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An ionic ultramicroporous polymer with engineered nanopores enables enhanced acetylene/carbon dioxide separation

Engineered nanopores within ionic ultramicroporous polymers enable selective capture of acetylene (C_2H_2) over carbon dioxide (CO_2). Extending the cationic framework doubles the C_2H_2/CO_2 selectivity, offering a promising route for efficient light hydrocarbon separation.

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An ionic ultramicroporous polymer with engineered nanopores enables enhanced acetylene/carbon dioxide separation†

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A nanopore engineering approach enhances acetylene (C₂H₂) over carbon dioxide (CO₂) selectivity in ionic ultramicroporous polymers (IUPs), an understudied class of sorbents. Extending the cationic arm of a prototypical IUP nearly doubles its C₂H₂/CO₂ selectivity from 4.9 to 8.5 (at 298 K, 1 bar), underpinned by further observations from dynamic separation experiments and bespoke computational insights.

Acetylene (C₂H₂) is a key industrial feedstock used in the production of plastics, pharmaceuticals, fuels, and other raw chemicals.¹ Traditionally, C₂H₂ is produced *via* methane combustion or petroleum cracking, processes that generate carbon dioxide (CO₂) as the primary impurity. The separation of these two gases is key to obtaining polymer-grade C₂H₂ (≥99.5%), but their similar molecular sizes (kinetic diameters ~ 3.3 Å), linear shapes, and close boiling points (189.2 K for C₂H₂ and 194.7 K for CO₂) make their separation highly challenging.² State-of-the-art processes still rely upon traditional purification methods, such as solvent extraction and cryogenic distillation, which are energy-intensive and inefficient, underscoring the need for more sustainable alternatives.^{3–5}

Adsorptive separation, particularly physisorption, offers clear advantages because of its minimal energy demand for sorbent recycling (*i.e.*, regeneration).⁶ Physisorbents that offer strong, selective binding for C₂H₂ over CO₂ appear particularly suited for the target C₂H₂/CO₂ separation.^{6,7} Reticular crystalline physisorbents like porous coordination networks (PCNs), such as metal–organic frameworks (MOFs)⁸ and hybrid

ultramicroporous materials (HUMs),^{9,10} and hydrogen bonded organic frameworks (HOFs)^{11,12} have lately been developed for C₂H₂/CO₂ separation. Whereas high selectivity has been realised by a handful of such crystalline reticular sorbents, and the total number of crystalline CNs in the Cambridge Structural Database (CSD) is soaring above 100 000,¹³ the labile nature of the metal–organic bonds/presence of metals have handicapped the performance benchmarks. With regard to chemical separations and/or purifications, such as light hydrocarbon separations, limited water stability has particularly kept the “spectrum of performance parameters” elusive for MOF physisorbents thus far.^{6,14} Conversely, porous organic polymers (POPs), constructed from covalent bonds, tend to be stable under aqueous conditions, their physisorptive separation performances are poor because of two key factors that drive purifications in ultramicroporous PCNs, especially HUMs: (a) wrong pore size to enable tight binding, *i.e.*, ultramicroporosity (<7 Å); (b) inappropriate pore chemistry for selective binding between the adsorbent and target molecule. Crystalline POPs, as exemplified by covalent organic frameworks (COFs) suffer from these weaknesses despite their well-defined structures. For example, **NKCOF-12**, though capable of high acetylene (C₂H₂) uptake at 298 K, exhibits a modest C₂H₂/CO₂ selectivity (<5), limiting its applicability.¹⁵ Amorphous POPs, such as porous aromatic frameworks (PAFs), offer high stability, scalability, and processability for membranes or monoliths, *etc.*, but fail to offer densely packed physisorption sites, *i.e.*, optimal combinations of pore size and chemistry key to strong and selective binding.

To overcome these oft-encountered limitations, ionic ultramicroporous polymers (IUPs), an advanced form of polyionic liquids (PILs)^{16,17} that feature strong electrostatic functionalities and high stability have recently come to the fore.⁵ However, the field is still in its infancy, with only a few reported examples and limited design principles for tailoring binding sites to selectively capture gases like C₂H₂, that could potentially afford binary C₂H₂/CO₂ separation performances. Among the handful of known IUPs, hitherto only one strategy, namely copolymerisation has been shown to improve the C₂H₂/CO₂ separation,¹⁸ thanks to the

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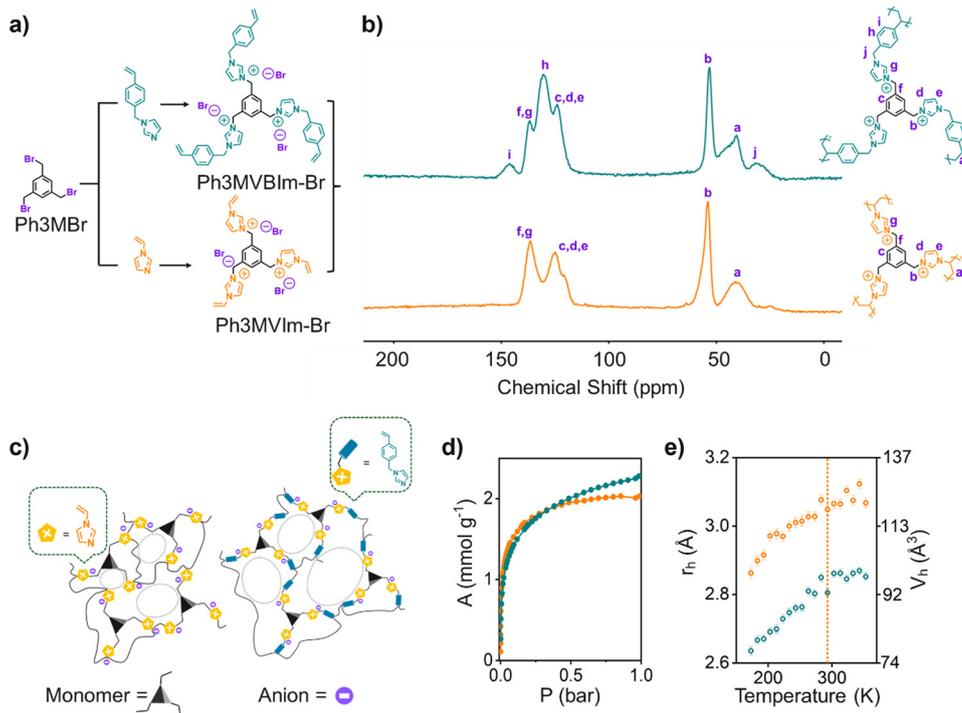


Fig. 1 (a) Synthesis scheme and chemical structures of the monomers; (b) solid-state ^{13}C NMR spectrum of **P(Ph3MVBIm-Br)** (green) and **P(Ph3MVIm-Br)** (orange); (c) schematic of the arm elongation strategy; (d) CO_2 adsorption isotherms for **P(Ph3MVBIm-Br)** (green) and **P(Ph3MVIm-Br)** (orange) at 195 K; (e) hole radii (r_h) and volumes (V_h) of the **P(Ph3MVBIm-Br)** (green) and **P(Ph3MVIm-Br)** (orange) from positron annihilation lifetime spectroscopy (PALS) experiment. The dotted line shows the results at room temperature of the as-synthesized sample.

authors controlling pore structure and functionality in **P(Ph3Im-Br-*n*DVB)** (Ph = phenyl, Im = vinylimidazolium cation, Br = bromide anion, DVB = divinylbenzene crosslinker, *n* = molar ratio of monomer and crosslinker). **P(Ph3Im-Br-0.5DVB)** registered a $\text{C}_2\text{H}_2/\text{CO}_2$ selectivity of 17.9 at 1 bar and 298 K, highlighting the necessity for further iteration of the IUP platform. Such compositional control in IUPs is likely to enable an improved, high-density distribution of the desired C_2H_2 binding sites. Herein, we report a nanopore engineering strategy by looking at IUPs as a tripartite composition, *i.e.*, a neutral central core (usually aromatic ring), cationic arm (having quaternized nitrogen) and counteranion. In this report, we have modulated the cationic arm by extending it with addition of an aromatic benzyl ring (Fig. 1a). This extended arm helped in almost doubling the selectivity from 4.9 for **P(Ph3MVIm-Br)** (Ph = phenyl, VIm = vinylimidazole, Br = bromide anion) to 8.5 for **P(Ph3MVBIm-Br)** (Ph = phenyl, VBIm = vinylbenzylimidazole, Br = bromide anion) at 1 bar and 298 K for equimolar mixtures of $\text{C}_2\text{H}_2/\text{CO}_2$.

IUPs were synthesized using a free radical polymerization technique, with detailed procedures provided in the ESI† (Fig. S1–S7). As shown in Fig. 1c, **P(Ph3MVBIm-Br)** features VBIm as its cationic arm, an extended version of VIm found in **P(Ph3MVIm-Br)**. During polymerization, the vinyl groups cross-links, forming a porous structure. Solid-state NMR highlights differences between the polymers. **P(Ph3MVBIm-Br)** exhibits additional aliphatic signals at ~ 30 ppm (CH_2 groups) and ~ 43 ppm (covalently linked vinyl carbons). Peaks at ~ 54 ppm correspond to methylene linkers, while ~ 124 ppm

and ~ 138 ppm can be attributed to aromatic carbons in the phenyl core and substituted imidazolium carbons, respectively. Unique signals in the aromatic region (h) and (i) confirm the presence of the benzene ring in the cationic arm of **P(Ph3MVBIm-Br)** (Fig. 1b). FT-IR spectra indicate successful polymerization, as the $\text{C}=\text{C}$ stretching band at 1650 cm^{-1} diminishes in the polymers (Fig. S6 and S7, ESI†).

The textural properties of the polymers were assessed *via* CO_2 adsorption isotherms at 195 K (Fig. 1d), with structural parameters summarized in Table S1 (Fig. S8–S11, ESI†). Horvath Kawazoe analysis (Fig. S8 and S10 inset, ESI†) indicated pore widths of 4–7 Å. Positron annihilation lifetime spectroscopy (PALS) provided further insights, showing average pore radii of 2.6–2.8 Å for **P(Ph3MVBIm-Br)** and 2.8–3.1 Å for **P(Ph3MVIm-Br)** (Fig. 1e), with *ortho*-positronium (*o*-Ps) lifetimes of 2.16 ns and 1.93 ns at 298 K, respectively (Fig. S12, ESI†). Thermogravimetric analysis (TGA) further demonstrated the excellent thermal stability of these materials, with an initial decomposition temperature of 290 °C under a nitrogen atmosphere (Fig. S13 and S14, ESI†). The surface chemical properties of **P(Ph3MVBIm-Br)** were analysed using X-ray photoelectron spectroscopy (XPS) (Fig. S15, ESI†). XPS detected carbon, nitrogen, oxygen, and bromine, with their percentage abundances detailed in Table S2 (Fig. S15a, ESI†). High-resolution spectra revealed three distinct C 1s peaks at 284.5 eV (aromatic and cross-linked carbons), 285.6 eV (C–N bonds in imidazole rings), and 286.6 eV (C–O bonds, can be attributed to the presence of



methanol solvent) (Fig. S15c, ESI†). N 1s spectra showed peaks at 399.3 eV (non-quaternized nitrogen) and 401.4 eV (quaternized nitrogen), confirming the polymer's cationic backbone (Fig. S15b, ESI†). Br 3d signals at 67.2 and 68.2 eV validated the presence of bromide anions as charge-balancing counterions (Fig. S15d, ESI†).

To evaluate the properties of IUPs in acetylene purification, adsorption isotherms of C₂H₂ and CO₂ were determined, revealing superior C₂H₂ uptake of 1.4 mmol g⁻¹ **P(Ph3MVBIm-Br)** and 1.0 mmol g⁻¹ **P(Ph3MVBIm-Br)** at 298 K and 1 bar, with CO₂ uptakes significantly lower at 0.65 mmol g⁻¹ and 0.4 mmol g⁻¹ (Fig. 2a and b). The IAST selectivity for C₂H₂/CO₂ mixtures improved from 4.96 to 8.49 upon extending the cationic arm (Fig. 2c and Fig. S16, S17, ESI†), surpassing many porous organic polymers *e.g.*, ZJUT-3 (3.2),¹⁹ NKCOF-12 (4.0),¹⁵ and 3D pts COF (3.8)²⁰ (Fig. 2d and Table S3, ESI†). Adsorption data at 273 K and 283 K showed higher C₂H₂ uptake and a stronger binding affinity ($Q_{st} = 46.7$ kJ mol⁻¹ for C₂H₂ *vs.* 39.7 kJ mol⁻¹ for CO₂), (Fig. S18–S22 and Table S4, ESI†) affirming effective separation. The higher S_{AC} for **P(Ph3MVBIm-Br)** *vs.* **P(Ph3MVBIm-Br)** (Fig. 2c) is found to be in contrast with the significantly higher C₂H₂ uptake registered by the latter (1.4 mmol g⁻¹) over the former (1.0 mmol g⁻¹). Upon closely looking at the CO₂ isotherms' differences, particularly under low pressures, the weaker CO₂ affinity for **P(Ph3MVBIm-Br)** turns out to be the key behind its higher S_{AC} .

The realization of **P(Ph3VBIm-Br)** for challenging C₂H₂/CO₂ separation highlights the potential of IUPs in industrial applications. We further assessed its performance under ambient conditions by conducting laboratory-scale dynamic column

breakthrough (DCB) experiments. Equimolar C₂H₂/CO₂ mixtures were passed through a packed column of activated **P(Ph3MVBIm-Br)** at 1 bar and 298 K. This showed delayed C₂H₂ breakthrough (24.33 min g⁻¹) compared to CO₂ (13.54 min g⁻¹), yielding a separation factor of 4.07 and a CO₂ purity of 99.12% during separation (Fig. 2e). Temperature-programmed desorption (TPD) confirmed facile regeneration at 60 °C, with high-purity fuel-grade C₂H₂ (>98%) eluted over 2.55–21.49 min g⁻¹ and laboratory-grade C₂H₂ (>99%) eluted over 3.06–19.96 min g⁻¹ (Fig. S23, ESI†). The peak C₂H₂ purity was 99.57%, with productivity reaching 1.53 L kg⁻¹ for fuel-grade and 1.34 L kg⁻¹ for lab-grade C₂H₂, demonstrating the material's industrial potential.

To gain insight into the mechanism underlying the separation performance, we conducted Canonical Monte Carlo (CMC) simulations using the crystallographic structure of the **Ph3MVBIm-Br** monomer as the basis (Table S5, ESI†). For molecular models of **P(Ph3MVBIm-Br)** and **P(Ph3MVBIm-Br)**, the CMC simulations at 298 K revealed that the C₂H₂ and CO₂ binding sites are located on the polymer surfaces (Fig. S32 and S33, ESI†). This surface-reliant binding is attributed to the morphology and high density of the polymers (Table S8, ESI†). Br⁻ ions afford a shielding layer on the surface (Fig. S30, ESI†), eliciting an electronegative environment that strongly interacts with C₂H₂ and CO₂, both polarizable in nature. Conversely, the Br⁻ ions limit diffusion into the dense interior (Fig. S30 and S31, ESI†).

Isosurface analyses, colour-mapped along potential energy (Fig. 3), revealed that C₂H₂ has the most favourable binding site on the surface, indicated by its lowest potential energy (Fig. 3a and c). This is driven by C₂H₂'s high polarizability, electron-rich triple bond, and acetylenic hydrogens with $pK_a \sim 25$, enabling

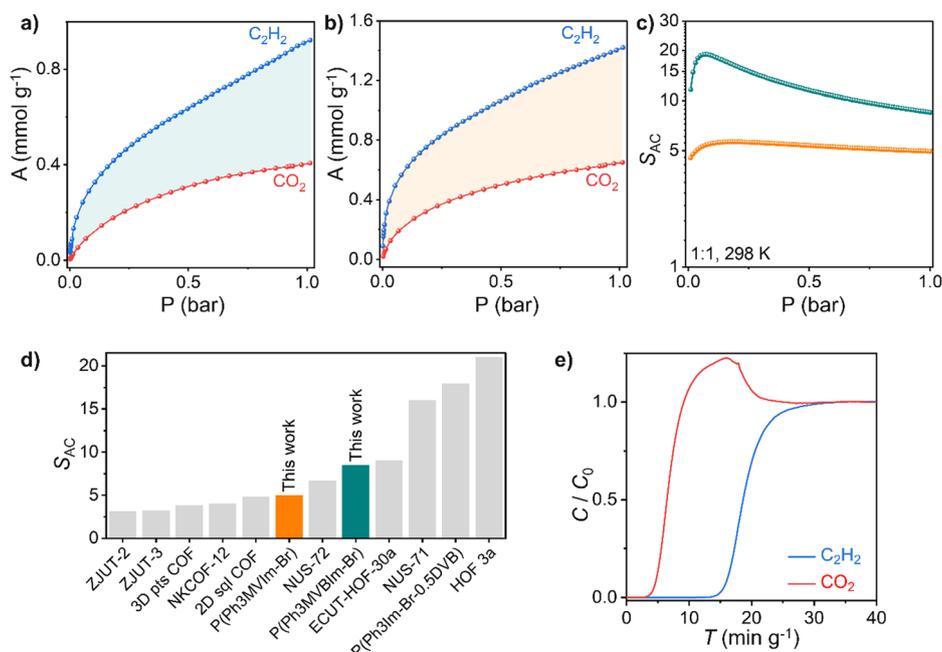


Fig. 2 (a) C₂H₂ and CO₂ adsorption isotherms on **P(Ph3MVBIm-Br)** at 298 K; (b) C₂H₂ and CO₂ adsorption isotherms on **P(Ph3MVBIm-Br)** at 298 K; (c) IAST selectivities of a C₂H₂/CO₂ (S_{AC}) (1:1) mixture for the IUPs at 298 K (turquoise: **P(Ph3MVBIm-Br)**, and orange: **P(Ph3MVBIm-Br)**); (d) comparison of IAST selectivities of the C₂H₂/CO₂ (1:1) mixture for porous organic polymers at 298 K, 1 bar; (e) dynamic column breakthrough profile recorded at 298 K for the C₂H₂/CO₂ (1:1, v/v) mixture for **P(Ph3MVBIm-Br)**.



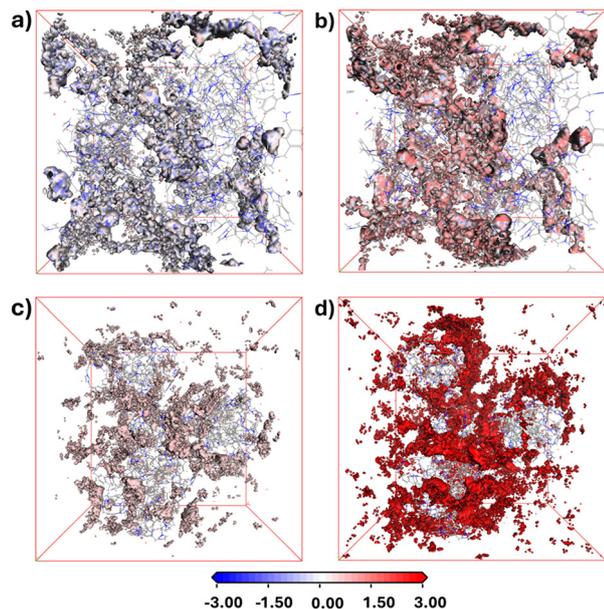


Fig. 3 Combined energy and density distribution information, coloured by potential energy of the adsorbate in kcal mol⁻¹ of (a) **P(Ph3MVIm-Br)** for C₂H₂ and (b) CO₂; (c) **P(Ph3MVBIm-Br)** for C₂H₂ and (d) CO₂.

strong electrostatic and dipole interactions with the cationic backbone and the anionic Br⁻. In contrast, CO₂ (Fig. 3c and d), with lower polarizability and no hydrogens, interacts weakly with the polymer surface, resulting in weak binding. Adsorbate binding density analysis revealed that **P(Ph3MVIm-Br)** features a higher density of binding sites for both C₂H₂ and CO₂ (Fig. S32, ESI[†]) vs. those in **P(Ph3MVBIm-Br)** (Fig. S33, ESI[†]), which leads to a higher uptake of both gases in **P(Ph3MVIm-Br)**. This is likely due to its compact structure, which may enhance adsorption through stronger dipole-quadrupole interactions between the closely packed imidazolium groups and the sorbate molecules. In **P(Ph3MVBIm-Br)**, an interplay of electrostatic interactions, steric hindrance from additional bulky phenyl groups, and the compact internal structure of the polymers further limits CO₂ adsorption (Fig. 3d), enhancing the selectivity for C₂H₂/CO₂.

Our findings demonstrate that tweaking the cationic arm of a prototypal IUP doubles the C₂H₂/CO₂ selectivity by limiting the CO₂ coadsorption. A detailed computational study reinforced the latter and further elucidated the importance of ionic

surfaces in fostering strong binding sites, vs. the often-emphasised impact of pore voids and channels. It is therefore highly likely that next generation IUP sorbents will exhibit a high-density of ionic sites and abundant ultramicroporosity to address challenging separations.

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Data availability

The data supporting this article are included in the ESI[†]. Crystallographic data for **Ph3MVIm-Br** can be accessed from the Cambridge Crystallographic Data Centre (CCDC) as deposition number 2418964.† Modelled polymerizations are included in the Videos entitled Ph3MVIm-Br.mp4, and Ph3MVBIm-Br.mp4.

Conflicts of interest

The authors have no conflicts to declare.

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