Galaxies in the early Universe that are bright at submillimetre wavelengths (submillimetre-bright galaxies) are forming stars at a rate roughly 1,000 times higher than the Milky Way. A large fraction of the new stars form in the central kiloparsec of the galaxy3–5, a region that is comparable in size to the massive, quiescent galaxies found at the peak of cosmic star-formation history4 and the cores of present-day giant elliptical galaxies. The physical and kinematic properties inside these compact starburst cores are poorly understood because probing them at relevant spatial scales requires extremely high angular resolution. Here we report observations with a linear resolution of 550 parsecs of gas and dust in an unlensed, submillimetre-bright galaxy at a redshift of $z \approx 4.3$, when the Universe was less than two billion years old. We resolve the spatial and kinematic structure of the molecular gas inside the heavily dust-obscured core and show that the underlying gas disk is clumpy and rotationally supported (that is, its rotation velocity is larger than the velocity dispersion). Our analysis of the molecular gas mass per unit area suggests that the starburst disk is gravitationally unstable, which implies that the self-gravity of the gas is stronger than the differential rotation of the disk and the internal pressure due to stellar-radiation feedback. As a result of the gravitational instability in the disk, the molecular gas would be consumed by star formation on a timescale of 100 million years, which is comparable to gas depletion times in merging starburst galaxies4.

Since the discovery of submillimetre-bright galaxies (SMGs) at high redshift in the early 1990s, studies of their global physical properties, such as redshift, gas mass and kinematics, have helped us to understand the origin of the extreme starbursts8–12. With the same goal in mind, we observed SMG COSMOS-AzTEC-1 (hereafter ‘AzTEC-1’) with the highest angular resolution yet achieved using the Atacama Large Millimeter/Submillimeter Array (ALMA). AzTEC-1 is one of the brightest unlensed objects of this type, with an extraordinarily high star formation rate of $1.186 \pm 0.036 \ M_\odot \ yr^{-1}$ (where $M_\odot$ is the mass of the Sun) and a compact starburst with a half-light radius of $R_{1/2} = 1.1 \pm 0.1 \ kpc$ measured in the 860-\micron continuum. These ALMA observations resolve the CO emission at a resolution of 0.08\arcsec (550 pc in the physical scale) to reveal the morphology and kinematics of molecular gas within the central 2 kpc of the galaxy. In Fig. 1 we show ALMA maps of the CO line and the dust continuum at 3.2 mm and 860\micron, the velocity field and the velocity dispersion. The spatial distributions of the CO line and the 3.2-mm continuum emission independently confirm the existence of two off-centre clumps (clump 2 and clump 3), which were first detected in the 860-\micron continuum. Previous lower-resolution (0.15"–0.3") observations 1,3,4,5 have found that SMGs and optically selected massive galaxies are associated with a very compact and dusty star-forming region with $R_{1/2} = 1–2 \ kpc$. However, our higher-resolution data demonstrate that the central structure of molecular gas and dust is more complicated than just a single, compact component. Such clumps of molecular gas are also seen in the central disk of the $z = 3$ gravitationally lensed star-forming galaxy SDP 815,16.

In addition, we made a 0.06"-resolution CO cube and a 0.05"-resolution 860-\micron continuum image with different visibility weightings, to filter out the underlying disk emission and to highlight the clump structures (Methods). The higher-resolution velocity-integrated CO maps show that the clumps of molecular gas are aligned with the dusty star-forming clumps in the 860-\micron continuum (Fig. 2). They are the second- and third-brightest clumps of 11 clumps identified previously at 860\micron. Because the brightest clump is very close to the nucleus, it is difficult to isolate even at a resolution of 0.06". Other faint star-forming clumps are not detected in the CO data, probably owing to poor sensitivity.

We fit the CO spectra of the clumps with a single Gaussian to derive full-width at half-maximum (FWHM) line widths of $250 \pm 50 \ km \ s^{-1}$ and $240 \pm 50 \ km \ s^{-1}$ for clumps 2 and 3, respectively. These line widths are one or two orders of magnitude larger than those of giant molecular clouds in nearby galaxies12. The integrated CO line flux is $S_{\text{CO},\text{d}} = 0.056 \pm 0.009 \ Jy \ km \ s^{-1}$ for clump 2 and $S_{\text{CO},\text{d}} = 0.042 \pm 0.007 \ Jy \ km \ s^{-1}$ for clump 3, indicating that each clump contains only a few per cent of the total gas mass. (Here and elsewhere, the errors quoted correspond to one standard deviation.) Adopting a CO-to-H$_2$ conversion factor of $\alpha_{\text{CO}} = 8.6 \ M_\odot$ (K km s$^{-1}$ pc$^2$)$^{-1}$ and a CO excitation of $R_{\text{CO}} = 0.91$, we derive gas masses of $M_{\text{CO, gas}} = (2.2 \pm 0.3) \times 10^9 M_\odot$ and $M_{\text{CO, gas}} = (1.7 \pm 0.3) \times 10^9 M_\odot$ for the two gas clumps (Methods), which are 3–5 orders of magnitude larger than the virial mass of giant molecular clouds. Therefore, these giant clumps are completely different from giant molecular clouds in nearby galaxies.

We fit the CO cube with a dynamical model to derive the kinematic properties of the CO-emitting gas. The observed velocity field is well characterized by a rotating disk with $R_{1/2} = 1.05 \pm 0.02 \ kpc$, a deprojected maximum rotation speed of $v_{\text{max}} = 227 \pm 6 \ km \ s^{-1}$ and a local velocity dispersion of $\sigma_0 = 74 \pm 1 \ km \ s^{-1}$. The starburst gas disk is rotation-dominated with a ratio of rotation velocity to velocity dispersion of $v_{\text{max}}/\sigma_0 = 3.1 \pm 0.1$. In the local Universe, 80% of massive early-type galaxies with stellar masses of $\log(M_{\text{stellar}}) > 11.8$ exhibit disk-dominated stellar kinematics with $v_{\text{max}}/\sigma_0 < 1$, whereas less-massive ones are rotation-dominated18,19. Given the large stellar mass of $M_{\text{stellar}} = (9.9 \pm 1.6) \times 10^{10} M_\odot$ (Methods), AzTEC-1 is near the massive end at $z = 4$ and might eventually evolve to become one of the most massive early-type galaxies at $z = 0$. If molecular gas and stars share the same kinematics, then the observed properties of the rotating disk suggest that the most massive galaxies do not lose much of their angular momentum during the subsequent evolution phase; instead, they lose it during such major mergers20.
Until recently, clumpy rotating disks at high redshift have been discovered from observations of ionized gas. Now, higher-resolution observations of molecular gas using ALMA can be used similarly. Observational and numerical studies show that giant clumps are spawned by gravitational instability in the outskirts of gas-rich disks and migrate inward by dynamical friction. Using the ALMA maps of the CO line intensity and velocity dispersion without any correction for beam smearing, we compute the local Toomre $Q$ parameter, which describes the balance between self-gravity of molecular gas and turbulent pressure by stellar radiation and other sources. A thick, rotating disk can become unstable against local axisymmetric perturbations if $Q < Q_{\text{crit}} = 0.7$. The local $Q$ values that we measured are less than $Q_{\text{crit}}$ over the entire disk, indicating that the gas disk should fragment and collapse through gravitational instability in the inter-clump regions.

Fig. 1 | CO morphology and kinematics of AzTEC-1. a–f. ALMA maps of the CO ($J = 4–3$) line (a), 3.2-mm continuum (b) and 860-μm continuum (c), velocity field (d), velocity dispersion (e) and Toomre Q parameter (f). The numbers in parentheses in b and c refer to the rest-frame wavelength. The angular resolution (indicated by the white ellipses) is 0.093″ × 0.072″ in all cases. The CO line is integrated in the velocity range $-315$ km s$^{-1}$ to $+315$ km s$^{-1}$. Contours in a–c are plotted every 2σ from $3\sigma$ to $11\sigma$ and every 5σ from $11\sigma$, where $1\sigma$ is the noise level; the contours in a are also overplotted in d–f.

Fig. 2 | Spectra and maps of the two large clumps. a. For Clump 2 (top) and clump 3 (bottom), CO spectra are extracted from the Briggs-weighted cube with an angular resolution of 0.069″ × 0.058″. The grey shaded region indicates the standard deviation of the noise spectra. b–d. ALMA maps of the CO line (b), 3.2-mm continuum (c) and 860-μm continuum (d) for the two clumps. The CO flux densities are integrated over the velocity range indicated by the yellow shaded regions in a. White filled circles represent the angular resolution of each map. The contours are plotted every 1σ from $2\sigma$ in b and c and from $4\sigma$ in d, and at every $5\sigma$ from $10\sigma$. 
regions. On the other hand, \( Q < Q_{\text{cri}} \) at the clump locations means that the gas is gravitationally bound rather than gravitationally unstable. We also derive radially averaged \( Q \) parameters using the best-fit kinematic parameters with corrections for beam smearing and inclination. Here, the uncertainties in \( Q \) arise mainly from measurements of gas mass. We tackle this issue by determining three independent estimates of gas mass, from the C I (\( J = 2 \rightarrow 1 \)), CO (\( J = 4 \rightarrow 3 \)) and dust continuum data. All three methods indicate that \( Q < 1 \) is in the central 2.5 kpc of the galaxy, even after allowing for some variations in carbon abundance, CO excitation and the gas-to-dust mass ratio (Fig. 3).

In the current framework of galaxy evolution, galaxies self-regulate star formation with a marginally unstable disk.\(^{25,26}\) If a galactic disk is unstable with \( Q < Q_{\text{cri}} \), intense stellar radiation temporarily boosts turbulent pressure and heats the disk until \( Q > Q_{\text{cri}} \). Once the disk is stable, star formation becomes inefficient, leading to a drop in turbulent pressure. On the other hand, gas accretion may increase the gas mass per unit area in the disk, and when the increased self-gravity of the gas overcomes the decreased pressure the disk becomes unstable again. Thus, galaxy disks are kept marginally unstable with \( Q \approx Q_{\text{cri}} \). In AzTEC-1, stellar radiation pressure is unlikely to support the self-gravity of gas, resulting in small \( Q \) values across the entire disk. The local velocity dispersion increases only slightly as the star-formation rate per unit area increases (Fig. 4), which suggests that stellar feedback by intense star formation does not control the velocity dispersion in the molecular gas in this case. We also find that the velocity dispersion of \( \sigma \approx 100 \) km s\(^{-1}\) in the two clumps is not much higher than in the rest of the disk. Our results imply that star-forming clumps are stable and not disrupted by radiative feedback. On the other hand, there is a strong correlation between the molecular gas mass per unit area (\( \Sigma_{\text{gas}} \)) and the star-formation rate per unit area (\( \Sigma_{\text{SFR}} \)), fitted by the linear relation \( \log \left[ \frac{\Sigma_{\text{SFR}}}{(M_\odot \text{ yr}^{-1} \text{ kpc}^{-2})} \right] = (1.4 \pm 0.2) \times \log \left[ \frac{\Sigma_{\text{gas}}}{(M_\odot \text{ pc}^{-2})} \right] + (-3.6 \pm 0.7) \) The gas mass per unit area derived for AzTEC-1 is extremely high, with \( \log \left[ \frac{\Sigma_{\text{gas}}}{(M_\odot \text{ pc}^{-2})} \right] = 3.8 \pm 0.4 \), similar in magnitude to that seen in nearby starburst galaxies.\(^{2}\) The implied gravitational instability is a consequence of the strong concentration of molecular gas.

In such a gravitationally unstable gas disk, molecular clouds are expected to be converted into stars efficiently. The gas depletion time in the starburst disk, defined as the gas mass divided by the star-formation rate, is comparable to the galaxy-averaged gas depletion time in nearby starburst galaxies (Fig. 4). The molecular gas reservoir of AzTEC-1 will be consumed by star formation within 100 million years, a timescale that is roughly ten times shorter than the gas depletion time in star-forming galaxies at \( z = 1 - 3 \)\(^{27}\) and comparable to the gas depletion times in nearby merging galaxies such as Arp 220 and Arp 299\(^{5}\) and the \( z = 3 \) lensed star-forming galaxy SDP 81\(^{16}\). An extreme starburst at high redshift may occur over a very short timescale, resulting in episodic bright periods in the submillimetre band. Otherwise, it requires new gas flowing into the central region to maintain the current level of star-formation activity.

It is still uncertain how a large amount of molecular gas is concentrated in the central 2 kpc of the galaxy. A gas-rich major merger is the most straightforward scenario, because several numerical simulations have successfully reproduced the physical properties of SMGs\(^{28}\), including the compact gas distribution and the enhanced star-forming activity. We cannot necessarily reject the major merger scenario for rotating disk because nearby merger remnants frequently host a rotationally supported structure\(^{29}\); however, we do not have direct evidence for a major merger in AzTEC-1. In addition to a past gas-rich major merger, multiple gas-rich minor mergers or clumpy gas streams could also lead to gas transport to the central 2 kpc\(^{29}\). Isolated galaxies require a non-axisymmetric structure such as spiral arms or a bar to remove the angular momentum and transport a large amount of gas into the galaxy centre. AzTEC-1 does not have such a non-axisymmetric structure. To determine the role of major mergers in extreme starbursts, we need to investigate morphological and kinematic structures in a large sample of nearby starburst galaxies\(^{3}\). The implied gravitational instability is a consequence of the strong concentration of molecular gas.

In such an unstable gas disk, molecular clouds are expected to be converted into stars efficiently. The gas depletion time in the starburst disk, defined as the gas mass divided by the star-formation rate, is comparable to the galaxy-averaged gas depletion time in nearby starburst galaxies. The molecular gas reservoir of AzTEC-1 will be consumed by star formation within 100 million years, a timescale that is roughly ten times shorter than the gas depletion time in star-forming galaxies at \( z = 1 - 3\) and comparable to the gas depletion times in nearby merging galaxies such as Arp 220 and Arp 299 and the \( z = 3 \) lensed star-forming galaxy SDP 81. An extreme starburst at high redshift may occur over a very short timescale, resulting in episodic bright periods in the submillimetre band. Otherwise, it requires new gas flowing into the central region to maintain the current level of star-formation activity.

It is still uncertain how a large amount of molecular gas is concentrated in the central 2 kpc of the galaxy. A gas-rich major merger is the most straightforward scenario, because several numerical simulations have successfully reproduced the physical properties of SMGs, including the compact gas distribution and the enhanced star-forming activity. We cannot necessarily reject the major merger scenario for rotating disk because nearby merger remnants frequently host a rotationally supported structure; however, we do not have direct evidence for a major merger in AzTEC-1. In addition to a past gas-rich major merger, multiple gas-rich minor mergers or clumpy gas streams could also lead to gas transport to the central 2 kpc. Isolated galaxies require a non-axisymmetric structure such as spiral arms or a bar to remove the angular momentum and transport a large amount of gas into the galaxy centre. AzTEC-1 does not have such a non-axisymmetric structure. To determine the role of major mergers in extreme starbursts, we need to investigate morphological and kinematic structures in a large sample of nearby starburst galaxies.
high-redshift SMGs using high-resolution (less than 0.1") and sensitive observations with ALMA.

Online content

Any Methods, including any statements of data availability and Nature Research reporting summaries, along with any additional references and Source Data files, are available in the online version of the paper at https://doi.org/10.1038/s41586-018-0443-1.

Received: 12 April 2018; Accepted: 29 June 2018; Published online 29 August 2018.

1. Swinbank, A. M. et al. Intense star formation within resolved compact regions in a galaxy at z = 2.3. Nature 464, 733–736 (2010).
2. Ikarashi, S. et al. Compact starbursts in z ~ 3–6 submillimeter galaxies revealed by ALMA. Astrophys. J. 810, 133 (2015).
3. Simpson, J. M. et al. The SCUBA-2 cosmology legacy survey: ALMA resolves the rest-frame far-infrared emission of sub-millimeter galaxies. Astrophys. J. 799, 81 (2015).
4. van Dokkum, P. et al. Forming compact massive galaxies. Astrophys. J. 813, 23 (2015).
5. Kennicutt, R. C. Jr. The global Schmidt law in star-forming galaxies. Astrophys. J. 498, 541–552 (1998).
6. Hughes, D. H. et al. High-redshift star formation in the Hubble Deep Field revealed by a submillimetre-wavelength survey. Nature 394, 241–247 (1998).
7. Barger, A. J. et al. Submillimetre-wavelength detection of dusty star-forming galaxies at high redshift. Nature 394, 246–251 (1998).
8. Chapman, S. C. et al. A redshift survey of the submillimetre galaxy population. Astrophys. J. 622, 772–796 (2005).
9. Bothwell, M. S. et al. A survey of molecular gas in luminous sub-millimetre galaxies. Mon. Not. R. Astron. Soc. 429, 3047–3067 (2013).
10. Vison, R. J. et al. Herschel-ATLAS: a binary HyLIRG pinpointing a cluster of starbursting protoclump. Astrophys. J. 772, 137 (2013).
11. Taconi, L. J. et al. Submillimeter galaxies at z ~ 2: evidence for major mergers and constraints on lifetimes, IMF, and CO-H2 conversion factor. Astrophys. J. 690, 246–262 (2008).
12. Hodge, J. A. et al. Evidence for a clumpy, rotating gas disk in a submillimeter galaxy at z = 4. Astrophys. J. 760, 11 (2012).
13. Iono, D. et al. Clumpy and extended starbursts in the brightest unlensed submillimeter galaxies. Astrophys. J. 829, L10 (2016).
14. Tadaki, K.-i. et al. Bulge-forming galaxies with an extended rotating disk at z ~ 2. Astrophys. J. 834, 135 (2017).
15. Swinbank, A. M. et al. ALMA resolves the properties of star-forming regions in a dense gas disk at z ~ 3. Astrophys. J. 806, L17 (2015).
16. Sharda, P. et al. Testing star formation laws in a starburst galaxy at redshift 3 resolved with ALMA. Mon. Not. R. Astron. Soc. 477, 4380–4390 (2018).
17. Bolatto, A. D. et al. The resolved properties of extragalactic giant molecular clouds. Astrophys. J. 686, 948–965 (2008).
18. Cappellari, M. Structure and kinematics of early-type galaxies from integral field spectroscopy. Annu. Rev. Astron. Astrophys. 54, 597–665 (2016).
19. Veale, M. et al. The MASSIVE survey – V. Spatially resolved stellar angular momentum, velocity dispersion, and higher moments of the 41 most massive local early-type galaxies. Mon. Not. R. Astron. Soc. 464, 356–384 (2017).
20. Naab, T. et al. The ATLAS3D project – XXV. Two-dimensional kinematic analysis of simulated galaxies and the cosmological origin of fast and slow rotators. Mon. Not. R. Astron. Soc. 444, 3357–3387 (2014).
21. Genzel, R. et al. The Sins survey of z ~ 2 galaxy kinematics: properties of the giant star-forming clumps. Astrophys. J. 733, 101 (2011).
22. Bournaud, F. et al. The long lives of giant clumps and the birth of outflows in gas-rich galaxies at high-redshift. Astrophys. J. 780, 57–75 (2014).
23. Mandelker, N. et al. The star formation in simulated high-z galaxies: in situ and ex situ migration and survival. Mon. Not. R. Astron. Soc. 443, 3675–3702 (2014).
24. Genzel, R. et al. The SINS/ZC-SINF survey of z ~ 2 galaxy kinematics: evidence for gravitational quenching. Astrophys. J. 785, 75 (2014).
25. Thompson, T. et al. Radiation pressure-supported starburst disks and active galactic nucleus fueling. Astrophys. J. 630, 167–185 (2005).
26. Caccianiga, M. et al. Evolution of violent gravitational disc instability in galaxies: late stabilization by transition from gas to stellar dominance. Mon. Not. R. Astron. Soc. 421, 818–831 (2012).
27. Tacconi, L. J. et al. Phibss: molecular gas content and scaling relations in z ~ 1–3 massive, main-sequence star-forming galaxies. Astrophys. J. 768, 74 (2013).
28. Narayanan, D. et al. The star-forming molecular gas in high-redshift submillimetre galaxies. Mon. Not. R. Astron. Soc. 400, 1919–1935 (2009).
29. Ueda, J. et al. Cold molecular gas in merger remnants. I. Formation of molecular gas disks. Astrophys. J. Suppl. Ser. 214, 1 (2014).
30. Dekel, A. et al. Cold streams in early massive hot haloes as the main mode of galaxy formation. Nature 457, 451–454 (2009).

Acknowledgements We thank J. Boba for discussions about a gravitational instability in SMGs. This work was supported by JSPS KAKENHI JP17J04449. We thank the ALMA staff and in particular the EA-ARC staff for their support. This research has made use of data from ALMA and HerMES project (http://hermes.sussex.ac.uk/). ALMA is a partnership of ESA (representing its member states), NSF (USA) and NINS (Japan), together with NRC (Canada), MOST and ASIAA (Taiwan), and KASI (South Korea), in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NRAO and NAOJ. HerMES is a Herschel Key Programme utilizing Guaranteed Time from the SPIRE instrument team. ESAC scientists and a mission scientist. Data analysis was in part carried out on the common-use data analysis computer system at the Astronomy Data Center (ADC) of the National Astronomical Observatory of Japan.

Reviewer information Nature thanks F. Bournaud and the other anonymous reviewer(s) for their contribution to the peer review of this work.

Author contributions K.T. led the project and reduced the ALMA data. K.T. and D.J. wrote the manuscript. M.S.Y. reduced the Large Millimeter Telescope data and edited the final manuscript. Other authors contributed to the interpretation and commented on the ALMA proposal and the paper.

Competing interests The authors declare no competing interests.

Additional information

Extended data is available for this paper at https://doi.org/10.1038/s41586-018-0443-1.

Supplementary information is available for this paper at https://doi.org/10.1038/s41586-018-0443-1.

Reprints and permissions information is available at http://www.nature.com/reprints.

Correspondence and requests for materials should be addressed to K.T.

Publisher’s note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.
In AzTEC-1, we carried out observations of the CO (4–3) emission line at the rest-frame frequency of 461.040 GHz (86.309 GHz in the observed line at the rest-frame frequency of 461.040 GHz, but do not discuss this information here. Global SED properties of AzTEC-1. We collected the photometric data for AzTEC-1 from the latest multi-wavelength catalogues (Subaru17, VISTA17, Spitzer18, Herschel18,19 and VLA20). After excluding marginal detections below 5σ and adding the ALMA photometry at 860-μm, 2.1 mm and 3.2 mm, we constrained the global spectral energy distribution (SED) from optical to radio (Extended Data Fig. 2). To account for possible zero-point offsets, we added a systematic uncertainty of 0.1 mag to the flux errors in the optical and near-infrared bands. Using the MAGPHYS code14,21, we fitted the observed SED to stellar population models45, taking into account dust attenuation and dust emission in a physically consistent way. The best-fitting SED model indicates that AzTEC-1 is a massive, star-forming galaxy with a stellar mass of M* = (9.9 ± 1.6) × 10^{10} M⊙ and a star-formation rate of SFR = 1.18 ± 0.36 M⊙ yr⁻¹. The dust emission is characterized by a total infrared luminosity of L_IR = (1.9 ± 0.5) × 10^{11} L⊙, a dust mass of M_dust = (1.1 ± 0.2) × 10^{10} M⊙, and a dust temperature of T_dust = 43 ± 3 K. The uncertainties are based on the 2.5th–97.5th-percentile range of the probability distributions.

Gas mass. We derived two independent estimates for the molecular gas mass for AzTEC-1 using the CO (4–3) line and [C i] line luminosities. For the gas-mass estimates based on the CO (4–3) luminosity, there are uncertainties about the CO excitation. The CO (4–3) line flux is F_CO = 2.6 Jy/beam and the CO-to-H₂ conversion factor is α_CO = M_H₂ / L_CO. Alternatively, the [C i] line is an independent, optically thin tracer of the molecular gas in nearby galaxies44,45 and having both [C i] line measurements provides useful constraints on the physical conditions of the emitting gas. First, we estimated an excitation temperature of T_ex = 27 ± 4.8 K from the C i (1–0)/C i (2–1) ratio of R_c = 0.52 ± 0.13 in the 1.7″ × 1.1″ resolution maps, using the relation45 T_ex = 38.8 K(l/21(Rc)). Then, using the C i (2–1) line flux in the range of 0.8° × 0.7° map, we computed a neutral carbon mass of M_CI = (1.7 ± 0.3) × 10^{10} M⊙ from M_CI = 4.566 × 10^{–6} Q(T_ex) / 1.5 × exp(62.5/T_ex) L_C i / 10^{17} cm⁻² s⁻¹, where Q(T_ex) = 1 + 3 exp(–23.6/T_ex) + 6 exp(–62.5/T_ex) is the partition function45. The uncertainty in the neutral carbon mass includes the error in the flux measurement and the uncertainty in the excitation temperature. The molecular gas mass derived from the [C i] line luminosity is M_CI = 2.1 ± 10^{10} M⊙, adopting a carbon abundance of Ω_C = 4 × 10⁻², which is average of the typical value of 3 × 10⁻² in normal star-forming galaxies, and the elevated value of 5 × 10⁻² in the central region of the local starburst galaxy M82. The resulting gas-to-dust mass ratio M_{gas,dust} = 65 ± 17 is smaller than the average value of 350 ± 28 in 18 nearby starburst galaxies, but is still in the 50th–95th-percentile range, l_{50} = 44–589. The CO (4–3) luminosity also gives a gas mass of M_{gas,CO} = 6.6 ± 0.1 × 10^{10} O_⊙ and a gas mass-to-light ratio of R_g = (1.1 ± 0.2) × 10^{10} O_⊙/L_CO. If the CO (4–3) line is thermalized (α_CO = 0.8 M⊙ km s⁻¹ pc⁻²), then the CO-based gas mass is similar to the C i-based gas mass. For consistency between C i and CO, we adopt a gas excitation of R_g = 0.91, which is larger than the average value for SMGs at high redshift (R_g = 0.46) and comparable with the average value for quasi-stellar objects (R_g = 0.87+0.071). Adopting α_CO = 4 M⊙ (K km s⁻¹ pc⁻²), commonly used in normal star-forming galaxies, is not appropriate because the CO-based gas mass substantially exceeds the C i-based gas mass. Modelling suggests that CO emission in dense clumps is more highly excited, compared with the entire disk14. If the gas is thermalized with R_g = 1, then the gas mass of clumps can be 10% smaller.

SFR and gas mass per unit area. We obtained the total star-formation rate SFRtotal and gas mass M_gas, total in AzTEC-1 as mentioned above. Because the 860-μm (160-μm) in the rest frame) continuum flux density S_860GHz traces star formation, we compute star-formation-rate surface densities in each pixel as S_{SFR} = S_{SFR,total} × (S_860GHz/S_860GHz, total) / ∆beam, where S_860GHz, total = 16.9 ± 0.7 mJy / ∆beam is the effective beam area of 0.344 kpc. Here, we use the 860-μm continuum map with a pixel scale of 0.07″ to avoid oversampling, although the original pixel scale is 0.01″. The uncertainties of S_{SFR} include errors in the flux measurements of S_860GHz, total and systematic errors in the SED modelling. In a similar way, using the CO (4–3) map, we derive gas mass surface densities as S_{gas} = M_{gas, total} × (S_CO/ S_CO, total) / ∆beam.

Disk modelling and dynamical mass. We fit the natural-weighted CO cube with dynamical models of a disk galaxy using the GalPaK20 code. We adopt a thin exponential disk with an arctan rotation curve of v(R) ≈ v_{max} arctan(R/R_c), where v_{max} is the maximum circular velocity and R_c is the turnover radius. A model galaxy consists of ten free parameters: centroid (x, y), systemic velocity v_{sys}, line width R_V, turn-over radius R_c, inclination angle θ, position angle PA, maximum circular velocity v_{max} and velocity dispersion σ_θ. These parameters are convolved with the clean beam and are fitted to the data cube using a Markov chain Monte Carlo (MCMC) algorithm. The CO spectra extracted along
the kinematic major axis in the observed cube together with the best-fitting model are shown in Extended Data Fig. 4. The observed CO kinematics is characterized by a rotating disk. The best-fit values are $55 \pm 0.02 - 0.01$ Jy km s$^{-1}$, $R_{1/2} = 1.05 \pm 0.03$ kpc, $R_0 = 0.18 \pm 0.03$ kpc, $i = 44^\circ \pm 1^\circ$, $PA = -64^\circ \pm 1^\circ$, $\nu_{\text{max}} = 227.6^{+2.3}_{-2.0}$ km s$^{-1}$ and $\sigma_0 = 74^{\pm 1}$ km s$^{-1}$. We adopt the median and the 95% confidence interval of the last 60% of the MCMC chain for 20,000 iterations as the best-fit values and the uncertainties (Extended Data Fig. 4). For a symmetric oblate disk, the inclination corresponds to the projected minor-to-major-axis ratio of $0.73$ using the best-fit kinematic parameters (Fig. 2). In Fig. 3, we show radially averaged CO fluxes and local and differential rotation when $Q_{\text{cri}}$ = 1. The growth rate and self-gravity of gas overcome the repelling forces by pressure leading to gravitational collapse of gas clouds. This condition is characterized by the Toomre Q parameter $Q = \kappa_0 \sigma_0 / (\pi G \Sigma_{\text{gas}})$, and the threshold value is $Q_{\text{cri}} = 1$ for a thin gas disk and $Q_{\text{cri}} = 0.67$ for a thick disk. When the disk consists of two components (gas and stars) with the same velocity dispersion, the threshold value increases to $Q_{\text{cri,2com}} = 1.3$. The self-gravity of gas overcomes the repelling forces by pressure and differential rotation when $Q < Q_{\text{cri}}$.

### Code availability

The ALMA data were reduced using the CASA pipeline version 5.1.1, available at https://casa.nrao.edu/casa_obtaining.shtml. The disk modelling code GaPak3D is publicly available at http://galpak.irap.omp.eu55.

**DATA AVAILABILITY.** This work makes use of the following ALMA data: ADS/IAO. ALMA#2017.1.00300.S and 2017.A.00032.S. Calibrated data that support the findings of this study are publicly available in the ALMA archive (https://almascience.eso.org/faq/project_code=2017.1.00300.S). The HERMES data were obtained through the Herschel Database in Marseille (Hedam; http://hedam.lam.fr), which is operated by CeSAM and hosted by the Laboratoire d'Astrophysique de Marseille.

31. Scott, K. B. et al. AzTEC millimetre survey of the COSMOS field – I. Data reduction and source catalogue. Mon. Not. R. Astron. Soc. 385, 2225–2238 (2008).
32. Yun, M. S. et al. Early science with the Large Millimeter Telescope: CO and [CII] emission in the $z = 4.3$ AzTEC J095942.9–022938 (COSMOS AzTEC-1). Mon. Not. R. Astron. Soc. 454, 3485–3499 (2015).
33. Tort, S. et al. Submillimeter galaxies as progenitors of compact quiescent galaxies. Astrophys. J. 782, 68 (2014).
34. Chabrier, G. The galactic disk mass function: reconciliation of the Hubble Space Telescope and nearby determinations. Astrophys. J. 586, L133–L136 (2003).
35. McMullin, J. P., Waters, B., Schiebel, D., Young, W. & Golap, K. CASA architecture and applications. ASP Conf. Ser. 376, 127–130 (2007).
Extended Data Fig. 1 | Galaxy-integrated CO (4–3), CO (1–0) and C i (2–1) spectra of AzTEC-1. The CO (4–3) spectrum is extracted using an 0.8″-diameter aperture in the natural-weighted map cube. The C i (1–0) and C i (2–1) spectra are extracted from the peak positions in map cubes with 1.7″ × 1.1″ and 0.8″ × 0.7″ resolution, respectively. Yellow shaded regions show the velocity range $v = -315 \text{ km s}^{-1}$ to $v = +315 \text{ km s}^{-1}$, in which the velocity-integrated line fluxes are measured.
Extended Data Fig. 2 | Galaxy-integrated SED of AzTEC-1. Red circles show the photometric data from Subaru (r′, i′, z′)37, VISTA (Ks)37, Spitzer (3.6 μm, 4.4 μm)37, Herschel (250 μm, 350 μm, 500 μm)38,39, ALMA (860 μm, 2.1 mm, 3.2 mm) and JVLA (10 cm)40. The black line shows the best-fitting SED model from MAGPHYS41,42.
Extended Data Fig. 3 | CO spectra along the kinematic major axis. Spectra are extracted at a position angle of PA = −64°. The spatial offset x from the galactic centre is shown at the upper left of each panel. Red lines indicate the spectra of the best-fitting dynamical model produced by GalPaK3D.
Extended Data Fig. 4 | Full MCMC chain for 20,000 iterations. Red solid lines and black dashed lines indicate the median and 95% confidence interval of the last 60% of the MCMC chain.
| Line    | Frequency (GHz) | $S_{\text{line}}dv$ (Jy km s$^{-1}$) | $L'_{\text{line}}$ ($10^{10}$K km s$^{-1}$ pc$^2$) |
|---------|-----------------|-------------------------------------|---------------------------------------------|
| CO (4-3)| 461.041         | 1.84±0.17*                          | 8.21±0.78                                   |
| CI (1-0)| 492.161         | 0.45±0.08†                          | 1.76±0.30                                   |
| CI (2-1)| 809.342         | 0.49±0.09‡                          | 0.70±0.13                                   |
| CI (2-1)| 809.342         | 0.63±0.11†                          | 0.92±0.16                                   |

*The flux within a 0.8″ aperture in the 0.093″ × 0.072″ map.
† The peak flux in the 1.7″ × 1.1″ map.
‡ The peak flux in the 0.8″ × 0.7″ map.