was used for blind offset to align the slit on the target source. With our chosen PA of 106° , there are traces from two galaxies on the slit, allowing us to accurately determine the location of the MACS1149-JD1 spectrum and to monitor the atmospheric transparency during the observations. We used the N1.25 camera and the fourth order of the 210 zJHK grating with a central wavelength of $1.25 \mu\text{m}$. This setup provides a resolving power of $R \sim 3000$ and wavelength coverage from 1.17 to $1.31 \mu\text{m}$, enabling Ly α emission to be detected in the redshift range between $z \simeq 7.7$ and 9.7 .

We adopted the LUCI long-slit data reduction pipeline from Bian et al. (2010) to reduce the spectra. We used the same method described in Section 2.1 to compute the flux limit of the spectrum of MACS1149-JD1. Figure 3 shows the 5σ EW_0 as a function of wavelength. The spectrum is reasonably complete ($>50\%$) to $\text{EW}_0 > 50 \text{ \AA}$ emission lines in the wavelength range spanning $1.17\text{--}1.26 \mu\text{m}$ ($7.7 < z_{\text{Ly}\alpha} < 9.3$). Between 1.26 and $1.30 \mu\text{m}$ ($9.3 < z_{\text{Ly}\alpha} < 9.7$), the 5σ EW_0 limit is close to $90 \text{ \AA}$.

Figure 2. Top panel: stacked sky-subtracted LBT/LUCI 2D spectrum of a $z \approx 7$ LBG. The upper frame is the positive spectrum and the bottom frame is the negative spectrum. The 2D spectrum demonstrates that the LBT/LUCI pipeline subtracts the sky background very well, which is crucial for $\text{Ly}\alpha$ emission searches. Middle panel: two sets of positive and negative simulated mock emission lines. The mock emission lines have an EW_0 of $55 \text{ \AA}$ and $J = 26$. Bottom panel: mock emission lines are artificially placed on the real 2D LUCI spectrum. The pair of emission lines on the left is between sky lines and could be identified by eye easily, while the pair on the right is on top of a strong sky line and is hard to identify.

Figure 3. 5σ EW_0 detection limits of MACS1149-JD1 (red curve); the two purple horizontal lines represent $\text{EW}_0 = 50 \text{ \AA}$ between 1.17 and $1.26 \mu\text{m}$, and $\text{EW}_0 = 90 \text{ \AA}$ between 1.26 and $1.31 \mu\text{m}$.

3. RESULTS

3.1. $\text{Ly}\alpha$ Emission Fraction in Luminous LBGs at $z \approx 7$

We visually inspected the stacked 2D spectra of $z \approx 7$ LBGs in the UDS field to search for the $\text{Ly}\alpha$ emission line features. No strong emission features were seen. The redshifts of the LBG candidates influence whether the $\text{Ly}\alpha$ emission features could be detected. If the $\text{Ly}\alpha$ is not in the LUCI wavelength coverage or right on a bright sky emission line, we would not be able to detect the desired line emission. To quantify this effect, we used the photometric redshift code Hyperz (Bolzonella et al. 2000) to obtain the redshift distributions of the LBG candidates based on the ground-based optical bands ($BVRIZY$ band), *HST*/ACS optical bands (F606W, F814W), *HST*/WFC3 near-IR bands (F140W, F160W), and *Spitzer*/IRAC mid-IR bands ([3.6], [4.5]). The magnitudes of the LBG candidates were obtained from the CANDELS UDS field multi-wavelength catalogs (Galametz et al. 2013). It has been pointed out that the strong rest-frame optical emission lines will significantly affect the stellar mass estimation of $z \sim 6$ galaxies as those features fall into IRAC bands (e.g., Stark et al. 2013). To test the impact of optical line contamination on the photometric redshifts, we artificially added 0.2 mag to IRAC [3.6] magnitude to reduce the contribution of the strong emission line to the broadband photometry and estimated the photometric redshift. We found that the photometric redshift did not

change significantly. As described in Section 2, we computed 5σ EW_0 limits as a function of each galaxy, taking care to account for the different J -band continuum magnitudes and the wavelength coverages. We conducted Monte Carlo (MC) simulations to estimate the possibility that $\text{Ly}\alpha$ emission with $\text{EW}_0 > 55 \text{ \AA}$ can be detected in the survey. We randomly picked a redshift based on the photometric redshift distribution derived from Hyperz for each LBG candidate. With the redshift, we obtained the observed-frame wavelength of the $\text{Ly}\alpha$ emission line and checked whether or not the $\text{Ly}\alpha$ emission is within the LUCI wavelength coverage and whether or not it is above the detection limits at that wavelength. For each galaxy, we conducted 1000 simulations. The ratio between the number of detected galaxies and the total number of the simulations is the probability that the galaxy can be detected in the survey. We found that the LUCI observation will recover 78% of $\text{Ly}\alpha$ emission lines with $\text{EW}_0 > 55 \text{ \AA}$, and we used this detection rate for further analysis in this paper.

As discussed above, the LBT/LUCI survey is sensitive to $z \approx 7$ luminous LBGs with $\text{Ly}\alpha$ $\text{EW}_0 > 55 \text{ \AA}$. As there is no $\text{Ly}\alpha$ emission detected in this survey, an upper limit of the fraction of $\text{Ly}\alpha$ emission with $\text{EW}_0 > 55 \text{ \AA}$ in $z \approx 7$ galaxies, $X_{\text{Ly}\alpha}(\text{EW}_0 > 55 \text{ \AA}, z \approx 7)$, is derived, which is 9.8%. To place a better constraint on the $\text{Ly}\alpha$ fraction in luminous LBGs, we combined the results of this study with the observations of $z \approx 7$ LBGs from Fontana et al. (2010), Pentericci et al. (2011), Vanzella et al. (2011), Ono et al. (2012), and Schenker et al. (2012). Together with the observation of 13 bright LBGs in this LBT/LUCI survey, a total of 40 $z \approx 7$ LBG candidates in the luminosity range $-21.75 < M_{\text{UV}} < -20.25$ have been observed, and there is only one LBG with $\text{Ly}\alpha$ $\text{EW}_0 > 55 \text{ \AA}$ detected in Pentericci et al. (2011).

Ono et al. (2012) suggested a very high $\text{Ly}\alpha$ recovered rate in their survey. Based on randomly putting mock $\text{Ly}\alpha$ emission line features in their deep 2D spectral images, they found that the probability to detect $\text{Ly}\alpha$ emission features with $\text{EW}_0 > 55 \text{ \AA}$ was 90%. Therefore, we do not correct the incompleteness for the sample of galaxies from Ono et al. (2012). Because the previous observations used in this study reach a depth similar to that in Ono et al. (2012), and we are interested in the high EW_0 $\text{Ly}\alpha$ emission feature in bright galaxies, we also did not correct the negligible incompleteness in the samples of galaxies from Fontana et al. (2010), Pentericci et al. (2011), Vanzella et al. (2011), and Schenker et al. (2012). After correcting the $\text{Ly}\alpha$ detection completeness of our LBT/LUCI survey, we found that $X_{\text{Ly}\alpha}(\text{EW}_0 > 55 \text{ \AA}, z \approx 7) = 2.6^{+3.2}_{-2.6}\%$. With the large sample

size, this is one of the best constraints on the Ly α emission fraction in luminous LBGs at $z \simeq 7$.

Stark et al. (2011) found a high Ly α emission fraction in galaxies at $z \simeq 6$, and this fraction was shown to increase with increasing redshifts between $z = 4$ and $z = 6$. The Ly α emission fraction is regulated by the variations in the kinematics and dust content of the host galaxies. The Ly α emission is known to be more frequent in less luminous galaxies (e.g., Ando et al. 2007; Stark et al. 2010), and it is also found to be weaker in galaxies with significant dust obscuration and redder UV-continuum slopes (β ; e.g., Kornei et al. 2010; Schenker et al. 2014). Therefore, it has been suggested that decreasing dust obscuration is the main reason for the increasing Ly α emission fraction over $3 < z < 6$ (Stark et al. 2011). Bouwens et al. (2014) found that the UV-continuum slope in $z \simeq 7$ galaxies with $M_{UV} \simeq -21$ is marginally bluer than that in $z \simeq 6$ galaxies in the same luminosity range, suggesting that the dust obscuration in the luminous galaxies may remain constant or even continuously decrease with increasing redshift beyond $z \simeq 6$. We computed the UV-continuum slopes (β) of the $z \sim 7$ galaxies in this study using the relation between the β and $HST J_{125} - H_{160}$ color derived in Bouwens et al. (2014). We adopted the J_{125} - and H_{160} -band total magnitudes in Galametz et al. (2013) for this calculation. We computed the inverse-variance-weighted mean of β for the sample of $z \sim 7$ LBGs and found that $\langle \beta \rangle = -1.84 \pm 0.30$, which is consistent with that found in $z \sim 7$ galaxies with similar luminosities (Bouwens et al. 2014). Therefore, if the neutral hydrogen fraction at $z \simeq 7$ is similar to that at $z \simeq 6$ (and assuming that abundance of optically thick absorbers remains similar), we expect that the Ly α emission fraction in the luminous $z \sim 7$ galaxies should be consistent with or be even higher than that in the luminous $z \simeq 6$ galaxies. To investigate the evolution of the Ly α emission fraction in luminous galaxies from $z \sim 4$ to $z \simeq 7$, we used the $X_{Ly\alpha}(EW_0 > 55 \text{ \AA})$ results in Stark et al. (2011) for bright LBGs at $z \sim 4$ and $z \sim 5$. To reduce the uncertainty of the $X_{Ly\alpha}(EW_0 > 55 \text{ \AA})$ at $z \simeq 6$, we combined the $z \simeq 6$ bright LBG samples from Pentericci et al. (2011), Jiang et al. (2011), and Stark et al. (2011). We obtained $X_{Ly\alpha}(EW_0 > 55 \text{ \AA}) = 8.8 \pm 4.4\%$ at $z \simeq 6$, which is consistent with $X_{Ly\alpha}(EW_0 > 55 \text{ \AA}) = 7.5 \pm 5.0\%$ found in Stark et al. (2011). The larger $z \simeq 6$ galaxy sample size reduces the uncertainties of the Ly α emission fraction at $z \sim 6$. We studied the Ly α emission fraction evolution in the following two scenarios: (1) We assumed that the expected $X_{Ly\alpha}(EW_0 > 55 \text{ \AA})$ increases from $z \sim 6$ to $z \sim 7$ by following the same increasing trend between $z \sim 4$ and $z \sim 6$. Based on this trend, we extrapolated the $X_{Ly\alpha}(EW_0 > 55 \text{ \AA})$ to redshift of $z \simeq 7$, and the expected $X_{Ly\alpha}(EW_0 > 55 \text{ \AA}, z \simeq 7)$ in $z \sim 7$ bright LBGs is $11\% \pm 6\%$. Figure 4 shows the redshift-dependent evolution of the Ly α emission fraction in luminous galaxies. The magenta square is the expected $X_{Ly\alpha}(EW_0 > 55 \text{ \AA}, z \simeq 7)$ at $z \simeq 7$ extrapolated from the observed $X_{Ly\alpha}(EW_0 > 55 \text{ \AA})$ at $z \simeq 4, z \simeq 5$ (black squares), and $z \simeq 6$ (blue square). The observed $X_{Ly\alpha}(EW_0 > 55 \text{ \AA}, z \simeq 7)$ (red square) is significantly lower than the expected $X_{Ly\alpha}(EW_0 > 55 \text{ \AA}, z \simeq 7)$. With the predicted $X_{Ly\alpha}(EW_0 > 55 \text{ \AA}, z \simeq 7)$, we expected to detect 2–7 Ly α -emitting galaxies out of 40 LBG candidates. We

Figure 4. Redshift-dependent evolution of the Ly α emission fraction with $EW_0 > 55 \text{ \AA}$ ($X_{Ly\alpha}(EW_0 > 55 \text{ \AA})$) in luminous LBGs ($M_{UV} \simeq -21$). The two black squares represent $X_{Ly\alpha}(EW_0 > 55 \text{ \AA})$ in bright $z \sim 4$ and $z \sim 5$ LBGs from Stark et al. (2011, S11). The blue square represents $X_{Ly\alpha}(EW_0 > 55 \text{ \AA})$ in bright $z \simeq 6$ LBGs from Pentericci et al. (2011, P11), Jiang et al. (2011, J11), and Stark et al. (2011, S11). The cyan square represents the predicted $X_{Ly\alpha}(EW_0 > 55 \text{ \AA}, z \simeq 7)$ in bright LBGs. The magenta square represents the upper limit of $X_{Ly\alpha}(EW_0 > 55 \text{ \AA}, z \simeq 7)$ from this study. The red square represents the $X_{Ly\alpha}(EW_0 > 55 \text{ \AA}, z \simeq 7)$ results by combining this study with $z \simeq 7$ bright LBGs from Fontana et al. (2010, F10), Pentericci et al. (2011, P11), Vanzella et al. (2011, V11), Schenker et al. (2012, S12), and Ono et al. (2012, O12).

carried out an MC simulation to estimate how significantly the observed $X_{Ly\alpha}(EW_0 > 55 \text{ \AA}, z \simeq 7)$ is lower than the expected $X_{Ly\alpha}(EW_0 > 55 \text{ \AA}, z \simeq 7)$ and found that the observed value is lower than the expected value at an 89% significance level. (2) We assumed that the expected $X_{Ly\alpha}(EW_0 > 55 \text{ \AA})$ at $z \simeq 7$ remains the same as that at $z \simeq 6$, which is $8.8\% \pm 4.4\%$. In this scenario, we expected to detect 2–5 Ly α -emitting galaxies out of 40 LBGs. We found that the number of observed $X_{Ly\alpha}(EW_0 > 55 \text{ \AA}, z \simeq 7)$ is lower than the expected $X_{Ly\alpha}(EW_0 > 55 \text{ \AA}, z \simeq 7)$ at 87% significance level. In both scenarios, the number of observed bright Ly α -emitting galaxies is significantly lower than the number of predicted bright Ly α -emitting galaxies at $z \simeq 7$. The decline of the fraction of Ly α -emitting galaxies suggests that neutral hydrogen in the IGM and/or optical thick local absorbers (e.g., Bolton & Haehnelt 2013) becomes the main cause to suppress the Ly α emission in galaxies at $z \simeq 7$.

The observed Ly α emission fraction could be affected by the contaminations from low-redshift interlopers in the LBG candidates. Spectroscopic surveys of LBGs at $z \sim 4$ –6 have suggested that the fraction of low-redshift interlopers in LBG samples should be less than 20% (e.g., Pentericci et al. 2011; Stark et al. 2011). If we assume that the contamination rate is 20%, the observed $X_{Ly\alpha}(EW_0 > 55 \text{ \AA}, z \simeq 7)$ would be $3.3^{+4.0}_{-3.3}\%$, which is still lower than the expected $X_{Ly\alpha}(EW_0 > 55 \text{ \AA}, z \simeq 7)$ at 86% significance level, if the expected $X_{Ly\alpha}(EW_0 > 55 \text{ \AA}, z \simeq 7)$ increases from $z \simeq 6$ to $z \simeq 7$, and 82% significance level, if that expected $X_{Ly\alpha}(EW_0 > 55 \text{ \AA}, z \simeq 7)$ remains constant from $z \sim 6$ to $z \sim 7$. We noticed that there was another confirmed $z = 7.1$ galaxy with $EW_0(\text{Ly}\alpha) = 50 \text{ \AA}$ from Vanzella et al. (2011) among the 40 luminous LBGs. The $EW_0(\text{Ly}\alpha)$ of this galaxy is

only marginally lower than the cutoff of $\text{EW}_0(\text{Ly}\alpha) > 55 \text{ \AA}$ adopted in this study. If we also took this galaxy into account when we compute the observed $X_{\text{Ly}\alpha}(\text{EW}_0 > 55 \text{ \AA}, z \simeq 7)$ at $z \simeq 7$, the observed $X_{\text{Ly}\alpha}(\text{EW}_0 > 55 \text{ \AA}, z \simeq 7)$ would be $6.6^{+5.6}_{-4.6}\%$. This observed $X_{\text{Ly}\alpha}(\text{EW}_0 > 55 \text{ \AA}, z \simeq 7)$ is lower than the expected $X_{\text{Ly}\alpha}(\text{EW}_0 > 55 \text{ \AA}, z \simeq 7)$ at 71% or 62% significance level for the cases in which the expected $X_{\text{Ly}\alpha}(\text{EW}_0 > 55 \text{ \AA}, z \simeq 7)$ increases or remains constant from $z \simeq 6$ to $z \simeq 7$, respectively.

We compared the $\text{Ly}\alpha$ emission fraction measurement in luminous galaxies at $z \simeq 7$ with a theoretical model from Dijkstra et al. (2011). This model quantifies the probability distribution function of the fraction of the $\text{Ly}\alpha$ photons transmitted through IGM for different neutral hydrogen fractions based on galactic-scale outflow models and large-scale semi-numeric simulations of reionization. If the intrinsic distribution of $\text{Ly}\alpha$ EW_0 in the bright LBGs at $z \simeq 7$ follows the same distribution in the bright LBGs at $z \simeq 6$, it would require the neutral hydrogen fraction to be 0.4–0.8. This result is consistent with the neutral hydrogen fraction found in Ono et al. (2012) and Schenker et al. (2012). This suggests rapid evolution of the neutral hydrogen fraction between $z \simeq 6$ and $z \simeq 7$. However, it is not clear whether such rapid evolution is realistic (e.g., Mesinger et al. 2016).

Besides the large neutral hydrogen fraction at $z \sim 7$, the possible explanations of the rapid decline of $\text{Ly}\alpha$ fraction are as follows: (1) The local optically thick absorption systems in the ionizing bubbles could significantly absorb the $\text{Ly}\alpha$ photons (Bolton & Haehnelt 2013). In this model, only about 10% neutral hydrogen can produce the observed decline of the $\text{Ly}\alpha$ emission fraction between $z \simeq 6$ and $z \simeq 7$. (2) The escape fraction of the ionization photons increases between $z \simeq 6$ and $z \simeq 7$, which will reduce the intrinsic $\text{Ly}\alpha$ emission fraction in galaxies at $z \simeq 7$ (e.g., Hayes et al. 2011; Dijkstra et al. 2014). Dijkstra et al. (2014) found that a small evolution in global neutral hydrogen fraction of $\Delta x_{\text{H}} \sim 0.2$ can reproduce the large decline of $\text{Ly}\alpha$ emission fraction between $z \simeq 6$ and $z \simeq 7$ after considering the evolution of the escape fraction. (3) Stark et al. (2015) found that the $\text{Ly}\alpha$ velocity offset relative to the systemic redshift in a $z \simeq 6$ galaxy is $\delta v = 120 \text{ km s}^{-1}$. This value is about three times smaller than those found in $z \sim 3$ galaxies (e.g., Steidel et al. 2010; Bian et al. 2012) and those placed in theoretical models (e.g., Dijkstra et al. 2011). This small offset velocity will result in a stronger impact from the IGM damping wing on the emerging $\text{Ly}\alpha$ profile.

The uncertainties in the expected and observed $X_{\text{Ly}\alpha}(\text{EW}_0 > 55 \text{ \AA}, z \simeq 7)$ significantly affect our conclusion. To draw more explicit conclusions, further spectroscopic follow-up surveys of $z \simeq 7$ LBGs using the multi-slit near-IR spectrograph, such as LBT/LUCI, Keck/MOSFIRE, and Very Large Telescope/KMOS, are required to build up a large sample of $z \simeq 7$ LBGs to reduce the statistical errors. With a flexible Bayesian framework, Treu et al. (2012) could better quantify the decline of the $\text{Ly}\alpha$ -emitting galaxy fraction from $z \sim 6$ to $z \sim 8$ (see also Treu et al. 2013; Tilvi et al. 2014). The uncertainty on estimating the expected $X_{\text{Ly}\alpha}(\text{EW}_0 > 55 \text{ \AA}, z \simeq 7)$ is mainly caused by the uncertainty of the $X_{\text{Ly}\alpha}(\text{EW}_0 > 55 \text{ \AA})$ at $4 < z < 6$. As shown in Figure 4, the $\text{Ly}\alpha$ emission fraction measurement at $z \simeq 6$ has the largest uncertainty compared to that at other redshifts. Observations of $z \simeq 6$ LBG candidates with a sample size of a few hundred

galaxies will enable us to achieve a comparable uncertainty of the $\text{Ly}\alpha$ emission fraction measured at $z \simeq 4$ and $z \simeq 5$. This will place strong constraints on the redshift-dependent evolution trend of the $\text{Ly}\alpha$ emission fraction and help us better understand how the trend changes beyond $z \simeq 6$. Schenker et al. (2014) found that the $\text{Ly}\alpha$ EWs increase toward bluer UV-continuum slopes. Therefore, studies on the dependence between the UV-continuum slopes and galaxy redshifts and luminosities (e.g., Finkelstein et al. 2012b; Dunlop et al. 2013; Bouwens et al. 2014) could help us predict the intrinsic $\text{Ly}\alpha$ EW distribution in $z \sim 7$ galaxies.

3.2. No Evidence for Strong $\text{Ly}\alpha$ Emission from MACS1149JD1 at $z \sim 7.7\text{--}9.3$

We determined the position of the MACS1149-JD1 in the 2D spectral image based on the two faint galaxies that fall into the slit. We visually inspected the 2D spectral image of MACS1149-JD1 to search for $\text{Ly}\alpha$ emission features. No emission features were seen. As discussed in Section 2.2, the LBT/LUCI observations are sensitive to $\text{Ly}\alpha$ emission with $\text{EW}_0 > 55 \text{ \AA}$ at the wavelength range between 1.17 and $1.26 \mu\text{m}$ ($z = 7.7\text{--}9.3$) and $\text{Ly}\alpha$ emission with $\text{EW}_0 > 90 \text{ \AA}$ at the wavelength range 1.26– $1.30 \mu\text{m}$ ($z = 9.3\text{--}9.7$). The photometric redshift of MACS1149-JD1 is 9.6 ± 0.2 (Zheng et al. 2012). Therefore, we could not rule out that MACS1149-JD1 has a weak $\text{Ly}\alpha$ emission feature and/or it has a redshift beyond $z \simeq 9.7$. Further deeper observations with longer-wavelength coverage up to $1.31 \mu\text{m}$ will place a better constraint on the $\text{Ly}\alpha$ emission line strength of MACS1149-JD1. However, as suggested in this study and other works, the $\text{Ly}\alpha$ emission in $z \simeq 9$ LBGs could be highly suppressed by the neutral hydrogen in the IGM. It is unlikely to detect any $\text{Ly}\alpha$ emission in MACS1149-JD1.

4. SUMMARY AND CONCLUSION

In this work, we present LBT/LUCI near-IR spectroscopic observations of a sample of $z \simeq 7$ LBG candidates selected in the UDS field and a $z \simeq 9$ lensed LBG, MACS1149-JD1, in the CLASH survey. The main scientific results are summarized as follows:

1. We obtained LBT/LUCI spectra of 13 luminous $z \simeq 7$ LBGs ($M_{\text{UV}} \simeq -21$) in the UDS field. The deep spectra enable us to detect $\text{Ly}\alpha$ with $\text{EW}_0 > 55 \text{ \AA}$. Among the 13 luminous LBGs, no $\text{Ly}\alpha$ with $\text{EW}_0 > 55 \text{ \AA}$ was detected, placing an upper limit on the $\text{Ly}\alpha$ emission fraction of $X_{\text{Ly}\alpha} < 9.8\%$ in luminous $z \simeq 7$ LBGs.
2. By combining our results with previous studies (Ono et al. 2012; Schenker et al. 2012), we found that the $\text{Ly}\alpha$ emission fraction is $2.6^{+3.2}_{-2.6}\%$. The fraction is lower than the fraction predicted based on that in $z < 6.5$ LBGs at the 89% significance level if we assume that the $\text{Ly}\alpha$ emission fraction increases from $z \sim 6$ to $z \sim 7$, or 87% significance level if we assume that the $\text{Ly}\alpha$ emission remains constant from $z \sim 6$ to $z \sim 7$. The low $\text{Ly}\alpha$ emission fraction suggests that the neutral hydrogen fraction at $z \sim 7$ is consistent with a neutral hydrogen fraction of 0.4–0.8 (e.g., Dijkstra et al. 2011; Bolton & Haehnelt 2013; Jensen et al. 2013).
3. We also obtained a deep LBT/LUCI spectrum of a $z \simeq 9$ lensed LBG candidate, MACS1149-JD1. We did not find any strong $\text{Ly}\alpha$ features at $z \simeq 7.3\text{--}9.6$, consistent with

the picture that the Ly α emission has been highly suppressed by the neutral IGM beyond the redshift of $z \simeq 7$.

The results of this study and many other works have shown that the Ly α emission lines become very difficult to detect beyond the redshift of $z = 7$, which raises the question how we can confirm the galaxies beyond $z \simeq 7$. Studies have shown that the C III] 1909 emission line strengths dramatically increase in low-metallicity galaxies (e.g., Erb et al. 2010; Stark et al. 2014, 2015). The strong C III] emission may provide an alternative way to confirm the galaxies at redshifts of $z = 7$ –11 spectroscopically (Stark et al. 2014, 2015). Furthermore, C III] provides a unique opportunity to study the gas kinematics to understand the formation of the first generation of galaxies at $z \geq 7$ using the near-IR IFU spectrograph on the *James Webb Space Telescope* and the planned 30 m class ground-based telescopes (GMT, TMT, E-ELT).

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Facility: LBT(LUCI)

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