Some Die Filthy Rich: The Diverse Molecular Gas Contents of Post-starburst Galaxies Probed by Dust Absorption

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Abstract

Quenched post-starburst galaxies (QPSBs) are a rare but important class of galaxies that show signs of rapid cessation or recent rejuvenation of star formation. A recent observation shows that about half of QPSBs have large amounts of cold gas. This molecular CO sample is, however, too small and is not without limitations. Our work aims to verify previous results by applying a new method to study a uniformly selected sample, more than 10 times larger. In particular, we present detailed analysis of $\text{H}α/\text{H}β$ ratios of face-on QPSBs at $z = 0.02$–0.15 and with $M_\star = 10^{10} – 10^{11} M_\odot$. We interpret the $\text{H}α/\text{H}β$ ratios by applying our recent gas mass calibration, which is based on non-PSB galaxies but predicts gas masses that are consistent with CO observations of $\sim 100$ PSBs. We estimate the molecular gas by either using PSBs with well-measured $\text{H}α/\text{H}β$ ratios or measuring them from stacked spectra. Our analysis reveals that QPSBs have a wide range of $\text{H}α/\text{H}β$ ratios and molecular gas fractions that overlap with the typical gas fractions of star-forming or quiescent galaxies: $\text{H}α/\text{H}β \approx 3$–8 and $f_{\text{H}_2} \approx 1%$–20% with median $f_{\text{H}_2} \approx 4%$–6%, which correspond to $M_{\text{H}_2} \approx (1–3) \times 10^9 M_\odot$. Our results indicate that large reservoirs of cold gas are still present in significant numbers of QPSBs and that they arguably were not removed or destroyed by feedback from active galactic nuclei.

Unified Astronomy Thesaurus concepts: Interstellar medium (847); Interstellar molecules (849); AGN host galaxies (2017); Starburst galaxies (1570); Interstellar dust extinction (837); Seyfert galaxies (1447); Galaxy evolution (594)

1. Introduction

Massive galaxies in the nearby universe fall into two broad categories: star-forming, gas-rich spiral galaxies and quiescent, gas-poor lenticular and elliptical galaxies. Understanding the origin of this bimodality has been the subject of considerable research for the past several decades. In the traditional picture, post-starburst (PSB) galaxies (Dressler & Gunn 1983; Quintero et al. 2004; Goto 2005; Wild et al. 2009; Yesuf et al. 2014; Pawlik et al. 2018) may exemplify objects in transition from the star-forming to quiescent phase owing to major mergers (Snyder et al. 2011). Minor mergers, however, may equal produce a large fraction of rejuvenated PSBs, by triggering new cycles of starbursts in passive, bulge-dominated galaxies (Dressler et al. 2013; Rowlands et al. 2018; Davis et al. 2019; Pawlik et al. 2019). In their quiescent phase, PSB spectra reveal very little ongoing star formation (weak emission lines) but a substantial burst of star formation (strong Balmer absorption lines) in their recent past ($< 1$ Gyr). Although PSBs are rare galaxies ($< 1%$), observational estimates of their rapid evolution timescale and number density indicate that a significant fraction of present-day ellipticals may have gone through the PSB evolutionary channel (e.g., Tran et al. 2004; Yesuf et al. 2014; Wild et al. 2016; Zahid et al. 2016). Several transformation mechanisms have been proposed to quench star formation by removing or heating gas in galaxies or their surrounding halos (Dekel & Silk 1986; Di Matteo et al. 2005; Dekel & Birnboim 2006; Hopkins et al. 2006; Martig et al. 2009; Peng et al. 2010). PSBs are ideal laboratories to test some of these mechanisms. Surprisingly, several studies discovered large amounts of atomic or molecular gas and dust in PSBs (Chang et al. 2001; Buyle et al. 2006; Zwaan et al. 2013; French et al. 2015; Rowlands et al. 2015; Alatalo et al. 2016b; Suess et al. 2017; Yesuf et al. 2017; Smercina et al. 2018; Li et al. 2019). Despite their small sample sizes, these studies reveal a new picture in which star formation is rapidly truncated, but the cold interstellar medium of some of these galaxies is not completely removed or destroyed. The common paradigm, based on simulations of gas-rich major mergers, has been that gas loses angular momentum and is funneled to galaxy centers during such catastrophic events. Intense nuclear starbursts and obscured active galactic nuclei (AGNs) are then triggered. The starburst rapidly depletes most of the cold gas. At the end of the starburst, the remnants of gas and dust are blown out of the host galaxy owing to feedback from the AGN (e.g., Barnes & Hernquist 1991; Di Matteo et al. 2005; Hopkins et al. 2006, 2008). However, in some simulations the effect of AGN feedback in PSBs is inconsequential (Wild et al. 2009; Snyder et al. 2011; Davis et al. 2019). French et al. (2015) studied 32 quenched PSBs (QPSBs). Almost all of these QPSBs show signatures of low-ionization nuclear emission-line regions (for a review, see Ho 2008), and about half of them have CO detections. Those detected in CO have molecular gas content comparable to those of star-forming galaxies (SFGs), while the nondetected PSBs have gas masses more similar to those of quiescent galaxies (QGs). Likewise, Yesuf et al. (2017) studied the molecular gas (CO) properties of 116 PSBs with a variety of AGN and star formation properties. They found that the distribution of molecular gas fractions ($f_{\text{H}_2} \equiv M_{\text{H}_2}/M_\star$, where $M_\star$ is the stellar mass) in PSBs is broad and significantly different from that of normal SFGs in the xCOLD GASS survey (Saintonge et al. 2017). PSBs whose active nuclei are classified as Seyferts have median (25%, 75%) $f_{\text{H}_2} = 2.3(1.7, 13)%$, SFGs$^4$ have median (25%, 75%) $f_{\text{H}_2} = 7(4, 11)%$, and QPSBs have median (25%, 75%) $f_{\text{H}_2} = 3%–14%$.

$^4$ SFGs are defined as galaxies with $\log(\text{SSFR}/\text{yr}) > -11$ and $\log(M_\star/M_\odot) > 10$, where $\text{SSFR} \equiv \text{SFR}/M_\star$ and SFR is the star formation rate. The 0.15–0.85 quantile range of $f_{\text{H}_2}$ is $3%–14%$.
75% \( f_{\text{IR}} \) = 3 (−, 8)% (Yesuf et al. 2017). The molecular gas fractions generally decrease as the PSBs age. AGN feedback does not seem to affect the cold gas content, at least in PSBs that are in early stages.

Davis et al. (2019) studied the cold interstellar medium of a large sample of PSB galaxies selected from the EAGLE cosmological simulations (Schaye et al. 2015). The formation mechanisms of the simulated PSBs are quite diverse, as are the mechanisms that rapidly deplete gas in these galaxies. Moreover, the simulated PSBs have \( 10^8 \rightarrow 10^{10} M_\odot \) of cold star-forming gas (the median mass is \( \sim 2 \times 10^9 M_\odot \) at \( z < 0.25 \)). The mechanisms that impact the cold gas and cause the simulated galaxies to become PSBs rapidly include both major and minor mergers, environmental effects, and bursts of AGN activity.

Directly measuring gas masses for large samples requires huge investments of telescope time. Alternatively, dust absorption or emission can be used to indirectly probe the cold interstellar medium of large samples of galaxies. Rest-frame far-infrared emission measurements, while more widely available than CO observations, are still not easily accessible for large galaxy samples. In Yesuf & Ho (2019), we showed that dust absorption is a dirt-cheap alternative to estimate molecular gas masses for large samples. This method can be applied to a variety of problems (e.g., Yesuf & Ho 2020; Zhuang & Ho 2020), of which this current study is but one example. In this work, we analyze the \( H_\alpha/H_\beta \) ratios of QPSBs and estimate their molecular gas content using our method. Although this method is indirect and accurate to within a factor of \( \sim 2–3 \), it enables a complementary, statistical study of molecular gas in a sample of QPSBs that is more than 10 times larger and more homogeneously selected than that of French et al. (2015).

In Section 2, we describe the data and methodology used to estimate molecular gas. In Section 3, we present the gas masses and gas fractions of QPSBs. Section 4 discusses our results in a general context of previous studies. A summary of this work and its main conclusions are given in Section 5.

## 2. Data and Methodology

This section describes the data used and the sample selection, the spectral stacking method and its validity, our method of estimating molecular gas masses using \( H_\alpha/H_\beta \) ratios, and the validity of applying it to study PSBs.

### 2.1. SDSS Data and Sample Selection

Our galaxy sample is taken from the Sloan Digital Sky Survey (SDSS; Abazajian et al. 2009; Alam et al. 2015). The publicly available Catalog Archive Server (CAS)\(^5\) is used to compile some of the measurements used in this work, including emission-line fluxes, spectral indices, median stellar masses, and the Petrosian half-light radii. To exclude edge-on galaxies, we additionally use ellipticities/axial ratios derived from single-component Sérsic fits from the catalog of Simard et al. (2011). The orientation effect may complicate the estimation of molecular gas mass from dust absorption in edge-on galaxies.

The SDSS CAS measurements are estimated using the same methods developed by the MPA-JHU group\(^6\) (details can be found in Kauffmann et al. 2003b; Brinchmann et al. 2004). Briefly, stellar masses are calculated using a Bayesian methodology and ugriz photometry alone, but corrected for contamination by nebular emission lines. The emission lines are measured after subtracting the best-fitting stellar population model of the continuum. The emission lines are fit simultaneously as Gaussians. The Balmer lines are required to have the same line width and velocity offset, and so, too, the forbidden lines.

Throughout this work (with the exception of Section 2.4), we select galaxies that have axial ratios \( b/a > 0.5 \), redshifts \( z = 0.02–0.15 \), and stellar masses \( M_* \geq 10^{10} M_\odot \). We also require that the median signal-to-noise ratio (S/N) per pixel of the entire spectrum of the galaxy be greater than 10; it is difficult to accurately model the continuum and measure absorption lines when the S/N is smaller than 10. The QPSBs are defined as galaxies with the equivalent width (EW) of \( H_\alpha < 3 \) Å (in emission) and \( H_\beta > 4 \) Å (in absorption). Only about 10% of QPSBs are excluded by the S/N requirement. We visually inspect the optical spectra of the QPSB sample resulting from the above definition and remove several tens of SFG contaminants with bad measurements.\(^7\) For comparison, we define QGs as galaxies with 4000 Å break \( D_n(4000) > 1.6 \), \( H_\alpha < 3 \) Å, and \( H_\beta < 2 \) Å (for the definitions of the indices, see Worthey & Ottaviani 1997; Balogh et al. 1999; Kauffmann et al. 2003b).

Selecting a complete and unbiased sample of the progenitors of QPSBs is not easy. Some attempts have been made to improve the definition of PSB to include galaxies with ongoing star formation and/or AGN activity (Wild et al. 2010; Yesuf et al. 2014). As a comparison sample, here we simply study the inferred gas content of Seyferts with \( H_\beta > 4 \) Å that possess early-type morphologies. We identify Seyferts (in contrast to SFGs) using the emission-line ratios \( [O \text{III}]/H_\beta \) and \([S \text{II}]/H_\alpha \) (Kewley et al. 2006), and we impose the additional cut \( H_\alpha > 3 \) Å. We use \( r \)-band concentration index, \( C = R_{90}/R_{50} > 2.6 \), and stellar mass surface density in \( z \) band, \( \Sigma_* = 0.5 M_*/(\pi R_{50})^2 > 10^8 M_\odot \text{ kpc}^{-2} \), as indicators of early-type morphology (Strateva et al. 2001; Kauffmann et al. 2003a, 2003c). About 80% of QPSBs and \( \sim 73 \) QGs satisfy these morphology cuts, while only \( \sim 24% \) of SFGs satisfy them.

### 2.2. Spectral Stacking Analysis

Figure 1 shows the distributions of \( H_\alpha/H_\beta \) ratios of QPSBs that have well-measured (\( > 3 \sigma \)) \( H_\alpha \) and \( H_\beta \) fluxes and those that have marginal (1–3\( \sigma \)) \( H_\beta \) detections. About 93% of all face-on QPSBs (total \( N = 535 \)) have well-measured \( H_\alpha \) fluxes, but only \( \sim 40\% \) of the QPSBs have well-measured \( H_\beta \) fluxes. This fraction increases to \( \sim 60\% \) of \( \sim 80\% \) if \( H_\beta \) detection significance is \( > 2\sigma \). Although we make S/N cuts on the emission-line flux (\( > 3 \sigma \)) and the continuum measurements (median \( S/N \text{ pixel}^{-1} > 10 \)), the individual measurements of \( H_\alpha/H_\beta \) should still be interpreted with caution. Some QPSBs (\( \sim 20\% \)) have \( H_\alpha/H_\beta < 2.5/2.8 \), which are unphysical and are likely underestimated owing to insufficient S/N of the QPSB spectra (\( S/N \text{ pixel}^{-1} < 25 \)) or imperfect deblending of...
Given the S/N limitation of the spectroscopic observations, we attempt to characterize the distributions of $H\alpha/H\beta$, $M_H$, and $f_{H\beta}$ for the QPSB sample by stacking spectra whose $H\alpha/H\beta$ cannot be accurately measured individually. We also demonstrate that this method gives consistent results with the high-S/N $H\alpha/H\beta$ measurements based on individual spectra.

To stack the SDSS spectra, each spectrum is shifted to its rest-frame wavelength and is normalized by the mean flux in the wavelength range 5445–5550 Å. This range is free of strong emission or absorption lines. The normalization ensures equal weighting of both faint and bright galaxies in the sample. The rest-frame spectra are then interpolated on a logarithmic wavelength grid with a bin of $\Delta \log \lambda = 10^{-4}$ dex, which is the same as the pixel spacing of the observed wavelength of SDSS spectra. A median composite spectrum is constructed from the median flux densities at a given wavelength bin of the rest-frame spectra. All spectra are given equal weights. The errors of the median composite spectrum are estimated using bootstrap resampling. Namely, we repeat the above stacking procedure to produce 200 median composite spectra by resampling with replacement using a subset of individual spectra of the same size as the original sample. The standard deviation of the median fluxes of the 200 composite spectra in a given wavelength bin is the error of the median flux at that given bin.

We use the penalized pixel-fitting (pPXF) code (Cappellari & Emsellem 2004; Cappellari 2017) to fit the stacked spectra with stellar population and ionized gas emission-line models. After masking out major emission-line regions, the code first determines the optimal linear combinations of simple stellar population templates. The templates are based on the MILES stellar library (Vazdekis et al. 2010), and they have spectral resolutions comparable to those of the SDSS spectra. The pPXF code allows the use of additive or multiplicative Legendre polynomials in order to adjust possible continuum mismatch between model templates and observed data. To that end, we use a 10th-order multiplicative polynomial. We have verified that the exact choice of polynomial order does not significantly affect the $H\alpha/H\beta$ measurements. Finally, the Balmer and forbidden emission lines are modeled using single-Gaussian line profiles. All Balmer lines have similar velocity dispersion as well as similar forbidden emission lines, but not necessarily the same velocity dispersion as that of the Balmer lines. Prior to the least-squares minimization, the model emission lines are convolved with the SDSS spectral resolution. Note that the flux errors calculated from the bootstrap scheme are also used as inputs to pPXF. Example co-added spectra of low-S/N QPSBs and their fits are shown in Figure 2.

Table 1 shows that the distributions of $H\alpha/H\beta$ resulting from the stacking analysis and individual spectra are generally consistent. The stacking analysis indicates that $H\alpha/H\beta$ ranges between $\sim$3 and 5 for the high-S/N QPSB sample. Based on the stacked analysis and the expectation from case B recombination physics, we deem the individual measurements of $H\alpha/H\beta$ below $\sim$2.9 inaccurate (underestimated). We use $A_V = 0$ mag for the high-S/N QPSBs with $H\alpha/H\beta < 2.9$ when estimating their molecular gas masses. Our conclusions are robust despite some individual QPSBs having inaccurate $H\alpha/H\beta$ measurements. This is because the $H\alpha/H\beta$ ratios are close enough to the dust-free, intrinsic ratio ($\sim$2.9–3.1) and do not have detectable dust absorption. Furthermore, Figure 1 suggests that QPSBs with marginally detected $H\beta$ are likely more dusty than those with well-measured $H\alpha$ and $H\beta$ fluxes.

Figure 1. Distribution of $H\alpha/H\beta$ ratios of face-on ($b/a > 0.5$) QPSBs and the comparison samples of SFGs in two stellar mass ranges. The three curves are kernel density estimates. QPSBs have a wide range of $H\alpha/H\beta$ ratios. Some are dust-free, while others are as dusty as SFGs. QPSBs whose $H\alpha/H\beta$ ratios are not well measured ($<3\sigma$) will be stacked. The $H\alpha/H\beta$ ratios measured from the stacked spectra will show that the QPSBs with low-S/N $H\alpha/H\beta$ are on average as dusty as SFGs. The high-S/N $H\alpha/H\beta$ measurements below the dashed line are underestimated, perhaps due to spectra with insufficient S/N. We set $A_V = 0$ mag for the objects below this line.

the Balmer emission and absorption lines (see, e.g., Ho et al. 1997). These measurements merely indicate that these objects do not have detectable dust absorption. Furthermore, Figure 1 suggests that QPSBs with marginally detected $H\beta$ are likely more dusty than those with well-measured $H\alpha$ and $H\beta$ fluxes.
not cause significantly different gas mass estimates, and we also confirm the gas estimates using the stacking analysis.

2.3. Estimation of Gas Masses from SDSS Data

We calculate the V-band dust absorption using the observed Hα/\(H\beta\) ratio and the dust attenuation curve of Charlot & Fall (2000; see also Wild et al. 2011) as follows:

\[
Q_\lambda = 0.6(\lambda/5500)^{-1.3} + 0.4(\lambda/5500)^{-0.7}.
\]

Assuming that the intrinsic Balmer decrement is \(H\alpha/\beta = 2.86\) for inactive galaxies and \(H\alpha/\beta = 3.1\) for AGNs (e.g., Ferland & Netzer 1983; Gaskell & Ferland 1984),

\[
A_V = \frac{2.5}{(Q_{4861} - Q_{6563})} \times \log \frac{H\alpha/\beta}{3.1 \text{ or } 2.86}.
\]

Figure 2. Example stacked spectra (black) of subsamples of QPSBs with low-S/N (1σ–3σ) \(H\alpha/\beta\) ratios. The model fits for the stellar population plus emission lines are shown in red, and the emission-line model components are shown in magenta. The models reproduce the data well. A significant number of the low-S/N QPSBs have high amounts of dust absorption.

This might cause the object’s predicted gas mass to be lower by up to \(\sim 0.1\) dex than it actually is. Such small changes are not important for our application. An object with \(H\alpha/\beta < 2.9–3.1\) might have \(\log(M_{H_2}/M_\odot) \lesssim 8.5–8.8\). For our purpose, knowing that the object has a gas mass similar to QGs is sufficient. We also use 2.86 as the intrinsic ratio when \(H\alpha/\beta\) ratios are measured from stacked spectra.

\[Q_{4861} - Q_{6563} = 0.31.\]
directly. In Yesuf & Ho (2019), we analyzed the molecular (and atomic) gas data of local representative galaxies \( (M_\text{HI} = 10^8 - 10^{12} \, M_\odot ) \) and \( z = 0.01-0.05 \) from the extended Galaxy Evolution Explorer (GALEX) Arecibo SDSS Survey (xGASS; Catinella et al. 2018) and xCOLD GASS (Saintonge et al. 2017). We fitted censored quantile regression to summarize the median and the 0.15/0.85 quantile multivariate relationships among \( M_\text{HI}, A_V, Z, \) and/or \( R_S0 \). These empirical relations are also consistent with independent gas data of galaxies in the Herschel Reference Survey compiled by Boselli et al. (2014).

For a QPSB galaxy whose \( \text{H}_\alpha / \text{H}_\beta \) ratio is measureable with high significance, its own \( \text{H}_\alpha / \text{H}_\beta \) ratio is used to estimate its molecular gas mass. On the other hand, for a galaxy whose \( \text{H}_\alpha / \text{H}_\beta \) ratio is not well measured, we use the \( \text{H}_\alpha / \text{H}_\beta \) value obtained from the stacked spectrum to which the galaxy contributed. Given the average \( \langle \text{H}_\alpha / \text{H}_\beta \rangle \) and its error \( \sigma_{\text{H}_\alpha / \text{H}_\beta} \) from fitting the stacked spectrum, we create, for each galaxy in the stack, 1000 random samples of \( \text{H}_\alpha / \text{H}_\beta \) from a uniform distribution in the interval \( [\langle \text{H}_\alpha / \text{H}_\beta \rangle - \sqrt{3} \sigma_{\text{H}_\alpha / \text{H}_\beta}, \langle \text{H}_\alpha / \text{H}_\beta \rangle + \sqrt{3} \sigma_{\text{H}_\alpha / \text{H}_\beta}] \). Then, we calculate 1000 samples of \( A_V \) and the corresponding \( M_\text{HI} \) values for each galaxy using its stellar mass and radius, as outlined above. Finally, we combine all log \( M_\text{HI} \) samples \( (1000 \times n, \text{where } n \text{ is the number of objects in a given stack} ) \) and calculate the median \( (15\%, 85\%) \) of the combined log \( M_\text{HI} \) as approximate summary statistics of the “true” distribution of log \( M_\text{HI} \) for galaxies in the stack. Using several subsamples of galaxies with well-measured \( \text{H}_\alpha / \text{H}_\beta \) ratios, we show that our method of approximating the actual distributions of log \( M_\text{HI} \) using the stacked spectra results in reasonably accurate inference. Table 1 also compares the \( M_\text{HI} \) distributions resulting from the stacking analysis and individual spectra.

We adopt two procedures to further capture and quantify additional galaxy-to-galaxy variations of \( \text{H}_\alpha / \text{H}_\beta \) ratios. In the first procedure, we create multiple stacked spectra by subdividing galaxies whose \( \text{H}_\alpha / \text{H}_\beta \) ratios are not well measured into subsamples using the limited information in \( \text{H}_\alpha / \text{H}_\beta \); poorly measured \( \text{H}_\alpha / \text{H}_\beta \) \( (<1\sigma) \), and marginally measured high, medium, and low \( \text{H}_\alpha / \text{H}_\beta \) \( (1\sigma-3\sigma) \). The second procedure uses the ratios of Wide-field Infrared Survey Explorer (WISE;\(^{10}\) Wright et al. 2010) 12–4.6 μm flux density, \( f_{12} / f_{4.6} \), to subdivide the stacked sample. Yesuf et al. (2017) found that this flux density ratio is tightly correlated with \( \text{f}_{\text{H}_\alpha} \) and is a good proxy for the average gas fraction for both PSBs and non-PSBs.

Table 1 shows that the dispersion of the \( M_\text{HI} \) distribution due to galaxy-to-galaxy variations can be teased out when the sample is separately stacked in three \( \text{H}_\alpha / \text{H}_\beta \) ranges. Stacking of all galaxies in the high-S/N QPSB sample nevertheless gives a valid and useful average (statistical) description of the \( M_\text{HI} \) distribution.

In an attempt to approximately reconstruct the log \( M_\text{HI} \) distribution of all PSBs, we combine the information from the individual measurements of log \( M_\text{HI} \) with those from the stacking analysis, as follows. For each independent i subsample of stacked spectra, we generate \( 1000 \times n_i \) samples of log \( M_\text{HI} \), as described above using the mean \( \text{H}_\alpha / \text{H}_\beta \) ratios. We then fit the distribution of log \( M_\text{HI} \) for each subsample with a lognormal function. When the analysis of all the subsamples is done, we draw 500 times samples of size \( n_i \) at a time from each i lognormal distribution. We then combine all these draws with 500 exact replications of the array of individual log \( M_\text{HI} \) measurements. The final log \( M_\text{HI} \) sample is binned and normalized to give a probability density function. Similarly, to reconstruct the probability density function of \( \text{f}_{\text{H}_\alpha} \), a Gaussian distribution is used instead of a lognormal distribution. When the stacking analysis results in a lower limit on \( \text{H}_\alpha / \text{H}_\beta, M_\text{HI} \) and \( \text{f}_{\text{H}_\alpha} \) are sampled uniformly within 0.5 dex above the corresponding gas lower limits. The results do not change qualitatively if instead galaxies with lower limits are sampled from (added to the numbers of) the closest detected subsamples.

### 2.4. Validating Gas Mass Estimator Using PSBs with CO Data

We compile a heterogenous sample of PSB galaxy candidates (French et al. 2015; Rowlands et al. 2015; Alatalo et al. 2016b; Yesuf et al. 2017) to show that our method presented in Yesuf & Ho (2019) can be applied to PSBs. The sample is heterogenous because the sample selection is different in different works, and the whole sample has a wide range of star formation and AGN properties (Figure 1 in Yesuf et al. 2017). About 100 (~85%) of the PSBs have well-measured \( \text{H}_\alpha / \text{H}_\beta \) ratios. The sample has the following median \( (15\%, 85\%) \) properties: (1) log \( (M_\text{HI}/M_\odot ) = 10.5(10.1, 10.9), (2) z = 0.05(0.03, 0.13), (3) \delta_{\delta_\text{HI}} = 5.6(4, 7) \AA, and (4) EW(H\alpha) = 9(2, 31) \AA. Thus, at least half have either significant amounts of star formation or strong AGN activity.

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\(^{10}\) The cross-matched WISE data are available in SDSS DR15 tables wISE_xmatch and wISE_allsky.
Among those that are classifiable, the Seyfert AGN fraction is \(\sim 40\%\). Note that about 15\% of the sample has H\(\delta_A < 4\) Å, but their near-ultraviolet−optical colors indicate that these galaxies are likely aged PSBs (Yesuf et al. 2017). We exclude one galaxy from French et al. (2015) labeled H01, because resolved Atacama Large Millimeter Array (ALMA) CO imaging showed that the gas is associated with a companion, not with the QPSB (French et al. 2018).

Figure 3(a) compares the \(M_{\text{H}_2}\) predicted by our empirical estimator and the observed CO luminosities of both quenched and quenching samples of PSB galaxies. Panel (a) shows all galaxies in the sample, while the other panels show various subsets: (b) PSBs with low H\(\alpha\) EW, (c) Seyfert PSBs, and (d) non-Seyfert PSBs. The dotted lines mark constant \(\alpha_{\text{CO}} \equiv M_{\text{H}_2}/L_{\text{CO}} = 1\) or \(4.3\) \(M_\odot\) (K km s\(^{-1}\) pc\(^2\))^\(-1\).

Considering the well-known uncertainty of converting CO luminosity to \(M_{\text{H}_2}\), this figure demonstrates that it is reasonable to apply our \(A_V\)-based dust-to-gas scaling relation to PSB galaxies. Our method works well for QPSBs, provided that their \(\alpha_{\text{CO}} \approx 4.3\) \(M_\odot\) (K km s\(^{-1}\) pc\(^2\))^\(-1\).

The predicted median \(M_{\text{H}_2}\) is moderately correlated with the observed CO luminosity (Kendall \(\tau \approx 0.5\); Spearman \(\rho \approx 0.6−0.7\).\(^{11}\) The ratios of the predicted median molecular masses to the observed CO luminosities give a median (15\%, 85\%) CO conversion factor of \(\alpha_{\text{CO}} \approx 4.8(1, 15)M_\odot\) (K km s\(^{-1}\) pc\(^2\))^\(-1\). Overall, the predicted median gas masses are in good agreement with the observed CO luminosities. Salim et al. deem their SFRs reliable even for PSBs, and that they are more likely to represent true levels of star formation averaged over the last 100 Myr for QPSBs. The SFRs are used to make supplementary points and are not essential for this work. The trend with SFR is also qualitatively similar if we instead use SFRs (upper limits) estimated from the WISE 12 \(\mu\)m luminosity (Hayward et al. 2014; Cluver et al. 2017).

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Figure 3(a) compares the \(M_{\text{H}_2}\) predicted by our empirical estimator and the observed CO luminosities of both quenched and quenching samples of PSB galaxies. Panel (a) shows all galaxies in the sample, while the other panels show various subsets: (b) PSBs with low H\(\alpha\) EW, (c) Seyfert PSBs, and (d) non-Seyfert PSBs. The dotted lines mark constant \(\alpha_{\text{CO}} \equiv M_{\text{H}_2}/L_{\text{CO}} = 1\) or \(4.3\) \(M_\odot\) (K km s\(^{-1}\) pc\(^2\))^\(-1\).

Considering the well-known uncertainty of converting CO luminosity to \(M_{\text{H}_2}\), this figure demonstrates that it is reasonable to apply our \(A_V\)-based dust-to-gas scaling relation to PSB galaxies. Our method works well for QPSBs, provided that their \(\alpha_{\text{CO}} \approx 4.3\) \(M_\odot\) (K km s\(^{-1}\) pc\(^2\))^\(-1\). Overall, the predicted median gas masses are in good agreement with the observed CO luminosities. Salim et al. deem their SFRs reliable even for PSBs, and that they are more likely to represent true levels of star formation averaged over the last 100 Myr for QPSBs. The SFRs are used to make supplementary points and are not essential for this work. The trend with SFR is also qualitatively similar if we instead use SFRs (upper limits) estimated from the WISE 12 \(\mu\)m luminosity (Hayward et al. 2014; Cluver et al. 2017).

The predicted median \(M_{\text{H}_2}\) is moderately correlated with the observed CO luminosity (Kendall \(\tau \approx 0.5\); Spearman \(\rho \approx 0.6−0.7\).\(^{11}\) The ratios of the predicted median molecular masses to the observed CO luminosities give a median (15\%, 85\%) CO conversion factor of \(\alpha_{\text{CO}} \approx 4.8(1, 15)M_\odot\) (K km s\(^{-1}\) pc\(^2\))^\(-1\). Overall, the predicted median gas masses are in good agreement with the observed CO luminosities. Salim et al. deem their SFRs reliable even for PSBs, and that they are more likely to represent true levels of star formation averaged over the last 100 Myr for QPSBs. The SFRs are used to make supplementary points and are not essential for this work. The trend with SFR is also qualitatively similar if we instead use SFRs (upper limits) estimated from the WISE 12 \(\mu\)m luminosity (Hayward et al. 2014; Cluver et al. 2017).

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\(^{11}\) The upper limits are used in computing Kendall \(\tau\).
agreement with the observed CO luminosities, provided that $\alpha_{\text{CO}} \approx 4$ $M_\odot$ (K km s$^{-1}$ pc$^2$)$^{-1}$ for most PSBs.

As shown in Figure 3(b), the PSBs with H$\alpha$ EW $< 9$ Å (half of the sample) lie close to the line of $\alpha_{\text{CO}} = 4.3$ $M_\odot$ (K km s$^{-1}$ pc$^2$)$^{-1}$. Therefore, our method works well for QPSBs, without appealing to $\alpha_{\text{CO}}$ values that are significantly different from that of the Milky Way. Similarly, for $\alpha_{\text{CO}} \approx 4.3$ $M_\odot$ (K km s$^{-1}$ pc$^2$)$^{-1}$, the predicted median gas masses for Seyfert PSB candidates are also consistent with the observed CO luminosities (Figure 3(c)). Unlike the three-quarters of PSBs that are not Seyferts in Figure 3(b), our model mean relation underpredicts their gas masses or their $\alpha_{\text{CO}} \approx 1$ $M_\odot$ (K km s$^{-1}$ pc$^2$)$^{-1}$. We think that the latter is more likely. If, instead, the former is true, it would weaken our conclusions; the trend goes in the opposite direction, and some of the PSBs will actually have more gas than predicted. The SFRs of some of the PSBs with CO data indicate that these galaxies lie above the ridge of the star-forming main sequence (i.e., they are starburst-like, and some of their morphology is very disturbed). Even with $\alpha_{\text{CO}} = 1$ $M_\odot$ (K km s$^{-1}$ pc$^2$)$^{-1}$, the molecular gas fractions of most of these galaxies are too high ($> 30\%$) to be consistent with nonstarburst galaxies of similar stellar masses (Saintonge et al. 2017). Could they just be misidentified starbursts? Supplementary analysis of the CO sample is given in Appendix A.

In their simulation, Renaud et al. (2019) found that $\alpha_{\text{CO}}$ changes with time after a starburst (i.e., with the evolution of the SFR). In addition to the prediction uncertainty of our method, the possible evolution of $\alpha_{\text{CO}}$ also contributes to the scatter in Figure 3. In agreement with what is shown in Figure 3, the results of Renaud et al. (2019) indicate that $\alpha_{\text{CO}} \approx 4$–$6$ $M_\odot$ (K km s$^{-1}$ pc$^2$)$^{-1}$ is more appropriate for QPSBs than $\alpha_{\text{CO}} \approx 1$ $M_\odot$ (K km s$^{-1}$ pc$^2$)$^{-1}$ observed in starbursts and ultraluminous infrared galaxies (Bolatto et al. 2013, and references therein).

CO (1–0) luminosities are estimated from CO(2–1) assuming that their ratio is unity for 24 galaxies (Yesuf et al. 2017). This assumption may be yet another source of uncertainty in Figure 3.

To summarize: given the large uncertainty of $\alpha_{\text{CO}}$ and the heterogeneity of the PSB sample in previous studies, we do not find a compelling indication that our method is inconsistent with these observations. In fact, the success of our gas estimator in reasonably recovering the existing data for the majority of PSBs gives us confidence to apply it in this work.

### 3. Results

Table 2 presents the summary statistics of the distributions of H$\alpha$/H$\beta$, $M_{f_{\text{H}}}$, and $f_{\text{HI}}$ for the face-on QPSB sample ($N = 204$) with well-measured ($> 3\sigma$) H$\alpha$ and H$\beta$ emission lines. For comparison, the table also presents the summary statistics of SFGs, early-type Seyferts ($C > 2.6$, and $\Sigma_* > 10^{8.5}$ $M_\odot$ kpc$^{-2}$), and QGs. Because the median $f_{\text{HI}}$ depends on stellar mass (Saintonge et al. 2017), we split the sample into two mass bins. As we will show soon, this high-S/N sample is likely biased against more dusty QPSBs. Nevertheless, it is already clear that QPSBs have a wide range of dust absorption (H$\alpha$/H$\beta$ $\approx 3$–5 or $A_\lambda \approx 0.1$–1 mag for the high-S/N sample) and, by inference, molecular gas content; most are gas-poor, while some are remarkably dusty and gas-rich. For example, for the mass range $\log(M/M_\odot) = 10.5$–11, the observed H$\alpha$/H$\beta$ distributions, using our gas scaling relation described in Section 2.3, correspond to median (15%, 85%) log($M_{\text{HI}}/M_\odot$) of 8.9 (8.7, 9.3) and median (15%, 85%) log $f_{\text{HI}}$ of $-1.8$ (−2.0, −1.4). Furthermore, there are significant overlaps among the $f_{\text{HI}}$ distributions of QPSBs, SFGs, Seyferts, and QGs for the two mass ranges. However, in general, the medians of the distributions progressively shift toward lower $f_{\text{HI}}$, from SFGs (~5%–8%) to Seyferts (~4%–5%) to QPSBs (~2%) to QGs (~1%–2%).

Furthermore, Figure 4 shows violin plots of the median and 0.15 quantile $f_{\text{HI}}$ distributions of QPSBs in comparison with those of SFGs, early-type Seyferts, and QGs. The distributions are visualized separately in the two mass ranges, log($M/M_\odot$) = 10.5–11 (blue) and log($M/M_\odot$) = 10.5–10.5 (orange). All galaxies plotted here have individually well-measured H$\alpha$ and H$\beta$ emission lines.

Having shown in Table 1 that the stacking analysis can be confidently applied to study objects with low-S/N (<3$\sigma$) H$\alpha$/H$\beta$ ratios, Table 3 presents the summary statistics of the distributions of H$\alpha$/H$\beta$, $M_{f_{\text{H}}}$, and $f_{\text{HI}}$ for the low-S/N QPSB sample ($N = 327$). In addition to stacking all galaxies with low-S/N H$\alpha$/H$\beta$ ratios, we further subdivide the sample into three or four bins. In most cases, the stacking analysis reveals subsamples that have significantly enhanced dust and molecular gas content compared to the high-S/N QPSB sample. For
Figure 4. Comparison of the distributions of (a) the median and (b) 0.15 quantile of the molecular gas fractions ($f_{HI}$) for SFGs, early-type Seyferts, and QGs. The distributions are compared in two mass bins. All galaxies have log($M_*/M_\odot$) = 10–11 and are required to have well-measured H$\alpha$ and H$\beta$ emission lines. The dashed or dotted lines on each distribution denote the median or the interquartile (25%–75%) range. The PSBs have a wide range of $f_{HI}$, but the medians/modes of their $f_{HI}$ distributions are intermediate between those of SFGs and QGs. Later, we will improve the QPSB distribution by stacking QPSBs with low-S/N H$\alpha$/H$\beta$ ratios, which are missing from the upper half of the $f_{HI}$ distribution.

Table 3
Spectral Stacking Analysis of Low-S/N QPSBs

| ID  | log($M_*/M_\odot$) | Stack H$\alpha$/H$\beta$ | Stack log($M_{HI}/M_*$) | Stack log($f_{HI}$) | H$\alpha$/H$\beta$ | log($M_{HI}/M_*$) | N Galaxies |
|-----|--------------------|--------------------------|--------------------------|----------------------|-------------------|-------------------|------------|
| 3   | 10.5–11            | 8.0 ± 1.1                | 10.0(9.8, 10.2)          | −0.7(−0.9, −0.5)     | 7.8(6.1, 10.9)    | 10.0(9.7, 10.4)   | 168        |
| 3a  | 10.5–11            | 8.1 ± 1.3                | 10.0(9.7, 10.3)          | −0.7(−1.0, −0.5)     | 7.8(6.1, 10.9)    | 10.0(9.7, 10.4)   | 47         |
| 3b  | 10.5–11            | 3.6 ± 0.4                | 9.0(8.8, 9.2)            | −1.7(−1.8, −1.5)     | 3.8(2.3, 3.0)     | 9.1(8.8, 9.4)     | 61         |
| 3c  | 10.5–11            | >5.6                     | >9.5                     | >−1.3                | ...               | ...               | 65         |
| 4   | 10–10.5            | 5.0 ± 0.3                | 9.3(9.1, 9.4)            | −1.1(−1.2, −0.9)     | ...               | ...               | 159        |
| 4a  | 10–10.5            | 5.4 ± 0.7                | 9.3(9.1, 9.5)            | −0.9(−1.2, −0.8)     | 7.2(5.4, 8.7)     | 9.7(9.3, 10)      | 36         |
| 4b  | 10–10.5            | 6.0 ± 1.1                | 9.5(9.2, 9.7)            | −0.8(−1.1, −0.6)     | 3.9(3.5, 4.8)     | 9.0(8.8, 9.2)     | 39         |
| 4c  | 10–10.5            | 2.3 ± 0.4                | 8.6(8.5, 8.7)            | −1.75(−1.8, −1.7)    | 2.1(1.5, 2.6)     | 8.6(8.5, 8.7)     | 31         |
| 4d  | 10–10.5            | >4.8                     | >9.1                     | >−1.2                | ...               | ...               | 53         |

Note. The two samples without letter identification include all galaxies in their corresponding stellar mass ranges. Galaxies in subsamples 3c and 4d are nondetections with S/N of H$\alpha$ or H$\beta$ emission lines < 1σ. The galaxies in the rest of the subsamples have well-measured (1σ–3σ) H$\alpha$ or H$\beta$ lines. Subsamples 3a and 3b are split using H$\alpha$/H$\beta$ ≥ 5.5 and H$\alpha$/H$\beta$ < 5.5, respectively. Likewise, subsamples 4a, 4b, and 4c are split using H$\alpha$/H$\beta$ < 5, H$\alpha$/H$\beta$ = 3–5, and H$\alpha$/H$\beta$ ≥ 5. Columns (6) and (7) give results that are based on individual spectra. The gas estimates use the median scaling relation. The lower limits of H$\alpha$/H$\beta$ (measured from the stacked spectra) are 3σ, namely, $H_\alpha/H_\beta = \frac{3 \sigma}{3.6}$. 

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example, for the stellar mass range \( \log(M_*/M_\odot) = 10.5-11 \), the mean \( \text{H}_\alpha/\text{H}_\beta \approx 8 \) (\( A_V \approx 3.6 \) mag). About a third to a half of the QPSBs (\( N \approx 50-80 \)) in this stacked sample might have \( M_{\text{H}_2} \gtrsim 10^{10} M_\odot \) and \( f_{\text{H}_2} \gtrsim 10\%-20\% \).

To further quantify the dispersion in gas content in the stacked galaxies, we repeat the stacking analysis in Table 4 by subdividing the sample using the WISE \( f_{12}/f_{4.6} \) ratios and then measuring \( \text{H}_\alpha/\text{H}_\beta \) from the stacked spectra (see also Appendix B). This analysis also indicates that most of the low-S/N QPSB subsamples (3/4) have average \( \text{H}_\alpha/\text{H}_\beta \approx 5-8 \) and average \( f_{\text{H}_2} \approx 5\%-20\% \).

Figure 5 shows the reconstructed \( M_{\text{H}_2} \) distributions of QPSBs with the addition of results from the stacking analysis. A similar figure for \( f_{\text{H}_2} \) and additional information are given in Appendix C. The combined analysis indicates that the high-S/N QPSB sample misses a substantial fraction of dusty and gas-rich QPSBs [\( \log(M_{\text{H}_2}/M_\odot) \gtrsim 9.5 \)]. About half of all face-on QPSBs have \( f_{\text{H}_2} \gtrsim 5\% \). This corresponds to \( M_{\text{H}_2} > 3 \times 10^9 M_\odot \) for the QPSBs with \( \log(M_*/M_\odot) = 10.5-11 \) and to \( M_{\text{H}_2} > 10^9 M_\odot \) for those with \( \log(M_*/M_\odot) = 10-10.5 \). Due to extra assumptions and complexities involved in reconstructing the gas distributions, this figure should be taken merely as a qualitative visual aid of our main results.

Together, the stacked and individual analyses of QPSBs spectra indicate that QPSBs have a wide range of \( \text{H}_\alpha/\text{H}_\beta \) ratios and \( f_{\text{H}_2} \); \( \text{H}_\alpha/\text{H}_\beta \approx 3-8 \) and \( f_{\text{H}_2} \approx 1\%-20\% \), with the median \( f_{\text{H}_2} \approx 4\%-6\% \) or the median \( M_{\text{H}_2} \approx (1-3) \times 10^9 M_\odot \).

4. Discussion

Understanding how and why the gas content of galaxies evolves will help reveal why galaxies stop forming stars. To that end, several studies, despite their small sample sizes, have attempted to quantify the gas and dust content of QPSBs (French et al. 2015; Smircica et al. 2018) and their possible precursors (Rowlands et al. 2015; Alatalo et al. 2016b;
Yesuf et al. 2017; Li et al. 2019). These studies have shown that PSBs have significant molecular gas and dust reservoirs, even when they are quiescent. As starbursts age, the molecular gas, SFR surface density, effective dust temperature, and dust-to-stellar mass ratio decrease on average (Rowlands et al. 2015; Yesuf et al. 2017; French et al. 2018; Li et al. 2019). The dust emission and masses are also broadly correlated with the molecular gas masses (Yesuf et al. 2017; Li et al. 2019).

Using dust absorption as a cost-effective probe for a much larger sample ($N \approx 530$), we confirm the previous result that large reservoirs of molecular gas are present in significant numbers of QPSBs. About half of all face-on QPSBs have $f_{\text{H}_2} \gtrsim 5\%$. Figure 5 overplots the QPSBs with CO data in the same mass and redshift ranges as our sample. The ranges of $M_{\text{H}_2}$ estimated from CO for these galaxies and those estimated by our method for the QPSBs in this work have a significant overlap. But the figure hints that the small CO sample may not be fully representative of the $M_{\text{H}_2}$ probability density functions inferred by our method.

The progenitors of QPSBs are likely more dusty and gas-rich (Yesuf et al. 2014; Alatalo et al. 2016a, 2016b; Yesuf et al. 2017). Here we also find that young and early-type Seyferts ($N \approx 320$), of which are plausibly either the precursors or the contemporaries of QPSBs, have statistically higher gas masses. Alatalo et al. (2016b) studied CO ($1\to0$) properties of 50 WISE 22 $\mu$m-detected PSBs with signatures of shocks or AGNs. The average $f_{\text{H}_2}$ of the PSBs in this sample is at least 2 times higher (median $f_{\text{H}_2} = 17\%$) than those of the comparison sample of normal SFGs and QPSBs (their Figure 5). The PSBs in Alatalo et al. (2016b) also have generally younger post-burst ages than QPSBs and may be progenitors of QPSBs (French et al. 2018). Furthermore, Yesuf et al. (2017) reanalyzed Alatalo et al. (2016b)’s sample with an additional 24 low-SFR (green-valley) PSBs. The combined samples of PSBs with Seyfert-like emission-line ratios have a broad distribution of gas fraction ($f_{\text{H}_2} = 3\%\text{–}30\%$), with mean $f_{\text{H}_2} \approx 9\%$. In comparison, here we find that Seyferts with strong H$\alpha$ and early-type morphologies have a median $f_{\text{H}_2} \approx 5\%$; only $\sim15\%$ have $f_{\text{H}_2} > 10\%$, and $\sim15\%$ have $f_{\text{H}_2} < 2\%$.

In contrast to the several hundred PSBs studied by dust absorption, the PSBs studied by far-infrared emission measurements are still small. Smercina et al. (2018), for example, studied the infrared properties of 33 QPSBs with CO observations (French et al. 2015). More than a third of these galaxies have compact ($\sim3$ kpc) and warm (infrared peak at $\sim70\text{–}75\mu$m) dust reservoirs with high abundances of polycyclic aromatic hydrocarbons. Li et al. (2019) extended the analysis of Smercina et al. (2018) by including an additional 23 younger PSBs from Rowlands et al. (2015) and Alatalo et al. (2016b) that have far-infrared data. Li et al. (2019) reported a significant inverse correlation (Spearman $\rho = -0.4$), albeit with large scatter, between the specific dust mass ($M_{\text{dust}}/M_*$) and the time elapsed since the end of the most recent starburst. The authors estimated an exponential dust depletion timescale of $\sim200$ Myr. They pointed out that this timescale suggests that the dust content of PSBs should be similar to that of early-type galaxies within $\sim1\text{–}2$ Gyr. The authors concluded that dust may be either destroyed, expelled, or rendered undetectable over $\sim1$ Gyr after the burst, presumably by AGN feedback. Our estimate, however, indicates that only a small fraction of all face-on QPSBs are dust-free, have $f_{\text{H}_2} \lesssim 1\%\text{–}2\%$, and, therefore, are consistent with having similar molecular gas content to QGs (Saintonge et al. 2017).

It should be noted that the post-burst age estimated by the methodology of French et al. (2018) indicates that QPSBs have a wide range of post-burst age\(^{12}\) ($\sim0.1\text{–}1.0$ Gyr). We do not find a clear indication that the young QPSBs in the French et al. (2018) sample have higher H$\alpha$/H$\beta$ and $f_{\text{H}_2}$ than do the old QPSBs in the same sample (see Appendix D for details). There is, however, a weak but statistically significant inverse correlation ($\rho \approx -0.3$) between $f_{\text{H}_2}$ and the post-burst age when the shocked/AGN PSBs are combined with the QPSBs that have well-measured H$\alpha$/H$\beta$ ratios. Although this mean trend agrees with previous studies (Yesuf et al. 2017; French et al. 2018; Li et al. 2019), because of the large scatter, we caution against concluding that the dust and gas in (all) PSBs are declining rapidly in a coherent fashion with the post-burst age. Taken at face value, our finding that about half of the Seyfert galaxies with H$\alpha$ > 4 $\AA$ and early-type morphology have $M_{\text{H}_2} \gtrsim 10^9 M_\odot$ does not support gas removal or destruction by AGN feedback. However, ALMA observations of HCN (1–0) and HCO$^+$ (1–0) in two CO-luminous QPSBs (French et al. 2018) indicate that there is a dearth in dense gas relative to the CO-traced molecular gas, suggesting unusual conditions in which some mechanism inhibits collapse to denser states. Future observations of dense gas in more PSBs are needed to better constrain the effect of AGNs on the interstellar media of their host galaxies.

To date, there is no direct, compelling evidence that, in most local PSBs, the global gas and dust reservoirs are expelled by stellar winds or AGN feedback (French et al. 2015; Rowlands et al. 2015). While there are some individual galaxies that may have experienced AGN-driven gas outflows (Baron et al. 2018), the observed galactic winds in most local PSBs are likely not powerful enough to sweep significant amounts of gas out of their halos (Yesuf et al. 2020). Nevertheless, the average evolutionary trends of molecular gas and dust content with post-burst age, despite their large scatter, might be an indication that some PSBs do experience rapid gas and dust depletion due to AGN feedback (Yesuf et al. 2017; French et al. 2018; Li et al. 2019). Furthermore, galactic-scale outflows may play a significant role in cold gas expulsion in high-redshift PSBs (Tremonti et al. 2007; Coil et al. 2011; Maltby et al. 2019). Some observations indicate that powerful outflows appear to be much more prevalent in high-redshift, compact PSBs (Tremonti et al. 2007; Maltby et al. 2019). These PSBs do not show signatures of strong AGNs in their optical spectra, suggesting either that the outflows were driven by stellar feedback or that if AGN feedback is responsible the episodes of strong AGNs are short-lived (Sell et al. 2014; Maltby et al. 2019).

As mentioned in the Introduction, according to some cosmological simulations, AGNs are not the dominant cause of gas removal in PSBs (Wild et al. 2009; Snyder et al. 2011; Davis et al. 2019), and not all simulated PSBs are gas-deficient. In particular, Davis et al. (2019) found that local simulated PSBs have a wide range ($10^8\text{–}10^{10} M_\odot$) of star-forming gas masses, with half of them having $>2 \times 10^9 M_\odot$ (their Figure 7). Our estimated $M_{\text{H}_2}$ distributions of QPSBs are consistent with their result. In addition, our work harbingersthe possibility in the future of using deep optical spectroscopy of local PSBs as a cost-effective alternative to constrain molecular gas distribution predicted by cosmological simulations more quantitatively and accurately.

Lastly, we raise an entirely different possibility. It is known that highly dust-enshrouded starbursts can mimic the optical

\(^{12}\) The post-burst age is defined as the time elapsed since 90% of the stars formed in the recent burst.
spectra of PSBs (e.g., Poggianti & Wu 2000; Shioya & Bekki 2000). Thus, the observed weak Balmer emission lines and large $H\alpha/H\beta$ ratios in some of our galaxies classified as “PSBs” may, instead, be masquerading as highly dust-obscured, still-starbursting galaxies. Future radio and far-infrared observations are needed to improve the PSB selection and rule out this possibility.

To summarize this section: the wide range of dust absorption and inferred molecular gas mass in face-on PSBs are consistent with several previous works. We do not find a clear indication that there is a coherent evolution (decline) of dust and molecular gas with the post-burst age among QPSBs. While some QPSBs might evolve rapidly (Yesuf et al. 2017; French et al. 2018; Li et al. 2019), significant numbers of QPSBs likely have not experienced complete exhaustion or expulsion of gas and dust during their lifetimes (~1 Gyr). Multiple episodes of starburst and AGN activity may be needed to complete the migration of these gas-rich QPSBs to the red sequence (Rowlands et al. 2015). Better understanding of the PSB sample selection and properties (e.g., SFR and age) and the scatters of the mean gas and dust evolution trends are needed to firmly establish whether or not the evolution of SFR and molecular gas in PSBs is rapid, and to test the role played by AGN feedback.

5. Summary and Conclusions

This work investigates the dust absorption ($H\alpha/H\beta$ ratio) and molecular gas content in face-on PSB galaxies at $z = 0.02–0.15$ with stellar masses $\log(M_*/M_\odot) = 10–11$, as well as their implications. We use an empirical calibration based on our recent work (Yesuf & Ho 2019), which linearly combines nebular dust absorption, average gas-phase metallicity inferred from the stellar mass, and the half-light radius to estimate molecular gas masses. We statistically infer the molecular gas either by using PSBs with well-measured $H\alpha/H\beta$ ratios or by measuring this ratio from stacked spectra. Using our new method, this work aims to confirm previous results based on CO (French et al. 2015; Rowlands et al. 2015; Alatalo et al. 2016b; Yesuf et al. 2017) or dust continuum emission (Smercina et al. 2018; Li et al. 2019). While the applicability of this method to all PSBs should be subjected to further scrutiny, its predictions are fully consistent with the existing, small sample of QPSBs with direct measurements of gas and dust emission. Our uniformly selected sample of QPSBs, more than an order of magnitude larger than previously available, also allows us to account for the weak trend of molecular gas fraction with stellar mass. Our main conclusions are as follows:

1. QPSBs have a wide range of $H\alpha/H\beta$ ratios, ~3–8. Some are dust-free, like most QGs, while a significant fraction (~40%) of QPSBs are as dusty ($A_V \approx 1.5–3$ mag) as SFGs of similar stellar masses.

2. Our dust-absorption-based gas estimator (Yesuf & Ho 2019) reasonably recovers existing CO-based molecular mass estimates of PSBs. This heterogeneous sample contains ~100 PSBs with different selection criteria, SFRs, and AGN properties. Nevertheless, the CO luminosities of previously studied PSBs correlate significantly (Kendall $\tau \approx 0.5$; Spearman $\rho \approx 0.6–0.7$) with the molecular gas masses predicted by our scaling relation. Comparison of our predicted molecular gas masses with the observed CO luminosities implies a median (15%, 85%) $\alpha_{CO} = 4.8(1, 15)M_\odot/(K \text{ km s}^{-1} \text{pc}^2)$–1. Almost all QPSBs have $\alpha_{CO}$ values that are consistent with the Milky Way value.

3. The 204 QPSBs that have well-measured $H\alpha/H\beta$ ratios (>3σ) exhibit a broad range of $f_{H\beta}$ (~1%–6%), with a median $f_{H\beta} \approx 2\%$. Most of the QPSBs have molecular gas content similar to that of QGs, while some are as gas-rich as SFGs (Tables 1). For those QPSBs with $\log(M_*/M_\odot) = 10.5–11$, the median $M_\text{H}_2 \approx 10^9 M_\odot$.

4. Stacking analysis of 327 QPSBs with low-S/N $H\alpha/H\beta$ indicates that they are on average more dusty than QPSBs with well-measured $H\alpha/H\beta$ (Tables 3 and 4). The average $H\alpha/H\beta \approx 5$ ($A_V \approx 2$ mag) for the low-mass bin, $H\alpha/H\beta \approx 8$ ($A_V \approx 3.6$ mag) for the high-mass bin, and median $f_{H\beta} \gtrsim 5\% – 20\%$. For example, ~67% (or 112 galaxies) of the stacked QPSBs with $\log(M_*/M_\odot) = 10.5–11$ have $M_\text{H}_2 \gtrsim (3 – 10) \times 10^8 M_\odot$.

5. The combined analysis of individual and stacked spectra suggests that close to half of all QPSBs have $f_{H\beta} \gtrsim 5\%$. This corresponds to a median $M_\text{H}_2 \approx 3 \times 10^9 M_\odot$ for the QPSBs with $\log(M_*/M_\odot) = 10.5–11$ and to $M_\text{H}_2 > 10^9 M_\odot$ for those with $\log(M_*/M_\odot) = 10–10.5$.

6. Seyfert galaxies ($N = 317$) with young stellar population ($H\delta_A > 4$ Å) and early-type morphology ($C > 2.6$, and $\Sigma_e > 10^{6.5} M_\odot \text{ kpc}^{-2}$) have a median $f_{H\beta} \approx 4\%–5\%$. This corresponds to a median $M_\text{H}_2 \approx (1–2) \times 10^9 M_\odot$. Their 0.15 or 0.85 quantiles have $f_{H\beta}$ as low as ~1%–2% or as high as ~8%–25%. Thus, large reservoirs of molecular gas are present in significant numbers of young galaxies with active black holes. The global interstellar medium of these galaxies evidently has not been blown out by AGN feedback.

Our results add to the accumulating evidence that strong AGNs are not necessarily gas-deficient (e.g., Ho et al. 2008; Husemann et al. 2017; Rosario et al. 2018; Shangguan et al. 2018; Ellison et al. 2019; Shangguan & Ho 2019; Zhuang & Ho 2020), and that they seemingly are not efficient at completely clearing gas out of galaxies rapidly (<1 Gyr). Better measurements of star formation, gas content, and AGN activity of PSBs are vital to put firm constraints on their star formation efficiency, thereby more accurately testing feedback models. Future studies that explain the cause of diversity in the gas fractions of PSBs will also be useful.

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Appendix A
Additional Analysis of PSBs with CO Data

We revisit the properties of the samples of PSBs with CO data, which are used in Section 2.4 to show that our method of predicting the molecular gas mass (Yesuf & Ho 2019) can be applied to PSBs. We show that these samples have a wide range of SFRs, spanning from those of starburst to QGs. Hence, a variable $\alpha_{\text{CO}}$ is expected. We further show that these samples exhibit a wide range of (stacked) $\text{H}\alpha/\text{H}\beta$ ratios, as expected from their CO luminosities.

A.1. Details on the Properties of PSBs with CO Measurements

Figure A1(a) overplots PSBs with CO data on the stellar mass versus SFR diagram of galaxies at $z < 0.15$. The SFRs are taken from version 2 of the GALEX-SDSS-WISE Legacy Catalog (GSWLC-2; Salim et al. 2016, 2018). GSWLC-2 uses WISE photometry in the 12 and 22 $\mu$m bands jointly with ultraviolet and optical photometry to perform spectral energy distribution fitting to derive more accurate SFRs. PSBs span 3 orders of magnitude in SFR, ranging from quiescent to starburst galaxies.

Figure A1(b) plots $\text{H}\alpha_4$ absorption versus $\text{H}\alpha$ EW, color-coded by SFR derived from spectral energy distribution fitting. With the exception of the Seyfert PSBs, most PSBs with strong $\text{H}\alpha$ EWs also have high SFRs, as expected. Some QPSBs have high SFRs despite their weak $\text{H}\alpha$ EWs. Salim et al. (2016) also showed that some galaxies may have weak $\text{H}\alpha$ but high SFRs, overlapping with the values of normal SFGs. Two explanations are possible. On the one hand, differences in star formation timescales can cause $\text{H}\alpha$ to be absent during a PSB phase, while ultraviolet and mid-infrared emission still persists after the O stars have died off. On the other hand, spatial gradients in star formation could be such that the SDSS fiber may miss off-centered regions of star formation.

It is customary to use SFR as a predictor of gas content (e.g., Saintonge et al. 2017; Catinella et al. 2018). Yesuf & Ho (2019) showed that $M_{\text{H}_2}$ can be predicted to within a factor of $\lesssim 2$, if SFR is used with $A_V$ and $R_{\text{SG}}$. Figure A2 compares $M_{\text{H}_2}$ predicted by this more accurate predictor and the observed CO luminosities of the PSBs. Because molecular gas and SFR may not necessarily track each other faithfully in PSBs (French et al. 2015; Li et al. 2019), and we want to study the molecular gas independent of SFR, we do not use this scaling relation in the main sections of the paper. The aim of Figure A2 is to show that the variation in $\alpha_{\text{CO}}$ likely has a significant contribution to the scatter in Figure 3, and that most PSBs are consistent with having $\alpha_{\text{CO}} \approx 4.3 M_\odot (\text{K km s}^{-1} \text{pc}^2)^{-1}$ and those that have high SFRs (starburst-like) are more consistent with $\alpha_{\text{CO}} \approx 1 M_\odot (\text{K km s}^{-1} \text{pc}^2)^{-1}$.

A.2. Stacking Analysis of PSBs with CO Measurements

We perform spectral stacking analysis of PSBs with CO data (French et al. 2015; Alatalo et al. 2016b; Yesuf et al. 2017). We show that these galaxies have diverse levels of dust absorption, as expected from their wide-ranging CO luminosities, gas fractions, and mid-infrared emission (Figure 8 of Yesuf et al. 2017).

Figure A3(a) shows the stacked spectrum of the 32 QPSBs from the sample of French et al. (2015). After fitting the spectra with stellar population and nebular emission models, we obtain $\text{H}\alpha/\text{H}\beta = 6.2 \pm 0.7$ ($A_V = 2.7 \pm 0.4$ mag). Incidentally, previous works have adopted 3 times lower mean $A_V$ for the low-S/N QPSBs in this sample (French et al. 2015; Li et al. 2019).
This likely will significantly change the estimates of their dust-corrected SFRs. Figure A3(b) shows the stacked spectrum and the stellar population plus emission-line model fit of the 50 PSBs with CO data from Alatalo et al. (2016b), which the authors have highlighted as having evidence for shock ionization. This subset of PSBs has average $H\alpha/H\beta = 5.5 \pm 0.4 \ (A_V = 2.3 \pm 0.3 \ \text{mag})$. Lastly, the 23 green-valley Seyfert PSBs (Figure A3(c)) from Yesuf et al. (2017) have $H\alpha/H\beta = 3.5 \pm 0.4 \ (A_V = 0.4 \pm 0.4 \ \text{mag})$.

### Appendix B

**WISE Flux Ratio $f_{12}/f_{4.6}$ as a Probe of Gas Fraction**

We present the distribution of the WISE flux density ratio of 12–4.6 μm, $f_{12}/f_{4.6}$, of QPSBs and discuss its relation with $f_{H\alpha}$ or $H\alpha/H\beta$ ratios. We also show that the stacking analysis of the high-S/N QPSB sample now subdivided by $f_{12}/f_{4.6}$ results

[Figure A2](#): Similar to Figure 3, here the gas scaling relation from Yesuf & Ho (2019) uses SFR from spectral energy distribution fitting, and the color-coding is by WISE 12 μm luminosity, which is also correlated with SFR (Cluver et al. 2017) and CO luminosity (Gao et al. 2019). The relation used here is more accurate and has an rms deviation of ≤0.3 dex. This figure suggests that the variation in $\alpha_{CO}$ likely makes a significant contribution to the scatter in Figure 3, and that most PSBs are consistent with having $\alpha_{CO} \approx 4.3 \ (\text{K km s}^{-1} \text{pc}^2)^{-1}$, while those with high, starburst-like SFRs are more consistent with $\alpha_{CO} \approx 1 \ (\text{K km s}^{-1} \text{pc}^2)^{-1}$. This figure is included only for illustrative purposes. Because molecular gas and SFR may not necessarily track each other well in PSBs, and the SFR of PSBs may not be very accurate, we do not use this scaling relation in the main sections of the paper.

[Figure A3](#): Stacked spectra of (a) QPSBs, (b) shocked PSBs, and (c) Seyfert PSBs with CO data (French et al. 2015; Alatalo et al. 2016b; Yesuf et al. 2017).

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13 http://pages.iu.edu/~salims/gswlc/
in $\text{H} \alpha/\text{H} \beta$ and $f_{\text{H} \alpha}$ distributions that are consistent with those inferred from individual spectra, similar to what we showed in Section 2.2.

Figure B1 shows the distribution of $f_{\text{H} \alpha}/f_{\text{H} \beta}$ for QPSBs in the two mass ranges having S/N $> 2$ in both WISE bands. The flux density ratio $f_{\text{H} \alpha}/f_{\text{H} \beta}$ is a good average proxy for gas fraction for both PSBs and ordinary galaxies (Yesuf et al. 2017; French et al. 2018). However, the correlation strength between $f_{\text{H} \alpha}/f_{\text{H} \beta}$ and $\text{H} \alpha/\text{H} \beta$ is only moderate ($\rho \approx 0.4$). The top axes of the figure show the calibration using the mean $f_{\text{H} \alpha}$ relation for the COLD GASS galaxies, $\log f_{\text{H} \alpha} = 1.13 \log (f_{\text{H} \alpha}/f_{\text{H} \beta}) + 1.8$. For the QPSBs with well-measured $\text{H} \alpha/\text{H} \beta$, adopting the WISE-COLD GASS relation gives approximately a median (15%, 85%) $\log f_{\text{H} \alpha} \approx -1.6 (-1.9, 1.3)$ for both mass ranges. The median $f_{\text{H} \alpha}$ is lower by $\sim 0.2$ dex if we instead adopt the mean relation for PSBs with CO data. This estimate is consistent with the estimates from the $\text{H} \alpha/\text{H} \beta$ ratio given in Table 1. The inferred gas fractions are also broadly similar (only slightly lower) for the low-S/N sample. However, the stacked analysis of $\text{H} \alpha/\text{H} \beta$ in Table 3 suggests a substantially higher median $\log f_{\text{H} \alpha} \approx -1$ for most low-S/N QPSBs. Although $f_{\text{H} \alpha}/f_{\text{H} \beta}$ is a good average $f_{\text{H} \alpha}$ indicator, due to substantial scatter in their relation, it may underestimate $f_{\text{H} \alpha}$ in very dusty QPSBs. On average, $f_{\text{H} \alpha}/f_{\text{H} \beta}$ of QPSBs is lower than that of SFGs. But there are a significant number of QPSBs that overlap with SFGs.

For completeness, Table B1 checks the stacking analysis by subdividing the high-S/N QPSB sample by $f_{\text{H} \alpha}/f_{\text{H} \beta}$. Again, the stacking analysis recovers well the results based on individual spectra.

**Appendix C**

**Details of the Reconstructed Gas Probability Density Functions**

We provide details of the statistical information used to approximately reconstruct the $f_{\text{H} \alpha}$ (Figure C1) or $M_{\text{H} \alpha}$ (Figure C2) distributions of QPSBs from the stacking analysis.

We fit normal and lognormal functions, parameterized by Equations (C1) and (C2), to the distributions of inferred...
The lognormal parameters can be transformed to a mean gas mass and its standard deviation as follows:

\[
\log \langle M_\text{H}_2 / M_\odot \rangle = 10 - 10.5
\]

\[
F(x = \log M_{\text{H}_2}, \mu', \sigma') \propto \frac{1}{\sigma} \exp \left[ - \frac{(\ln x - \mu')^2}{2\sigma^2} \right].
\]

**Appendix D**

**Gas Trends with Post-burst Age**

This appendix provides supporting analysis to the statement in the Discussion section that there is no clear indication that the young QPSBs in the French et al. (2018) sample have higher Hα/\Hβ and \fH2 than do the old QPSBs in the same sample.

French et al. (2018) attempted to accurately measure ages and burst properties of QPSBs by fitting stellar population synthesis models to ultraviolet–optical photometry and optical spectra. We use their publicly available catalog on VizieR\textsuperscript{14} to check whether there are clear trends between post-burst ages of QPSBs and their Hα/\Hβ ratios or their inferred molecular gas content. As in the main text, we restrict the QPSB sample to \(z = 0.02 \pm 0.15\) and \(\log(M_{\text{H}_2} / M_\odot) = 10 - 11\). This results in 286 QPSBs. Table D1 presents the summary statistics of the distributions of Hα/\Hβ, \MH2, and \fH2 for various subsets of QPSBs stacked by subdividing according to their post-burst ages. Although there is a weak inverse correlation (\(\rho \lesssim -0.3\)) between \fH2 and the post-burst age when the shocked/AGN PSBs are combined with the QPSBs, the stacking analysis does not indicate that the young QPSBs from French et al. (2018) have higher Hα/\Hβ and \fH2 than do the old QPSBs. The stacking analysis is consistent with no trend or, at best, a weak positive trend. We are unable to explain the diversity of gas and dust content of QPSBs as a sequence in post-burst age. Future studies should revisit this problem with better data and more thorough analysis. We note that Davis et al. (2019; their Figure 8) showed that the star-forming gas fractions of simulated PSBs decrease systematically from \(\sim 30\%\) to \(\sim 3\%\) for PSBs younger

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\textsuperscript{14} http://vizier.u-strasbg.fr/viz-bin/VizieR?-source=J/Apl/862/2
than ~600 Myr; the scatter increases thereafter, and aged PSBs have a wide range (0.1%–30%) of gas fractions.

Appendix E

Additional Analysis of Individual High-S/N QPSBs

This section provides additional visualization of the gas fractions of high-S/N (median continuum S/N/pixel >10) QPSBs and the comparison samples. We also show that some PSBs have Hα/Hz < 2.5, which is unphysical, likely due to spectra with still insufficient S/N (S/N/pixel < 25) or imperfect deblending of the Balmer emission and absorption lines (see, e.g., Ho et al. 1997).

Figures E2(a) and (b) plot Hδ_A absorption versus Hα emission EW, color-coded by the median molecular gas fraction f_H_2. The contours show the number density of all SDSS galaxies for the given stellar mass range at z = 0.02–0.15. We, however, only use galaxies with detectable Hα and Hz lines to calculate the median f_H_2, and we only show bins that have 10 or more galaxies. For most (nonbursty) galaxies, Hα emission correlates with Hδ_A absorption. As expected, the median f_H_2 is also correlated with Hα EW for normal galaxies. QPSB galaxies (colored circles), with weak emission (Hα < 3 Å) but strong absorption (Hδ_A > 4 Å), deviate from the locus of normal galaxies because their star formation quenched rapidly. The colored squares are early-type Seyferts. The main point of the figures is to show that QPSBs have a broad range of f_H_2, which overlaps with the typical gas fractions of SFGs or QGs. Some of the Seyferts also have similar f_H_2 to SFGs. By definition, QPSBs do not contain strong AGNs. We include the young, early-type Seyferts in our analysis to strengthen our main conclusion that significant numbers of QPSBs have copious amounts of dust and gas, which probably are not removed or destroyed during their previous AGN activities. Although a recent cold gas accretion

cannot be ruled out, the simpler explanation that the gas was not removed in the first place is preferred, lacking further evidence to the contrary.

Figures E2(c) and (d) plot D_0(4000) index versus u − g color, again color-coded by the median f_H_2. The 4000 Å break quantifies the central mean stellar age (in the fiber), while u − g color is sensitive to the galaxy-wide SFR over a timescale of several hundred Myr. Both quantities increase as the stellar population ages. Dust extinction affects u − g color distributions of the low-S/N QPSBs are similar to those of the high-S/N QPSBs.

Finally, Table E1 splits the high-S/N QPSB sample into two, and it shows that there is a correlation between the S/N of the continua and the statistical properties of Hα/Hz. As the S/N increases, the 15% quantile of Hα/Hz distribution shifts toward higher, more physical values. Likewise, the 85% quantile of Hα/Hz distribution increases to higher values (~5–6 depending on M_α), strengthening the conclusion that some QPSBs are very dusty. Generally, plotting Hα/Hz versus EW Hα for all galaxies with high-S/N (>3) emission lines indicates that the unphysical Hα/Hz ratios are primarily associated with weak emission lines (EW Hα < 1–3 Å). Therefore, in some cases, despite the high-S/N continua, the unavoidable template mismatch from the continuum subtraction will pose a limit to how accurately one can measure the weak Hz emission lines on top of strong absorption lines of some PSBs.

Table D1

| ID | Age/Myr | log(M_α/M_☉) | Stack Hα/Hz | Stack log(M_β/Hz) | Stack log f_H_2 | N Galaxies |
|----|---------|--------------|-------------|------------------|----------------|------------|
| 9a | >415    | 10.5–11      | >8.3        | >9.9             | >–0.8         | 42         |
| 9b | >295–415| 10.5–11      | 5.7 ± 1.2   | 9.6(9.2, 9.8)    | –1.2(–1.5, –0.9)| 44         |
| 9c | <295    | 10.5–11      | 4.8 ± 0.7   | 9.4(9.2, 9.6)    | –1.4(–1.6, –1.1)| 42         |
| 10a| >540    | 10–10.5      | 5.7 ± 0.8   | 9.3(9.1, 9.6)    | –0.9(–1.1, –0.7)| 50         |
| 10b| >360–540| 10–10.5      | 4.1 ± 0.6   | 8.9(8.7, 9.2)    | –1.3(–1.6, –1.1)| 47         |
| 10c| <360    | 10–10.5      | 3.5 ± 0.3   | 8.8(8.6, 9.0)    | –1.5(–1.7, –1.4)| 61         |
| 11a| >415    | 10.5–11      | 4.2 ± 1.0   | 9.2(8.8, 9.5)    | –1.5(–1.9, –1.2)| 10         |
| 11b| >295–415| 10.5–11      | 3.3 ± 0.9   | 8.9(8.7, 9.2)    | –1.8(–2.1, –1.5)| 9          |
| 11c| <295    | 10.5–11      | 3.5 ± 0.5   | 9.0(8.8, 9.2)    | –1.7(–2.0, –1.5)| 14         |
| 12a| >540    | 10–10.5      | 5.7 ± 1.1   | 9.3(9.0, 9.6)    | –0.9(–1.2, –0.6)| 19         |
| 12b| >360–540| 10–10.5      | 3.3 ± 0.4   | 8.6(8.5, 8.8)    | –1.6(–1.7, –1.4)| 24         |
| 12c| <360    | 10–10.5      | 3.6 ± 0.4   | 8.8(8.6, 9.0)    | –1.5(–1.7, –1.3)| 36         |
| 13a| >415    | 10.5–11      | >7.5        | >9.8             | >–0.9         | 31         |
| 13b| >295–415| 10.5–11      | >6.3        | >9.6             | >–1.1         | 33         |
| 13c| <295    | 10.5–11      | 4.2 ± 0.6   | 9.2(9.0, 9.4)    | –1.5(–1.8, –1.3)| 28         |
| 14a| >540    | 10–10.5      | 5.3 ± 1.3   | 9.3(8.9, 9.6)    | –1.0(–1.4, –0.7)| 27         |
| 14b| >360–540| 10–10.5      | 3.9 ± 1.5   | 9.0(8.5, 9.4)    | –1.4(–1.8, –0.9)| 22         |
| 14c| <360    | 10–10.5      | 4.2 ± 0.8   | 9.1(8.8, 9.4)    | –1.3(–1.6, –1.0)| 25         |

Note. All QPSBs are stacked in subsamples 9 and 10. In subsamples 11 and 12, only those with well-measured Hα and Hz are stacked, while in subsamples 13 and 14 only the low-S/N QPSBs are stacked.
Possible Systematic Effects of the Continuum S/N on Hα/Hβ Measurements

| log(M_*/M_☉) | Hα/Hβ S/ | Hα/Hβ S/ | Hα/Hβ S/ |
|--------------|---------|---------|---------|
|              | N >10   | N = 10–25 | N >25   |
| 10–11        | 3.3(2.3, 4.6) | 3.0(2.1, 4.3) | 3.7(2.7, 5.2) |
| 10.5–11      | 3.3(2.6, 4.7) | 3.1(2.4, 4.5) | 3.8(2.9, 6.2) |
| 10–10.5      | 3.2(2.1, 4.5) | 3.0(2.0, 4.3) | 3.5(2.7, 4.7) |

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Figure E1. Comparison of molecular gas fractions (f_M) of QPSBs with those of SFGs and QGs. The contours show the number density of SDSS galaxies at redshifts z = 0.02–0.15 with stellar masses log(M_*/M_☉) = 10–10.5 or log(M_*/M_☉) = 10.5–11. The colors denote f_M (Section 3). The colored circles are high-S/N QPSBs, while the colored squares are early-type Seyferts. Panels (a) and (b) plot Hα absorption against Hβ emission EW. Panels (c) and (d) plot the central (fiber) 4000 Å break index vs. the galaxy-wide u − g color. The dotted lines in panels (c) and (d) indicate the boundaries inside which no color scale is shown for clarity; they are not used in the sample selection of QPSBs. It is clear that PSBs have a wide range of gas fractions that overlap with those observed in SFGs or QGs.

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