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KECK SPECTROSCOPY OF FAINT $3 > z > 7$ LYMAN BREAK GALAXIES: A HIGH FRACTION OF LINE EMITTERS AT REDSHIFT SIX

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ABSTRACT

As Lyα photons are scattered by neutral hydrogen, a change with redshift in the Lyα equivalent width (EW) distribution of distant galaxies offers a promising probe of the degree of ionization in the intergalactic medium and hence when cosmic reionization ended. This simple test is complicated by the fact that Lyα emission can also be affected by variations in the kinematics and dust content of the host galaxies. In the first paper in this series, we demonstrated both a luminosity- and redshift-dependent trend in the fraction of Lyα emitters seen within color-selected "Lyman break" galaxies (LBGs) over the range $3 < z < 6$; lower luminosity galaxies and those at higher redshift show an increased likelihood of strong emission. Here, we present the results from 12.5 hr exposures with the Keck DEIMOS spectrograph focused primarily on LBGs at $z \simeq 6$ which enable us to confirm the redshift dependence of line emission more robustly and to higher redshift than was hitherto possible. We find that 54% ± 11% of faint $z \simeq 6$ LBGs show strong ($W_{\mathrm{Ly}\alpha,0} > 25$ Å) emission, an increase of 55% from a sample of similarly luminous $z \simeq 4$ galaxies. With a total sample of 74 $z \simeq 6$ LBGs, we determine the luminosity-dependent Lyα EW distribution. Assuming continuity in these trends to the new population of $z \simeq 7$ sources located with the Hubble WFC3/IR camera, we predict that unless the neutral fraction rises in the intervening 200 Myr, the success rate for spectroscopic confirmation using Lyα emission should be high.

Key words: galaxies: evolution – galaxies: formation – galaxies: high-redshift – galaxies: starburst

Online-only material: color figures

1. INTRODUCTION

The reionization of neutral hydrogen in the intergalactic medium (IGM) was a landmark event in cosmic history, rendering the universe transparent to UV photons. In spite of its importance, there are few robust constraints on when reionization occurred. Polarization measures of the microwave background radiation (Larson et al. 2011) demonstrate scattering by free electrons in the redshift range $7 < z < 20$ but do not describe the evolving neutral fraction, $x_{\mathrm{H\,I}}$. Absorption line spectra of high-z quasars are sensitive to the very late stages of reionization (Fan et al. 2006), but progress has been slow due to the paucity of sources so far detected beyond $z \simeq 6.5$.

One of the most promising probes of reionization with current facilities is through the study of Lyα emission from star-forming galaxies. Since Lyα photons are resonantly scattered by neutral hydrogen, the abundance of Lyα emitters (LAEs) should decrease as observations probe into the era where there are pockets of neutral gas. Studies of the redshift-dependent luminosity function (LF) of LAEs selected via narrowband filters have revealed a possible decline in abundance between $z = 5.7$ and $z = 7.0$ (Kashikawa et al. 2006; Iye et al. 2006; Ota et al. 2008; Ouchi et al. 2010), offering tantalizing evidence that this short time interval (≃200 Myr) may correspond to one during which there is some evolution in the neutral fraction. But since a number of astrophysical factors can also affect the presence of Lyα emission, it may be dangerous to directly link evolution in the Lyα LF to reionization (e.g., Dayal et al. 2011). These factors include time-dependent changes in the host galaxy number density, dust obscuration and interstellar gas content, and kinematic properties (e.g., Verhamme et al. 2008; Atek et al. 2008; Hayes et al. 2010). By enlarging the LAE samples, it may be possible to bypass some of these complications by testing for the expected change in their spatial clustering and line profiles as the neutral era is entered (Ouchi et al. 2010).

A complementary approach introduced in Stark et al. (2010, hereafter Paper I) is to spectroscopically measure the fraction of strong LAEs within the Lyman break galaxy (LBG) population. By tracing the redshift-dependent fraction, the host galaxy number density is not a factor. Evolution in dust obscuration can be independently tracked using the continuum colors and interstellar medium (ISM) kinematics through deep spectroscopy (Steidel et al. 2010; Bouwens et al. 2009, 2010a; Vanzella et al. 2009). Although demanding observationally, high throughput spectrographs, such as FORS2 on the ESO Very Large Telescope (VLT) and DEIMOS on the Keck II telescope, have enabled progress in recent years (Paper I; Vanzella et al. 2009; Douglas et al. 2010). With this additional information on the abundances and dust properties of the LBG population, we can hope to more reliably link any redshift dependence in the Lyα fraction to ionization changes in the IGM. Most importantly of all, the proposed approach can now be readily extended to $z \simeq 7$–8 and beyond given the availability of LBG samples at these early epochs following the advent of the WFC3/IR camera on board *Hubble Space Telescope* (*HST*; e.g., Bouwens et al. 2010a).

In Paper I, we demonstrated the practical details of the above method through analyses of the Lyα fraction ($X_{\mathrm{Ly}\alpha}$) in a new Keck spectroscopic survey of B-band ($z \simeq 4$) and V-band

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($z \simeq 5$) dropouts to which we added i'-band ($z \simeq 6$) dropouts drawn from other programs (e.g., Vanzella et al. 2009; A. Bunker et al. 2011, in preparation). We found that Lyα emission is more frequent in less luminous systems, and correlations between the line strength and the UV continuum slope suggest that reduced dust obscuration is the main cause. The data also revealed an increase in $X_{\rm Ly\alpha}$ with redshift ($dx_{\rm Ly\alpha}/dz \simeq 0.05 \pm 0.03$), consistent with that required to explain the evolving UV LF of LAEs (Ouchi et al. 2008). However, given the limited size of our archival $z \simeq 6$ samples, this redshift evolution was primarily derived from data between $z \simeq 4$ and $z \simeq 5$.

To use Lyα emission as a probe of reionization, ideally one would construct the full equivalent width (EW) distribution function of emission for a range of UV luminosities at the highest redshift where the IGM is known to be highly ionized, i.e., $z \simeq 6$. This could then form the basis for comparisons with spectroscopic data at $z > 7$ where reionization may be incomplete. With this motivation, we have thus extended the sample introduced in Paper I, through ultra-deep spectroscopy of a sample of i'-band dropouts in the GOODS-North field. The increased sample size and deep spectroscopic exposures provide statistically significant constraints on the EW distribution of low-luminosity ($M_{\rm UV} \simeq -19$) sources, ensuring an adequate basis for comparisons with higher redshift spectroscopic samples.

Throughout the Letter, we adopt a Λ-dominated, flat universe with $\Omega_\Lambda = 0.7$, $\Omega_M = 0.3$, and $H_0 = 70\,h_{70}$ km s^{-1} Mpc^{-1}. All magnitudes in this Letter are quoted in the AB system (Oke & Gunn 1983).

2. OBSERVATIONS

Our data set is primarily comprised of spectra obtained using the DEep Imaging Multi-Object Spectrograph (DEIMOS) at the Nasmyth focus of the 10 m Keck II telescope (Faber et al. 2003). We direct the reader to Paper I for a full description of our survey strategy. In Paper I we presented analysis of 513 DEIMOS spectra, including 268 unique B-drops and 95 unique V-drops. To this we added publicly available spectra from the VLT/FORS2 survey of $z \simeq 4$, 5, and 6 LBGs (Vanzella et al. 2009) and 2 unique $z \simeq 6$ LBGs from the Keck survey of A. Bunker et al. (2011, in preparation). As discussed in Paper I, we retrospectively imposed the Keck photometric selection criteria on the VLT samples to ensure survey homogeneity and ensured that the initial VLT selection does not bias our results. The total sample drawn from Paper I is thus 351 B-drops, 151 V-drops, and 44 i'-drops.

The major step forward here is the inclusion of new $z \simeq 6$ spectra following ultra-deep Keck exposures of faint i'-band dropouts in GOODS-North. The archival data in Paper I were mostly based on the equivalent of 3–4 hr exposures with a 10 m aperture. The new sample consists of 23 i'-band dropouts with 12.5 hr exposures (and an additional 7 with 3.67 hr of integration) enabling constraints to be placed further down the EW distribution at $z \simeq 6$ (allowing a uniform sampling over the full redshift range) and increasing the total $z \simeq 6$ LBG sample by nearly $\simeq$70% to 74 galaxies across both GOODS fields.

The new data were taken during 2010 April. Over April 11–12, we obtained 12.5 hr of on-source integration in good seeing ($<0\farcs8$) for one mask containing 23 i'-band dropouts. Over April 13–14, we obtained 3.67 hr of integration on a separate mask containing seven i'-band dropouts. For both masks, we used the 830 line mm^{-1} grating, typically providing spectral coverage between 7000 Å and 10400 Å. Slit lengths were generally $\simeq 7''$, and slit widths were $1''$. Skylines are measured to have a Gaussian σ of 1.1 Å. Reduction was performed using the spec2d IDL pipeline developed for the DEEP2 survey (Davis et al. 2003).[7] Wavelength calibration was performed using Ne+Xe+Cd+Hg+Zn reference arc lamps. As in Paper I, we flux calibrate our data using the spectra of alignment stars included on the slitmask (observed in $2''$ by $2''$ boxes). We compared this calibration to that obtained using spectroscopic standard stars and found it to be consistent to within $\pm 20\%$ (with no significant systematic offset) for the alignment stars. Using the flux calibration, we computed our survey sensitivity as a function of wavelength. The 5σ limiting line flux varies with wavelength but in the redshift range sampled is typically $(3.1 \pm 0.5) \times 10^{-18}$ erg cm^{-2} s^{-1} (assuming a range of Lyα line widths typical of our LBG samples), implying that we should be able to detect Lyα with rest-frame EWs of greater than 20 ± 3 Å for i' drops with $z_{850} \simeq 27$.

Table 1
Summary of Spectroscopically Confirmed Lyα Emitters from Keck/DEIMOS Observations of i'-band Dropouts in GOODS-North

ID	R.A.	Decl.	z_{850}	Redshift
43_3982	12:36:09.427	+62:14:51.3	27.0	5.71
42_6706	12:36:19.135	+62:08:30.8	26.8	5.97
42_11475	12:36:33.377	+62:11:12.8	26.9	5.95
42_13066	12:36:37.533	+62:11:51.8	25.8	5.61
41_13100	12:36:37.623	+62:06:55.2	27.2	5.81
32_16773	12:36:47.483	+62:11:59.9	27.2	5.97
33_17705	12:36:49.966	+62:13:55.7	26.7	5.80
33_19990	12:36:55.444	+62:15:08.4	26.7	5.99
35_22248	12:37:00.963	+62:21:14.2	26.5	5.70
35_22381	12:37:01.296	+62:21:27.9	25.8	5.70
34_24923	12:37:08.280	+62:17:15.0	26.8	5.94
24_26902	12:37:13.821	+62:19:24.4	27.1	5.94
24_28120	12:37:17.153	+62:17:24.4	26.1	5.97

Notes. The IDs correspond to section names and numbers from the GOODS v2 photometry catalog. The z_{850} magnitudes are taken from the same catalog (the MAG_AUTO parameter) and are not corrected for Lyα emission.

3. ANALYSIS

We searched for Lyα emission at the spatial position of the targeted LBGs in the Keck spectra. Line fluxes and EWs were calculated following the procedures discussed in Paper I. We account for the effects of line contamination and Lyα forest absorption (estimated using relations presented in Meiksin 2006) on the observed z_{850}-band fluxes. Of the 23 i'-band dropouts for which we obtained ultra-deep spectra, 11 show Lyα emission, while 2 of the 7 i'-drops for which we obtained 3.67 hr integrations show Lyα (Figure 1). In Table 1, we present the details of those sources confirmed with DEIMOS. These results imply that a large fraction of i' drops have prominent Lyα emission. The rest-frame EWs for the i'-drops range between 9.4 Å and 350 Å. The vast majority of the emission lines are detected with high significance. Even so, we take a conservative cut, limiting our analysis to those sources with rest-frame EWs greater than 25 Å and S/N > 7. As a result, even among the faintest sources, the emission lines used in our analysis are very confidently detected (ranging from S/N = 7 to 20), removing concern regarding spurious features.

[7] The spec2d pipeline can be downloaded at http://juno.as.arizona.edu/∼cooper/deep/spec2d/

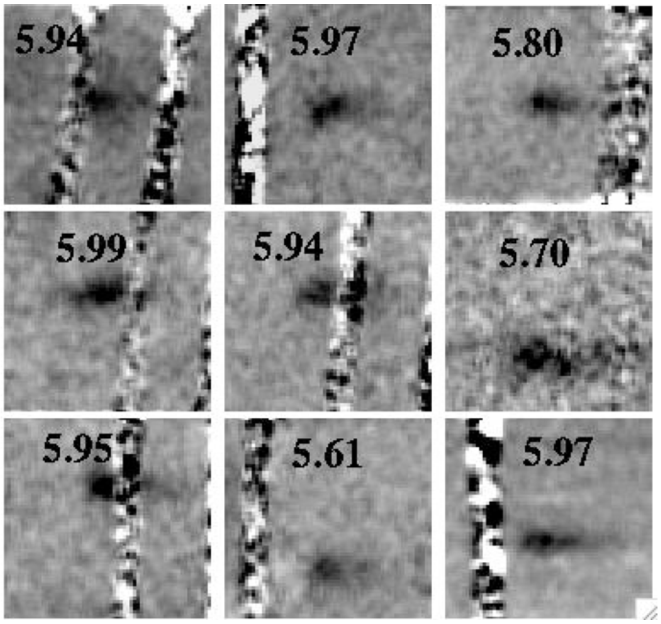

Figure 1. Montage of two-dimensional Lyα detections in the 2010 April DEIMOS run targeting i'-band dropouts in the GOODS-North field. The color scale is inverted with black corresponding to positive flux. Each cutout spans 7.1 arcsec × 28 Å. The i'-band dropouts that we observed are faint, with optical magnitudes spanning $26.0 < z_{850} < 27.5$. The Lyα detections are coincident with the spatial position of a UV continuum dropout satisfying the i'-band dropout color criteria ($i'{-}z > 1.3$ and containing no detections in deep B_{435} or V_{606} imaging). Only emission lines with $W_{\mathrm{Ly}\alpha,0} > 25$ Å are included in the analysis in Sections 3 and 4, ensuring that the EW distribution is derived from robust detections.

As in Paper I, we determine the completeness of our Lyα detections as a function of wavelength by adding and recovering fake emission lines at random positions across the two-dimensional spectra. We compute the Lyα recovery rate as a function of absolute magnitude and wavelength for all masks observed (including those in Paper I) and make appropriate corrections. This test demonstrates that in our deep 12.5 hr mask we are >90% complete to lines with $W_{\mathrm{Ly}\alpha,0} > 50$ Å even for the faintest i'-drops on our mask ($z_{850} \simeq 27$). For lines with $W_{\mathrm{Ly}\alpha,0} \simeq 20$ Å, the completeness implied by our simulations is ≃75%–80% for sources in the faintest magnitude bin covered by our $z \simeq 6$ spectra. The completeness is of course lower on the DEIMOS mask observed for only 3.67 hr, reaching below ≃50% for faint sources with $W_{\mathrm{Ly}\alpha,0} \simeq 20$ Å, and we therefore do not include these sources when computing the fraction of LBGs with low EW Lyα emission.

An additional concern is that the color-cut and z-band selection of i'-band dropouts are affected by Lyα emission and Lyα forest absorption. We investigate the extent to which these effects transform the observed EW distribution using Monte Carlo simulations. We create a large sample (>10^6) of artificial galaxies with intrinsic absolute magnitudes (normalized at 1500 Å) spanning $-21.5 < M_{\mathrm{UV}} < -18.5$ and redshifts spanning $5.6 < z < 6.5$. The intrinsic luminosity distribution of the fake galaxies matches the observed i'-drop LF (e.g., Bouwens et al. 2006). For the spectral shape, we use synthetic templates (S. Charlot & G. Bruzual 2011, in preparation) with parameters fixed to those which provide reasonable photometric fits for similarly bright i'-dropouts (e.g., Stark et al. 2009). Changing these parameters to other reasonable values does not affect our results. We attach Lyα luminosities to each of the galaxies according to an assumed Lyα EW distribution (which we describe below) and we also account for Lyα forest absorption using the relations presented in Meiksin (2006). Finally we derive i'_{775} and z_{850}-band magnitudes from the model spectral energy distributions (SEDs) and construct an artificial sample of i'-drops which satisfy the color criteria and z-band magnitude limit.

We find that the output EW distribution matches the input EW distribution of galaxies at the mean redshift of the i'-drop population. For example, if we adopt an input EW distribution with the form $p(W_{\mathrm{Ly}\alpha,0} = \exp[-W_{\mathrm{Ly}\alpha,0}/W_0])$ and set $W_0 =$ 20.0 Å, we find that the output EW distribution is nearly identical to the input distribution ($W_0 = 20.1$ Å). It should be noted that Poisson noise (which tends to scatter faint sources toward slightly brighter magnitudes) will alter the EW distribution if the intrinsic EW distribution is luminosity dependent, as suggested by Paper I. But this effect should occur at each redshift and hence should not affect the measured redshift evolution in the EW distribution.

4. RESULTS

We now derive the EW distribution and Lyα fraction ($X_{\mathrm{Ly}\alpha}$) for 74 $z \simeq 6$ galaxies and compare with the lower redshift samples of Paper I. As discussed in Paper I, we derive the fraction of emitters assuming that all our photometrically selected dropouts are genuinely at $z \sim 6$, even if we failed to confirm many spectroscopically. Although foreground emission lines (e.g., [O II]) can be readily distinguished from Lyα with our spectroscopic resolution, our analysis requires that we have a reliable sample of LBGs for which no emission line is seen. The likely contamination of this sample by foreground sources is discussed extensively in Paper I (Section 3.4) to which the reader is referred. We find negligible contamination for luminous examples ($-22 < M_{\mathrm{UV}} < -20$) rising to 10% for less luminous sources. These contamination rates are consistent with simulations undertaken by Bouwens et al. (2007) and allowed for in the uncertainties quoted below.

We group our i'-drop sample into two bins of rest-UV continuum absolute magnitude, taking care to apply minor corrections to the observed broadband magnitudes to compensate for the effects of Lyα emission and IGM Lyα forest absorption. For galaxies without Lyα emission, we correct for Lyα forest absorption statistically using the redshift distribution predicted from the Monte Carlo simulations in Section 3.

In Figure 2, we present our observed Lyα EW distribution, with emission lines grouped in 30 Å bins. For the luminous sub-sample, the distribution, $p(W_{\mathrm{Ly}\alpha,0})$, rises toward lower EW widths, reaching $p = 12\% \pm 6.8\%$ in the lowest EW bin considered. When compared to the EW distribution of luminous sources at $4 < z < 5$ (from Paper I), we find that while Lyα is marginally more common in each EW bin at $z \simeq 6$, the uncertainties are too large to distinguish the two distributions. In contrast, in the lower luminosity bin, the EW distribution shows stronger positive evolution from $4 < z < 5$, with Lyα more prevalent among $z \simeq 6$ LBGs.

We next compute the LBG Lyα fraction by integrating the EW distribution above our adopted limit of 25 Å and, separately above 55 Å, to yield the fractions $X^{25}_{\mathrm{Ly}\alpha}$ and $X^{55}_{\mathrm{Ly}\alpha}$. We group galaxies in the same two luminosity bins as in the analysis above. In the faint subset, we find 54% ± 11% have $W_{\mathrm{Ly}\alpha,0} > 25$ Å and 27% ± 8.0% have $W_{\mathrm{Ly}\alpha,0} > 55$ Å. Luminous galaxies exhibit Lyα emission less frequently, with 20% ± 8.1% and 7.4% ± 5.0% observed with Lyα emission in excess of 25 and 55 Å. Combining our results with those from Paper I, we find that

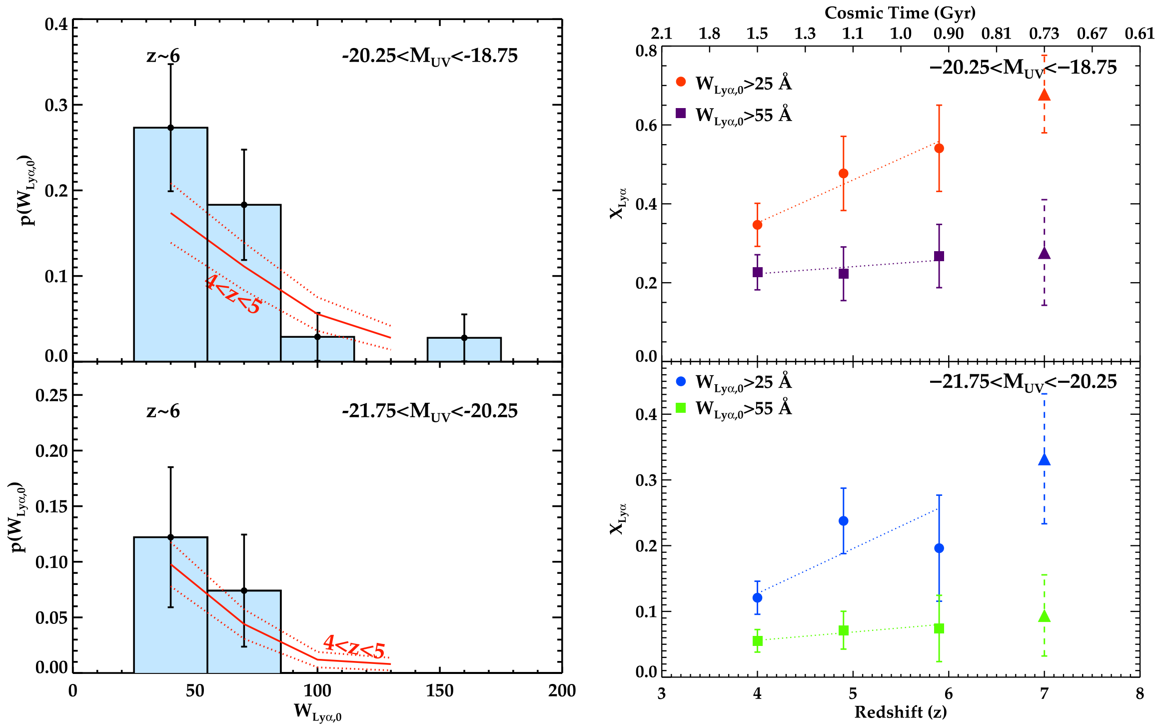

Figure 2. Left: the differential rest-frame Lyα EW distribution, $p(W_{\mathrm{Ly}\alpha})$ (computed in bins spanning $\Delta W_{\mathrm{Ly}\alpha,0} = 30$ Å) for star-forming galaxies at $z \simeq 6$ in two luminosity ranges ($-21.75 < M_{\mathrm{UV}} < -20.25$ on bottom and $-20.25 < M_{\mathrm{UV}} < -18.75$ on top). Overplotted in red is the Lyα EW distribution for LBGs at $4 < z < 5$ derived from the sample in Paper I (dotted lines provide 1σ uncertainties). Right: evolution in the overall fraction of Lyα emitters ($X_{\mathrm{Ly}\alpha}$) in the LBG population over $4 < z < 6$. Luminous LBGs are considered in the bottom panel and less luminous systems in the top panel. In each panel, we derive the Lyα fraction of LBGs with Lyα EWs larger than 25 Å (circles) and 55 Å (squares). Assuming a linear relationship between $X_{\mathrm{Ly}\alpha}$ and z, we extrapolate these trends to $z \simeq 7$ (triangles with dashed-line error bars).

(A color version of this figure is available in the online journal.)

the fraction of LAEs among the LBG population shows evidence of an increase with redshift for lower luminosity galaxies. Assuming a linear relationship between $X_{\mathrm{Ly}\alpha}$ and redshift, we find $dX^{25}_{\mathrm{Ly}\alpha}/dz = 0.11 \pm 0.04$. In contrast, less evolution is seen in the larger EW bin ($dX^{55}_{\mathrm{Ly}\alpha}/dz = 0.018 \pm 0.036$), consistent with the findings from Paper I. For the more luminous subsample, the data are noisier but consistent with the above trends, with the lowest EW bin showing the strongest indications of positive evolution with redshift.

5. THE EXPECTED VISIBILITY OF Lyα EMISSION IN $z \simeq 7$ LBGs

Our new results, taken together with those in Paper I, now suggest that $\simeq$54% of moderately faint ($-20.25 < M_{\mathrm{UV}} < -18.75$) $z \simeq 6$ LBGs exhibit very strong Lyα emission. Recent analyses of the colors of the $z \simeq 7$ LBGs indicate that these systems are yet bluer than those at $z \simeq 6$ (Bouwens et al. 2010a), implying even less or no dust obscuration. Hence, the redshift trend in the Lyα fraction in Figure 2 should continue to $z \simeq 7$ suggesting that Lyα should be readily detectable in deep spectroscopic campaigns.

Given the short cosmic time spanning $6 < z < 7$ ($\simeq$170 Myr), it seems plausible to use the EW distribution and Lyα fractions presented in Figure 2 to predict the expected Lyα visibility for sources at $z \simeq 7$, assuming Lyα flux is not significantly attenuated by neutral hydrogen in the IGM. Motivated by the blue $z \simeq 7$ UV slopes discussed above, we extrapolate the evolution in $X_{\mathrm{Ly}\alpha}$ to $z \simeq 7$ (Figure 2). For low-luminosity sources, this results in a small increase in the Lyα fraction ($\Delta X^{25}_{\mathrm{Ly}\alpha} = 0.14$) which we divide into the three EW bins using weights set by $p(W_{\mathrm{Ly}\alpha,0})$. We follow the same procedure for the luminous sources. The results, presented in Figure 3, suggest a survey of $\simeq$20–30 galaxies drawn from the now-available

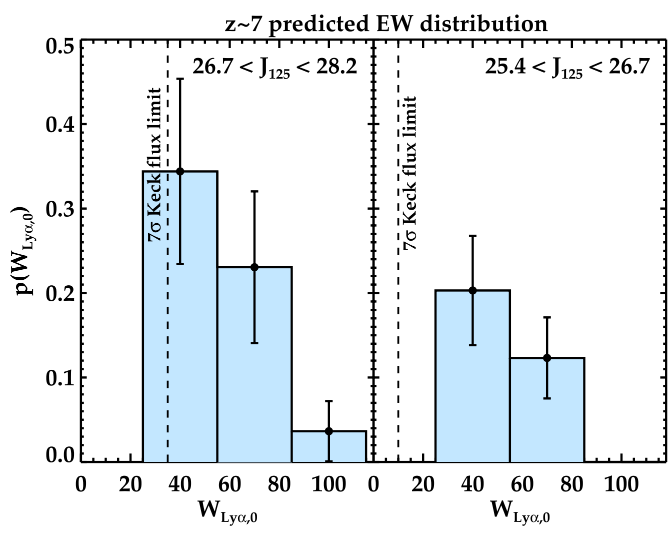

Figure 3. Predicted rest-frame Lyα EW distribution (in bins of $\Delta W_{\mathrm{Ly}\alpha,0} = 30$ Å) for $z \simeq 7$ LBGs based on an extrapolation of trends from Figure 2 assuming that the Lyα fraction increases linearly with redshift. Uncertainties are based on statistical error in our lower redshift samples. The dashed line indicates the limits that could be reached $\simeq$4 hr of integration with Keck/NIRSPEC. Significant deviations below this prediction may arise if the IGM is partially neutral.

(A color version of this figure is available in the online journal.)

WFC3/IR target list (e.g., McLure et al. 2010; Bouwens et al. 2010b; Bunker et al. 2010; Finkelstein et al. 2010) would yield interesting results. While uncertainty in the observed Lyα trends and their extrapolation to $z \simeq 7$ obviously affects our prediction, it seems clear that Lyα should be common in $z \simeq 7$ samples if the IGM is highly ionized. The failure to detect emission in such a sample might therefore be a strong indicator of a rising neutral fraction beyond $z \simeq 6$ as claimed originally by Kashikawa et al. (2006) from the LF of LAEs.

How practical is a search for line emission to the EW limit of 20 Å discussed above? In terms of an integrated line flux $F_{\mathrm{Ly}\alpha}$, the EW limit corresponds to $F_{\mathrm{Ly}\alpha} \simeq 3(7) \times 10^{-18}$ erg cm^{-2} s^{-1} for $z \simeq 7$ galaxies with $M_{\mathrm{UV}} = -20(-21)$ (corresponding to galaxies with apparent AB magnitudes of $J \simeq 27$ and 26, respectively). Such line flux limits are feasible with spectrographs on 8–10 m telescopes such as the Near InfraRed SPECtrograph (NIRSPEC) on Keck II (McLean et al. 1998). Earlier work with NIRSPEC has reached such a limit at 5σ significance between the atmospheric sky lines in the Y and J bands in $\simeq$4 hr (Stark et al. 2007; Richard et al. 2008). As more multi-object infrared spectrographs become available, it will be feasible to observe many $z > 7$ sources simultaneously, allowing ultra-deep exposures of galaxies at least as faint as $M_{\mathrm{UV}} \simeq -19$.

6. CONCLUSIONS

We present new ultra-deep spectroscopic observations of 30 i'-band dropouts in GOODS-N using DEIMOS on the Keck II telescope. By adding these spectra to the large database of DEIMOS and FORS2 spectra of B-, V-, and i'-band dropouts discussed in Paper I, we demonstrate more robustly the rise with redshift over $4 < z < 6$ in the fraction of low-luminosity LBGs that show prominent Lyα emission. We also derive a much-improved EW distribution of Lyα at $z \simeq 6$, the highest redshift where the IGM is known to be highly ionized. Provided the IGM does not become significantly neutral at $z \simeq 7$, our results suggest that Lyα emission should be detectable in the $z \simeq 7$ galaxies recently discovered with *HST*/WFC3 using current facilities.

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