Big Three Dragons. III: A Study of Molecular Gas in a Bright Lyman-Break Galaxy at $z = 7.15$ with ALMA

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ABSTRACT

We report ALMA Band 3 observations of CO(6-5), CO(7-6) and [CI](2-1) in B14-65666 (“Big Three Dragons”), one of the brightest Lyman-Break Galaxies at $z > 7$ in the rest-frame ultraviolet continuum, far-infrared continuum, and emission lines of [OIII] 88 µm and [CII] 158 µm. None of CO(6-5), CO(7-6) and [CII](2-1) are detected, whose $3\sigma$ upper limits on the luminosities are about 50 times fainter than the [CII] luminosity. Based on three methods of i) [CII] luminosity and a [CII]-to-H$_2$ conversion factor reported in local metal-poor dwarf galaxies, ii) a dust mass and metallicity-dependent dust-to-gas mass ratio, and iii) a dynamical mass estimate, we obtain the molecular gas mass ($M_{mol}$) to be $(0.05 - 11) \times 10^{10} M_\odot$, which is consistent with its upper limit inferred from the non-detection of mid-J CO and [CII](2-1). Albeit with large uncertainty in $M_{mol}$, we estimate a high molecular gas-to-stellar mass ratio ($\mu_{gas}$) of 0.65 – 140 and a short gas depletion time ($t_{dep}$) of 2.5 – 550 Myr, which are broadly consistent with extrapolations of $\mu_{gas}$ and $t_{dep}$ as functions of redshift, specific-star formation rate, and stellar mass as reported in previous studies. The short $t_{dep}$ partly reflects the starburst nature of the target, likely to be induced by a major-merger event. B14-65666 can be an ancestor of a passive galaxy at $z \gtrsim 4$ if no gas is fueled from outside the galaxy. Overall, our observations highlight difficulty in obtaining robust conclusion from mid-J CO alone particularly in the epoch of reionization, and motivate studies that use other tracers as an alternative gas mass tracer.

Keywords: galaxies: high-redshift, galaxies: ISM, galaxies: star formation,
Understanding molecular gas properties through the cosmic time is an important topic in galaxy formation and evolution as molecular gas is the fuel for star formation. The molecular gas mass, $M_{\text{mol}}$, is often studied by luminosity of carbon monoxide ($^{12}$CO; hereafter CO) (e.g., Bolatto et al. 2013), measurements of dust mass (e.g., Magdis et al. 2012), and emission from cold dust that is sensitive to the dust mass (e.g., Scoville et al. 2016). Based on $M_{\text{mol}}$ estimates, previous studies have established that high redshift ($z > 6$) galaxies have i) a higher molecular gas-to-stellar mass ratio ($\mu_{\text{gas}} \equiv M_{\text{mol}}/M_*$) and ii) a shorter molecular gas depletion time that is defined as the ratio of $M_{\text{mol}}$ to the star formation rate ($t_{\text{dep}} \equiv M_{\text{mol}}/$SFR) than local galaxies (Tacconi et al. 2020 and references therein).

So far, CO line detection in the epoch of reionization (EoR; $z \gtrsim 6$) has been limited mainly to dusty star-forming galaxies (DSFGs: Walter et al. 2012; Riechers et al. 2013; Combes et al. 2012; Vieira et al. 2013; Asboth et al. 2016; Stradet et al. 2017; Riechers et al. 2017; Casey et al. et al. 2019; Jarugula et al. et al. 2021; Vieira et al. 2021) and quasar host galaxies (e.g., Walter et al. 2003; Riechers et al. 2009; Wang et al. 2010, 2011; Carilli & Walter 2013; Venemans et al. 2017a, b; Carniani et al. 2019) that have large SFRs ($\gtrsim 100 - 1000$ $M_\odot$ yr$^{-1}$). Indeed, there has been a few CO observations in “normal” star forming galaxies in the EoR: Wagg et al. (2009) and Wagg & Kankel (2012) have reported nondetections of CO($J = 1 \rightarrow 0$) and CO($J = 2 \rightarrow 1$), respectively, in galaxies with moderate SFRs ($\sim 10 - 100$ $M_\odot$ yr$^{-1}$ at $z \approx 6 - 7$ with the Green Bank Telescope, where J indicates the rotational quantum number. Pavesi et al. (2019) have observed CO($J = 2 \rightarrow 1$) with the Very Large Array in two normal star-forming galaxies at $z \approx 5 - 6$ characterized by high stellar masses ($M_* \sim 10^{10}$ $M_\odot$) and moderate SFRs ($\sim 50 - 100$ $M_\odot$ yr$^{-1}$). The authors report detection of the line from a Lyman-Break Galaxy (LBG), a typical high-z galaxy population selected via rest-frame ultraviolet (UV) continuum, where $E_{\text{upper}}/k_B \sim 116$ (155) K and the critical density $n_{\text{crit}} \sim 3 (4.5) \times 10^5$ cm$^{-3}$ (e.g., Guillberg et al. 2016). Importantly, based on zoom-in cosmological hydrodynamical simulations implementing radiative transfer calculations, Vallini et al. (2019) have shown that EoR galaxies have a high gas excitation condition with a CO luminosity peak at an upper rotational level ($J_u \approx 6 - 7$ as a result of e.g., their high star-formation surface density and warm temperature of giant molecular clouds (but see also e.g., Obreschkow et al. 2009 who have shown that CO observations become difficult in the EoR due to attenuation effects by the cosmic microwave background, CMB, to the lines). The authors show that these mid-$J$ CO lines are detectable in a reasonable amount of integration time with superb sensitivity of the Atacama Large Millimeter/Submillimeter Array (ALMA) telescope.

Indeed, D’Odorico et al. (2018) have detected the CO($J = 6 \rightarrow 5$) line from a damped Ly$\alpha$ system at $z = 5.67$ with SFR $\approx 100$ $M_\odot$ yr$^{-1}$ based on ALMA observations. These results motivate mid-$J$ CO observations of galaxies deep into the EoR ($z \gtrsim 6 - 7$), which can be eventually used to place constraints on theoretical models as well as to study the evolution of molecular gas properties out to the EoR.

As a pilot study, here we present new ALMA Band 3 observations of B14-65666 (“Big Three Dragons”) at $z = 7.1520$. The target is one of the brightest LBGs without gravitational lensing at $z \gtrsim 6$ in the rest-frame ultraviolet (UV) continuum, far-infrared (FIR) continuum, and FIR emission lines of [OIII] 88 $\mu$m and [CII]158 $\mu$m (Bowler et al. 2014; Furusawa et al. 2016; Hashimoto et al. 2019; Sugahara et al. 2021). At this redshift, a single ALMA Band 3 tuning can simultaneously target CO($J = 6 \rightarrow 5$) and CO($J = 7 \rightarrow 6$). In addition, the [CII] $^3P_2 \rightarrow ^3P_1$ line can be also observed adjacent to CO($J = 7 \rightarrow 6$). The [CII] $^3P_2 \rightarrow ^3P_1$ line has $E_{\text{upper}}/k_B \sim 62$ K and $n_{\text{crit}} \sim 10^3$ cm$^{-3}$, and is proposed as an alternative tracer of the molecular gas mass (e.g., Papadopoulos et al. 2004).

There are two reasons why molecular gas properties of B14-65666 are of interest. Firstly, the large luminosity in infrared and [CII] implies the presence of a significant amount of dust and neutral gas, respectively. These would lead to effective shielding of CO from UV radiation, making B14-65666 an ideal target for mid-$J$ CO observations. Secondly, previous studies have shown that B14-65666 is an example of the highest-$z$ starburst galaxies due to a major-merger event (Bowler et al. 2017; Hashimoto et al. 2019). Thus, detailed molecular gas properties of the target might provide information on a connection between merger, starburst, emergence of quasars, and quenching of star formation at high-$z$ (e.g., Hopkins et al. 2008).

The paper is structured as follows. In §2 and §3, we introduce the target and describe our ALMA Band 3 data, respectively. In §4, we measure quantities of dust continuum at the rest-frame wavelength, $\lambda_{\text{rest}}$, of 400 $\mu$m and emission lines of CO($J = 6 \rightarrow 5$), CO($J = 7 \rightarrow 6$), and [CII] $^3P_2 \rightarrow ^3P_1$. In this section, we also present...
correction for the CMB attenuation to the lines. In §5, we obtain the molecular gas mass of the target based on techniques of i) mid-J CO luminosity, ii) [CI] $^3P_2 \rightarrow ^3P_1$ luminosity, iii) [CII] 158 $\mu$m luminosity, iv) dust, and (v) dynamical mass. Discussions in the context of $\mu_{\text{gas}}$ and $t_{\text{dep}}$ are presented in §6, followed by our conclusions in §7. Throughout this paper, magnitudes are given in the AB system (Oke & Gunn 1983), and we assume a $\Lambda$CDM cosmology with $\Omega_m = 0.272$, $\Omega_b = 0.045$, $\Omega_L = 0.728$ and $H_0 = 70.4$ km s$^{-1}$ Mpc$^{-1}$ (Komatsu et al. 2011). The solar luminosity, $L_\odot$, is $3.839 \times 10^{36}$ erg s$^{-1}$. Hereafter, we denote CO($J = 6 \rightarrow 5$), CO($J = 7 \rightarrow 6$), and [CI] $^3P_2 \rightarrow ^3P_1$ as CO(6-5), CO(7-6), and [CI](2-1), respectively.

2. OUR TARGET, “BIG THREE DRAGONS”

Previous observations of our target is summarized in Table 1. The target has been discovered by Bowler et al. (2014) based on wide-field imaging data of the UltraVISTA survey (e.g., McCracken et al. 2012). The object has a UV absolute magnitude of $M_{\odot}$ ISTA survey (e.g., McCracken et al. 2012). The object ($20140104$) based on wide-field imaging data of the UltraVISTA survey (e.g., McCracken et al. 2012). The object has been discovered by Bowler et al. ($\approx -4.5$) and the target is experiencing a merger event indicating that the target is experiencing a merger event (Bowler et al. 2017).

The spectroscopic redshift of the target has been first obtained with the Faint Object Camera and Spectrograph (FOCAS) on Subaru at $z = 7.17$ with Ly$\alpha$ (Furusawa et al. 2016). Later, spectroscopy with ALMA has resulted in detections of [OIII] 88 $\mu$m and [CI] 158 $\mu$m (Hashimoto et al. 2019) and a non-detection of [NII] 122 $\mu$m (Sugahara et al. 2021), determined its spectroscopic redshift at 7.1520 ± 0.0003. Notably, Hashimoto et al. (2019) have shown that [OIII] and [CI] can be spatially decomposed into two components associated with the two UV clumps which are kinematically separated by $\approx 150$ km s$^{-1}$, supporting the merger interpretation.

In addition, ALMA has detected dust continuum emission at $\lambda_{\text{rest}} \approx 90$ (Hashimoto et al. 2019), 120 (Sugahara et al. 2021), and 160 $\mu$m (Bowler et al. 2018, 2022; Hashimoto et al. 2019), with ALMA Band 8, 7, and 6, respectively. As such, the target is one of the best star-forming galaxies in the EoR with well-sampled dust spectral energy distribution (SED). With modified-black body radiation models for the dust continuum radiation, Sugahara et al. (2021) have constrained the total-infrared luminosity ($L_{\text{TIR}}$ integrated at $8 - 1000$ $\mu$m) to be 4.0 and 12.6 $\times 10^{11}$ $L_\odot$ at a parameter set of ($T_d$, $\beta$) = (40 K, 2.0) and (80 K, 1.0), respectively, where $T_d$ and $\beta$ are the dust temperature and emissivity index, respectively.

3. ALMA OBSERVATIONS AND DATA REDUCTION

Our observations are summarized in Table A1. We performed ALMA Band 3 observations during 2019 Sep 17 – 22 as a Cycle 6 program (ID: 2018.1.01673.S, PI: T. Hashimoto). We used 41 – 45 antennas with the baseline lengths of 15 – 2954 m, resulting in the maximum recoverable scale of $\approx 6''$. The total on-source exposure time was about 3.75 hours. The phase-tracking center was set to the position of the target, ($\alpha_{\text{ICRS}}, \delta_{\text{ICRS}}$) = ($10^h01^m40^s690.001545252^s750$). Four spectral windows were set at the central frequencies of 85.00, 86.88, 97.15, and 98.95 GHz, which are referred to as SPW1, SPW2, SPW3, and SPW4. The CO(6-5) line was observed in SPW1, while the CO(7-6) and [CI](2-1) lines were observed in SPW3. In these SPWs, we used the FDM correlator to reliably search for emission lines. The bandwidths were 1.875 GHz with a channel spacing of 7.813 MHz. In the remaining two SPWs, SPW2 and SPW4, we used the TDM correlator to effectively observe the continuum emission whose bandwidths were 2.000 GHz with a channel spacing of 15.625 MHz. A quasar J1008+0029 was used for complex gain calibration. Two quasars, J0854+0026 and J1037-2934, were used for bandpass calibration. Flux was scaled using

### Table 1. Summary of Previous Measurements

| Parameters | Measurements | Ref. |
|------------|--------------|------|
| $L_{\text{UV}}$ [$L_\odot$] | $2.0 \times 10^{11}$ | B17 |
| $L_{\text{[OIII]}}$ [$L_\odot$] | $(3.4 \pm 0.4) \times 10^{9}$ | H19 |
| $L_{\text{[CII]}}$ [$L_\odot$] | $(1.1 \pm 0.1) \times 10^{9}$ | H19 |
| $L_{\text{[NII]}}$ [$L_\odot$] | $< 8.1 \times 10^{7}$ | S21 |
| $L_{\text{TIR}}$ ($T_d = 40$ K, $\beta = 2.0$) [$L_\odot$] | $4.0 \times 10^{10}$ | S21 |
| $L_{\text{TIR}}$ ($T_d = 80$ K, $\beta = 1.0$) [$L_\odot$] | $12.6 \times 10^{11}$ | S21 |
| $L_{\text{TIR}}$ ($T_d = 40$ K, $\beta = 2.0$) [$L_\odot$] | $3.1 \times 10^{11}$ | - |
| $L_{\text{EIR}}$ ($T_d = 80$ K, $\beta = 1.0$) [$L_\odot$] | $5.3 \times 10^{11}$ | - |

Note—The upper limit is $3\sigma$. The total-infrared luminosity, $L_{\text{TIR}}$, and far-infrared luminosity, $L_{\text{FIR}}$, are estimated by integrating the modified-black body radiation at 8 – 1000 and 42.5 – 122.5 $\mu$m, respectively. Following Sugahara et al. (2021), we consider two combinations of ($T_d$, $\beta$) = (40 K, 2.0) and (80 K, 1.0). References are B17 (Bowler et al. 2017), H19 (Hashimoto et al. 2019), and S21 (Sugahara et al. 2021).
Continuum maps were created using all channels expected to be line-free\(^1\). The synthesized beam has a size of 0\(\prime\)46 \(\times\) 0\(\prime\)41 in the FWHM and a positional angle (BPA) of 61\(\degree\), with the sensitivity of 4.6 \(\mu\)Jy beam\(^{-1}\) in r.m.s. The beam size is smaller than the target’s beam-size of 0\(\prime\)45. Hereafter, we use the \(uv\)-tapered maps and cubes unless otherwise specified.

As the dust continuum was undetected in ALMA Band 3, we created line cubes without performing the CASA task \texttt{uvcontsub}. The cubes were rebinned to a velocity resolution of 50 km s\(^{-1}\). For SPW1 (SPW3) targeting CO(6-5) [CO(7-6) and [C\textsc{i}](2-1)], we also created a \(uv\)-tapered data cube, using a Gaussian taper with a width of 0\(\prime\)40 (0\(\prime\)45). This cube has a synthesized beam size of 0\(\prime\)78 \(\times\) 0\(\prime\)68 (0\(\prime\)78 \(\times\) 0\(\prime\)68) and a typical sensitivity of 107 (93) \(\mu\)Jy beam\(^{-1}\). Hereafter, we use the \(uv\)-tapered maps and cubes unless otherwise specified.

### 4. RESULTS

#### 4.1. Dust continuum emission at \(\lambda_{\text{rest}} \approx 400 \mu\)m

Our newly taken ALMA Band 3 data probe the dust continuum emission at \(\lambda_{\text{rest}} \approx 400 \mu\)m. Figure 1 shows the dust continuum map overlaid on the \(HST\) F140W image. The contours are drawn at \((-3, -2, -1, +1, +2, +3) \times \sigma\), where the positive and negative contours are indicated by black solid and dashed lines, respectively. The \(\sigma\) value is \(\approx 5.3 \mu\)Jy beam\(^{-1}\). The ellipse at the lower left corner indicates the synthesized beam size of ALMA (Table 2). No significant emission has been detected.

\(^1\) In this procedure, we excluded the channels that potentially include the emission lines by assuming the full width at the half maximum (FWHM) of the lines to be 400 km s\(^{-1}\), which is comparable to the observed FWHMs of \(\sim 400\) km s\(^{-1}\) in [O\textsc{iii}] and [C\textsc{i}] (Hashimoto et al. 2019).
to place a strong constraint on the dust emissivity index, $\beta$, it validates assumptions of $\beta = 1 - 2$ used in previous studies in the target (Hashimoto et al. 2019; Sugahara et al. 2021; Bowler et al. 2018, 2021).

4.2. CO(7-6), CO(6-5), and [C\textsc{i}](2-1) Emission

We have searched for the presence of emission lines in the cubes at the position of the target. At $z = 7.1520$, the CO(6-5), CO(7-6), and [C\textsc{i}](2-1) emission lines are expected to be at the observed frequency of 84.82, 98.95, and 99.28 GHz, respectively.

Top and bottom panels of Figure 3 show the integrated intensity maps (i.e., moment 0 maps) and spectra, respectively, of CO(6-5), CO(7-6), and [C\textsc{i}](2-1). In these maps, we integrate the velocity range from $-200$ to $+200$ km s$^{-1}$ with the CASA task \texttt{immoments}, which is comparable to the FWHM of [O\textsc{iii}] and [C\textsc{ii}] (Hashimoto et al. 2019)$^2$. The spectra are obtained in a 1$''$-diameter aperture centered on the target. We conclude that the CO(6-5), CO(7-6), and [C\textsc{i}](2-1) lines are undetected.

From the integrated intensity maps, we obtain the 3$\sigma$ upper limits of 0.0447, 0.0420, and 0.0417 Jy beam$^{-1}$ km s$^{-1}$ for CO(6-5), CO(7-6), and [C\textsc{i}](2-1), respectively. To convert these into the upper limits on the velocity-integrated flux, $S_{\text{line}\Delta v}$, we assume that mid-$J$ and [C\textsc{i}](2-1) have the same emitting region as the dust continuum$^3$. We thus obtain 3$\sigma$ upper limits of $S_{\text{line}\Delta v}$ as 0.0447, 0.0420, and 0.0417 Jy km s$^{-1}$ for CO(6-5), CO(7-6), and [C\textsc{i}](2-1), respectively.

4.2.1. Correction for the CMB effects

Before obtaining upper limits on line luminosities, we need to correct for the CMB attenuation effects. We explain below the CMB effect on CO; its effect on [C\textsc{i}](2-1) can be examined in the same manner. There are two CMB effects on CO observations as discussed in previous works (e.g., Sakamoto 1999; Combes et al. 1999; Papadopoulos et al. 2000; Obreschkow et al. 2009; da Cunha et al. 2013; Zhang et al. 2016). Firstly, high CMB temperature increases the population of high rotational levels and enhance the luminosity of mid- to high-$J$ transitions. Secondly, high CMB temperature also becomes a higher background against which the line is detected. The net effect is that the CMB can significantly decrease the observed CO luminosity at high-$z$. Following equation (32) of da Cunha et al. (2013), the fraction of the intrinsic line flux observed against the CMB is written

2 Although we do not know the exact FWHM values of the mid-$J$ CO and [C\textsc{i}](2-1) lines of the target, several studies show that CO(6-5) and [C\textsc{i}](2-1) have similar FWHMs (e.g., Wang et al. 2013, 2016; Strandet et al. 2017; Venemans et al. 2017a; Zavala et al. 2018; Carniani et al. 2019). Likewise, some studies show that CO(7-6) and [C\textsc{i}](2-1) lines have comparable FWHMs (e.g., Brisbin et al. 2019, see also Venemans et al. 2017a). Thus, our assumption would be reasonable as a first step.

3 Previous studies show that there is no clear trend on comparisons between emitting regions of CO and dust: Firstly, Kaasinen et al. (2020) have compared the sizes of CO(2-1) or CO(3-2) with that of dust continuum in three normal star-forming galaxies at $z \sim 2$. The authors find that two among the three objects, ALPS.1 and ALPS.3, have CO emission more spatially extended than dust continuum. Similarly, Tadaki et al. (2017, 2019) and Chen et al. (2020) have compared the sizes of CO(2-1) or CO(3-2) with that of dust continuum in three normal star-forming galaxies at $z \sim 2$. The authors find that two among the three objects, ALPS.1 and ALPS.3, have CO emission more spatially extended than dust continuum. Secondly, a quasar at $z = 6.0$ (J2310+1855) has similar spatial sizes of CO(6-5) and dust (e.g., Feruglio et al. 2018; Li et al. 2020). Finally, a $z = 6.3$ quasar observed in CO(6-5) (J30100+2802; Wang et al. 2019) and a normal $z \sim 2$ SFG observed in CO(2-1) (ALPS.2; Kaasinen et al. 2020) show that their CO is spatially more compact than dust continuum. Under these situations, our assumption would be reasonable as a first step.
Figure 3. (Top) From left to right, integrated intensity maps of CO(6-5), CO(7-6), and [CI](2-1) overlaid on the 5″×5″ cutout image of HST F140W image. In each panel, the contours are drawn at (-3, -2, -1, +1, +2, +3) × σ, where the σ values are ≈ 14.9, 14.0, and 13.9 mJy beam\(^{-1}\) km s\(^{-1}\) for the CO(6-5), CO(7-6), and [CI](2-1) maps, respectively. The white dashed circle at the center shows the 1″-diameter aperture used to extract spectra in the bottom panels. (Bottom) Top, middle, and bottom panel shows the spectrum of CO(6-5), CO(7-6), and [CI], respectively. The black dotted curve shows the noise spectrum. The vertical dashed line shows the velocity range from −200 to +200 km s\(^{-1}\) that is used to create the integrated intensity maps in the top panels. The velocity width is set to 50 km s\(^{-1}\). No significant emission has been detected.
as

\[ f_{\text{CMB}} = \frac{S_{J_u}[\text{obs against CMB}]}{S_{J_u}[\text{intrinsic}]} = 1 - \frac{B_v[T_{\text{CMB}}(z)]}{B_v[T_{\text{exc}}]}, \quad (1) \]

where \( S_{J_u}[\text{intrinsic}] \) and \( S_{J_u}[\text{obs against CMB}] \) represent the intrinsic and observed flux density of the transition of \( J_u \), respectively. \( T_{\text{CMB}}(z) = (1 + z) \times 2.73 \text{ K} \) is the CMB temperature at \( z \), and \( T_{\text{exc}} \) is the excitation temperature in units of K. \( B_v(T) \) is the Planck function. To properly evaluate the CMB effect with eq. (1), we need information on the optical depth and the excitation temperature \( T_{\text{exc}} \) of each transition, which requires us to consistently treat the statistical equilibrium and radiative transfer (da Cunha et al. 2013; van der Tak et al. 2007). This is impossible for our case where we only have non-detections of CO(6-5) and CO(7-6). Therefore, we first quantitatively estimate the CMB effect under the assumption of the local thermal equilibrium (LTE) of molecular clouds (see similar procedures in e.g., Dessauges-Zavadsky et al. 2017; Venemans et al. 2017b; Jin et al. 2019). We then qualitatively discuss the CMB effect in a non-LTE case. Table 3 summarizes the correction factors.

In the LTE case, all rotational levels are thermalized and thus \( T_{\text{exc}} \) becomes equal to gas kinetic temperature, \( T_{\text{kin}} \). If dust and gas is in thermal equilibrium (Goldsmith 2001), one can eventually assume \( T_{\text{exc}} = T_{\text{kin}} = T_{\text{dust}} \). Sugahara et al. (2021) have obtained the luminosity-weighted dust temperature \( T_{\text{dust}} \approx 40 \) (80) K assuming \( \beta = 2.0 \) (1.0), which can be used as a proxy of \( T_{\text{kin}} \) (e.g., Jiao et al. 2019; Valentino et al. 2020a). With eq. (1), we obtain \( f_{\text{CMB}} = 0.62 \), 0.65 (0.85), and 0.65 (0.87) for CO(6-5), CO(7-6), and [Cl](2-1), respectively, at \( T_{\text{exc}} = 40 \) (80) K (Table 3).

In the non-LTE case, \( f_{\text{CMB}} \) depends on a variety of parameters such as \( T_{\text{kin}} \), the number density of H\(_2\) molecules, \( n_{\text{H}_2} \), and the number density of CO molecules (da Cunha et al. 2013). Because the number of CO collisions with H\(_2\) becomes small at low \( n_{\text{H}_2} \), mid- to high-J CO transitions with higher critical density significantly depart from the LTE case. This leads to \( T_{\text{CMB}} \sim T_{\text{exc}} < T_{\text{kin}} \), and results in severe CMB attenuation for mid- to high-J transitions, even worse than low-J transitions (see also Fig. 8 in Combes et al. 1999).

From Fig. 10 of da Cunha et al. (2013), the correction factor in the non-LTE case is about 0.06 and 0.6 in the case of \( n_{\text{H}_2} = 10^{1.2} \) and \( 10^{4.2} \text{ cm}^{-3} \), respectively, at a fixed \( T_{\text{kin}} = 40 \) K. The former (latter) corresponds to \( T_{\text{exc}} \sim 23 \) (40) K, according to eq. (1). Although we cannot measure \( n_{\text{H}_2} \) in B14-65666 with the current data, the values of \( n_{\text{H}_2} = 10^{3.2} \) and \( 4.2 \text{ cm}^{-3} \) are similar to those found in \( z \sim 2 - 4 \) DSFGs with \( \log(L_{\text{FIR}}/L_{\odot}) \sim 12 - 13 \) (Yang et al. 2017; Cañameras et al. 2018). Thus, the cases with \( T_{\text{exc}} = 23 \) and 40 K cannot be rejected for B14-65666.

In summary, \( f_{\text{CMB}} \approx 0.06, 0.6, \) and 0.9 at \( T_{\text{exc}} = 23, 40, \) and 80 K, respectively (Table 3). Hereafter, due to the large uncertainty in \( f_{\text{CMB}} \), we treat it as a parameter unless otherwise specified. Based on the 3\( \sigma \) upper limits on \( S_{\text{line}} \Delta v \) (§4.2), we estimate the 3\( \sigma \) upper limits on the CMB-corrected line fluxes, \( S_{\text{line}} \Delta v(\text{corr.}) \), to be \( 0.0447 \frac{\text{Jy}}{\text{km s}^{-1}} \) and \( 0.9417 \frac{\text{Jy}}{\text{km s}^{-1}} \) for CO(6-5), CO(7-6), and [Cl](2-1), respectively, as shown in Table 4.

4.2. Upper limits on line luminosities

We obtain 3\( \sigma \) upper limits on two types of line luminosity (Solomon et al. 1992; Carilli & Walter 2013), which are summarized in Table 4. The first one, \( L_{\text{line}} \), in units of \( L_{\odot} \), is written as

\[ L_{\text{line}} = 1.04 \times 10^{-3} \times S_{\text{line}} \Delta v D_L^2 \nu_{\text{obs}}, \quad (2) \]

where \( S_{\text{line}} \Delta v \) is the velocity-integrated flux in units of Jy km s\(^{-1}\), \( D_L \) is the luminosity distance in Mpc, and \( \nu_{\text{obs}} \) is the observed frequency in GHz. We obtain the 3\( \sigma \) upper limits with \( S_{\text{line}} \Delta v \) (Table 4) as \( 2.08 \frac{\text{Jy}}{\text{km s}^{-1}} \frac{\text{pc}}{\text{kpc}} \), \( 2.28 \frac{\text{Jy}}{\text{km s}^{-1}} \frac{\text{pc}}{\text{kpc}} \), and \( 2.27 \frac{\text{Jy}}{\text{km s}^{-1}} \frac{\text{pc}}{\text{kpc}} \times 10^7 \text{ L}_{\odot} \) for CO(6-5), CO(7-6), and [Cl](2-1), respectively.

The second one, \( L'_{\text{line}} \), corresponds to the areal-integrated source brightness in units of K km s\(^{-1}\) pc\(^2\). It is written as

\[ L'_{\text{line}} = 3.25 \times 10^7 \times S_{\text{line}} \Delta v \frac{D_L^2}{(1+z)^2} \nu_{\text{obs}}^2. \quad (3) \]

Again, we derive the 3\( \sigma \) upper limits as \( L'_{\text{line}} < \frac{1.06}{f_{\text{CMB}}} \frac{\text{Jy}}{\text{km s}^{-1}} \frac{\text{pc}}{\text{kpc}} \), \( \frac{1.36}{f_{\text{CMB}}} \frac{\text{Jy}}{\text{km s}^{-1}} \frac{\text{pc}}{\text{kpc}} \times 10^9 \text{ K} \text{ km s}^{-1} \text{ pc}^2 \) for CO(6-5), CO(7-6), and [Cl](2-1), respectively.

4.3. Comparison of luminosity

4.3.1. mid-J CO and [Cl] vs. far-infrared luminosity

In the local universe, a compiled sample of star-forming galaxies, AGNs, and U/LIRGs observed by Herschel/SPIRE shows a positive correlation between the mid-J CO as well as [Cl](2-1) line luminosities and the far-infrared (FIR) luminosity, \( L_{\text{FIR}} \) (e.g., Liu et al. 2015; Kamenetzky et al. 2016). The relation holds also at \( z \sim 1.3 \) (Valentino et al. 2020b). The correlation is naturally expected as the \( J_{\text{upp}} = 6 \) or 7 transitions probe warm and dense molecular gas that is responsible for star formation. At higher-\( z \), the relation would have a large dispersion due to a large intrinsic scatter in the CMB attenuation correction factor, \( f_{\text{CMB}} \).

Figure 4 shows a comparison of our target with the local objects (Kamenetzky et al. 2016), where the FIR.
modified-black body radiation at 42.5 – 122.5 μm (Table 1). In each panel, we show six cases as follows: the \( L_{\text{FIR}} \) value of our target is calculated with two sets of \( T_{\text{dust}} = 40 - 80 \) K in B14-65666 (Sugahara et al. 2021), we adopt three cases for \( T_{\text{exc}} \). In the first case, \( T_{\text{exc}} = 23 \) K, we assume non-LTE with \( T_{\text{kin}} = T_{\text{dust}} = 40 \) K and low gas density of \( n_{\text{H}_2} = 10^{3.2} \text{ cm}^{-3} \). In the second case, \( T_{\text{exc}} = 40 \) K, we assume i) non-LTE with \( T_{\text{kin}} = T_{\text{dust}} = 40 \) K and high gas density of \( n_{\text{H}_2} = 10^{4.2} \text{ cm}^{-3} \) (Fig. 10 of da Cunha et al. 2013) or ii) LTE with \( T_{\text{kin}} = T_{\text{dust}} = 40 \) K. In the third case, \( T_{\text{exc}} = 80 \) K, we assume LTE with \( T_{\text{kin}} = T_{\text{dust}} = 80 \) K.

### Table 3. CMB Attenuation to the Observed Lines

| Correction factor \( f_{\text{CMB}} \) | CO(6-5) | CO(7-6) | [CII](2-1) | Assumptions |
|-------------------------------------|---------|---------|-------------|--------------|
| \( f_{\text{CMB}}(T_{\text{exc}} = 23 \text{ K}) \) | 0.06 | 0.06 | 0.06 | Non-LTE with \( T_{\text{kin}} = T_{\text{dust}} = 40 \) K and \( n_{\text{H}_2} = 10^{3.2} \text{ cm}^{-3} \) |
| \( f_{\text{CMB}}(T_{\text{exc}} = 40 \text{ K}) \) | 0.62 | 0.65 | 0.65 | i) Non-LTE with \( T_{\text{kin}} = T_{\text{dust}} = 40 \) K and \( n_{\text{H}_2} = 10^{4.2} \text{ cm}^{-3} \) |
| \( f_{\text{CMB}}(T_{\text{exc}} = 80 \text{ K}) \) | 0.85 | 0.87 | 0.87 | ii) LTE with \( T_{\text{kin}} = T_{\text{dust}} = 40 \) K |

Note—The CMB attenuation correction factor \( f_{\text{CMB}} \) to the lines of CO(6-5), CO(7-6) and [CII](2-1). Under the assumption of dust-gas thermal coupling in conjunction with an estimate of \( T_{\text{dust}} = 40 - 80 \) K in B14-65666 (Sugahara et al. 2021), we adopt three cases for \( T_{\text{exc}} \). In the first case, \( T_{\text{exc}} = 23 \) K, we assume non-LTE with \( T_{\text{kin}} = T_{\text{dust}} = 40 \) K and low gas density of \( n_{\text{H}_2} = 10^{3.2} \text{ cm}^{-3} \) (Fig. 10 of da Cunha et al. 2013). In the second case, \( T_{\text{exc}} = 40 \) K, we assume i) non-LTE with \( T_{\text{kin}} = T_{\text{dust}} = 40 \) K and high gas density of \( n_{\text{H}_2} = 10^{4.2} \text{ cm}^{-3} \) (Fig. 10 of da Cunha et al. 2013) or ii) LTE with \( T_{\text{kin}} = T_{\text{dust}} = 40 \) K. In the third case, \( T_{\text{exc}} = 80 \) K, we assume LTE with \( T_{\text{kin}} = T_{\text{dust}} = 80 \) K.

### Table 4. Summary of Our Measurements

| Parameters \( S_{\text{line}}\Delta v \) [Jy km s\(^{-1}\)] | CO(6-5) | CO(7-6) | [CII](2-1) |
|-----------------------------------------------|---------|---------|-------------|
| \( \text{CMB} \) \( f_{\text{CMB}} \) (corr.) | \(< 0.0447\) | \(< 0.0420\) | \(< 0.0417\) |
| \( L_{\text{line}} \) \( [10^7 L_\odot] \) | \(< 2.08\) | \(< 2.28\) | \(< 2.27\) |
| \( L_{\text{line}} \) (corr.) \( [10^7 L_\odot] \) | \(< 2.08\) | \(< 2.28\) | \(< 2.27\) |
| \( L_{\text{line}} \) (corr.) \( [10^9 \text{ K km s}^{-1} \text{ pc}^2] \) | \(< 1.96\) | \(< 1.36\) | \(< 1.34\) |
| \( L_{\text{line}} \) (corr.) \( [10^5 \text{ K km s}^{-1} \text{ pc}^2] \) | \(< 1.96\) | \(< 1.36\) | \(< 1.34\) |
| \( L_{\text{H}}/L_{\text{line}} \) | \( > 163\) | \( > 149\) | \( > 150\) |
| \( L_{\text{H}}/L_{\text{line}} \) (corr.) | \( > 163 f_{\text{CMB}} \) | \( > 149 f_{\text{CMB}} \) | \( > 150 f_{\text{CMB}} \) |
| \( L_{\text{CII}}/L_{\text{line}} \) | \( > 53\) | \( > 48\) | \( > 48\) |
| \( L_{\text{CII}}/L_{\text{line}} \) (corr.) | \( > 53 f_{\text{CMB}} \) | \( > 48 f_{\text{CMB}} \) | \( > 48 f_{\text{CMB}} \) |

Note—The upper and lower limits correspond to 3σ. The values after the CMB correction are shown with “(corr.)”, where \( f_{\text{CMB}} \) is listed in Table 3.

luminosity of B14-65666 is calculated by integrating the modified-black body radiation at 42.5 – 122.5 μm (Table 1). In each panel, we show six cases as follows: the \( L_{\text{FIR}} \) value of our target is calculated with two sets of \( (T_d, \beta) = (80 \text{ K, } 1.0) \) and \( (40 \text{ K, } 2.0) \) following Sugahara et al. (2021). Red and blue symbols show the line luminosity before and after the CMB attenuation correction, respectively. We assume \( T_{\text{exc}} = 23 \) and \( 40 \) K as examples for the CMB-corrected line luminosity (Table 3). At \( T_{\text{exc}} = 23 \) K, the data points shift +1.2 dex toward a higher luminosity value (i.e., loose constraint).

Figure 4 shows that the non-detection of the lines is due to the insufficient sensitivity of our observations. The large uncertainty in \( f_{\text{CMB}} \) makes it difficult to predict the required sensitivity to detect the lines. We recommend the readers to consider the uncertainty in \( f_{\text{CMB}} \) for future observations targeting CO in the EoR. Note that we do not attempt to plot data points of other high-z objects in Figure 4 because of the potentially large uncertainty in the \( f_{\text{CMB}} \) hence the CMB-corrected luminosity.

#### 4.3.2. mid-J CO vs. [CII] 158 μm luminosity

The [CII]-to-CO line luminosity ratio, along with the mid-J-to-FIR luminosity ratio (§4.3.1), is useful to examine properties of photo-dissociation regions (PDRs) such as the gas density and the far-ultraviolet radiation field (e.g., Kaufman et al. 1999, 2006; Pound & Wolfire 2008). In general, a high luminosity ratio of \( L_{\text{CII}}/L_{\text{CO}(6-5)} \) and/or \( L_{\text{CII}}/L_{\text{CO}(7-6)} \) indicates that the PDR has a high gas density. In B14-65666, we find
that the [CII] 158 µm line is \( \geq 50 \times \) brighter in luminosity than the mid-J CO lines before the CMB attenuation correction (3\( \sigma \); Table 4). We compare \( L_{\text{[CII]}}/L_{\text{CO(6-5)}} \) and \( L_{\text{[CII]}}/L_{\text{CO(7-6)}} \) with those obtained in other galaxy populations at similar redshifts, i) LBGs, ii) DSFGs, and iii) quasar host galaxies. Here we use luminosity in units of \( L_{\odot} \), and all luminosity ratios are before the CMB attenuation correction.

Firstly, Vieira et al. (2021) have studied CO(6-5) in a sample of star-forming galaxies that include an LBG at \( z = 5.654 \), HZ10 (Capak et al. 2015). The authors report a non-detection of CO(6-5) in the LBG, which corresponds to \( L_{\text{[CII]}}/L_{\text{CO(6-5)}} \gtrsim 21 \) (3\( \sigma \)). Secondly, there are four DSFGs at \( z > 6 \), all of which have detections of the mid-J and [CII] lines: Gravitationally-lensed pair SMGs at \( z = 6.90 \), SPT0311-058W and E, have \( L_{\text{[CII]}}/L_{\text{CO(6-5)}} \sim L_{\text{[CII]}}/L_{\text{CO(7-6)}} \sim 20 \) and 80 – 90, respectively (Jarugula et al. 2021). Another two lensed SMGs, HFLS3 at \( z = 6.34 \) and G09 83808 at \( z = 6.0 \), have \( L_{\text{[CII]}}/L_{\text{CO(6-5)}} \sim 15 \pm 5 \) and 42 \( \pm 5 \), respectively (Riechers et al. 2013; Zavala et al. 2018; Fudamoto et al. 2017). Finally, mid-J CO lines are observed in two \( z > 7 \) quasars (Novak et al. 2019; Venemans et al. 2017b) and more than 15 quasars at \( z > 6 \) (e.g., Venemans et al. 2017a; Shao et al. 2019; Carniani et al. 2019; Li et al. 2020; Feruglio et al. 2018; Yang et al. 2019; Walter et al. 2003; Wang et al. 2010, 2019, 2011). QSO J1342+0928 at \( z = 7.54 \) has \( L_{\text{[CII]}}/L_{\text{CO(7-6)}} \geq 33 \) (3\( \sigma \); Novak et al. 2019), while QSO J1120+0641 at \( z = 7.08 \) has \( L_{\text{[CII]}}/L_{\text{CO(7-6)}} \geq 13 \) (3\( \sigma \); Venemans et al. 2017b). Three QSO host galaxies at \( z = 6.6 – 6.9 \) are detected in both CO(6-5) and CO(7-6), yielding the line ratios spanning in the range of 12 to 55. Similarly, three bright QSO host galaxies at \( z \sim 6 \) have \( L_{\text{[CII]}}/L_{\text{CO(6-5)}} \sim 15 – 30 \) (Shao et al. 2019, see also Carniani et al. 2019).

If we naively compare the line luminosity ratios before the CMB correction, B14-65666 seems to have relatively high lower-limits on the luminosity ratios. However, its interpretation is complicated due to the large uncertainty in \( f_{\text{CMB}} \) (Table 3). If B14-65666 has low \( n_{\text{H}_2} \) and/or gas temperature compared with DSFGs or QSOs at a similar redshift, \( f_{\text{CMB}} \) in B14-65666 becomes small. In this case, B14-65666 has lower-limits more consistent with the measurements obtained in high-\( z \) DSFGs and QSOs. As an example, the lower-limit on \( L_{\text{[CII]}}/L_{\text{line}} \) becomes as small as 4 if we adopt \( T_{\text{exc}} = 23 \) K (Tab. 4).

To make matters worse, the CMB attenuation on [CII] 158 µm (e.g., Kohandel et al. 2019) further increases the

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**Figure 4.** Far-infrared luminosity defined in the range of 42.5 – 122.5 µm plotted against the line luminosity. In each panel, we show six data points of B14-65666: \( L_{\text{FIR}} \) values are calculated from modified blackbody radiation models with two parameter sets of \((T_d, \beta) = (80 \text{ K}, 1.0) \) and \((40 \text{ K}, 2.0) \) following Sugahara et al. (2021). Red circles with arrows show the 3\( \sigma \) upper limits on the line luminosities before the CMB correction. Two blue squares with arrows indicate the CMB-corrected line luminosities \((3\sigma) \), where we assume \( T_{\text{exc}} = 23 \) and 40 K as examples (Table 3). The correction shifts the data points +1.2 and +0.2 dex along the x-axis at \( T_{\text{exc}} = 23 \) and 40 K, respectively. For the display purpose, the symbols are placed at a slightly different \( L_{\text{FIR}} \) value at a given set of \((T_d, \beta) \). Small open circles show a compilation of local objects including star-forming galaxies, AGNs, and U/LIRGs observed with *Herschel*/SPIRE (Kamenetzky et al. 2016), where objects with \( > 3 \sigma \) detection are plotted. For the display purpose, objects with \( x < 7 \) or \( y < 10 \) are displayed at \( x = 7 \) and/or \( y = 10 \) with arrows.
uncertainty in the intrinsic line ratios. Although the attenuation effect on [CII] is less significant compared with mid-$J$ or [Cl](2-1) owing to the higher frequency of [CII] (1900 GHz), a study of Laporte et al. (2019) shows that the CMB attenuation factor ranges from 0.3 to 1 at $z \sim 7$ based on the simulations of Lagache et al. (2018).

To summarize this section, the current data is insufficient to examine the difference in the CMB-corrected $L_{\text{CII}}/L_{\text{line}}$ in B14-65666 and other high-$z$ objects. The results also imply that care must be taken when comparing the luminosity ratios of galaxies in the EoR.

5. ESTIMATE OF MOLECULAR GAS MASS

We now attempt to estimate the molecular gas mass of B14-65666. Taking advantage of the rich data set, we adopt five techniques as summarized in Table 5.

5.1. Estimates with CO(6-5) and CO(7-6)

The molecular gas mass is estimated with CO lines as

$$\frac{M_{\text{mol}}^\text{CO}}{M_\odot} = \alpha_{\text{CO}} \ r_{j1}^{-1} L_{\text{CO},J-J-1}'$$

where $\alpha_{\text{CO}}$ is the CO-to-H$_2$ conversion factor in units of $M_\odot$ (K km s$^{-1}$)$^{-1}$, and $r_{j1}$ is the excitation correction factor defined as

$$r_{j1} = \frac{L_{\text{CO}, J-J-1}'}{L_{\text{CO}1-0}'} = \frac{L_{\text{CO}1-0}}{L_{\text{CO}1-0}'} \frac{1}{J^2}. \quad (5)$$

Note that our CO-based estimate is highly uncertain due to the unknown factors of $r_{j1}$ and $\alpha_{\text{CO}}$ as explained below.

In general, high gas excitation (i.e., large $r_{j1}$) is achieved in galaxies with e.g., high star formation efficiency, SFR surface density ($\Sigma_{\text{SFR}}$), dust temperature where high gas density and/or temperature is realized (Daddi et al. 2015; Valentino et al. 2020b, see also Vallini et al. 2018). In particular, a theoretical work of Narayanan & Krumholz (2014) has shown that the CO excitation ladders can be parametrized with $\Sigma_{\text{SFR}}$ (see also Bournaud et al. 2015) based on simulation of disc galaxies combined with CO line radiative transfer. The relation is qualitatively supported by observations up to $z \sim 1.2$ (Valentino et al. 2020b). With eq. (19) of Narayanan & Krumholz (2014) and $\Sigma_{\text{SFR}} = 3.8^{+2.1}_{-1.4}$ $M_\odot$ yr$^{-1}$ kpc$^{-2}$ obtained in our target$^4$, we estimate $r_{61} = 0.18^{+0.03}_{-0.02}$ and $r_{71} = 0.09^{+0.02}_{-0.02}$. These indicate that CO(6-5) and CO(7-6) are subthermal, and the non-LTE assumption is appropriate for B14-65666 (§4.2.1).

We also refer to the excitation ladders obtained in high-$z$ DSFGs as an extreme case. High-$z$ DSFGs have high excitation correction factors of $r_{61} = 0.28^{+0.83}_{-0.14}$ and $r_{71} = 0.24^{+0.78}_{-0.12}$ (Figure 45 in Casey et al. 2014; see also Bothwell et al. 2013; Spilker et al. 2014), where the uncertainty indicates the ranges observed in the compilation by Casey et al. (2014).

Considering these, we broadly assume $r_{61} \geq 0.16$ and $r_{71} \geq 0.07$ for our target. Note that a conservative upper limit on $M_{\text{mol}}^\text{CO}$ can be obtained with a lower $r_{j1}$ value. Thus, with $r_{71} = 0.07$ and the upper limit on the CO(7-6) luminosity (Table 4), we obtain $L_{\text{CO}, 7-6}' < 5.1 \times 10^{10} \text{K km s}^{-1} \text{pc}^2$. With eq. (19) and $\epsilon_{\text{CO}} = 25$ $M_\odot$ (K km s$^{-1}$)$^{-1}$ (2011; Narayanan et al. 2012) as a result of increased CO photodissociation (Madden et al. 2020). In this study, we adopt the conversion factor of Tacconi et al. (2018), which is the geometric mean of the relations in Bolatto et al. (2013) and Genzel et al. (2012),

$$\alpha_{\text{CO}} = 4.36 \times \sqrt{\frac{10^{-1.27(12+\log(O/H)-8.67)}}{67 \exp(0.36 	imes 10^{-12+\log(O/H)-8.67})}}$$

where a Helium contribution to the mass (36%) is included.

The gas-phase metallicity of B14-65666 is estimated to be $0.4^{+0.4}_{-0.2} Z_\odot$ based on SED fit taking into account multi-wavelength data ranging from rest-frame UV to FIR (Hashimoto et al. 2019), which is consistent with an independent estimate in Jones et al. (2020) based on [OIII] 88 $\mu$m luminosity and SFR. With a broad range of $0.2 \leq 0.8 Z_\odot$ (i.e., $12+\log(O/H) = 8.0 - 8.6$), we obtain $\alpha_{\text{CO}} \approx 5 - 25 M_\odot$ (K km s$^{-1}$ pc$^2$)$^{-1}$. Finally, with $\alpha_{\text{CO}} = 25 M_\odot$ (K km s$^{-1}$ pc$^2$)$^{-1}$ and the 3$\sigma$ upper limit on $L_{\text{CO}, J-J-1}'$, we estimate the molecular gas mass to be $M_{\text{mol}}^\text{CO} < 4.85 \times 10^{11} M_\odot$ (3$\sigma$). With $f_{\text{CMB}}$ at $T_{\text{exc}} = 23, 40$ and $80$ K (Table 3), we quantitatively obtain the 3$\sigma$ upper limit $\approx 81, 7.5$ and $5.6 \times 10^{11} M_\odot$, respectively. Similarly, we obtain the 3$\sigma$ upper limit of $3.99 \times 10^{11} M_\odot$ with CO(6-5), corresponding to $51, 4.9$ and $3.6 \times 10^{11} M_\odot$ at $T_{\text{exc}} = 23, 40$ and $80$ K, respectively (Table 5).

5.2. Estimate with [Cl](2-1)

The [Cl](1-0) and [Cl](2-1) lines are recognized as an alternative molecular gas mass tracer (e.g., Papadopoulos et al. 2004, 2018; Walter et al. 2011; Alaghband-Zadeh et al. 2013; Jiao et al. 2019; Boogaard et al. 2021;
Jarugula et al. (2021). This is motivated by observational results that CO(1-0) and [CII](1-0) are spatially co-located in the PDRs of local giant molecular clouds such as Orion-A (e.g., Ieda et al. 1999; Shimajiri et al. 2013) as well as in local galaxies (e.g., Jiao et al. 2019), and that the CO(1-0) luminosity is linearly correlated with [CII](1-0) and [CII](2-1) luminosity (e.g., Jiao et al. 2017, 2019).

Under a reasonable assumption that [CII] is optically thin (Weiß et al. 2003), the neutral carbon mass, $M_{\text{CI}}$, can be obtained from the [CII] luminosity and $T_{\text{exc}}$. In the case of [CII](2-1), we estimate $M_{\text{CI}}$ following Weiß et al. (2003) as

$$\frac{M_{\text{CI}}}{M_\odot} = 4.566 \times 10^{-4} Q(T_{\text{exc}}) \frac{1}{5} e^{62.5/T_{\text{exc}}} \frac{L'_{[\text{CII}](2-1)}}{f_{\text{CMB}}}, \quad (7)$$

where $Q(T_{\text{exc}}) = 1 + 3 e^{-T_1/T_{\text{exc}}} + 5 e^{-T_2/T_{\text{exc}}}$ is the [CII] partition function, $T_1 = 23.6$ K and $T_2 = 62.5$ K is the temperature of each transition from the ground state. With three $T_{\text{exc}}$ (Table 3) and the CMB-corrected luminosity of [CII](2-1) (Table 4), we obtain $M_{\text{CI}} < 74, 3.3$ and $1.7 \times 10^6 M_\odot (3\sigma)$ at $T_{\text{exc}} = 23, 40$ and 80 K, respectively.

Assuming the abundance ratio of $X[\text{[CII]]}/X[\text{H}_2] \sim 1.6 \times 10^{-5}$ obtained in $z \sim 1$ main-sequence galaxies (Valentino et al. 2018), we find the [CII](2-1)-based molecular gas mass to be $M_{\text{mol}}^{[\text{CII}]} < 20.0, 0.9$ and $0.5 \times 10^{10} M_\odot (3\sigma)$ at $T_{\text{exc}} = 23, 40$ and 80 K, respectively, where we include the contribution of Helium. As discussed in Valentino et al. (2018), the abundance ratio can change at high-$z$ or in different galaxy populations. Indeed, a recent work of Heintz & Watson (2020) has revealed that the mass conversion factor of the [CII](1-0) transition, $\alpha_{[\text{CII}](1-0)} = M_{\text{mol}}/L'_{[\text{CII}](1-0)}$, depends on metallicity based on observations of [CII]($J = 1$) absorption lines in rest-frame UV toward a sample of gamma-ray burst (GRB) and quasar absorption systems at $z \sim 1.9 - 3.4$: $\alpha_{[\text{CII}](1-0)}$ becomes about 10 times higher at 0.2$z_\odot$ than at $z_\odot$. Thus, if we assume that the mass conversion factor of [CII](2-1) similarly changes with metallicity, our upper limits can be high by a factor of ten, $M_{\text{mol}}^{[\text{CII}]} \lesssim 74, 3.3$ and $1.7 \times 10^{11} M_\odot$ at $T_{\text{exc}} = 23, 40$ and 80 K, respectively (3$\sigma$) (Table 5).

### Table 5. Estimates of Molecular Gas Mass in B14-65666

| Method | $M_{\text{mol}}$ | Assumptions | Ref. |
|--------|------------------|--------------|-----|
| CO(6-5) | $< 510$ (23 K), $< 49$ (40 K), $< 36$ (80 K) | $r_{\text{CO}} = 0.16; \alpha_{\text{CO}}(Z) = 25 M_\odot (\text{K km s}^{-1} \text{pc}^2)^{-1}$ | §5.1 |
| CO(7-6) | $< 810$ (23 K), $< 75$ (40 K), $< 56$ (80 K) | $r_{\text{CO}} = 0.07; \alpha_{\text{CO}}(Z) = 25 M_\odot (\text{K km s}^{-1} \text{pc}^2)^{-1}$ | §5.1 |
| [Cl](2-1) | $< 740$ (23 K), $< 33$ (40 K), $< 17$ (80 K) | $X[\text{Cl}]/X[\text{H}_2] = 1.6 \times 10^{-6}$ | §5.2 |
| [Cl] 158 µm | $2.9 - 31$ | $f_{\text{[Cl]}} = 0.3 \pm 0.2; M_{\text{mol}}/M_\odot = 1.36 \times 10^{2.12} \times (L'_{[\text{CI}]}/L_{\odot})^{0.97}$ | §5.3 |
| dust | 0.05 - 17 | $M_{\text{dust}} = 10^{6.4-7.5} M_\odot; \delta_{\text{GDR}} = 200 - 5500$ | §5.4 |
| dynamical mass | $< 11$ | $M_{\text{dyn}} = (3 - 11) \times 10^{10} M_\odot; M_\odot = 7.7^{+1.0}_{-0.8} \times 10^8 M_\odot$ | §5.5 |

Note—Summary of our estimates of molecular gas mass ($M_{\text{mol}}$). In the case of mid- J CO and [Cl](2-1), values in parentheses show the $T_{\text{exc}}$ values we adopt to correct for the CMB attenuation (Table 3). The estimate based on the dynamical mass ($M_{\text{dyn}}$) provides the upper limit on $M_{\text{mol}}$.

Recent studies propose that the [Cl] 158 µm line can be also used to probe the molecular gas mass based on following observations: A variety of study has shown that there is a correlation between $L_{\text{CO(1-0)}}$ and $L_{[\text{Cl}]}$ from the local to high-$z$ universe (Gullberg et al. 2015; Hughes et al. 2017a; Accurso et al. 2017 and references therein). Later, Zanella et al. (2018) have compiled estimates of $L_{[\text{Cl}]}$ and molecular gas masses for a compiled sample of $z = 0-6$ objects including both main-sequence and starburst galaxies. The authors show that $L_{[\text{Cl}]}$ well correlates with $M_{\text{mol}}$, obtaining a conversion factor $\alpha_{[\text{Cl}]} \equiv M_{\text{mol}}/L_{[\text{Cl}]} \approx 30 M_\odot (\text{K km s}^{-1} \text{pc}^2)^{-1}$ with a standard deviation of 0.3 dex. This technique has been applied to and validated in a sample of [Cl] 158 µm emitters on the main-sequence at $z = 4.5 - 5.9$ from an ALMA large program, ALPINE (Le Fèvre et al. 2020) by Dessauges-Zavadsky et al. (2020). In addition, Uzgil et al. (2021) have applied this conversion factor to a sample of LBGs at $z \sim 6 - 8$ observed in [Cl] by the ASPECS survey (e.g., Walter et al. 2016; Aravena et al. 2016). Recently, based on the Herschel dwarf galaxy survey sample, Madden et al. (2020) have shown that local

$^5 J$ refers to the total angular momentum quantum number for this transition.
metal-poor dwarf galaxies have a different relation,

\[ \frac{M_{\text{H}_2}}{M_\odot} = 10^{2.12} \left( \frac{L_{\text{[CII]}}}{L_\odot} \right)^{0.97}, \tag{8} \]

with a standard deviation of 0.14 dex. We use eq. (8) because the metallicity of B14-65666 (0.2 – 0.8Z_\odot) is well within the range where the relation from Madden et al. (2020) is applicable (sub-solar to 0.2Z_\odot).

To use the equation, we need to apply two corrections to the [CII] luminosity. Firstly, we remove the [CII] contribution originating from the HII region. This is often calculated based on the line ratio of [CII] and [NII] 205 \mu m lines: Because [CII] and [NII] 205 \mu m have similar electron critical densities of \sim 44 and 40 cm^{-3} at the electron temperature of 8000 K, respectively, the [CII] emission from the HII region can be estimated under the assumption of a C/N abundance ratio (e.g., Oberst et al. 2006; Croxall et al. 2017; Herrera-Quintana et al. 2018). These studies have shown that the [CII] contribution from the HII region becomes negligible in galaxies with e.g., low-Z. Based on the metallicity of our target and Fig. 9 of Cormier et al. (2019), we estimate the contribution from the HII region to be 30 \pm 20\%. Thus, we estimate the [CII] luminosity emitted from the PDR to be \((7.7 \pm 2.2) \times 10^8 L_\odot\).

Secondly, we correct for the CMB attenuation effect to [CII]. With the CMB attenuation factor on [CII] (0.3 – 1.0; §4.3.2), the intrinsic [CII] luminosity from the PDR is \approx (5.5 – 33) \times 10^8 L_\odot. Finally, we obtain \(M_{\text{mol}}^{\text{CII}} \sim (2.9 – 31) \times 10^{10} M_\odot\), where we have included the helium contribution and taken into account a standard deviation of 0.14 dex in the relation of eq. (8).

5.4. Estimate with dust mass

Dust continuum information can be used to infer the molecular gas mass. At the Rayleigh-Jeans tail (\lambda > 250 \mu m), the dust continuum emission is likely to be optically thin and directly traces the dust mass. Motivated by this, Scoville et al. (2016) have linked the dust continuum flux density at \lambda_{\text{rest}} = 850 \mu m to the total molecular gas mass under the assumption of a dust-to-gas ratio (DGR) of 0.01 (see also Scoville et al. 2017; Hughes et al. 2017b; Kaasinen et al. 2019). As stressed in Kaasinen et al. (2019), the method is calibrated against massive (\(M_\star > 2 \times 10^{10} M_\odot\)) galaxies at \(z = 0 – 2\), and the technique may not be applicable to high-z, low-mass, low-metallicity galaxy (e.g., Privon et al. 2018; Dessauges-Zavadsky et al. 2020).

We therefore simply use the metallicity-dependent DGR (Magdis et al. 2011; Rémy-Ruyer et al. 2014; De Vis et al. 2019; Li et al. 2019). Specifically, we use the prescription of Li et al. (2019), which is described as

\[ \log \text{DGR} = (2.445 \pm 0.006) \log (Z/Z_\odot) – (2.029 \pm 0.003). \tag{9} \]

The relation is based on cosmological hydrodynamical simulations implementing the process of dust production, growth, and destruction. At the metallicity of B14-65666, we obtain DGR \approx 1.8 \times 10^{-4} – 5.3 \times 10^{-3} (i.e., the gas-to-dust mass ratio \(\delta_{\text{GDR}} \approx 200 – 5500\)). Combined with the dust mass of our target, \(\log (M_{\text{dust}}) \approx 6.4 – 7.5\) (Sugahara et al. 2021), we estimate the (molecular + atomic) gas mass to be \(M_{\text{gas}} \approx (0.05 – 17) \times 10^{10} M_\odot\).

If we assume that gas is predominantly in the molecular phase (see the same assumptions in e.g., Boogaard et al. 2021; Venemans et al. 2017a and estimates in e.g., Riechers et al. 2013), the above values can be regarded as the molecular gas mass.

5.5. Upper limit with dynamical mass

Finally, we calculate an upper limit on \(M_{\text{mol}}\) from the dynamical mass, \(M_{\text{dyn}}\), subtracted by the stellar mass contribution. In Hashimoto et al. (2019), we have obtained \(M_{\text{dyn}}\) of two individual clumps of B14-65666 based on the line width and the beam-deconvolved size of [CII] 158 \mu m under the assumption of the virial theorem. The dynamical mass of the whole system is estimated to be \(M_{\text{dyn}} = (8.8 \pm 1.9) \times 10^{10} M_\odot\), where the error only considers the measurement uncertainties. As discussed in Hashimoto et al. (2019), the dynamical mass can be reduced by a factor of about three due to the systematic uncertainty in assumptions such as the relative contributions from random and rotational motions to the [CII] velocity field (see their Section 3.3). Considering these, we adopt \(M_{\text{dyn}} \sim (3 – 11) \times 10^{10} M_\odot\) as a fiducial value. With a stellar mass obtained from SED fitting (\(M_\star = 7.7^{+1.0}_{-0.8} \times 10^8 M_\odot\); Hashimoto et al. 2019), we obtain a conservative upper limit on \(M_{\text{mol}}\) to be \(11 \times 10^{10} M_\odot\).

Figure 5 summarizes the results in this section. Combining the \(M_{\text{mol}}\) estimates from the [CII] luminosity, dust mass, and dynamical mass, we obtain \(M_{\text{mol}} = (0.05 – 11) \times 10^{10} M_\odot\). The range is consistent with the upper limits on \(M_{\text{mol}}\) inferred from the non-detections of mid-J CO and [CII](2-1).

6. DISCUSSION

6.1. Strategy for Improvements in Molecular Gas Estimates

Although our ALMA observations is a pioneering work that attempts to study molecular gas properties in a star-forming galaxy without a clear signature of AGN at \(z > 7\), there remains a number of limitation in our
estimates of \( M_{\text{mol}} \). Here we discuss how to overcome these issues in future observations.

(A) CMB attenuation: The CO- and [C\textsc{i}](2-1)-based molecular-gas mass estimates are highly uncertain due to the unknown CMB attenuation correction factor, \( f_{\text{CMB}} \) (§4.2.1). Although current ALMA cannot target CO lines with \( J_{\text{up}} \leq 6 \) nor [C\textsc{i}](1-0) at \( z = 7 \), the next generation Very Large Array (ngVLA) is expected to observe lower-\( J \) lines as well as [C\textsc{i}](1-0) with high sensitivity (e.g., Decarli et al. 2018). Once multiple CO lines are detected, one can perform a non-LTE code to obtain \( T_{\text{kin}} \) and \( n_{\text{H}_2} \) by solving the statistical equilibrium radiative transfer (e.g., van der Tak et al. 2007), which in turn can be used to estimate \( f_{\text{CMB}} \) (Fig. 10 in da Cunha et al. 2013). Note that ngVLA is expected to directly observe CO(1-0) at high-\( z \), so uncertainties related to CO excitation ladders could be also solved.

(B) Gas-phase metallicity: The uncertainty in gas-phase metallicity has lead to an additional large uncertainty in the gas mass conversion factors of \( \alpha_{\text{CO}} \) and \( \alpha_{\text{[C\textsc{i}](2-1)}} \), as well as in the dust-to-gas mass ratio (§5). Indeed, the current large uncertainty in \( M_{\text{mol}}^{\text{dust}} \) (0.05–11 \times 10^{10} \( M_{\odot} \)), i.e., a factor of 220) is partly due to the DGR which is uncertain by a factor of 27. The uncertainty in metallicity also gives rise to the uncertainty in the estimate of [C\textsc{i}] 158 \( \mu \text{m} \) emission from the neutral gas (§5.3). Another caveat is that the gas-phase metallicity in eq. (6) refers to that based on Pettini & Pagel (2004) which uses the rest-frame optical H\( \alpha \) and [N\textsc{ii}] 6583Å lines, while our metallicity is based on SED fitting (Hashimoto et al. 2019). While this is the current best effort, a systematic bias due to the different techniques should be treated with caution. In the near future, constraints on the gas-phase metallicity of B14-65666 is expected to be improved with James Webb Space Telescope (JWST) NIRSpec and MIRI GTO that will target rest-frame optical lines from [O\textsc{iii}] \( \lambda \lambda 3727,3729 \) to [S\textsc{ii}] \( \lambda 6717,6731 \).

(C) Dust temperature: A more accurate estimate of the dust mass is essential. Because the current ALMA observations only probe \( \lambda_{\text{rest}} \approx 90 – 400 \mu \text{m} \), the dust SED’s peak is not determined (Fig. 2). This leads to an uncertainty in the dust temperature hence dust mass. Future observations targeting shorter wavelength with ALMA Band 9 and 10 will be useful to overcome this issue. Indeed, in a gravitationally-lensed galaxy at \( z = 7.13 \), A1689-zD1 (Watson et al. 2015; Knudsen et al. 2017; Inoue et al. 2020), Bakx et al. (2021) have shown that adding ALMA Band 9 observations can improve the dust mass estimate by a factor of 6.

6.2. Molecular Gas Properties of B14-65666

Albeit with large uncertainty in \( M_{\text{mol}} \) (§6.1), we examine two physical quantities related with molecular gas. The first one is the molecular-to-stellar mass ratio, \( \mu_{\text{gas}} \equiv M_{\text{mol}}/M_\star \). With \( M_{\text{mol}} = (0.05 – 11) \times 10^{10} \ M_{\odot} \) (§5) and the stellar mass obtained from SED fitting (Hashimoto et al. 2019), \( M_\star = 7.7^{+1.0}_{-0.5} \times 10^8 \ M_{\odot} \), we obtain \( \mu_{\text{mol}} \approx 0.65 – 140 \). The second one is the gas depletion time, \( t_{\text{dep}} \equiv M_{\text{mol}}/\text{SFR} \). With \( M_{\text{mol}} \) and SFR

\[ \log \frac{M_{\text{mol}}}{M_{\odot}} = 11.3 \]

\[ \log \frac{M_{\text{mol}}}{M_{\odot}} = 11.6 \]

\[ \log \frac{M_{\text{mol}}}{M_{\odot}} = 11.9 \]

\[ T_{\text{exc}} = 23 \text{ K} \]

\[ T_{\text{exc}} = 40 \text{ K} \]

\[ T_{\text{exc}} = 80 \text{ K} \]
In the context of galaxy formation and evolution, studies have shown that $\mu_{\text{gas}}$ ($t_{\text{dep}}$) increases (decreases) at high-$z$, and depends on the stellar mass, $M_*$, and deviation from the star-formation main sequence, $\delta\text{MS}$ ($\equiv$ SFR/$\text{SFR}_{\text{MS}}$) (e.g., Scoville et al. 2017; Tacconi et al. 2018; Liu et al. 2019 and references therein). The relation of Scoville et al. (2017) and Tacconi et al. (2018) is based on a compiled sample of galaxies at $z \sim 0 - 4$, while that of Liu et al. (2019) is based on a sample at $z \sim 0 - 6$. Due to the difference of the sample as well as in techniques, these studies present different functional forms of $\mu_{\text{gas}}(z, M_*, \delta\text{MS})$ and $t_{\text{dep}}(z, M_*, \delta\text{MS})$.

We predict $\mu_{\text{gas}}$ and $t_{\text{dep}}$ based on a parameter set of $(z, M_*, \delta\text{MS})$ in B14-65666 with eq. (4), (5), and (11) of Liu et al. (2019). Although the main-sequence at $z = 7$ is not well established (e.g., Stark et al. 2013; Santini et al. 2017), if we compare the specific SFR (sSFR defined as SFR/$M_*$) of our target, $260^{+119}_{-57}$ Gyr$^{-1}$ (Hashimoto et al. 2019), with predictions of Speagle et al. (2014) as shown in Fig. 19 in Liu et al. (2019), we can assume log($\delta\text{MS}$) $\approx 1.0 - 1.6$. With a parameter set of $(z, M_*, \delta\text{MS}) = (7.15, 7.7 \times 10^8 \, M_\odot, 1 - 1.6)$, we obtain $\mu_{\text{gas}} = 422 - 657$, $11 - 23$, and $71 - 105$ if we use the relations of Scoville et al. (2017), Tacconi et al. (2018), and Liu et al. (2019), respectively. Similarly, we obtain $t_{\text{dep}} = 28 - 75$, $45 - 83$, and $303 - 795$ Myr with the relations of Scoville et al. (2017), Tacconi et al. (2018), and Liu et al. (2019), respectively. Figure 6 summarizes these results, and show that our measurements of $\mu_{\text{gas}}$ and $t_{\text{dep}}$ are in broad agreements with the extrapolation of the previous studies. Although $\mu_{\text{gas}}$ predicted by Scoville et al. (2017) may be in tension with our estimates, due to the aforementioned uncertainty (§6.1), we do not regard this as a severe issue. These results indicate that our $M_{\text{mol}}$ estimate is reasonable.

Finally, we discuss evolution of B14-65666 based on our estimates of $t_{\text{dep}}$. We obtain a short gas depletion time of 2.5 and 550 Myr in the case of $M_{\text{mol}} = 0.05$ and $11 \times 10^{10} \, M_\odot$, respectively. The short $t_{\text{dep}}$ partly reflects the starburst nature of B14-65666, which is likely to be induced by a major-merger event (Bowler et al. 2017; Hashimoto et al. 2019). In the case of $t_{\text{dep}} = 550 (2.5)$ Myr, the target will consume the molecular gas as early as $z \approx 4.5$ (7) if no gas is fueled from outside of the galaxy, whose final stellar mass is about $1 \times 10^{11} (1 \times 10^9) \, M_\odot$. This implies that B14-65666 can evolve into passive galaxies at $z \gtrsim 4$. To further examine this hypothesis, we compare the volume number density of galaxies like B14-65666 with that of $z \sim 3 - 4$ passive galaxies. The number density of galaxies like B14-65666 ($M_{\text{UV}} = -22.4$) is $\sim 1 \times 10^{-6}$ Mpc$^{-3}$ based on the bright-end of the UV luminosity function at $z \sim 7$ (Bowler et al. 2017; Harikane et al. 2021). The observed number density of $z \sim 3 - 4$ passive galaxies is recently compiled by Valentino et al. (2020c), which is $\mathcal{O}(10^{-6}) - \mathcal{O}(10^{-5})$ Mpc$^{-3}$ at $M_* \geq 4 \times 10^{10} \, M_\odot$. The authors have also derived the number density by analyzing the Illustris TNG cosmological simulation public release data (e.g., Springel et al. 2018). In the simulation, the volume number density of $z = 3.7$ passive galaxies is estimated

Note: Figure 6 shows the top and bottom panels are permitted ranges of the molecular-to-stellar mass ratio ($\mu_{\text{gas}}$) and the gas depletion time ($t_{\text{dep}}$) in B14-65666, respectively. The leftmost value is based on our estimate of $M_{\text{mol}} (0.05 - 11 \times 10^{10} \, M_\odot)$. Also plotted are estimates from the extrapolations of the functional forms of S17 (Scoville et al. 2017), T18 (Tacconi et al. 2018), and L19 (Liu et al. 2019). Our measurements of $\mu$ and $t_{\text{dep}}$ are in broad agreements with the expectations from S17, T18 and L19.
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to be $\mathcal{O}(10^{-6})$ Mpc$^{-3}$ at $M_\star \geq 4 \times 10^{10}$ $M_\odot$. While the discussion above remains speculative, a broad agreement in the number densities supports the idea that moderate starburst galaxies at $z > 7$ such as B14-65666 can be ancestors of $z \sim 3 – 4$ passive galaxies (c.f., Valentino et al. 2020c).

7. CONCLUSION

We have presented results of ALMA Band 3 observations of CO(6-5), CO(7-6) and [CI](2-1) in B14-65666 (“Big Three Dragons”). The target has made the first detections of Ly$\alpha$, [OIII] 88 $\mu$m, [CII] 158 $\mu$m, and dust continuum in the EoR (Hashimoto et al. 2019), and is one of the brightest Lyman-Break Galaxies at $z > 7$.

Despite relatively long exposure time (3.75 hours on-source), we do not detect CO(6-5), CO(7-6), nor [CI](2-1) (Fig. 3). The 3σ upper limit on the line luminosity is $\approx (2.1 - 2.3) \times 10^7$ $L_\odot$ [i.e., $(1.3 - 2.0) \times 10^9$ K km s$^{-1}$ pc$^2$], which is about 50 times fainter than the [CII] 158 $\mu$m luminosity before the CMB attenuation correction (Table 1). The presence of a significant amount of dust (FIR) and neutral gas ([CII]) makes B14-65666 an ideal target to study molecular gas properties of a normal star-forming galaxy deep into the EoR. Our results are summarized as follows.

• To interpret the non-detection, we need information on a CMB attenuation correction factor to the lines, $f_{\text{CMB}}$, that depends on the excitation temperature of each transition. Without detection of mid-$J$ CO and [CI](2-1) lines alone, we have no choice but to assume physical properties in B14-65666 so as to obtain $f_{\text{CMB}}$. In an optimistic case of LTE and under the assumption of gas-dust thermal coupling, $f_{\text{CMB}}$ is about 0.85 (0.62) if we adopt the dust temperature of 80 (40) K estimated from dust SED fitting with the dust emissivity index ($\beta$) of 1.0 (2.0) (Sugahara et al. 2021). In a more realistic non-LTE case, $f_{\text{CMB}}$ can be as low as 0.05 according to a theoretical work of da Cunha et al. (2013). This indicates that properties derived from mid-$J$ CO or [CI](2-1) are highly uncertain in this study (Table 3).

• The dust continuum at $\lambda_{\text{rest}} \approx 400$ $\mu$m is not detected, and we place a 3σ upper limit of 15.9 $\mu$Jy on the flux density. Assuming the modified-black body radiation, our 3σ upper limit is consistent with the previously derived FIR SED assuming $\beta > 1$ (Figs. 1 and 2).

• We have attempted to estimate the molecular gas mass, $M_{\text{mol}}$, of B14-65666 based on five techniques of i) mid-$J$ CO luminosity, ii) [CI](2-1) luminosity, iii) [CII] 158 $\mu$m luminosity, iv) dust mass and a dust-to-molecular gas mass ratio (DGR), and v) dynamical mass. In these estimates, we have taken into account the metallicity dependence of luminosity-to-mass conversion factors ($\alpha_{\text{CO}}$, $\alpha_{\text{[CII]}}(2-1)$, and $\alpha_{\text{[CI]}}$) and the DGR: we have assumed the gas-phase metallicity of $0.4_{-0.2}^{+0.4}$ $Z_\odot$ previously determined from SED fitting. In the case of mid-$J$ CO, we have also assumed a CO excitation ladder ($r_{61} \geq 0.16$ and $r_{71} \geq 0.07$) deduced from the SFR surface density of the target, $\Sigma_{\text{SFR}} = 3.8_{-1.4}^{+2.1}$ $M_\odot$ yr$^{-1}$ kpc$^{-2}$, and a theoretical work of Narayanan & Krumholz (2014). Based on three methods of [CII], dust mass, and dynamical mass, we obtain $M_{\text{mol}} = (0.05 - 11) \times 10^{10} M_\odot$, which is consistent with its upper limit inferred from the non-detection of mid-$J$ CO and [CI](2-1) (Fig. 5 and Table 5).

• Albeit with large uncertainty in $M_{\text{mol}}$, we estimate a high molecular gas-to-stellar mass ratio ($\mu_{\text{gas}}$) of 0.65 – 140 and a short gas depletion time ($t_{\text{dep}}$) of 2.5 – 550 Myr. Comparing these estimates with extrapolations of $\mu_{\text{gas}}$ and $t_{\text{dep}}$ as functions of redshift, sSFR (= SFR/$M_\star$), and stellar mass as reported in previous studies (Scoville et al. 2017; Tacconi et al. 2018; Liu et al. 2019), we find broad agreements, showing that our $M_{\text{mol}}$ estimate is reasonable (Fig. 6). The short gas depletion time of B14-65666 partly reflects the starburst nature of the target, which is likely to be induced by a major-merger event. If no gas is fueled from outside the galaxy, we conjecture that B14-65666 can be an ancestor of $z \geq 4$ passive galaxies, which is supported by a broad agreement of the number volume density of galaxies like B14-65666 and $z \sim 3 – 4$ passive galaxies.

We stress again that our target, B14-65666, is one of the brightest LBGs in the EoR. The UV luminosity of our target is about $3 – 4$ times brighter than the typical UV luminosity at $z = 7$ (e.g., Bouwens et al. 2021). The non-detection of mid-$J$ CO lines even with a moderately deep ALMA observations indicates that it is not easy to observe mid-$J$ CO lines in normal SFGs with typical UV luminosities in a statistical manner without aid of the gravitational lensing effect. Overall, our observations highlight the difficulty in obtaining robust conclusion from mid-$J$ CO observations alone particularly in the EoR, and motivate studies that use other tracers as an alternative gas mass tracer, supporting previous arguments in e.g., Boogaard et al. (2021) at $z = 3 – 4$. 
Table A1. Summary of our ALMA Band 3 observations

| UT start time | Baseline lengths | N_ant | Central frequency | Integration time | mean PWV |
|---------------|------------------|-------|-------------------|------------------|----------|
| YYYY-MM-DD hh:mm | (m) | (GHz) | (min) | (mm) |
| (1) | (2) | (3) | (4) | (5) | (6) |
| 2019-Sep-17 12:04 | 41.4 – 2953.5 | 41 | 85.00, 86.88, 97.15, 98.95 | 45.0 | 2.4 |
| 2019-Sep-17 13:10 | 41.4 – 2953.5 | 41 | 85.00, 86.88, 97.15, 98.95 | 45.0 | 2.2 |
| 2019-Sep-21 17:03 | 15.1 – 2953.5 | 42 | 85.00, 86.88, 97.15, 98.95 | 45.0 | 2.4 |
| 2019-Sep-22 12:37 | 15.1 – 2953.5 | 45 | 85.00, 86.88, 97.15, 98.95 | 45.0 | 4.6 |
| 2019-Sep-22 13:52 | 15.1 – 2953.5 | 45 | 85.00, 86.88, 97.15, 98.95 | 45.0 | 5.0 |

Note—(1) The observation date; (2) the ALMA’s baseline length; (3) the number of antenna used in the observation; (4) the central frequencies of four spectral windows. The bandwidth of each SPW is 1.875, 2.000, 1.875, and 2.000 GHz, respectively; (5) the on-source integration time; and (6) the precipitable water vapor. At the ALMA site, this corresponds to high (≈ 95 – 97%) transmission at the observed frequency.

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Facilities: ALMA

APPENDIX
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