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The dicarbon bonding puzzle viewed with photoelectron imaging

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Bonding in the ground state of C_2 is still a matter of controversy, as reasonable arguments may be made for a dicarbon bond order of 2, 3, or 4. Here we report on photoelectron spectra of the C_2^- anion, measured at a range of wavelengths using a high-resolution photoelectron imaging spectrometer, which reveal both the ground $X^1\Sigma_g^+$ and first-excited $a^3\Pi_u$ electronic states. These measurements yield electron angular anisotropies that identify the character of two orbitals: the diffuse detachment orbital of the anion and the highest occupied molecular orbital of the neutral. This work indicates that electron detachment occurs from predominantly s -like ($3\sigma_g$) and p -like ($1\pi_u$) orbitals, respectively, which is inconsistent with the predictions required for the high bond-order models of strongly sp -mixed orbitals. This result suggests that the dominant contribution to the dicarbon bonding involves a double-bonded configuration, with 2π bonds and no accompanying σ bond.

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Despite the relative simplicity of homonuclear diatomic molecules, the bonding nature of dicarbon, C_2 , has long been a topic of debate. This discussion has been driven by recent advances in computational methods, with various studies suggesting the carbon–carbon bond may have a bond order of 2, 3, or even 4, with the latter from ab-initio studies¹. Standard qualitative theories predict different values for the dicarbon bond order^{2,3}. From a simple Lewis electron-pair repulsion description, the 8 valence electrons in C_2 are predicted to form a quadruple bond. However, this bonding assignment seems unlikely, with stable quadruple bonds typically only found between transition metal elements that have partially filled *d*-orbitals⁴. In contrast, a hybrid-orbital (HO) style approach invokes sp^1 hybridisation to predict a triple bond between the carbons. However, if molecular orbital (MO) theory is used, a ground-state valence electron configuration for C_2 of $KK(\sigma_{2s})^2(\sigma_{2s}^*)^2(\pi_{2p})^4$ is predicted, yielding a bond order of 2, with the unusual situation of a π double bond with no accompanying σ bond.

From an ab-initio approach, standard Hartree–Fock-based calculations support a dicarbon double bond; however, more advanced theoretical studies have suggested that the C–C bond may be better described by a higher bond order^{5–8}. A recent high-level full configuration–interaction calculation, combined with valence bond (VB) theory, identified four distinct contributions to the bonding in C_2 ¹. This included contributions from a σ bond, $2 \times \pi$ bonds, plus an interaction between the outward pointing sp^1 hybrid orbitals¹. The strength of this inverted bond between the sp^1 orbitals has since been calculated at various levels of theory and is estimated to contribute ~ 50 – 80 k mol^{−11,5,9,10}. This high bond-order model is further supported by a subsequent quantum chemistry calculation, which found higher magnetic shielding in C_2 compared with C_2H_2 , supporting a bulkier C–C bond¹¹. However, not all of the recent studies are in agreement, with some research preferring the notion of a double¹², triple³, or quasi double–triple¹³ bond, whereas other studies note that the theoretical approaches are not sufficient to definitively discern between the different bonding models^{14–16}.

Despite advances in spectroscopic techniques, experimental studies have not been able to confirm any of the suggested bonding structures, with the majority of the debate currently driven by the results of ab-initio calculations². Due to the highly reactive nature of C_2 , most experimental studies involve flame-emission^{17–20} or plasma-discharge^{21,22} spectroscopy. These studies support a bond order between 2 and 3, with a measured C–C bond length of 1.243 Å, longer than a typical alkyne triple bond, but shorter than a typical alkene double bond¹⁹. Likewise, a measured C–C bond dissociation energy of 602 kJ mol^{−1}, as well as a calculated bond restoring force of 12 N¹⁴, also lie between double and triple bond limits²³.

As the dicarbon anion C_2^- is stable, photoelectron spectroscopy may be used to probe the reactive C_2 neutral molecule^{24,25}. The first dicarbon photoelectron experiment was performed by Ervin et al.²⁴, on C_2^- anions produced in an $O^-/HCCH$ afterglow ion source. This source produced hot anions, with multiple hot bands present in the spectrum, and defined an accurate value for the electron affinity of C_2 of 3.269(6) eV²⁴. A later study by Bragg et al.²⁶ probed the low-lying excited states of C_2 , in a single wavelength measurement at 264 nm (as part of a larger study, employing time-resolved photoelectron spectroscopy to examine transitions from excited anion states). This study provided the first experimental anisotropy measurement of photodetachment from the C_2^- anion.

In this work, the photoelectron spectrum of C_2^- is revisited using a high-resolution photoelectron imaging (HR-PEI) spectrometer. Although it is now well established that the photoelectron angular

distributions indicate the character of the relevant molecular anion orbitals²⁷, electric dipole selection rules also influence the electron anisotropy via the character of the final neutral states, providing insight to understand the nature of the bonding between carbon atoms in C_2 . Here we report on photoelectron angular distributions measured at a range (290 to 355 nm) of wavelengths, to probe the character of the C_2 orbitals. This reveals detachment occurs from pure *s*-like ($3\sigma_g$) and *p*-like ($1\pi_u$) orbitals, suggesting that the dominant contribution to the dicarbon bonding involves a double-bonded configuration, with 2π bonds and no accompanying σ bond.

Results and Discussion

Theoretical discrepancies. The simple idea of a bond order, defined as

$$\frac{\text{Bonding electrons} - \text{Antibonding electrons}}{2} \quad (1)$$

is often a useful way for chemists to describe the bonding nature in molecules. However, this can be an oversimplification in systems where the contribution from different bonding/anti-bonding electrons are unequal. Furthermore, the concept breaks down entirely in systems, which are intrinsically multi-reference in nature. Thus, when discussing the bonding in a molecule as subtle as C_2 , it is important to keep in mind that there are multiple configurations all contributing to the overall state.

Ab-initio descriptions of the bonding are also complicated by the multi-reference nature of C_2 . Specifically, it is the quasi-degeneracy of the $2\sigma_u^*$, $1\pi_u$ and $3\sigma_g$ molecular orbitals, responsible for the numerous low-lying excited electronic states of C_2 , which muddle the bonding picture. Much of this uncertainty is influenced by the nature of the $2\sigma_u^*$ orbital, which is predicted to be a very weakly anti-bonding orbital^{1,28}. To account for this behaviour, an alternative orbital scheme has been proposed, involving hybridisation of the $2\sigma_u^*/3\sigma_g$ molecular orbitals, forming sp^1 -like singly occupied hybrid orbitals ($2\sigma_u^* + 3\sigma_g$) and ($2\sigma_u^* - 3\sigma_g$)⁵, as depicted in Fig. 1.

To visualise the differences between these possible bonding pictures, ab-initio calculations were performed in this work using NWChem²⁹ and Q-Chem³⁰ software. Most standard methods for approximately solving the Schrödinger equation for molecules are based on Hartree–Fock [or self-consistent field (SCF)] theory, utilising a mean-field approximation. However, for molecules with quasi-degenerate or low-lying excited states, a multi-configurational complete active space (CASSCF) approach may be required. This approach accounts for states that are a linear combination of several quasi-degenerate configurations, allowing for non-integer orbital occupation numbers.

The molecular orbitals for C_2 were calculated with both SCF and CASSCF methods, using a cc-pVTZ Dunning basis set³¹, as shown in Fig. 2. The key difference between the two approaches is the ordering of the $2\sigma_u^*$ orbital, with the multiconfigurational calculation increasing the orbital energy due to possible mixing between the $2\sigma_u^*/3\sigma_u^*$ and $2\sigma_g/3\sigma_g$ orbitals. This mixing is also illustrated in the occupation numbers, with a substantial (~ 0.4) occupation found in the $3\sigma_g$ orbital. As the dominant weight in this mixed orbital lies with the anti-bonding $2\sigma_u^*$, these occupation numbers suggest a bond order of three, consistent with a pure hybrid-orbital theory argument⁶. However, if this $2\sigma_u^*/3\sigma_u^*$ and $2\sigma_g/3\sigma_g$ mixing is allowed to occur before the calculation, using hybrid orbitals $\varphi_L = 2\sigma_u + 3\sigma_g$ and $\varphi_R = 2\sigma_u - 3\sigma_g$, the predominant configuration is for each orbital to be singly occupied, with one electron on each of the carbons⁵. From Hund's Rule, one may expect the lowest energy

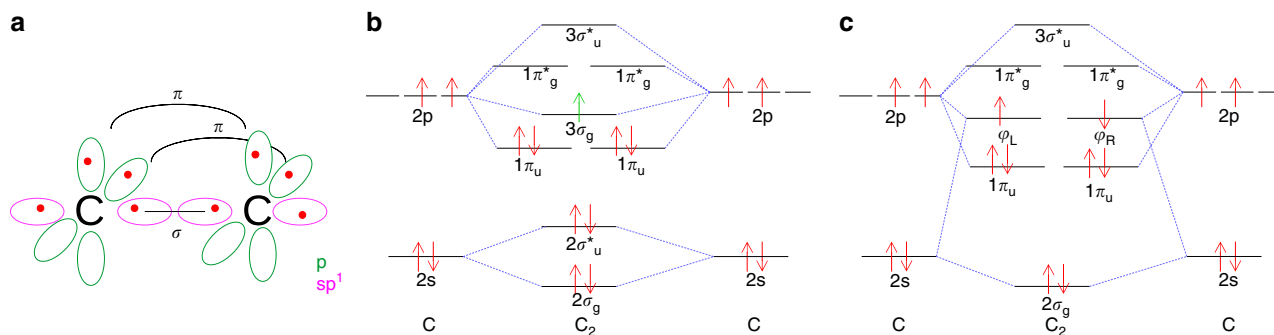


Fig. 1 Orbital descriptions of C_2 using different approaches, highlighting the uncertain bond nature of dicarbon. **a** Hybrid-orbital picture of C_2 , involving sp^1 hybridisation on the carbon atoms. This approach suggests a triple-bonded dicarbon molecule, with one σ and 2π bonds, as represented by solid black lines. **b** Molecular orbital diagram for C_2 , predicting a double bond between the C atoms consisting of 2π bonds, without an accompanying σ bond. The additional electron for the anion C_2^- is shown in green. **c** Orbital diagram for C_2 from a valence-bond viewpoint. Due to the quasi-degenerate nature of orbitals $2\sigma_u$, $3\sigma_g$ and $1\pi_u$, the $2\sigma_u$ and $3\sigma_g$ orbitals mix to form sp^1 -like hybrid orbitals on each of the carbons. Valence bond theory suggests a fourth bond involving the interaction between the outward pointing φ orbitals

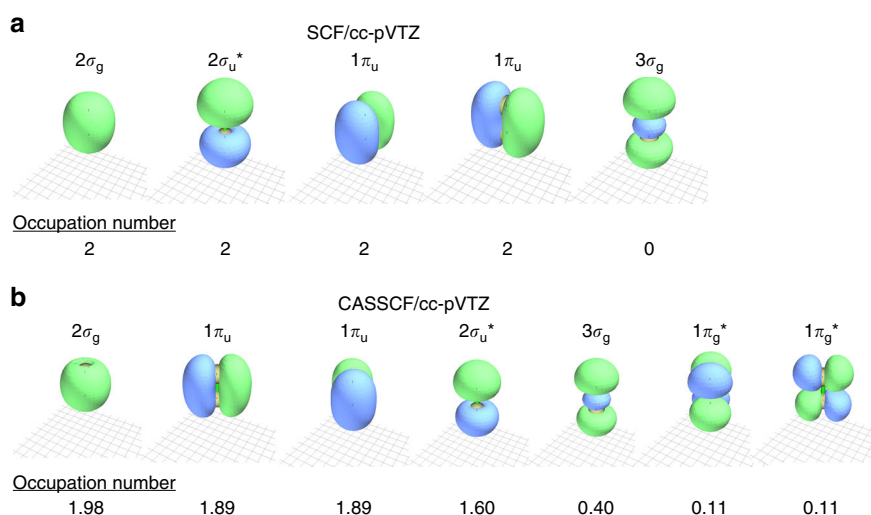


Fig. 2 Valence molecular orbitals of C_2 calculated using NWChem software²⁹. **a** Orbitals calculated using an SCF (self-consistent field) approach, recreating the molecular orbital diagram in Fig. 1b. **b** Orbitals calculated using a multiconfigurational CASSCF (complete active space self-consistent field) approach, which agree with the valence bond orbital diagram (Fig. 1c). Orbital occupation numbers are also given

configuration to be the triplet state, with the odd electrons occupying the degenerate hybrid orbitals in the same spin state. However, generalized valence bond calculations, using the principal of maximum coupling between overlapping atomic orbitals, have shown that the energy gain from the coupling interaction between the singlet-paired electrons in each hybrid orbital is greater than the energy cost from violating Hund's Rule^{1,32}. This is consistent with the VB picture (Fig. 1c), used to suggest a dicarbon quadruple bond, whereas the SCF results are consistent with the double-bonded MO picture (Fig. 1b). Orbitals of the C_2^- anion were also calculated using the same (cc-pVTZ) basis. The addition of an electron has a minimal impact on the structure of the inner orbitals, with a calculated overlap integral of the π_u anion and neutral orbitals giving 85% similarity, with the 15% difference accounted for by the slight change in the C_2 bond length.

High-resolution photoelectron imaging. To investigate the uncertainty regarding the bonding nature of dicarbon, photoelectron spectra of C_2^- were measured, using the HR-PEI spectrometer at the Australian National University. Dicarbon anions are produced in a single pulsed-jet discharge source of pure ethylene, with the subsequent ion mass separated by time-of-flight. Ions are then

photodetached at 355 nm using the third harmonic of a Nd:YAG laser, with the electrons mapped onto a detector using velocity-map imaging (VMI). This allows for energetic and angular information to be measured simultaneously. A raw velocity-mapped image of C_2^- photodetachment, corresponding to 414,511 electrons, is presented in Fig. 3. The image contains two rings, corresponding to the $C_2X^1\Sigma_g^+ + e^- \leftarrow C_2^-X^2\Sigma_g^+ + h\nu$ and $C_2a^3\Pi_u + e^- \leftarrow C_2^-X^2\Sigma_g^+ + h\nu$ photodetachment transitions. Because of the quasi-degeneracy of the $2\sigma_u^*$, $1\pi_u$ and $3\sigma_g$ molecular orbitals, the dicarbon neutral molecule has many low-lying electronic states, which leads to the unusual property whereby the term energy of the first excited state [718.318(2) cm^{-1} ³³] is smaller than the vibrational frequency [$\omega_e = 1854.5(8) \text{ cm}^{-1}$ ²⁴]. Consequently, at a detachment wavelength of 355 nm we observe two electronic transitions, but only the vibrational original of each state.

Rotational band models for the $C_2(X^1\Sigma_g^+) \leftarrow C_2^-(X^2\Sigma_g^+)$ and $C_2(a^3\Pi_u) \leftarrow C_2^-(X^2\Sigma_g^+)$ electronic transitions have been constructed using methods similar to those developed by Buckingham et al.³⁴. A detailed derivation of the molecular rotational model may be found in the Supplementary Discussion. The Hund's case-(b) to case-(b) and case-(b) to case-(a) rotational models were fitted the

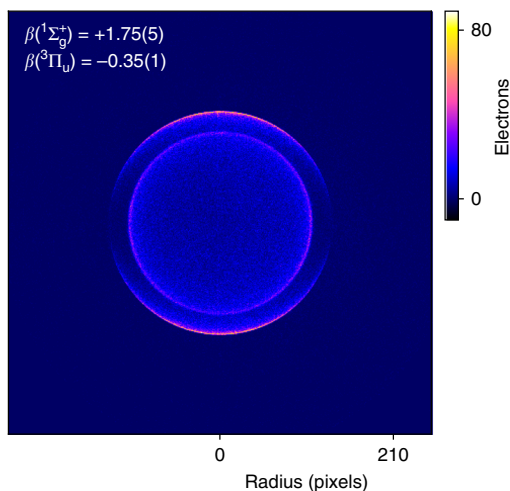


Fig. 3 Velocity-map image of C_2^- at 355 nm. Fast electrons are mapped to the detector edge with slow electrons at the centre, whereas the laser polarisation defines the vertical axis. Two transitions are observed, with detachment to the ground $X^1\Sigma_g^+$ state observed as an outer ring and detachment to the first excited $a^3\Pi_u$ state represented by the inner ring. The two transitions display opposite anisotropies, with the $^1\Sigma_g^+$ electrons preferentially distributed at the poles of the image and the $a^3\Pi_u$ electrons weakly focused around the horizontal axis

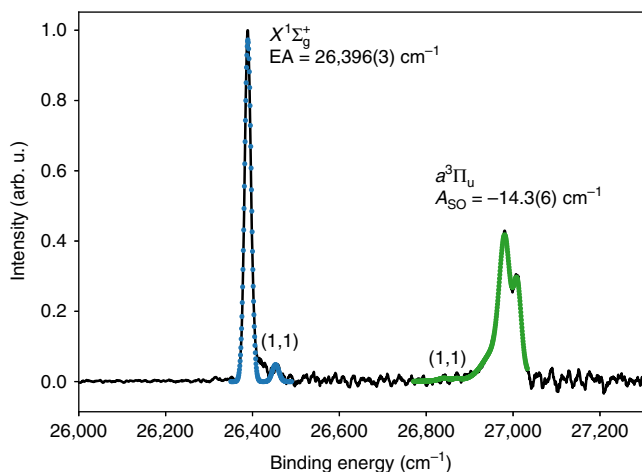


Fig. 4 Photoelectron spectrum of C_2^- at 355 nm. Two electronic transitions $C_2(X^1\Sigma_g^+) \leftarrow C_2(X^2\Sigma_g^+)$ and $C_2(a^3\Pi_u) \leftarrow C_2(X^2\Sigma_g^+)$ are observed, separated by 612 cm^{-1} . The experimental spectrum is shown in black, with a rotational band model ($X \leftarrow X$ shown in blue, $a \leftarrow X$ shown in green) fitted to each transition. This highlights the presence of a hot band (1, 1)

the ground ($X^1\Sigma_g^+$) and excited ($a^3\Pi_u$) photoelectron transitions, respectively, as shown in Fig. 4. The model fit yields an anion rotational temperature of $T = 197(2)\text{ K}$, whereas the Gaussian full-width half-maximum of each transition gives an energy resolution of $\Gamma_{X^1\Sigma} = 15(1)\text{ cm}^{-1}$ and $\Gamma_{a^3\Pi} = 18(1)\text{ cm}^{-1}$, which are consistent with expectations for the spectrometer at electron kinetic energies of $\epsilon \sim 0.3\text{ eV}$.

The rotational model also shows additional weak transitions to the right of the $X \leftarrow X$ peak and to the left of the $a \leftarrow X$ peak. These signatures are assigned to the (1, 1) hot-band transition. In the earlier measurement of Ervin et al.²⁴, strong (0, 1) hot-band transitions were observed; however, only the (1, 1) transitions appear to be present in the photoelectron spectrum presented here, possibly due to a lower source temperature. To

Table 1 Franck–Condon factors for the vibrational transitions in C_2^- photodetachment

	$X^1\Sigma_g^+ \leftarrow X^2\Sigma_g^+$	$a^3\Pi_u \leftarrow X^2\Sigma_g^+$
(0, 1)	0.090	0.231
(0, 0)	0.902	0.756
(1, 0)	0.096	0.209
(1, 1)	0.726	0.365
(2, 1)	0.177	0.287
(2, 2)	0.198	0.089

validate the assignment of the (1, 1) bands in Fig. 4, Franck–Condon factors were calculated. Potential energy curves of the anion $X^2\Sigma_g^+$ and neutral $X^1\Sigma_g^+$ and $a^3\Pi_u$ states were constructed using the Rydberg–Klein–Rees inversion method, with the resulting vibrational wavefunction overlap integrals presented in Table 1.

Table 1 confirms that photodetachment from vibrationally hot anions yielding $C_2(X^1\Sigma_g^+)$ will have a maximum intensity at (1, 1), explaining the absence of the (0, 1) hot band in the spectrum in Fig. 4. Photodetachment yielding $C_2(X^3\Pi_u)$ also has a maximum intensity at (1, 1); however, this transition has a much smaller Franck–Condon factor than the corresponding transition in the ground state. Consequently, this transition has less intensity in the experimental spectrum. From the relative intensities of the (0, 0) and (1, 1) transitions in the photoelectron spectrum, the vibrational temperature of the C_2^- anion may be defined. This analysis reveals a temperature of $T_{\text{vib}} \sim 900\text{ K}$, which is significantly higher than the rotational temperature derived from the model fit in Fig. 4 [$T_{\text{rot}} = 197(2)\text{ K}$]. This is also higher than the normal operating conditions of the spectrometer, suggesting that the high-voltage discharge source preferentially produces dicarbon anions in vibrationally excited states.

The photoelectron spectrum in Fig. 4 may be calibrated using the term energy [$T_e = 718.318(1)\text{ cm}^{-1}$] of the excited $a^3\Pi_u$ state, which is well-defined from neutral flame-emission spectroscopy studies³⁵. The rotational band model provides an accurate position for the band origin, allowing for the precise determination of molecular constants (listed in the Supplementary Table 1). From the calibration of the high-resolution photoelectron spectrum presented here, a precise value for the electron affinity of $EA = 3.2727(4)\text{ eV}$ is determined, in agreement with the previously accepted value of Lineberger et al.²⁴ of $EA = 3.269(6)\text{ eV}$. The anion ground-state rotational [$B = 1.746(1)\text{ cm}^{-1}$] and vibrational [$\omega_e = 1782(2)\text{ cm}^{-1}$] constants are also extracted.

To investigate the relationship between the photoelectron spectrum of C_2^- and the laser detachment energy, additional measurements were recorded by pumping a Sunlite Optical Parametric Oscillator (OPO) with the third harmonic of a Nd:Yag laser. To achieve photon energies greater than the electron affinity [$3.2727(4)\text{ eV}$], the OPO output was doubled using a Continuum FX-Doubler. This allowed for photoelectron spectra of C_2^- to be measured at a range of wavelengths (290–325 nm), as shown in Fig. 5. The OPO measurements show both the origin (0, 0) and first excited (1, 0) vibrational transitions for the ground $X^1\Sigma_g^+$ and excited $a^3\Pi_u$ electronic states.

Bonding insights from the anisotropy. The angular distribution of the photoelectrons, as measured by the VMI lens, is typically not isotropic and is related to the character of the parent anion molecular orbital. For detachment using linearly polarised light,

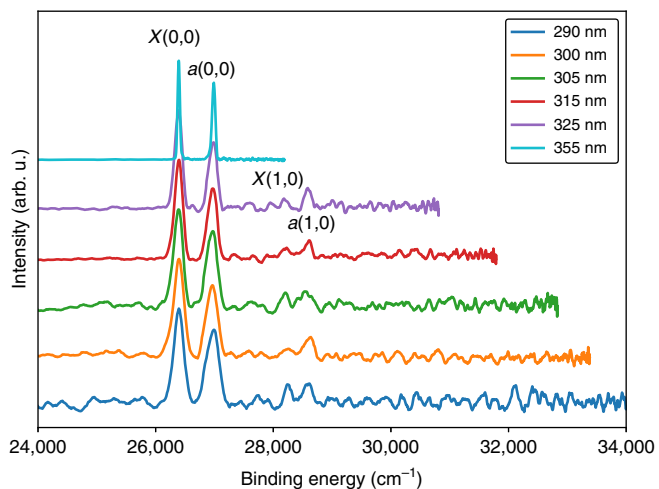


Fig. 5 Photoelectron spectra of C_2^- at a range (290–355 nm) of detachment wavelengths. The vibrational origin transitions are observed for the ground $X^1\Sigma_g^+$ and first excited $a^3\Pi_u$ electronic states. The OPO measurements (290–325 nm) also show the (1, 0) vibrational transition for each state

the differential cross-section is given by

$$\frac{d\sigma}{d\Omega} = \frac{\sigma_{total}}{4\pi} [1 + \beta P_2(\cos \theta)], \quad (2)$$

where θ is the angle between the ejected electron and the (vertical) laser polarisation, and P_2 is the second-order Legendre polynomial. The anisotropy parameter (β) may take values ranging from -1 to 2 , for purely perpendicular and parallel electronic transitions, respectively³⁴. β is a quantitative measure of how anisotropic the electron distribution is, with $\beta = 0$ corresponding to a perfectly isotropic distribution.

A qualitative description of the anisotropy parameter may be determined by visual inspection of the velocity-map image in Fig. 3. Noticeably, the two electronic transitions have different photoelectron angular distributions, with the electrons from detachment to $X^1\Sigma_g^+$ preferentially distributed at the poles of the image signalling a strong positive anisotropy parameter, whereas the $a^3\Pi_u$ electrons appear to have a slight negative anisotropy parameter, with the distribution skewed towards the horizontal. Quantitative values are obtained by fitting Eq. (2) to radially integrated transition intensities, as a function of angle. Applying this to the inverse Abel transformed velocity-mapped image of Fig. 3 gives anisotropy parameters $\beta(X^1\Sigma_g^+) = +1.75(5)$ and $\beta(a^3\Pi_u) = -0.35(1)$.

The measured anisotropy parameters are directly related to the interference of detachment partial waves by the well-known Cooper–Zare anisotropy formula, applicable for a central potential,

$$\beta_\ell = \frac{\ell(\ell-1)\chi_{\ell,\ell-1}^2 + (\ell+1)(\ell+2)\chi_{\ell,\ell+1}^2 - 6\ell(\ell+1)\chi_{\ell,\ell+1}\chi_{\ell,\ell-1}\cos(\delta_{\ell+1} - \delta_{\ell-1})}{(2\ell+1)[\ell\chi_{\ell,\ell-1}^2 + (\ell+1)\chi_{\ell,\ell+1}^2]}, \quad (3)$$

where $\chi_{\ell,\ell\pm 1}$ is the radial transition dipole matrix element for the $\ell \pm 1$ partial wave emitted from the initial atomic orbital ℓ and $\delta_{\ell\pm 1}$ are the associated phase shifts³⁶. Qualitatively, Eq. (3) describes the variation of the anisotropy of an electron distribution, with kinetic energy ϵ , for detachment from an orbital with angular momentum ℓ . Therefore, a measurement of the anisotropy of C_2^- detachment is sensitive to the character of the relevant anion molecular orbitals.

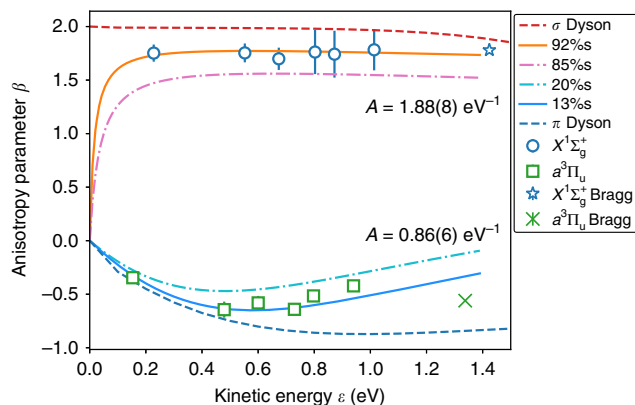


Fig. 6 Anisotropy parameters for C_2^- photodetachment. Experimental values are shown for detachment at 295–355 nm [from this work (circles/squares)] and at 264 nm [from ref. 26 (stars/crosses)]. Detachment to the ground $X^1\Sigma_g^+$ state has a Hanstorp coefficient of $A = 1.88(8) \text{ eV}^{-1}$ with an orbital character of $f = 92\%s$ (orange curve), whereas detachment to the excited $a^3\Pi_u$ state has a Hanstorp coefficient of $A = 0.86(6) \text{ eV}^{-1}$ and an orbital character of $f = 13\%s$ (blue curve). Anisotropy curves calculated from Dyson orbitals are also shown (red and blue dashed lines). Error bars represent 1 SD, defined by the covariance matrix of the least-squares fit to Eq. (2)

For detachment from an s -orbital, $\ell = 0$, Eq. (3) becomes

$$\beta_s = \frac{2\chi_{0,1}^2}{\chi_{0,0}^2} = 2. \quad (4)$$

A strong positive anisotropy close to $+2$, such as $\beta(X^1\Sigma_g^+) = +1.75(5)$, is indicative of a dominant s orbital character. Conversely, for a p orbital with $\ell = 1$, Eq. (3) becomes

$$\beta_p = \frac{2A^2\epsilon^2 - 4A\epsilon \cos(\delta_1 - \delta_0)}{1 + 2A^2\epsilon^2} \quad (5)$$

where

$$A\epsilon = \frac{\chi_{1,2}}{\chi_{1,0}} \quad (6)$$

and where the Hanstorp coefficient A is used to represent the ratio of radial matrix elements³⁷. Equation (6) shows that as $\epsilon \rightarrow 0$, $\beta \rightarrow 0$. A negative β parameter close to threshold, such as $\beta(a^3\Pi_u) = -0.35(1)$, is typical of detachment from a p -like orbital, as seen in similar diatomic molecules BN ³⁸ and NO ^{27,39} where an electron is detached from a π -orbital.

Assuming that the relevant molecular orbitals in C_2^- may be accurately described by a mixture of s and p character, photodetachment will be governed by the modified Cooper–Zare equation⁴⁰,

$$\beta_{sp} = \frac{2Z\epsilon + 2A\epsilon^2 - 4\epsilon \cos(\delta_2 - \delta_0)}{1/A + 2A\epsilon^2 + Z\epsilon}, \quad (7)$$

where $Z = (1-f)B_d/(fA_d)$, for an orbital $\sqrt{1-f}|s\rangle + \sqrt{f}|p\rangle$. Parameters A_d and B_d from Eq. (7) represent the scaling of the different radial dipole integrals, with the ratio $B_d/A_d = 8/3$ for $2s/2p$ mixing, whereas $\cos(\delta_2 - \delta_0)$, the phase shift between the outgoing waves, is ≈ 1 ⁴⁰. This leaves the parameter f , associated with the fractional percentage of s and p character ($f = 0$ for pure s , $f = 1$ for pure p), and the Hanstorp coefficient A in Eq. (7), as the only fitting parameters.

The experimental anisotropy parameters for C_2^- photodetachment at 355–295 nm (to both the ground and first-excited neutral states) are plotted in Fig. 6, together with the values of Bragg et al.²⁶ measured at 264 nm. By fitting the anisotropies for each wavelength

to the sp character model Eq. (7), values for the Hanstorp coefficients, A , and fractional character percentage of the detachment orbital, f , may be determined. This fitting process gives values of $A = 1.88(8) \text{ eV}^{-1}$ and $f = 0.081(9)$ for $\text{C}_2 X^1\Sigma_g^+ \leftarrow \text{C}_2^- X^2\Sigma_g^+$ detachment and values of $A = 0.86(6) \text{ eV}^{-1}$ and $f = 0.87(1)$ for the excited $a^3\Pi_u \leftarrow X^2\Sigma_g^+$ transition. This corresponds to a ground-state detachment orbital with $\sim 92\%$ s character, whereas the excited state corresponds to detachment from an orbital with $\sim 87\%$ p character.

Modified Cooper–Zare curves (Eq. (7)) are shown in Fig. 6 for different values of sp orbital character percentages, with $f = 0.081, 0.15, 0.8,$ and 0.87 . This graph highlights a general rule of sp mixing, with a higher percentage of s character associated with a β close to $+2$, whereas orbitals with more p character produce β parameters close to -1 . From comparison to the experimental data points, it can be seen that $f(X^1\Sigma_g^+) < 0.15$ and $f(a^3\Pi_u) > 0.8$, giving lower limits on the amount of s/p character of each detachment orbital.

Another useful comparison is to construct Dyson orbitals ϕ^d , which are defined as the overlap between the initial $\phi_i^{(n)}$ and final $\phi_f^{(n-1)}$ states of the molecule,

$$\phi^d = \sqrt{N} \int \phi_i^{(n)}(1, \dots, n) \phi_f^{(n-1)}(2, \dots, n) dn, \quad (8)$$

so that the photoelectron dipole moment D_k may be written in terms of the Dyson orbital ϕ^d and the outgoing electron plane wave ψ_k ⁴¹,

$$D_k \propto \langle \phi^d | e \cdot \mathbf{r} | \psi_k \rangle. \quad (9)$$

As Dyson orbitals may be constructed using quantum chemistry software, this will provide a direct link between the ab-initio theory and the experimental results. Dyson orbitals corresponding to C_2^- photodetachment to both the ground and first excited state were calculated using Q-Chem software³⁰ at the CCSD(T) level of theory with a 6-311 + G(4+)(3df) basis set. Anisotropy parameters were then calculated over a range of electron kinetic energies using ezDyson software⁴². As anisotropy calculations are sensitive to the asymptotic tails of the Dyson orbitals, it has been shown in previous studies that the contribution from the diffuse Gaussian orbitals may need to be adjusted to get better agreement between experiment and theory⁴³. In this case it was found that increasing the contribution from the diffuse orbitals by a factor of two was required. The resulting anisotropy curves for detachment from the $3\sigma_g$ and $1\pi_u$ orbitals are also shown in Fig. 6.

Each of the bonding schemes, double, triple and quadruple, may be compared with the above limits to deduce which one best aligns with the orbital information gained from the present experimental measurements. The double-bonded structure suggested by the MO diagram in Fig. 1b predicts that the $\text{C}_2 X^1\Sigma_g^+ + e^- \leftarrow \text{C}_2^- X^2\Sigma_g^+ + h\nu$ transition involves detaching an electron out of the $3\sigma_g$ bonding orbital and the transition to form the lowest triplet state ($a^3\Pi_u$) would involve detachment from the $1\pi_u$ bonding orbital. The $3\sigma_g$ orbital possesses predominant s -character and the $1\pi_u$ orbital possesses significant p -character (Fig. 2), as confirmed by the Dyson orbital calculations. Therefore, this orbital scheme is consistent with the angular distributions measured in Fig. 3, satisfying the orbital character requirements of at least 85% s and 80% p character, for the singlet and triplet transitions, respectively.

The triple-bonded structure, predicted by HO theory (Fig. 1a), suggests that C_2 possesses σ bond, 2π bonds, and singly occupied sp^1 orbitals on each of the carbons. However, as the sp^1 hybrid orbitals will have close to 50% s and 50% p character, they are not

suitable for either the singlet or triplet detachment. Multi-configurational CASSCF calculations have also been used to predict a C_2 bond order of 3, with a calculated orbital configuration of $\text{KK}(2\sigma_g)^2(1\pi_u)^2(1\pi_u)^2(2\sigma_u^*)^{1.6}(3\sigma_g)^{0.4}$ (Fig. 2). Detachment to the $X^1\Sigma_g^+$ ground state would most likely occur out of what is primarily a $3\sigma_g$ orbital. However, as this orbital is mixed with both the $2\sigma_u^*$ and higher lying $1\pi_g^*$ orbitals, achieving an s character purity of over 85% would seem unlikely. Furthermore, the triplet transition may involve detachment from what is primarily a $2\sigma_u^*$ orbital, which, especially when orbital mixing with $3\sigma_g$ is accounted for, is unlikely to satisfy the 80% p character requirement.

Likewise, the suggestion of a quadruple bond faces a similar problem. In this scenario, it is suggested there are one σ and two π bonds, as before, as well as a weak bond-like interaction between the singly occupied sp^1 hybrid orbitals on the carbons. However, even if the highest occupied molecular orbitals/lowest unoccupied molecular orbitals are not pure 50:50 sp^1 orbitals, it is very unlikely that they would represent over 85% s purity, as is required for the $\text{C}_2(X^1\Sigma_g^+) \leftarrow \text{C}_2^-(X^2\Sigma_g^+)$ transition.

It is important to note that, as an intrinsically multi-reference system, it is not possible to exclusively assign the structure of C_2 to any one bonding configuration. However, the anisotropy results presented here strongly suggest that the dominant contribution arises from a double bond-like configuration, with the unusual case of having 2π bonds without an accompanying σ bond.

Ab-initio calculations give a complete multi-configuration picture, with the possibility of many different configurations contributing to the overall state. In this work the experimental photoelectron angular distribution decomposes the detachment orbital as a linear combination of atomic-like orbitals (s, p, d). The measurements indicate almost pure atomic character, which supports a molecular orbital configuration for the $\text{C}_2^-(X^2\Sigma_g^+)$ anion of $\text{KK}(2\sigma_g)^2(2\sigma_u^*)^2(1\pi_u)^4(3\sigma_g)^1$. The anisotropy parameters reported here are consistent with a double-bond configuration for the neutral C_2 molecule, with 2π bonds and no accompanying σ bond. This suggests that although multiple configurations may contribute to the overall state, the 2π bond configuration is likely the dominant contributor to the overall bonding structure. This would also appear to be in agreement with the other experimental observations that have been made, namely the measured C–C bond length of 1.243 \AA ¹⁹, which lies between the usual lengths for double and triple bonds. The fact that this bond differs from a standard C=C double bond, may be due to the unique nature of having two π bonds, as opposed to the usual $\sigma + \pi$ bond configuration. This work suggests that triple and quadruple bond configurations, based on the hybridisation of sp orbitals, will only have a small influence on the overall bonding nature, as opposed to what some calculations and theoretical approaches have suggested recently.

Methods

High-resolution photoelectron imaging spectrometer. A velocity-map imaging lens, a modified version of the original concept of Eppink and Parker⁴⁴, is incorporated co-axially into a fast-beam spectrometer. Details of the apparatus are given in refs. 39,45. Dicarban anions C_2^- are produced by passing pure ethylene gas (C_2H_4) through a pulsed-valve nozzle at a stagnation pressure of $\sim 2 \text{ atm}$, with supersonic expansion through a pulsed high-voltage discharge. Negative ions are extracted, accelerated to 500 eV and focused into an ion gating, bunching and potential re-referencing unit⁴⁶. Anion mass separate travelling over a 2 m time-of-flight tube, with each mass packet bunching to an $\sim 2 \text{ mm}^3$ volume at the interaction region, where an electrostatic gate selects the mass packet of interest. This ion packet is crossed with a detachment laser beam, generated from a Continuum Powerlite 9010 Nd:YAG laser, operated at its third harmonic, 355 nm. The laser produces between 20 and 50 mJ per pulse at 10 Hz, measured near the interaction

region. A Continuum Sunlite EX OPO combined with an FX-Doubler was used to produce wavelengths at 295, 300, 305, 315 and 325 nm, with laser powers of 2–10 mJ. The precise wavelength of the laser light is measured using a wavemeter (HighFinesse WS7 UV), giving calibrated wavelengths of 289.612(1), 299.593(1), 304.596(1), 314.581(1), 324.548(1) and 354.8071(9) nm.

Photodetached electrons are velocity mapped to a 75 mm diameter MCP/phosphor screen detector (Burle), which is imaged by a 2048 × 2048 pixel monochrome CCD camera (PCO 2000). Each camera frame is transferred to a computer at a 10 Hz repetition rate and is processed in real time to identify individual electron events, centroiding position to a sub-pixel accuracy. The electron positions are written to a data file for subsequent analysis.

Image analysis. An image of the velocity-mapped photodetached electrons at the detector is then obtained through binning of the centroided electron-event positions into a rectangular pixel-grid image, of arbitrary pixel number, based on signal-to-noise ratio. The velocity-map image is centred and then circularised by an angular-dependent radial scaling determined by comparing adjacent radial slice intensity profiles⁴⁷. An inverse Abel transformation of the VMI, based on the algorithm of Hansen and Law^{48,49}, returns a slice image of the 3D electron source distribution.

Absolute energy calibration of the photoelectron spectra is achieved using published measurements of species, including O⁻⁴⁵ and O₂⁻⁵⁰, which have been studied under similar conditions as used for the C₂⁻ measurements.

Data availability

All data supporting the findings of this study are available within the Article and from the corresponding author upon reasonable request. Experimental data are available at <https://physics.anu.edu.au/research/portal/vmi>.

Code availability

All of the computer code supporting the findings of this study are available from the corresponding author upon reasonable request. The code used in the velocity-map image analysis is available at <https://github.com/PyAbel/PyAbel>.

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References

- Shaik, S. et al. Quadruple bonding in C₂ and analogous eight-valence electron species. *Nat. Chem.* **4**, 195–200 (2012).
- Macrae, R. M. Puzzles in bonding and spectroscopy: the case of dicarbon. *Sci. Prog.* **99**, 1–58 (2016).
- de Sousa, D. W. O. & Nascimento, M. A. C. Is there a quadruple bond in C₂? *J. Chem. Theory Comput.* **12**, 2234–2241 (2016).
- Radius, U. & Breher, F. To boldly pass the metal–metal quadruple bond. *Angew. Chem. Int. Ed.* **45**, 3006–3010 (2006).
- Zhong, R., Zhang, M., Xu, H. & Su, Z. Latent harmony in dicarbon between VB and MO theories through orthogonal hybridization of 3[σ] and 2[σ]u. *Chem. Sci.* **7**, 1028–1032 (2016).
- Huntley, D. R., Markopoulos, G., Donovan, P. M., Scott, L. T. & Hoffmann, R. Squeezing C–C bonds. *Angew. Chem. Int. Ed.* **44**, 7549–7553 (2005).
- Wu, C. J. & Carter, E. A. Ab initio thermochemistry for unsaturated C₂ hydrocarbons. *J. Phys. Chem.* **95**, 8352–8363 (1991).
- Hay, P. J., Hunt, W. J. & Goddard, W. A. Generalized valence bond description of simple alkanes, ethylene, and acetylene. *J. Am. Chem. Soc.* **94**, 8293–8301 (1972).
- Shaik, S., Danovich, D., Braida, B. & Hiberty, P. C. A Response to a Comment by G. Frenking and M. Hermann on: “The Quadruple Bonding in C₂ Reproduces the Properties of the Molecule”. *Chem. Eur. J.* **22**, 18977–18980 (2016).
- Shaik, S., Danovich, D., Braida, B. & Hiberty, P. C. The quadruple bonding in C. *Chem. Eur. J.* **22**, 4116–4128 (2016).
- Karadakov, P. B. & Kirsopp, J. Magnetic shielding studies of C₂ and C₂H₂ support higher than triple bond multiplicity in C₂. *Chem. Eur. J.* **23**, 12949–12954 (2017).
- Kepp, K. P. Trends in strong chemical bonding in C₂, CN, CN-, CO, N₂, NO, NO-, and O₂. *J. Phys. Chem. A* **121**, 9092–9098 (2017).
- Zou, W. & Cremer, D. C₂ in a box: determining its intrinsic bond strength for the X¹Σ_g ground state. *Chem. Eur. J.* **22**, 4087–4099 (2016).
- Grunenberg, J. Quantum chemistry: Quadruply bonded carbon. *Nat. Chem.* **4**, 154–155 (2012).
- Frenking, G. & Hermann, M. Comment on “the quadruple bonding in C₂ reproduces the properties of the molecule”. *Chem. Eur. J.* **22**, 18975–18976 (2016).
- Cooper, D. L., Penotti, F. E. & Ponec, R. Why is the bond multiplicity in C₂ so elusive? *Comput. Theor. Chem.* **1053**, 189–194 (2015).
- Lloyd, G. M. & Ewart, P. High resolution spectroscopy and spectral simulation of C₂ using degenerate four-wave mixing. *J. Chem. Phys.* **110**, 385–392 (1999).
- Kaminski, C. F., Hughes, I. G. & Ewart, P. Degenerate four-wave mixing spectroscopy and spectral simulation of C₂ in an atmospheric pressure oxy-acetylene flame. *J. Chem. Phys.* **106**, 5324–5332 (1997).
- Brewer, L., Hicks, W. T. & Krikorian, O. H. Heat of sublimation and dissociation energy of gaseous C₂. *J. Chem. Phys.* **36**, 182–188 (1962).
- Douay, M., Nietmann, R. & Bernath, P. F. New observations of the A¹Π_u – X¹Σ_g transition (phillips system) of C₂. *J. Mol. Spectrosc.* **131**, 250–260 (1988).
- Martin, M. C₂ spectroscopy and kinetics. *J. Photochem. Photobiol. A* **66**, 263–289 (1992).
- Chan, M.-C., Yeung, S.-H., Wang, N. & Cheung, A. S.-C. Laser absorption spectroscopy of the d³Π_g ← c³Σ_u transition of C₂. *J. Phys. Chem. A* **117**, 9578–9583 (2013).
- Szwarc, M. The determination of bond dissociation energies by pyrolytic methods. *Chem. Rev.* **47**, 75–173 (1950).
- Ervin, K. M. & Lineberger, W. C. Photoelectron spectra of dicarbon(1-) and ethynyl(1-). *J. Phys. Chem.* **95**, 1167–1177 (1991).
- Arnold, D. W., Bradforth, S. E., Kitsopoulos, T. N. & Neumark, D. M. Vibrationally resolved spectra of C₂ – C11 by anion photoelectron spectroscopy. *J. Chem. Phys.* **95**, 8753–8764 (1991).
- Bragg, A. E., Wester, R., Davis, A. V., Kammrath, A. & Neumark, D. M. Excited-state detachment dynamics and rotational coherences of C₂AlS via time-resolved photoelectron imaging. *Chem. Phys. Lett.* **376**, 767–775 (2003).
- Khuseynov, D., Blackstone, C. C., Culberson, L. M. & Sanov, A. Photoelectron angular distributions for states of any mixed character: An experiment-friendly model for atomic, molecular, and cluster anions. *J. Chem. Phys.* **141**, 124312 (2014).
- Shaik, S., Rzepa, H. S. & Hoffmann, R. One molecule, two atoms, three views, four bonds? *Angew. Chem. Int. Ed.* **52**, 3020–3033 (2013).
- Valiev, M. et al. Nwchem: a comprehensive and scalable open-source solution for large scale molecular simulations. *Comput. Phys. Commun.* **181**, 1477–1489 (2010).
- Shao, Y. et al. Advances in molecular quantum chemistry contained in the Q-Chem 4 program package. *Mol. Phys.* **113**, 184–215 (2015).
- Dunning, T. H. Gaussian basis sets for use in correlated molecular calculations. I. The atoms boron through neon and hydrogen. *J. Chem. Phys.* **90**, 1007–1023 (1989).
- Su, P. et al. Bonding conundrums in the C₂ molecule: a valence bond study. *J. Chem. Theory Comput.* **7**, 121–130 (2011).
- Herzberg, G. *Molecular Spectra and Molecular Structure - Spectra of Diatomic Molecules*, Vol. I, pp. 110–140, 168–212 (Van Nostrand Reinhold Company, 1950).
- Buckingham, A. D., Orr, B. J. & Sichel, J. M. A Discussion on photoelectron spectroscopy - angular distributions and intensity in molecular photoelectron spectroscopy I. General theory for diatomic molecules. *Phil. Trans. R. Soc. A* **268**, 147–157 (1970).
- Amiot, C., Chauville, J. & Maillard, J.-P. New analysis of the C₂ Ballik-Ramsay system from flame emission spectra. *J. Mol. Spectrosc.* **75**, 19–40 (1979).
- Cooper, J. & Zare, R. N. Angular distribution of photoelectrons. *J. Chem. Phys.* **48**, 942–943 (1968).
- Hanstorp, D., Bengtsson, C. & Larson, D. J. Angular distributions in photodetachment from O⁻. *Phys. Rev. A* **40**, 670–675 (1989).
- Asmis, K. R., Taylor, T. R. & Neumark, D. M. Anion photoelectron spectroscopy of BN⁻. *Chem. Phys. Lett.* **295**, 75–81 (1998).
- Laws, B. A., Cavanagh, S. J., Lewis, B. R. & Gibson, S. T. NOO peroxy isomer exposed with velocity-map imaging. *J. Phys. Chem. Lett.* **8**, 4397–4401 (2017).
- Sanov, A., Grumblin, E. R., Goebbert, D. J. & Culberson, L. M. Photodetachment anisotropy for mixed s-p states: 8/3 and other fractions. *J. Chem. Phys.* **138**, 054311 (2013).
- Gozem, S. et al. Photoelectron wave function in photoionization: plane wave or Coulomb wave? *J. Phys. Chem. Lett.* **6**, 4532–4540 (2015).
- Gozem, S. & Krylov, A. I. “ezDyson”. <https://iopshell.usc.edu/downloads/ezdyson> (2016).
- Oana, C. M. & Krylov, A. I. Cross sections and photoelectron angular distributions in photodetachment from negative ions using equation-of-motion coupled-cluster dyson orbitals. *J. Chem. Phys.* **131**, 124114 (2009).
- Eppink, A. T. J. B. & Parker, D. H. Velocity map imaging of ions and electrons using electrostatic lenses: application in photoelectron and photofragment ion imaging of molecular oxygen. *Rev. Sci. Instrum.* **68**, 3477–3484 (1997).
- Cavanagh, S. J. et al. High resolution velocity-map imaging photoelectron spectroscopy of the O⁻ fine-structure transitions. *Phys. Rev. A* **76**, 052708 (2007).
- Dedman, C. J., Roberts, E. H., Gibson, S. T. & Lewis, B. R. Fast 1 kV MOSFET switch. *Rev. Sci. Instrum.* **72**, 3718–3720 (2001).

47. Gascooke, J. R., Gibson, S. T. & Lawrance, W. D. A “circularisation” method to repair deformations and determine the centre of velocity map images. *J. Chem. Phys.* **147**, 013924 (2017).
48. Hansen, E. W. & Law, P.-L. Recursive methods for computing the Abel transform and its inverse. *J. Opt. Soc. Am. A* **2**, 510–520 (1985).
49. Hickstein, D. D., Gibson, S. T., Yurchak, R., Das, D. D. & Ryazanov, M. A direct comparison of high-speed methods for the numerical abel transform. *Rev. Sci. Instrum.* **90**, 065115 (2019).
50. Van Duzor, M. et al. Vibronic coupling in the superoxide anion: the vibrational dependence of the photoelectron angular distribution. *J. Chem. Phys.* **133**, 174311 (2010).

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Author contributions

B.A.L. performed the experiments and ab-initio calculations. B.A.L. and S.T.G. were involved in the data analysis, the experiment design, and wrote the computer codes used to examine the experimental data. B.A.L., S.T.G., B.R.L. and R.W.F. interpreted the results in relation to bonding in C_2 . B.A.L. wrote the manuscript, with input, comments and discussion from S.T.G., B.R.L. and R.W.F.

Competing interests

The authors declare no competing interests.

Additional information

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