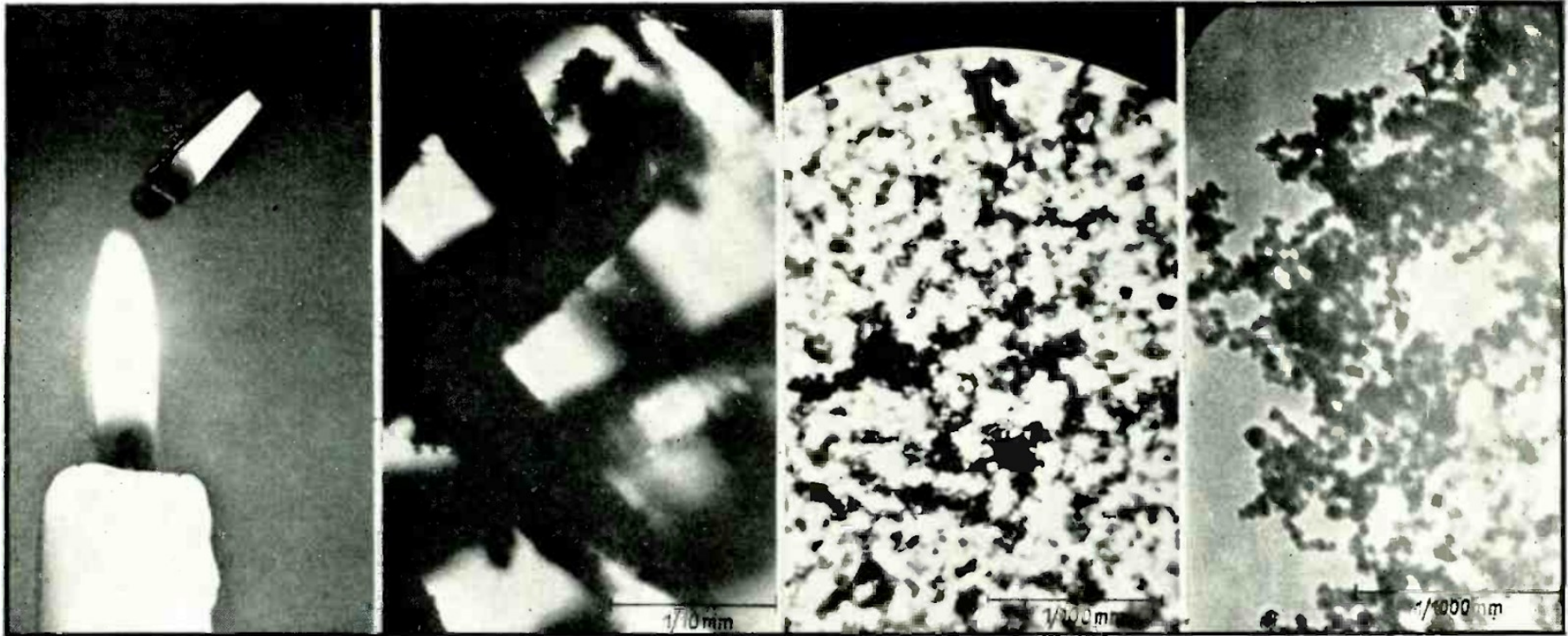


Carbon products without the emissions

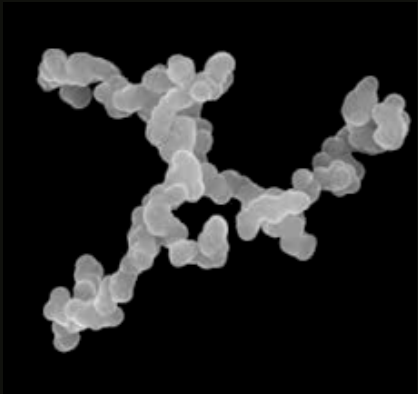
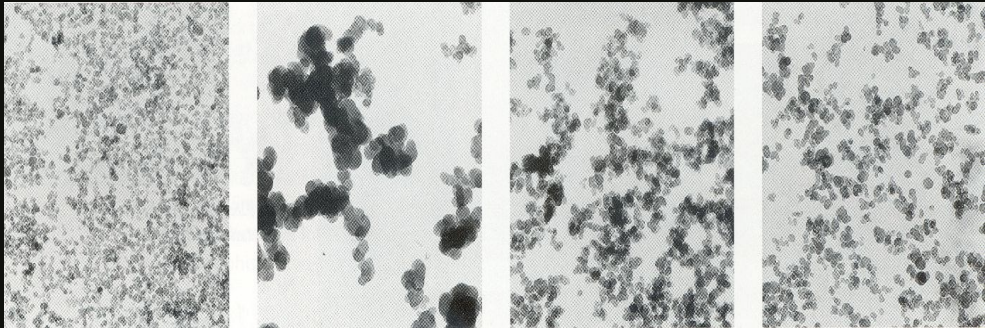
Carbonaceous particles formation and structure



What do carbon blacks and soot look like?

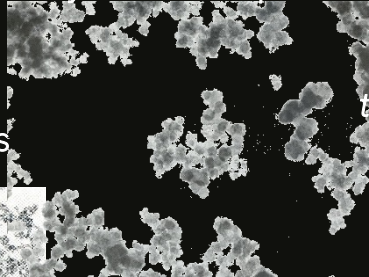
Furnace blacks

Fine 14 nm Coarse 50 nm High structure Low structure

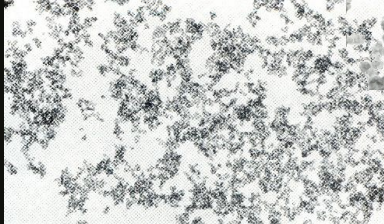


Scanning Electron Micrograph (SEM) of carbon black (Orion)

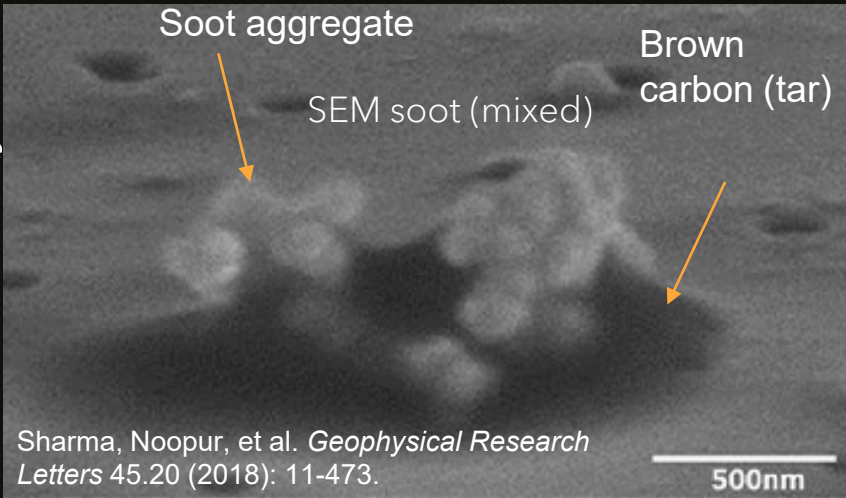
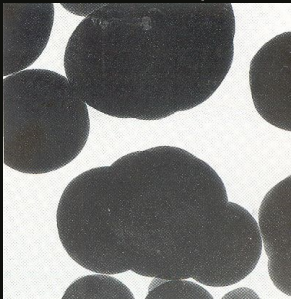
acetylene black particles



gas black particles



thermal black particle



Sharma, Noopur, et al. *Geophysical Research Letters* 45.20 (2018): 11-473.

Curtin Carbon Group



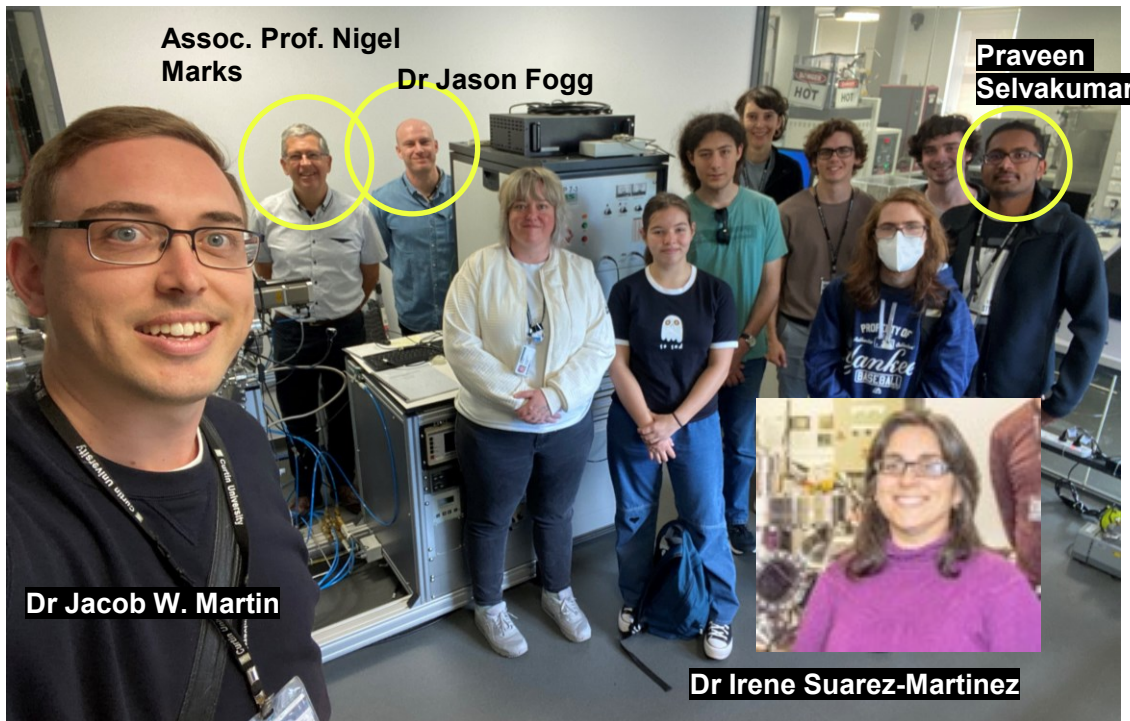
Curtin University

INSTITUTE FOR ENERGY
TRANSITION



TRAILBLAZER
RESOURCES TECHNOLOGY & CRITICAL MINERALS

Carbon Materials Scientists in the Department of Physics and Astronomy



Assoc. Prof. Nigel Marks

Dr Jason Fogg

Praveen Selvakumar

Dr Jacob W. Martin

Dr Irene Suarez-Martinez

John de Laeter Centre

MICROSCOPY
AUSTRALIA



FUTURE
ENERGY
EXPORTS
Cooperative Research Centre

HSRG
Hydrogen Storage Research Group

FUTURE
BATTERY
INDUSTRIES CRC



ARC Centre of Excellence for
Carbon Science
& Innovation

J.W.M. acknowledges the support of the Forrest Research Foundation. I.S.-M. acknowledges the support of the Australian Research Council (No. FT140100191). Characterisation of the samples was undertaken at the John de Laeter Centre, Curtin University.

Computational resources were provided by the Pawsey Centre with funding from the Australian Government and the Government of Western Australia. The authors acknowledge the facilities, and the scientific and technical assistance of Microscopy Australia at the Centre for Microscopy, Characterisation & Analysis, The University of Western Australia, a facility funded by the University, State and Commonwealth Governments.

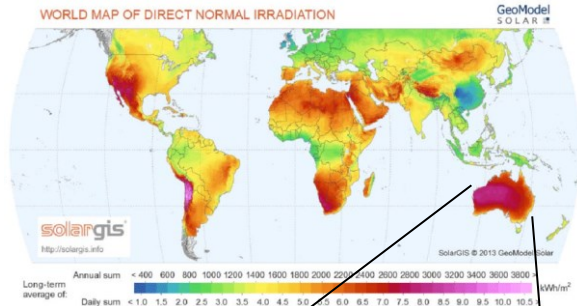
I would like to acknowledge the Whadjuk People of the Noongar nation on whose land this work was undertaken



Curtin University

Why Perth?

Renewable energy



Western
Australia

Perth

NetZero Australia
solar scenario 2050

Battery minerals

Majority of Lithium
mined in WA



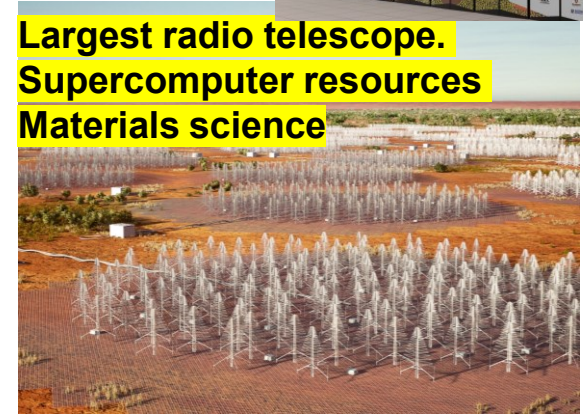
Curtin University

School of mines
leading mining uni



Physics
Department

Largest radio telescope.
Supercomputer resources
Materials science



Rottnest Island

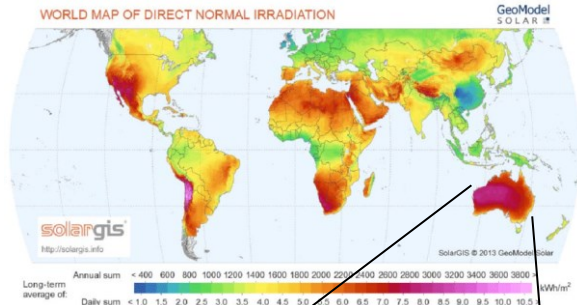
Short ferry ride from city



Curtin University

Why Perth?

Renewable energy



Western Australia

Perth

NetZero Australia
solar scenario 2050

Battery minerals

Majority of Lithium
mined in WA



Curtin U

School of mine
leading mining



Physics Department

Largest radio telescope.



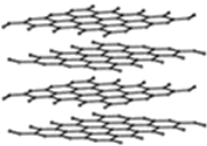
Quokkas on Rottnest Island



Curtin University

Carbon for products not fuels

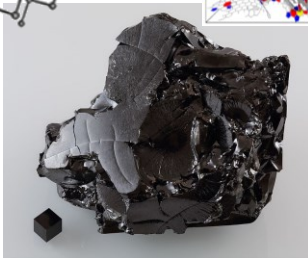
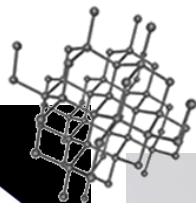
Carbon Materials Science



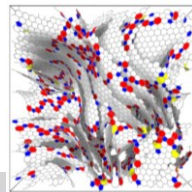
Graphite



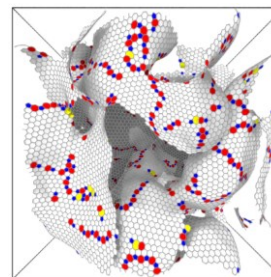
Diamond



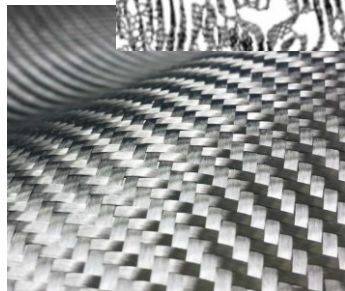
Glassy carbon



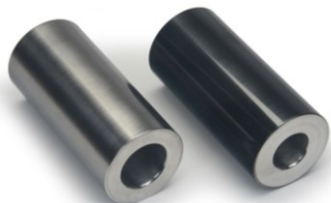
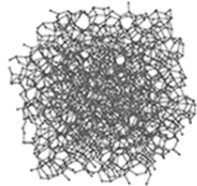
Activated carbon



Carbon black



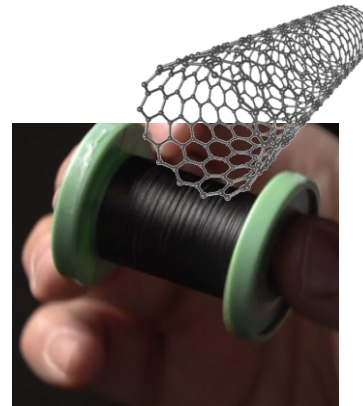
Carbon fibres



**Diamond-like
(amorphous) carbon**



Fullerenes



Nanotubes

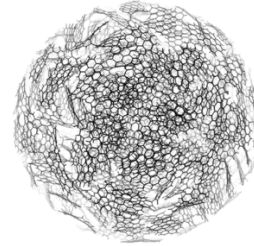
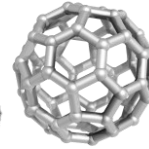
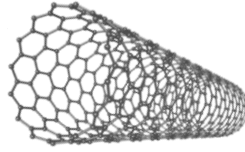
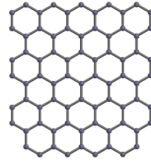


Graphene

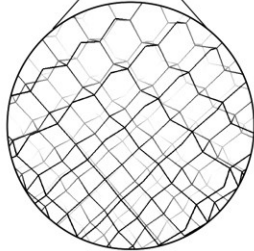
Structure-disorder

Nanocarbons

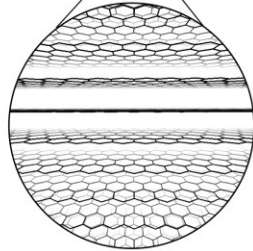
Carbon black (soot)



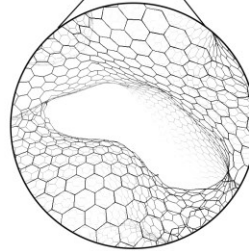
Diamond



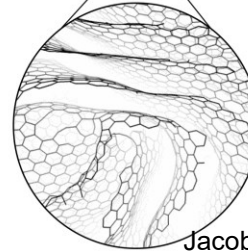
Graphite



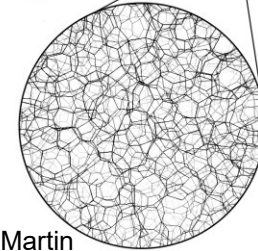
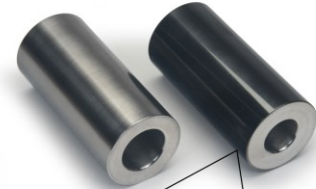
Activated carbon



Glassy carbon



Amorphous carbon



Jacob W. Martin

Crystalline

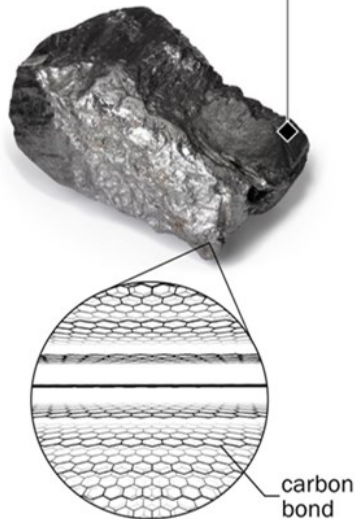
Disordered

Amorphous

Carbon materials powering our green technology

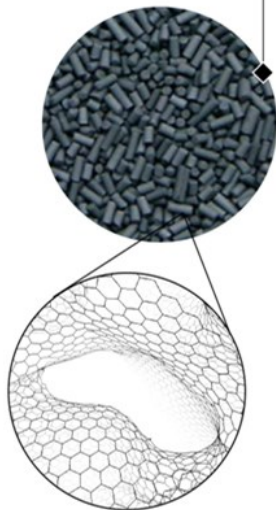
New and improved carbon materials are needed to drive our green transition

Graphite for
lithium ion batteries



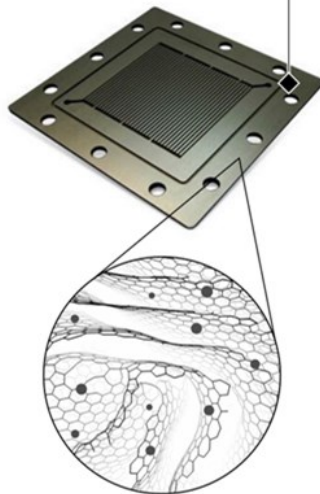
The carbon atoms are arranged in layered hexagonal sheets. It is between these sheets that lithium is stored.

Activated carbon for
hydrogen storage and
supercapacitors



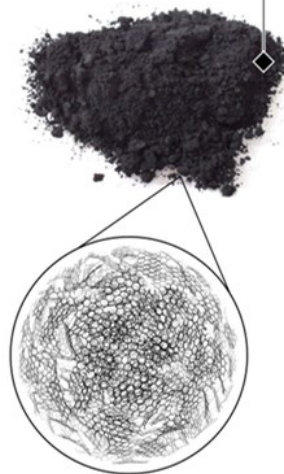
The carbon sheets are curved opening up pores to store hydrogen or ions for supercapacitors.

Carbon catalysts for
hydrogen fuel cells
and electrolyzers



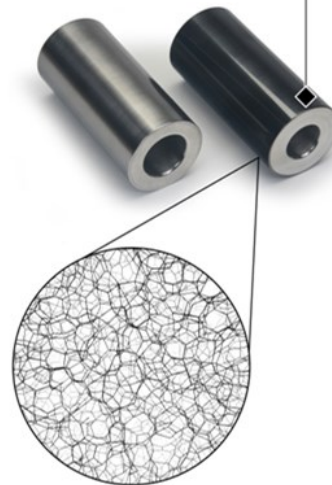
Single metal (iron/nickel) catalysts embedded into the sheets can replace costly platinum.

Carbon black for
CO₂-free hydrogen
from methane



Small sheets arranged concentrically form into balls and then join together to form chains.

Carbon coatings for
protecting steel from
hydrogen embrittlement



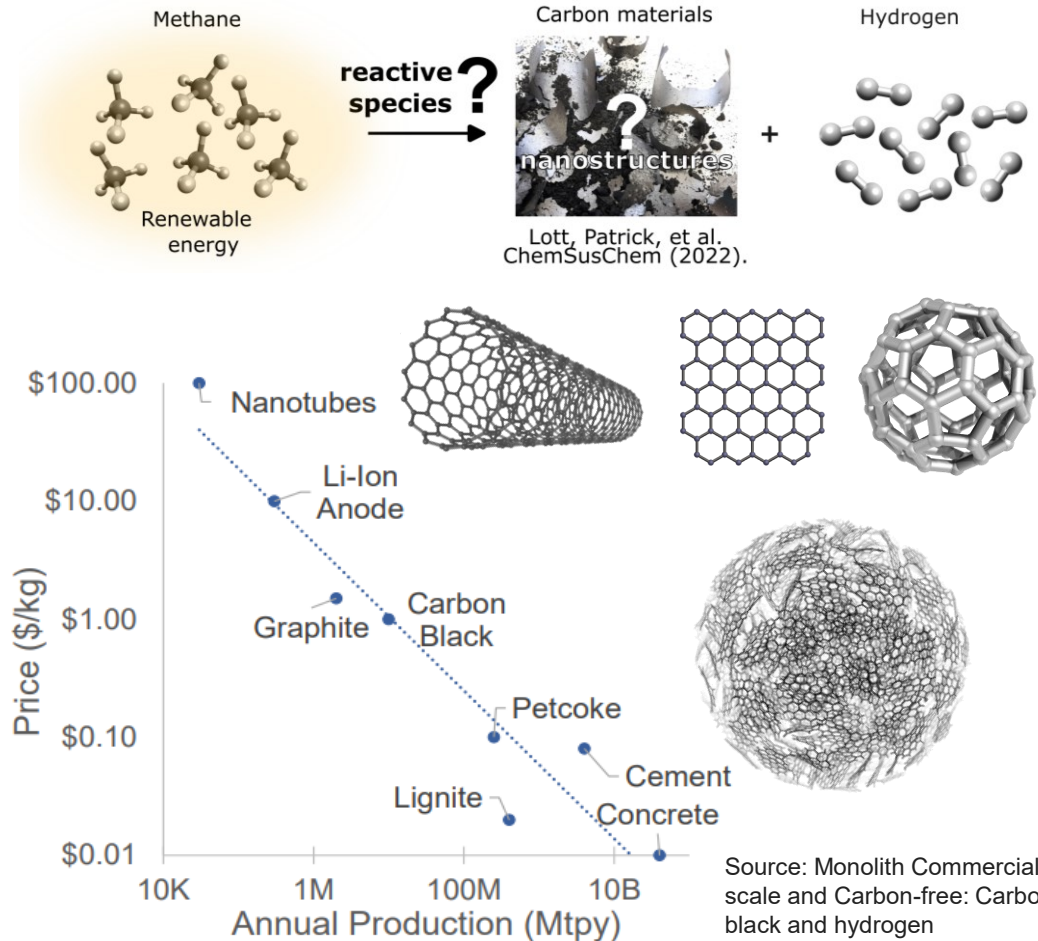
Amorphous carbon with tetrahedral arrangement of carbon that are hard and impermeable.

Pyrolysis for products

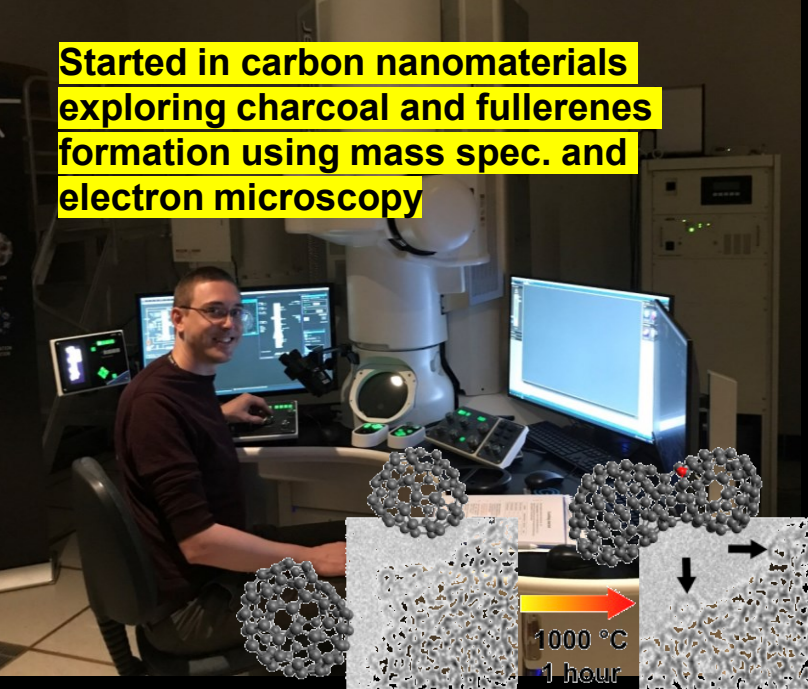
Challenges and opportunities

- How can we produce carbon materials without CO₂?
- How can we produce more valuable carbon products?
- How can we increase the efficiency of carbon production?
- How can we stop carbon forming where we don't want it?

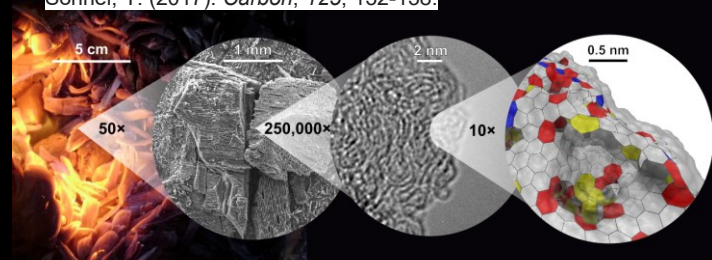
1. *Identify key reactive species*
2. *Control carbon nanostructures produced in pyrolysis*



**Started in carbon nanomaterials
exploring charcoal and fullerenes
formation using mass spec. and
electron microscopy**

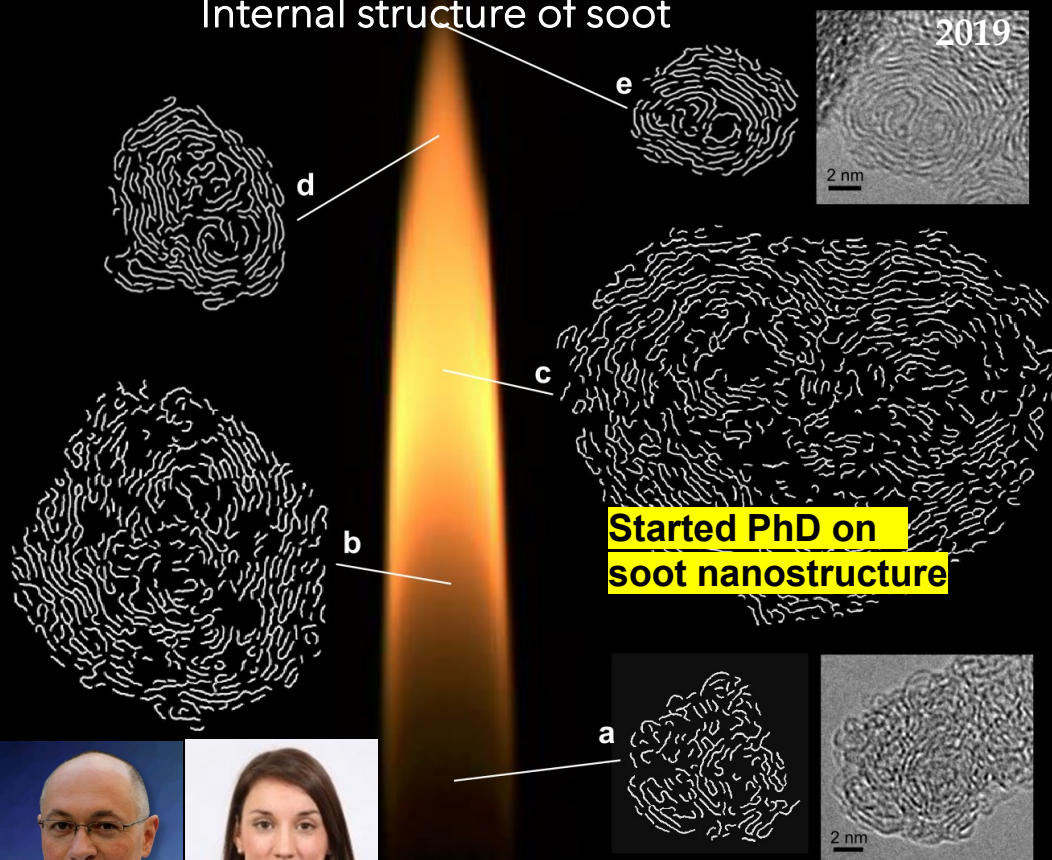


Martin, J. W., McIntosh, G. J., Arul, R., Oosterbeek, R. N., Kraft, M., & Söhnel, T. (2017). *Carbon*, 125, 132-138.



Martin, J. W., Nyadong, L., Ducati, C., Manley-Harris, M., Marshall, A. G., & Kraft, M. (2019) *Environmental science & technology*, 53(7), 3538-3546.

Internal structure of soot



**Started PhD on
soot nanostructure**

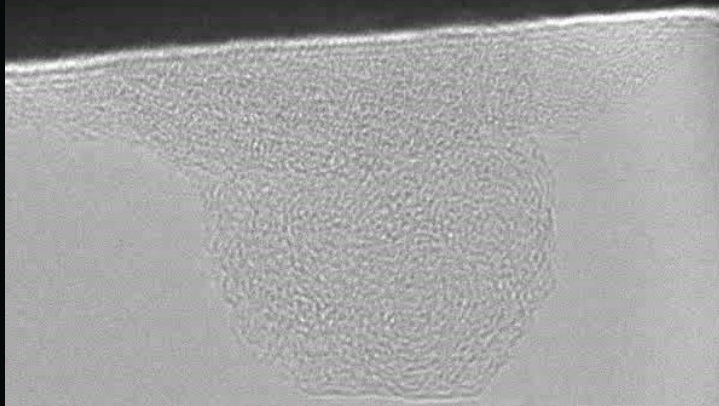


Markus
Kraft

Maria
Botero

Botero, M. L., Sheng, Y., Akroyd, J., Martin, J., Dreyer, J. A., Yang, W., & Kraft, M. (2019). Internal structure of soot particles in a diffusion flame. *Carbon*, 141, 635-642.

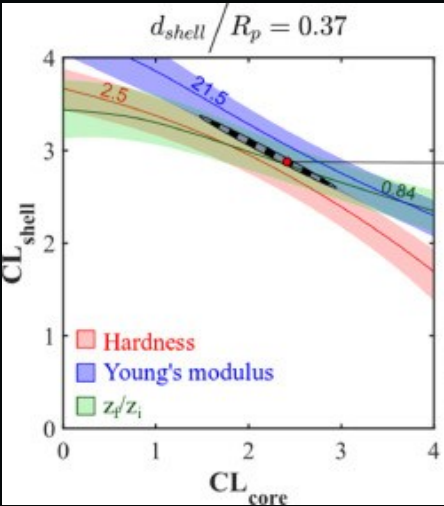
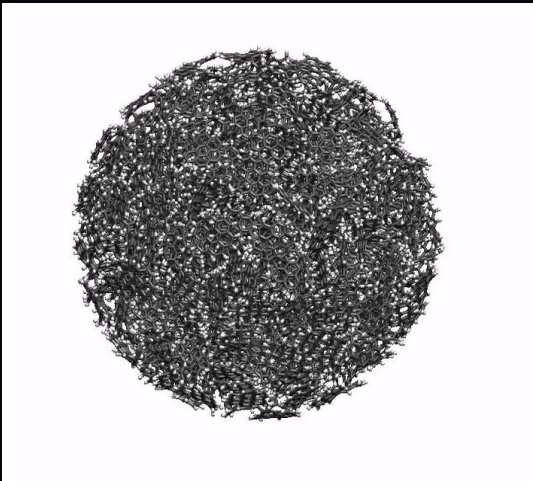
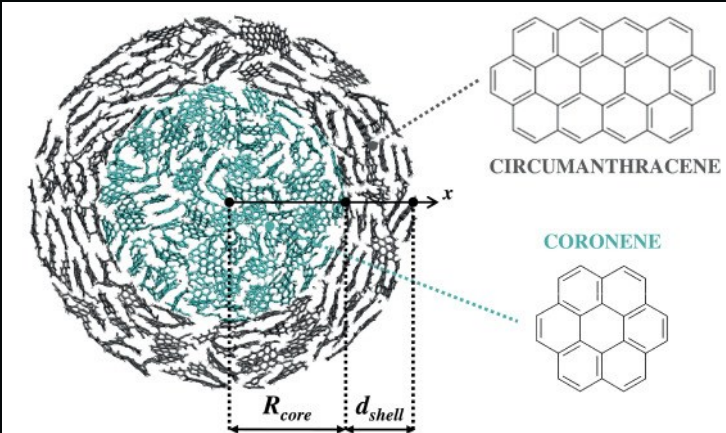
Squishing soot to measure hardness



Jenei, Istvan Zoltan, et al.
Nanotechnology 29.8 (2018): 085703.

Soot is hard like charcoal but has a softer centre

Pascazio, Laura, Martin, Jacob, et al.
Combustion and Flame 219 (2020): 45-56.

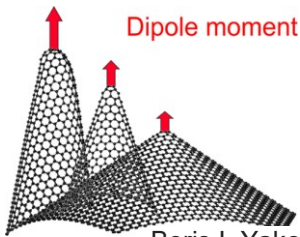
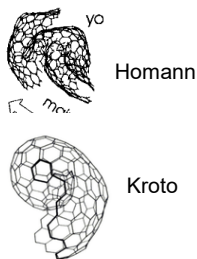


Markus Kraft



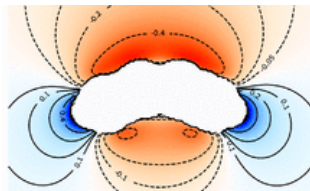
Laura Pascazio

First hypothesis – curved PAH + chemiions



Boris I. Yakobson

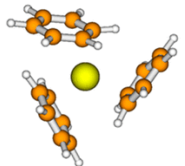
Kvashnin, Alexander G., Pavel B. Sorokin, and Boris I. Yakobson. *The Journal of physical chemistry letters* 6.14 (2015): 2740-2744.



Martin, Jacob W., et al. *The Journal of Physical Chemistry C* 121.48 (2017): 27154-27163.



Radomir Slavchov



Kolakkandy, S., Pratihari, S., Aquino, A. J., Wang, H., & Hase, W. L. (2014). *The Journal of Physical Chemistry A*, 118(40), 9500-9511.

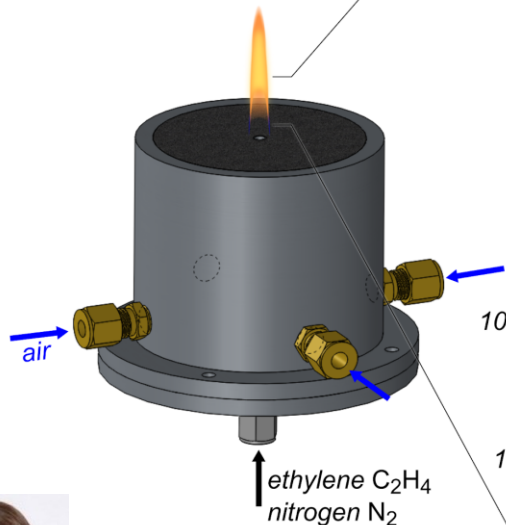


Hai Wang



Maria Botero

Martin, J. W., Botero, M., Slavchov, R. I., Bowal, K., Akroyd, J., Mosbach, S., & Kraft, M. (2018) *The Journal of Physical Chemistry C*, 122(38), 22210-22215.

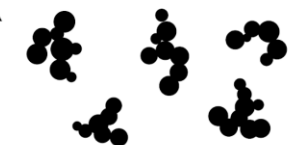


50 ms

10 ms

1 ms

reaction time



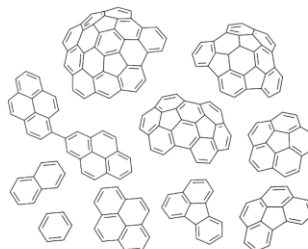
aggregates
50–500 nm



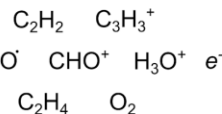
primary
particles
20–30 nm



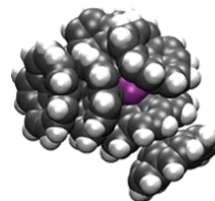
soot nuclei
1–3 nm



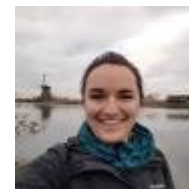
curved PAH
formation
0.5–1 nm



precursor
pyrolysis



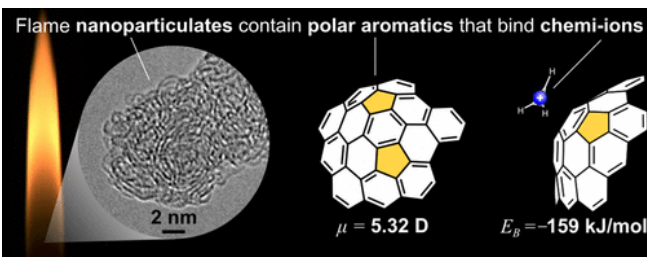
Bowal, K., Martin, J. W., Misquitta, A. J., & Kraft, M. (2019) *Combustion Science and Technology*, 191(5-6), 747-765.



Kimberly Bowal

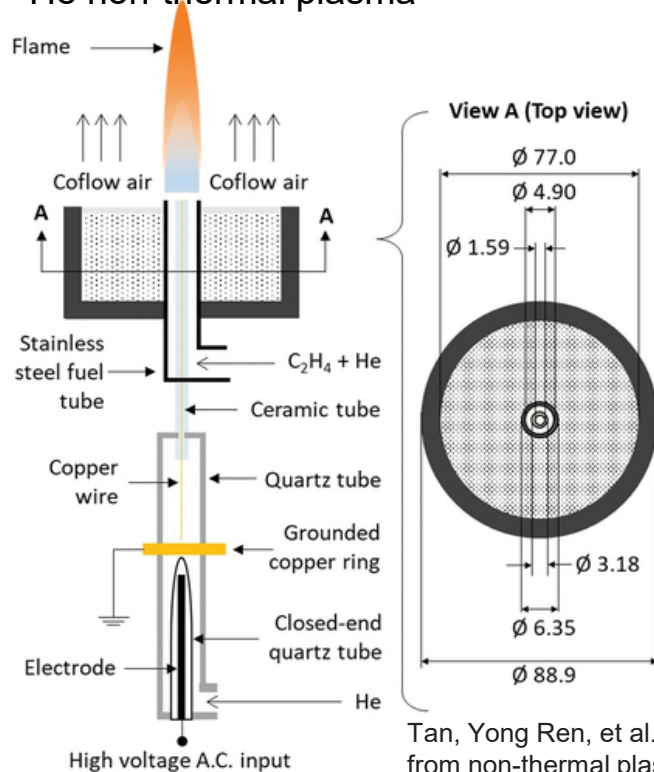


Alston J. Misquitta

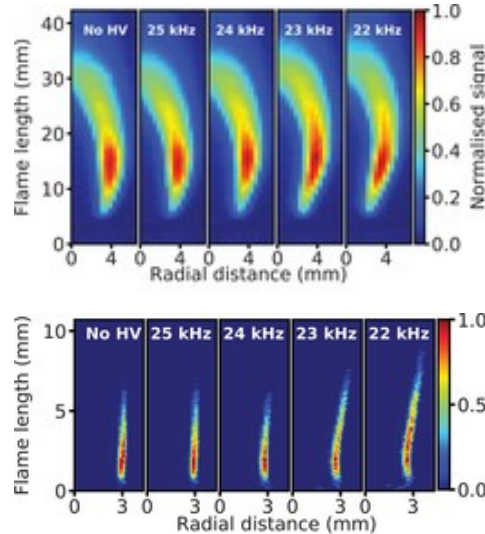


Non-thermal helium plasma injection

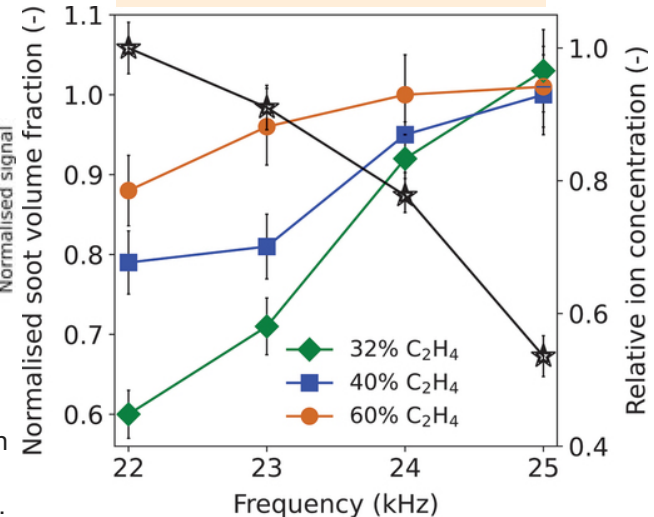
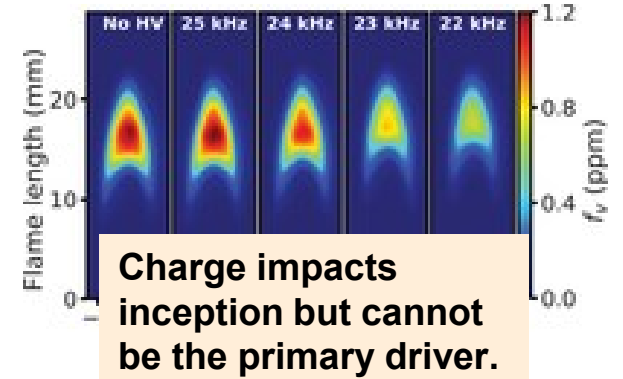
He non-thermal plasma



CH* and OH* not significantly changed

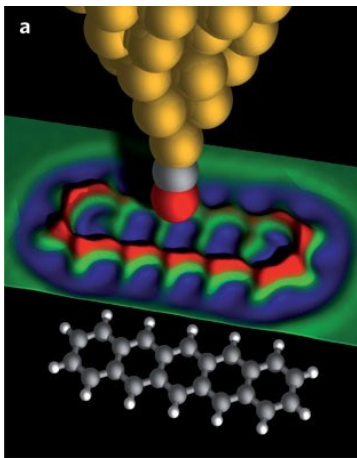


Soot emissions reduced



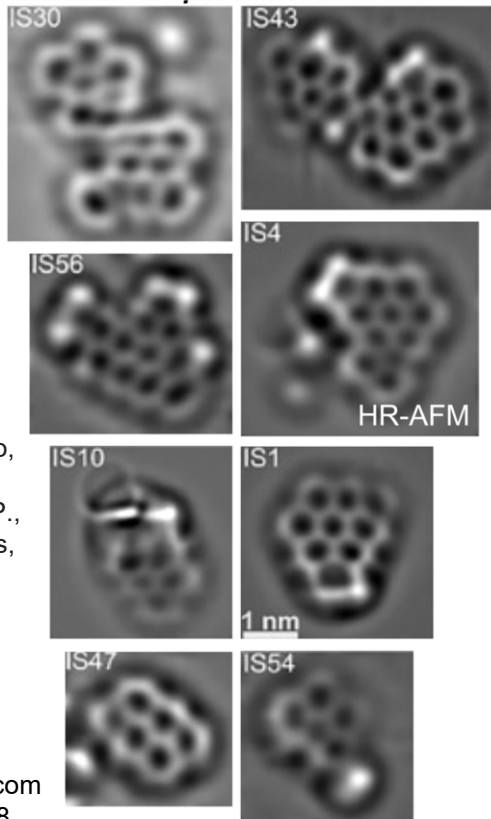
Tan, Yong Ren, et al. "Investigation on the effect of Charge injection from non-thermal plasma on soot formation in Laminar coflow diffusion flame." *Combustion Science and Technology* (2023): 1-22.

Reactive species – Dublin symp.



Schulz, F., Commado, M., Kaiser, K., De Falco, G., Minutolo, P., Meyer, G., ... & Gross, L. (2019). *Proceedings of the Combustion Institute*, 37(1), 885-892.

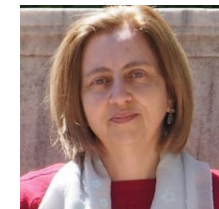
<https://www.nature.com/articles/nchem.1008>



Andrea D'Anna



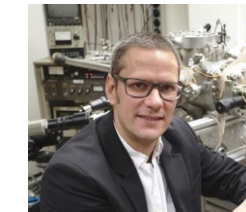
Mario Commado



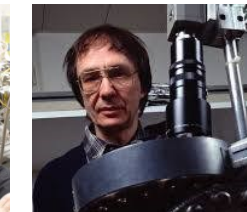
Patrizia Minutolo



Gianluigi De Falco



Leo Gross



Gerhard MEYER

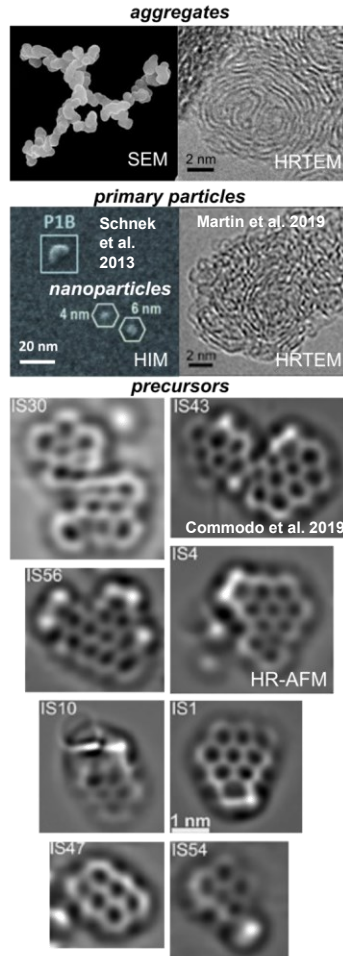
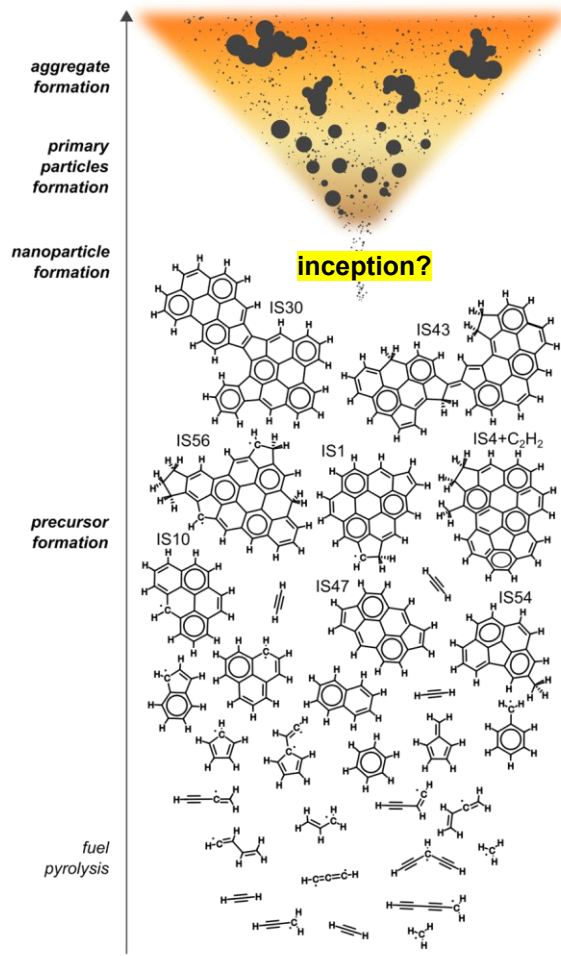


Fabian Schulz



Katharina Kaiser





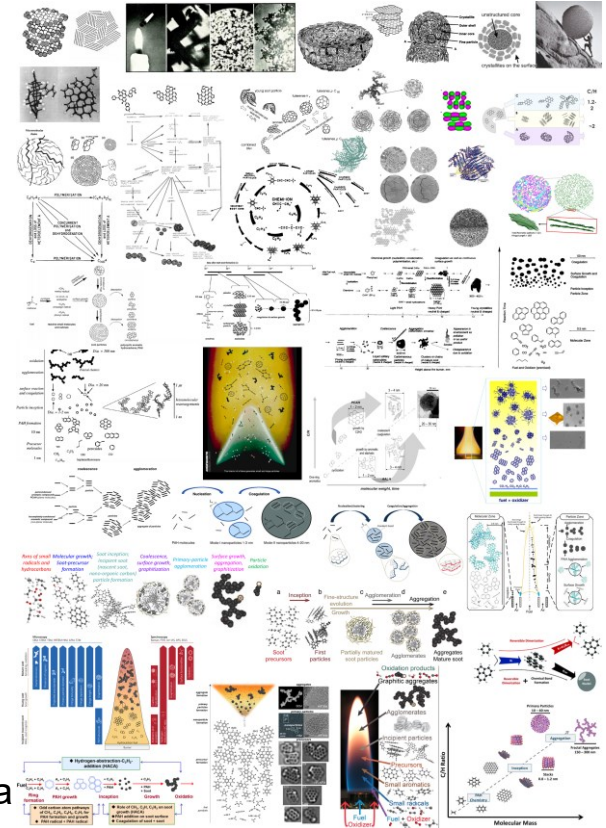
Martin, Jacob W., Maurin Salamanca, and Markus Kraft.
 "Soot inception: Carbonaceous nanoparticle formation in flames."
Progress in Energy and Combustion Science 88 (2022): 100956.

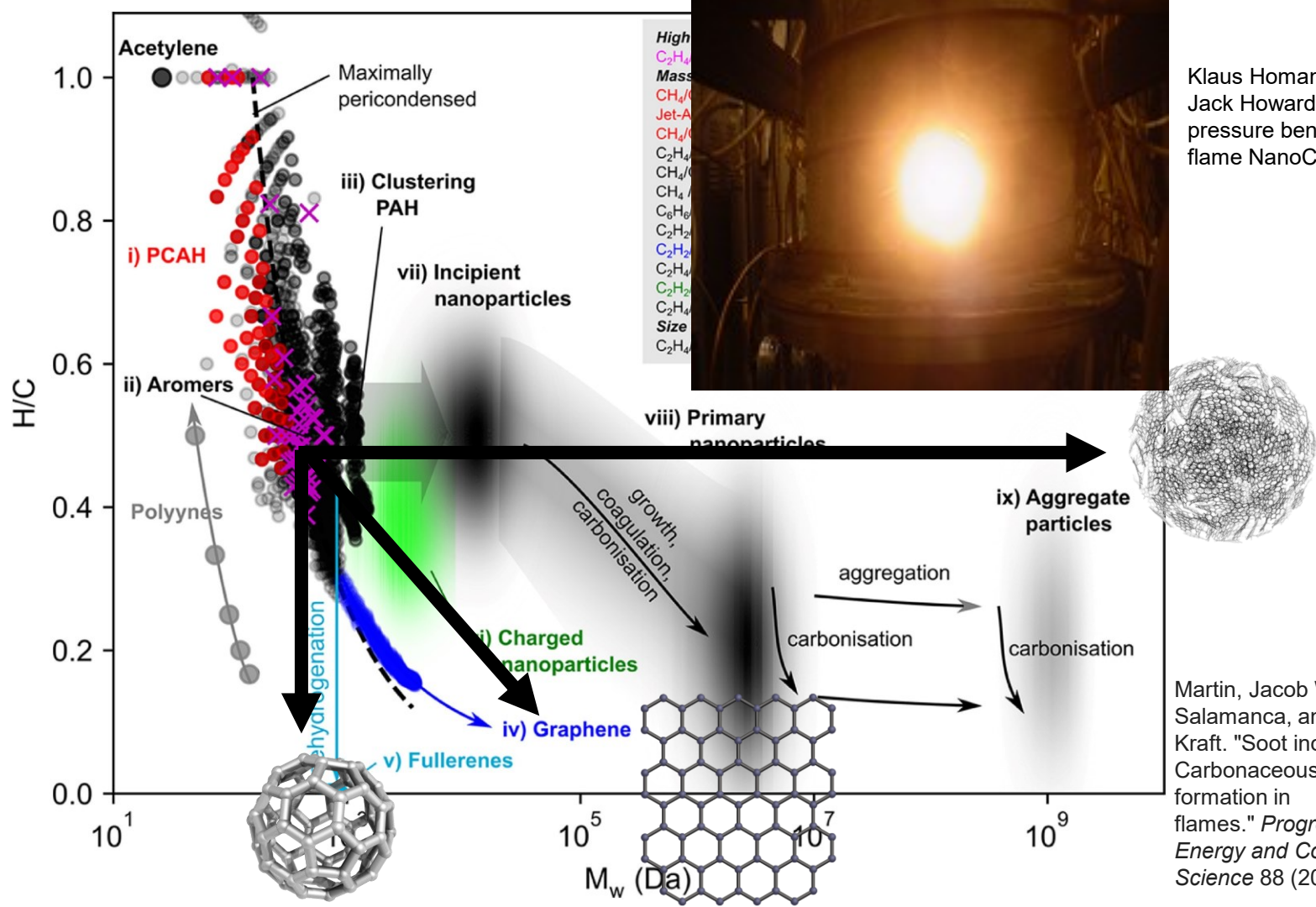


Markus Kraft



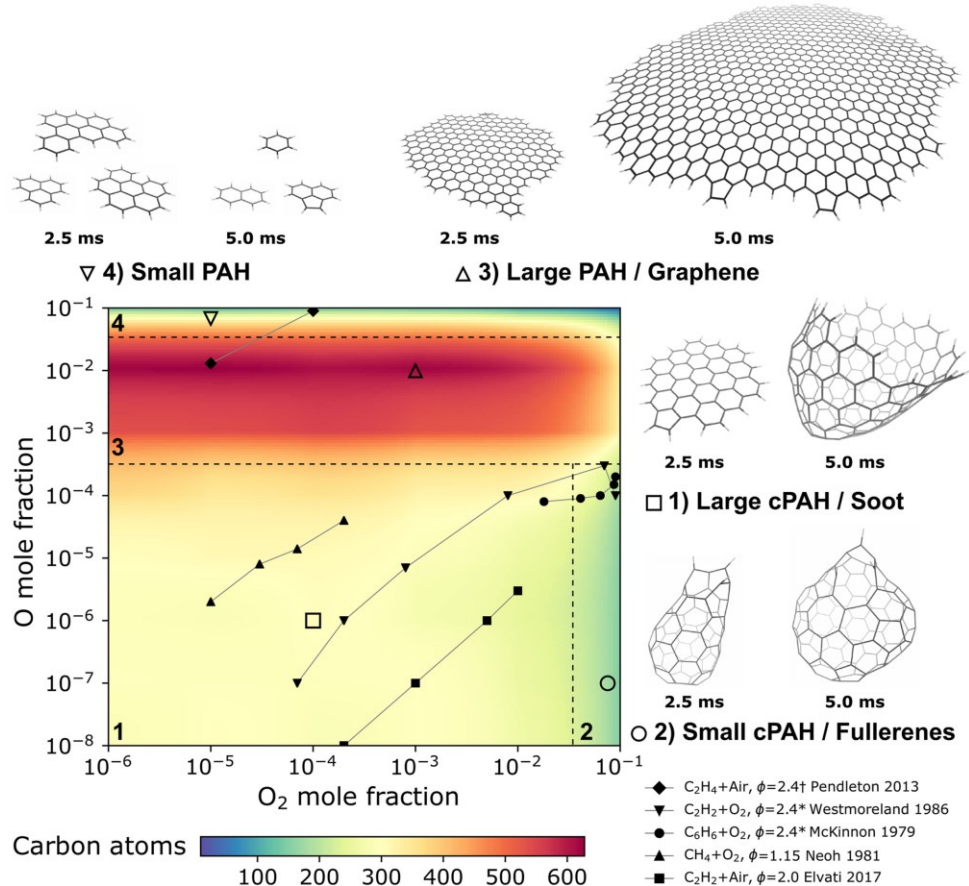
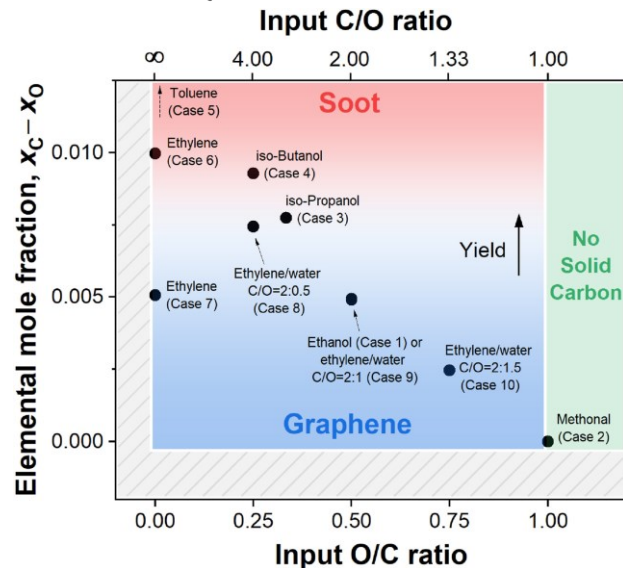
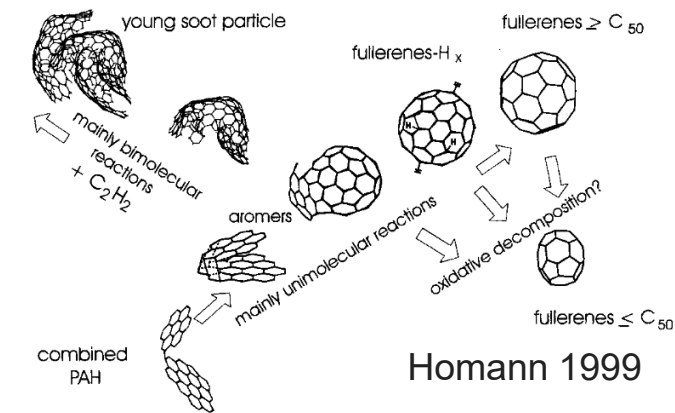
Maurin Salamanca



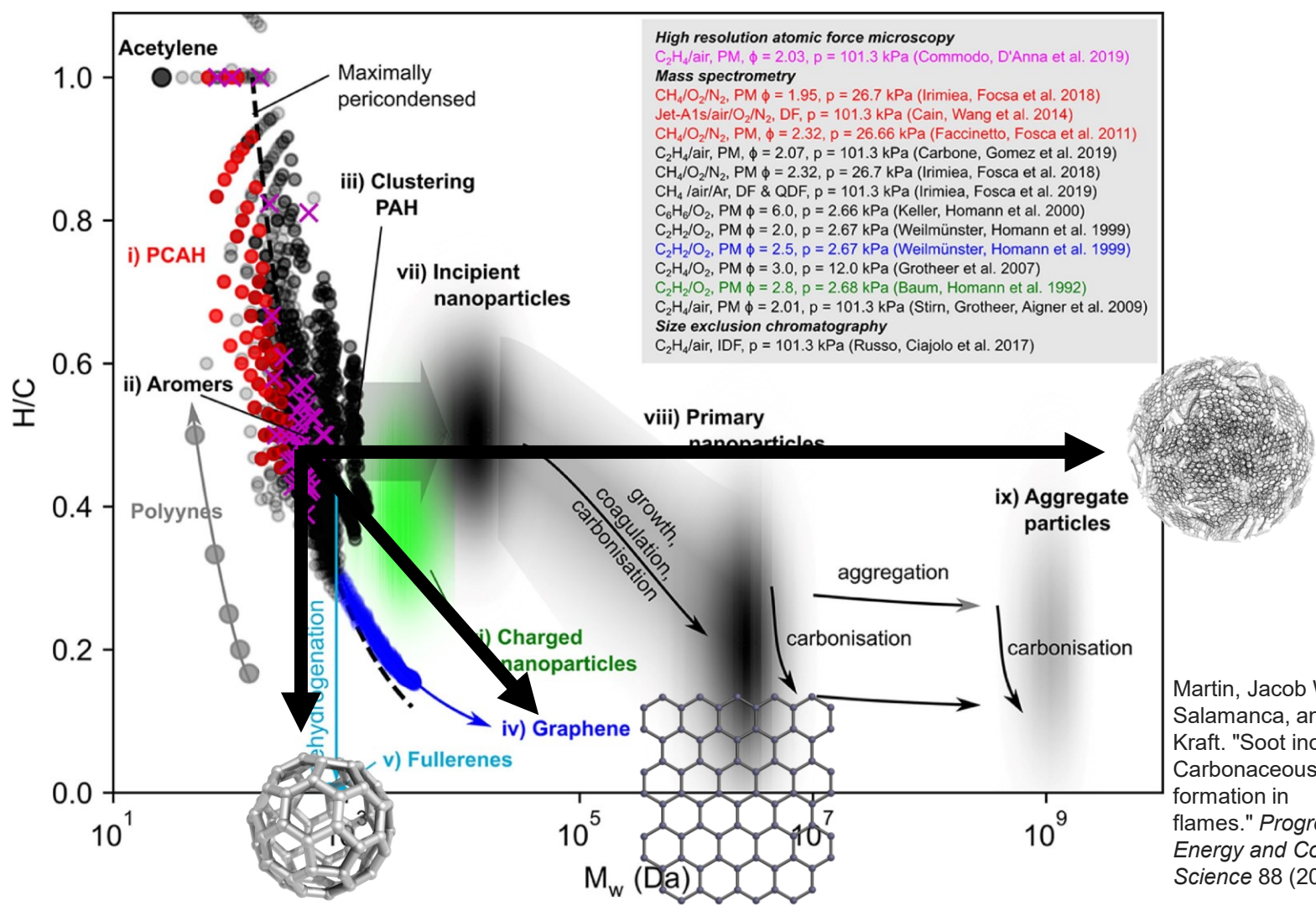


Klaus Homann
Jack Howard low-pressure benzene flame NanoC

Martin, Jacob W., Maurin Salamanca, and Markus Kraft. "Soot inception: Carbonaceous nanoparticle formation in flames." *Progress in Energy and Combustion Science* 88 (2022): 100956.



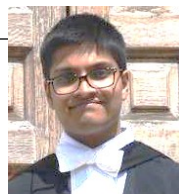
Leon, Gustavo, et al. "The role of oxygenated species in the growth of graphene, fullerenes and carbonaceous particles." *Carbon* 182 (2021): 203-213.



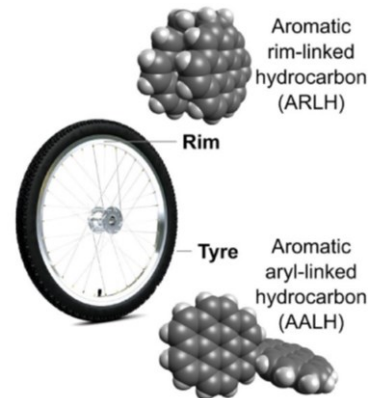
Martin, Jacob W., Maurin Salamanca, and Markus Kraft. "Soot inception: Carbonaceous nanoparticle formation in flames." *Progress in Energy and Combustion Science* 88 (2022): 100956.

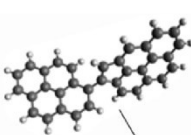
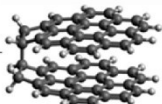
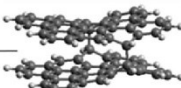
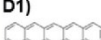
Kinetics of chemical mechanisms

Strong bonds but kinetics are slow



Angiras Menon



	aryl σ -radical	localised π -radical		delocal. π -radical	diradicaloid	rim-based pentagon	cPAH	low aromaticity		Classes		
	A1)	A2)	B1)	B2)	C)	D1)	D2)	E)	F1)	F2)	F3)	Structures
 aromatic aryl-linked hydrocarbons (AALH)	-130.4	-125.3	-97.3	-91.0	Chemical mechanisms are strong but kinetically slow					8.3	-36.2	
		-120.8	-92.6	-86.8							-33.7	-33.8
 aromatic rim-linked hydrocarbons (ARLH)			-61.9	-34.0	Localised π -radicals provide thermally stable bonds and stacking provides stability							
				-50.9								
aromatic multicentre-linked hydroc. (AMLH)					Delocalised π -radicals weak bonds							
 aromatic zigzag-linked hydrocarbons (AZLH)					Diradicaloids weak bonds							

Gaussian 16

bond energy,
(kcal/mol)

-190 -40

Chemical mechanisms are strong but kinetically slow

Localised π -radicals provide thermally stable bonds and stacking provides stability

Delocalised π -radicals weak bonds

Diradicaloids weak bonds

Martin, Jacob W., et al. "Reactivity of polycyclic aromatic hydrocarbon soot precursors: implications of localized π -radicals on rim-based pentagonal rings." *The Journal of Physical Chemistry C* 123.43 (2019): 26673-26682.

Menon, A., Martin, J. W., Akroyd, J., & Kraft, M. (2020). Reactivity of polycyclic aromatic hydrocarbon soot precursors: Kinetics and equilibria. *The Journal of Physical Chemistry A*, 124(48), 10040-10052.

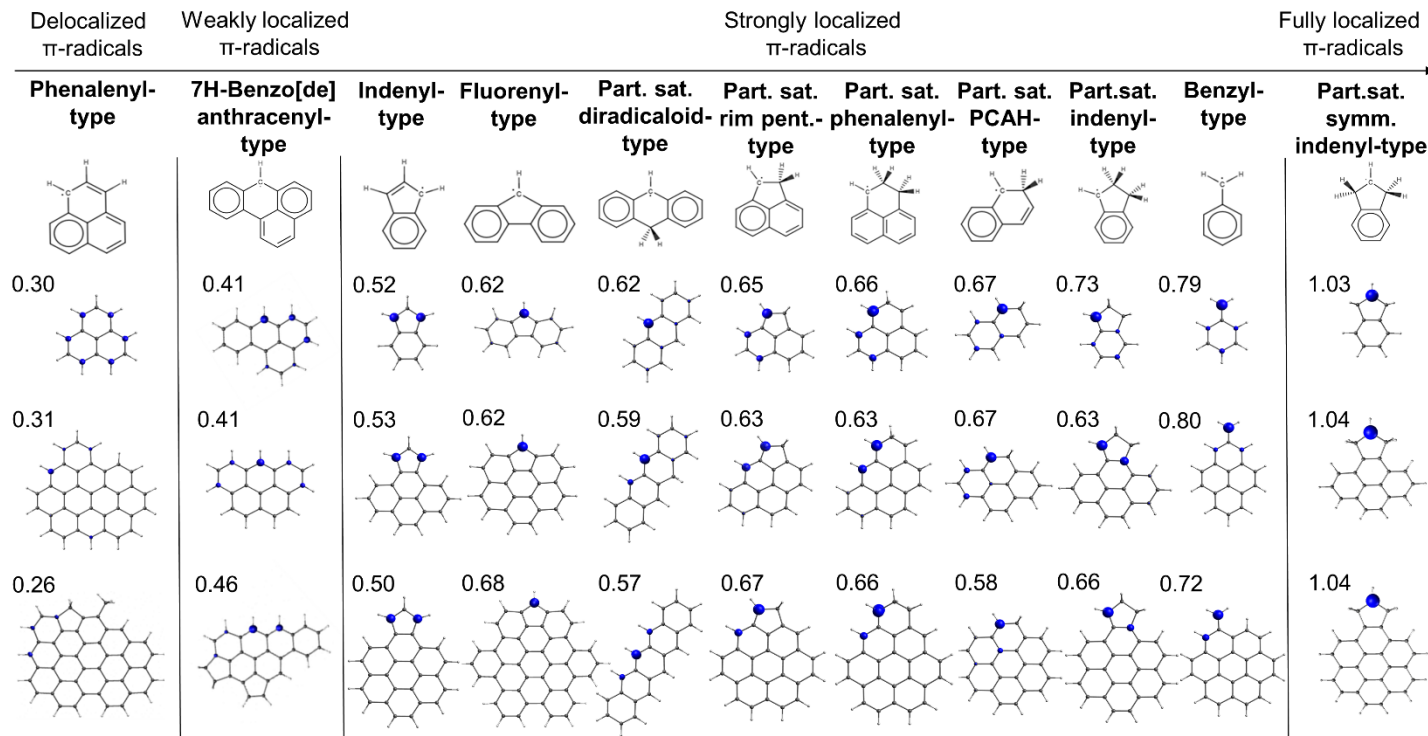
Electrons pinned to the edge

Localisation of π -radicals due to aromaticity

Selvakumar, Praveen K., et al. "Role of π -Radical Localization on Thermally Stable Cross-Links Between Polycyclic Aromatic Hydrocarbons." *The Journal of Physical Chemistry A* 127.33 (2023): 6945-6952.

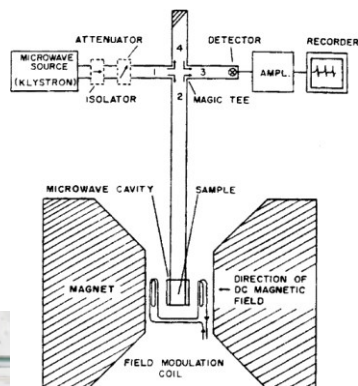


Praveen Selvakumar

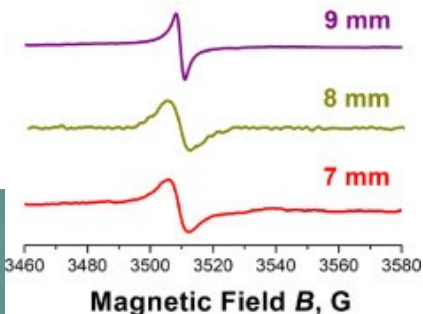


Electrons pinned to the edge

Electron paramagnetic resonance

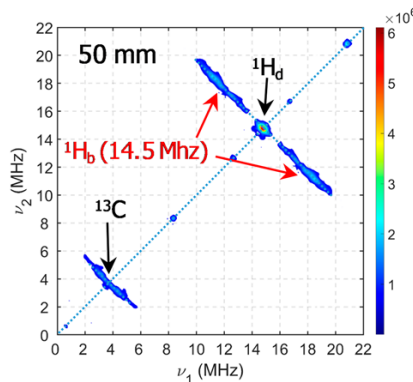


Vitiello, G., De Falco, G., Picca, F., Commiato, M., D'Errico, G., Minutolo, P., & D'Anna, A. (2019). Combustion and Flame, 205, 286-294.

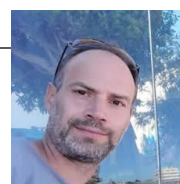
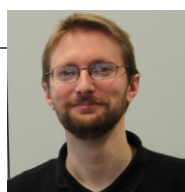


Alessandro Faccineto Xavier Mercier

Elias, J., Faccineto, A., Vezin, H., & Mercier, X. (2023). Communications Chemistry 6(1) 99



Evidence for localised pi-radicals from pulsed EPR experiments.



Herve Vezin

Methane pyrolysis for hydrogen production: carbon formation and nanostructure

Previous title: Character of n-radicals involved in carbon formation: A DFT study

Praveen K. Selvakumar,* Maurizio Di Lorenzo, Mark Paskevicius, Craig E. Buckley and Jacob W. Martin*, Physics and Astronomy, Curtin University, Perth, Australia, *p.selvakumar@postgrad.curtin.edu.au, jacob.w.martin@curtin.edu.au

Methane pyrolysis enables hydrogen production using renewable energy without carbon dioxide emissions but significant challenges remain:

- 1) How can the carbon nanostructure be controlled?
- 2) Can carbon reactor scaling be eliminated?
- 3) Can the reactivity of catalysts be maintained?

Our focus has been on understanding the key reactive species present in carbon formation and developing methods to characterise the carbon nanostructures formed during methane pyrolysis.

What are the reactive species involved in formation?

The software package ORCA (1) was used to perform the electronic structure calculations and geometry optimisation at the B3LYP/6-311++G(2p) level of theory with the EPR-II as a range of reactive radicals. EasySpin (2) was used to compare the electron paramagnetic resonance spectroscopy.

1) Localisation of π -electron needed for thermally stable crosslinks

Perfluorinated and methylene groups were used to concentrate the π -electron to enable thermally stable crosslinks, but which are important for carbon formation?

2) EPR spectroscopy suggests unsaturated π -radicals

Electron paramagnetic spectroscopy (EPR) measures the magnetic interactions between the unpaired π -radicals and the hydrogen protons through microwave absorption (4). In a magnetic field the Zeeman effect splits up and down electrons, which are further split by hyperfine interactions with protons.

Experimental broadening seen in the literature for soot sampled from flames.

Computed EPR spectrum for π -radicals unsaturated (left) and saturated (right)

3) Pulsed EPR suggests localised unsaturated π -radicals

Short microwave pulses can access forbidden transitions between hyperfine levels. Multipulse sequences are needed to capture the weak signal through repolarising an echo just like in NMR.

Experimental HSCORE spectrum of soot

Correlative HSCORE

Bending from strong orientational dependence of delocalised radicals

Localised radicals must closely reproduce experimental spectrum.

What are the carbon nanostructures produced?

We applied two techniques to differentiate the carbon structures produced in pyrolysis. Pulse heating to ultra-high temperatures inspired from laser heating.

Mild oxidation imaging of graph from a pyrolytic carbon from the University

1) Pulse heat

2) Mild oxidation

Pyrolytic carbon commercially sourced

Pyrolytic carbon

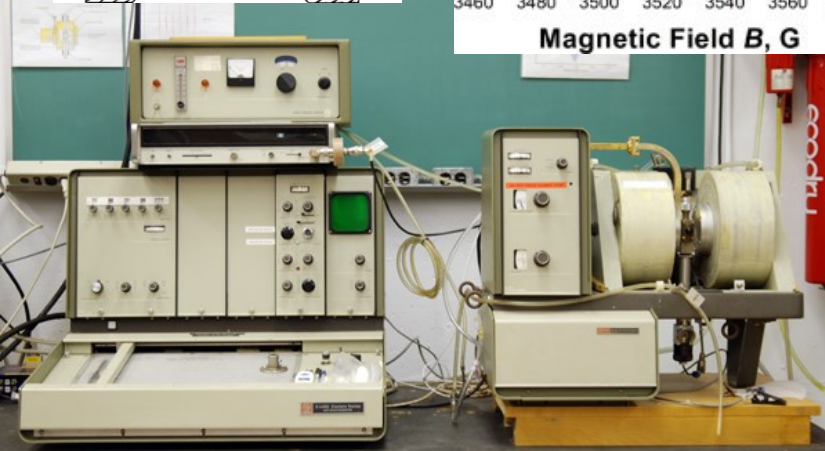
Clear edge structure

Hexagonal lattice

Disorder reveals shell

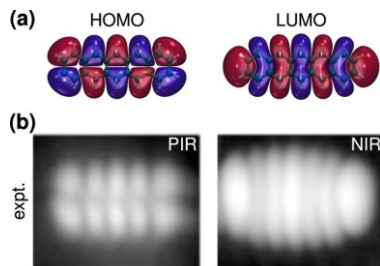
3) Raman shows regions of higher crystallinity in carbon film

Regions of high crystallinity appear to be due to surface ordering. HRD did not reveal any fast graphitisation but only slow graphitisation for the pyrolytic carbon



Electrons pinned to the edge

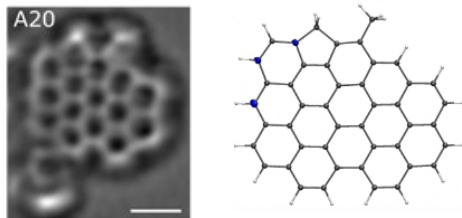
STM - π -electrons



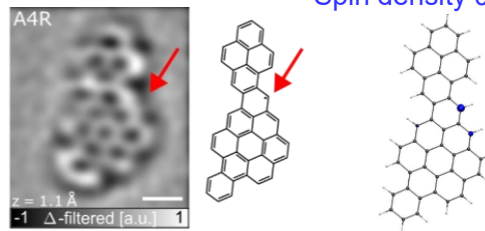
Leonard-Alexander
Lieske

Vasiliki
Benekou

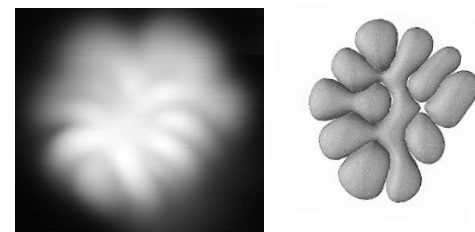
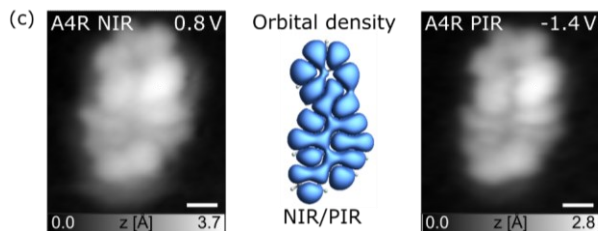
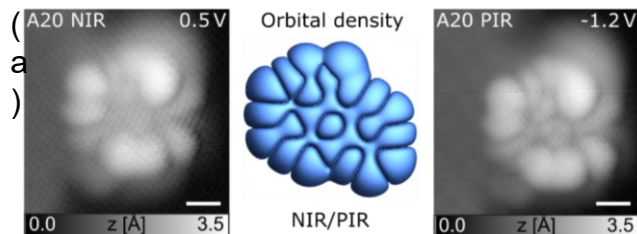
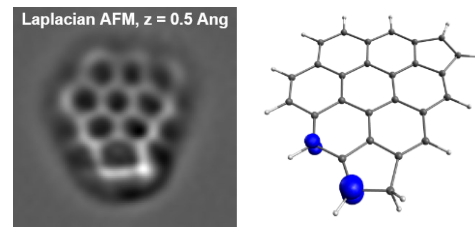
Spin density 0.26



Spin density 0.41



Spin density 0.67

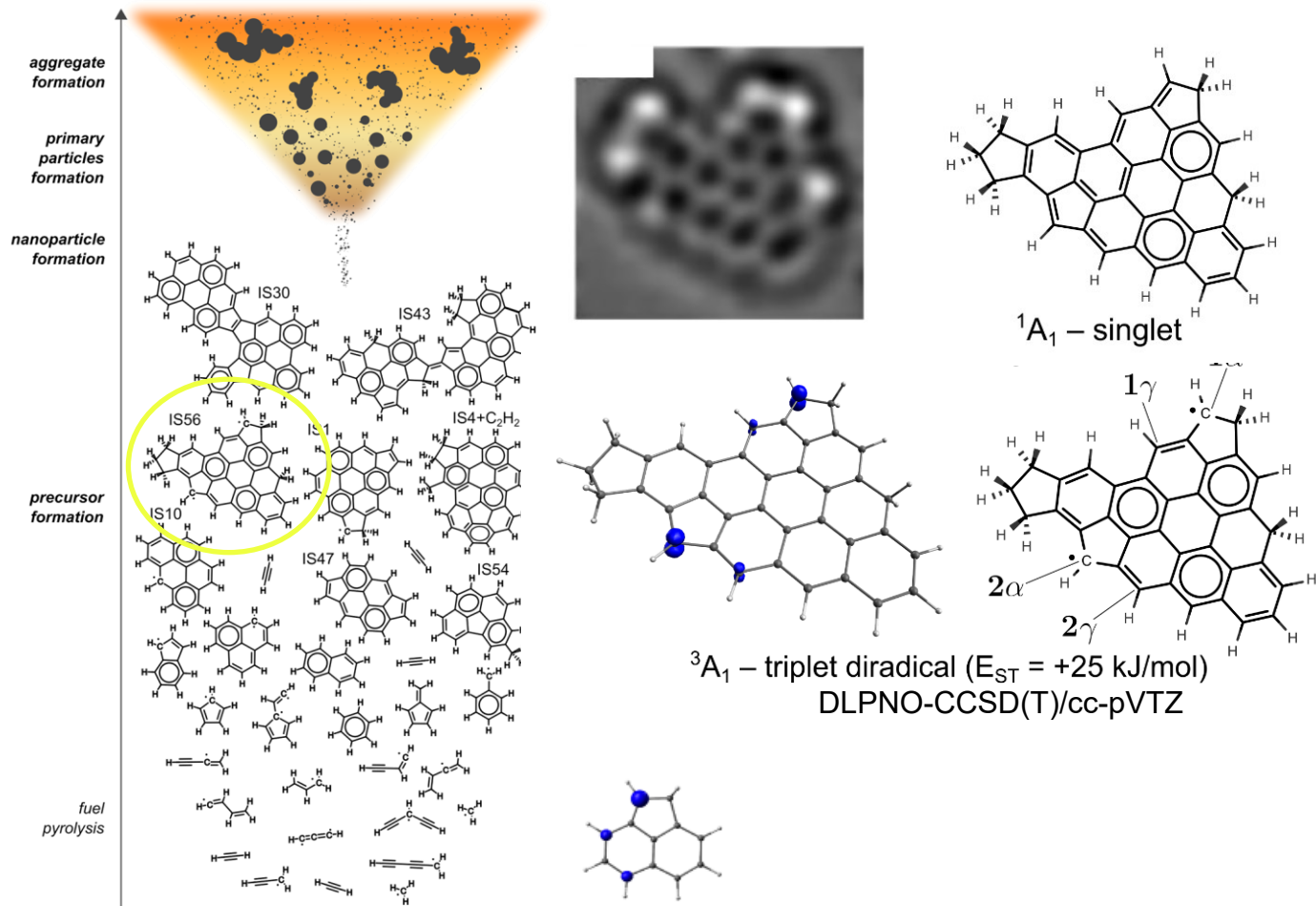


Portraits of Soot Molecules Reveal Pathways to Large Aromatics, Five-/Seven-Membered Rings, and Inception through π -Radical Localization

Leonard-Alexander Lieske,[#] Mario Commado,[#] Jacob W. Martin, Katharina Kaiser, Vasiliki Benekou, Patrizia Minutolo, Andrea D'Anna,^{*} and Leo Gross^{*}

Cite This: ACS Nano 2023, 17, 13563–13574

Read Online



π -Diradical Aromatic Soot Precursors in Flames

Jacob W. Martin,[▽] Laura Pascasio,[▽] Angiras Menon, Jethro Akroyd, Katharina Kai Mario Commodo, Andrea D'Anna, Leo Gross, and Markus Kraft[✉]

Cite This: *J. Am. Chem. Soc.* 2021, 143, 12212–12219

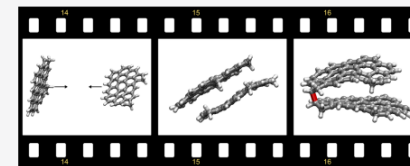
Read Online

ACCESS |

Metrics & More

Article Recommendations

Supp



ABSTRACT: Soot emitted from incomplete combustion of hydrocarbon fuels contributes to global warming. The mechanism by which soot nanoparticles form within hydrocarbon flames is still an unsolved science. Mechanisms proposed to date involving purely chemical growth are limited by slow reaction rates relying on solely physical interactions between molecules are limited by weak intermolecular interactions at temperatures. Here, we show evidence for a reactive π -diradical aromatic soot precursor imaged using microscopy. Localization of π -electrons on non-hexagonal rings was found to allow for Kekulé aromatic soot triplet diradical ground state. Barrierless chain reactions are shown between these reactive sites, which aromatic rim-linked hydrocarbons under flame conditions. Quantum molecular dynamics simulation condensation of aromatics that survive for tens of picoseconds. Bound internal rotors then enable the reaction and become chemically cross-linked before dissociation. These species provide a rapid, thermally stable carbon nanoparticle formation and could provide molecular targets for limiting the emission of these toxic compounds.

INTRODUCTION

Soot emitted into the atmosphere contributes to global warming, and when deposited on ice, soot lowers ice's albedo, increasing melting.¹ Recent estimates place the atmospheric radiative forcing of black carbon at 0.5–1.0 W/m², similar to that of methane.¹ Additionally, soot and other <2.5 μ m combustion products (PM_{2.5}) have been directly correlated with increased morbidity and respiratory diseases.² Most pressing is preliminary evidence that an increase of only 1 μ m³ of PM_{2.5} in the urban environment is associated with an 11% increase in COVID-19 related deaths (in preliminary data from the USA).³ Recent lockdown measures also demonstrated how quickly soot emissions can drop in the atmosphere with a 12% reduction in PM_{2.5} emissions in 50 major cities

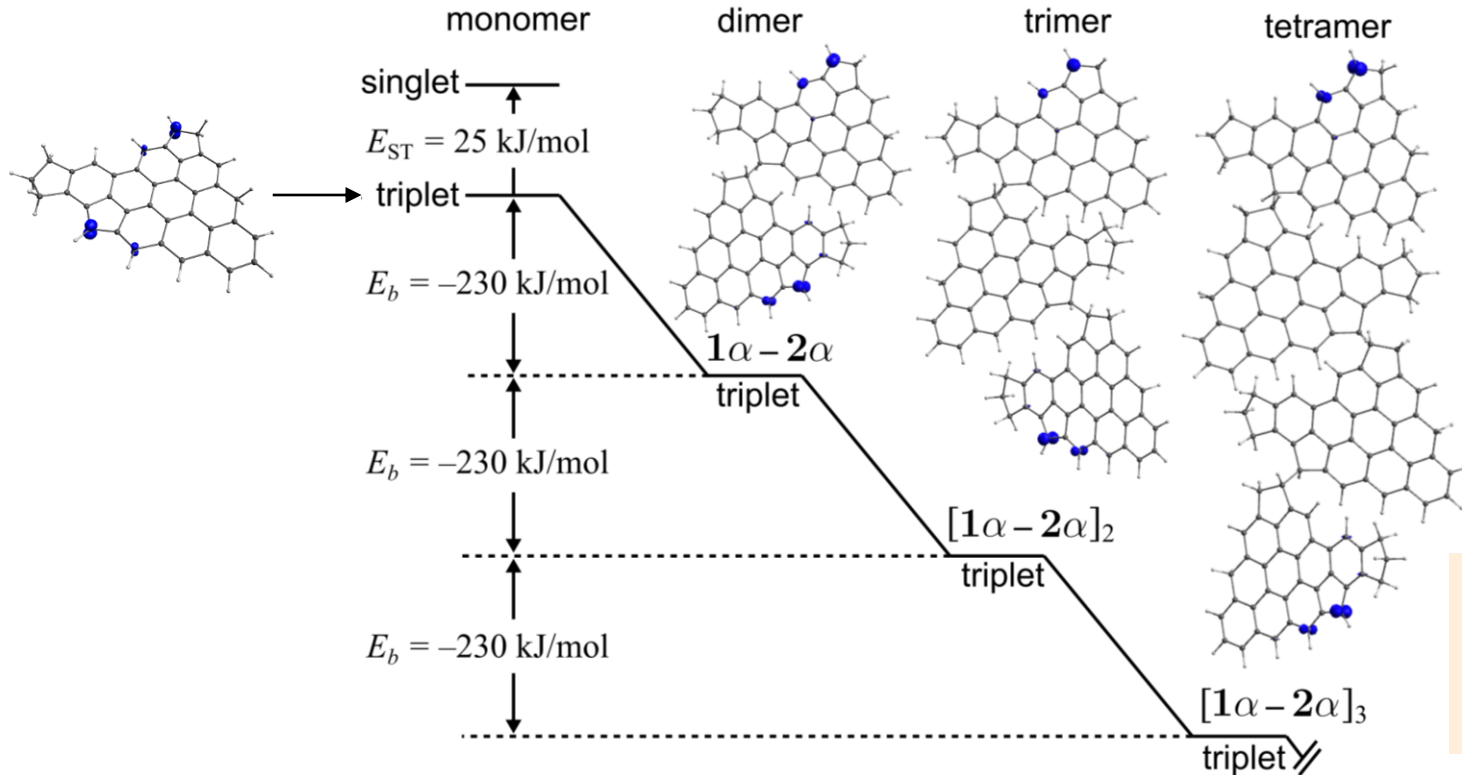
are found in the atmospheres of planets.

Thin.⁴ No predictive model yet exists for particle formation, inhibiting our ability to predict and tune new nanomaterials from combustion systems' produce and tune new nanomaterials from combustion systems' formation is inception (or nucleation) of aromatic soot precursors cluster to form a soot particle (Figure 1). Three main requirements for soot formation are: (1) The species involved in the reaction where reactivity or condensation through subsequent monomer addition must be thermally stable with bond

Received: May 15, 2021

Polymerisation

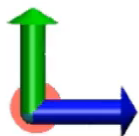
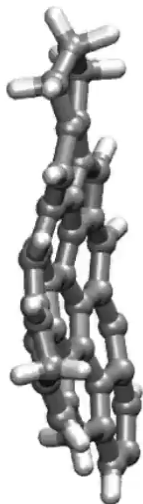
Barrierless chain reactions



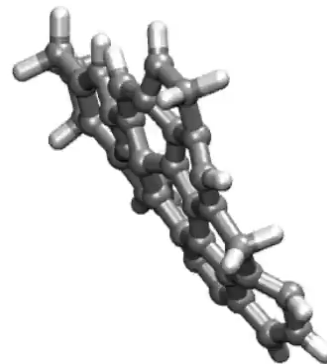
Polymerisation of aromatic rim-linked hydrocarbons (PARLH).

IS56 CLASSIC MD

MM (GROMACS): OPLS intramolecular and
isoPAHAP intermolecular
QM (ORCA): meta hybrid GGA DFT BS-M06-
2X/def2-SVP



0.00 ps



π -Diradical aromatic soot precursors in flames. Journal of the
American Chemical Society. 2021 Aug 2;143(31):12212-9.

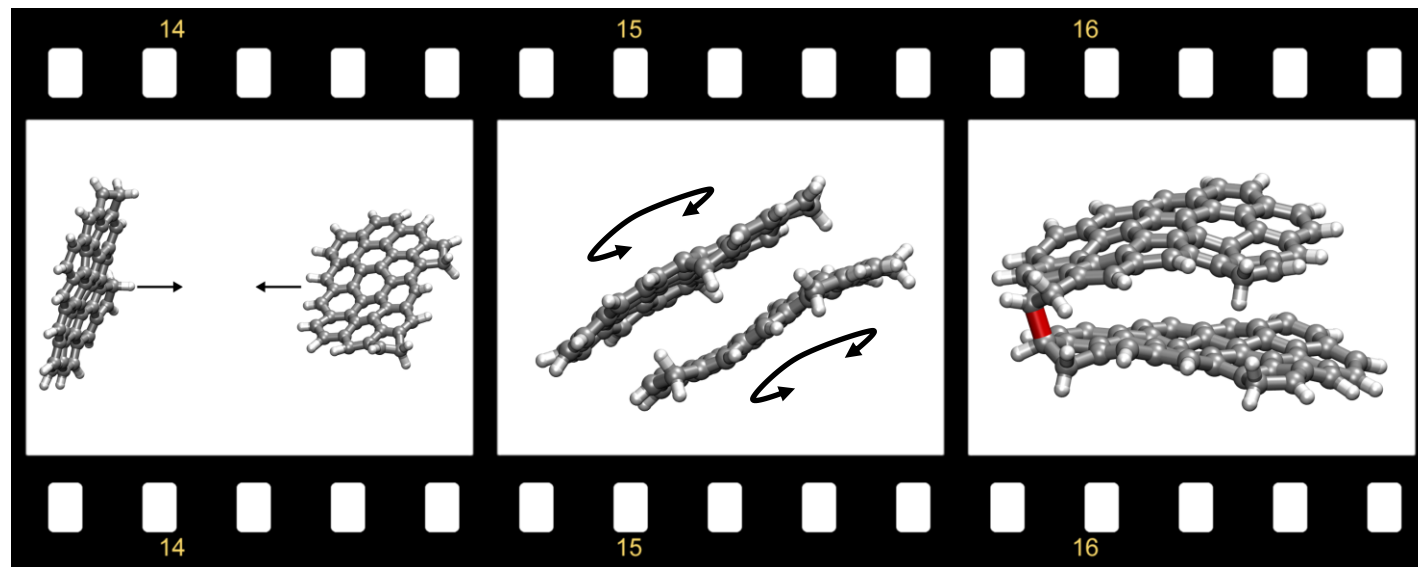


Laura Pascazio

Localised π -diradical

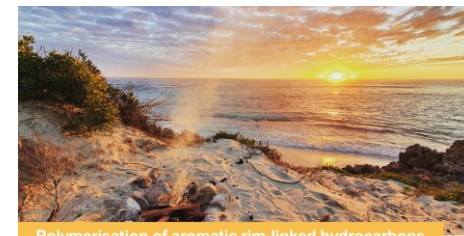
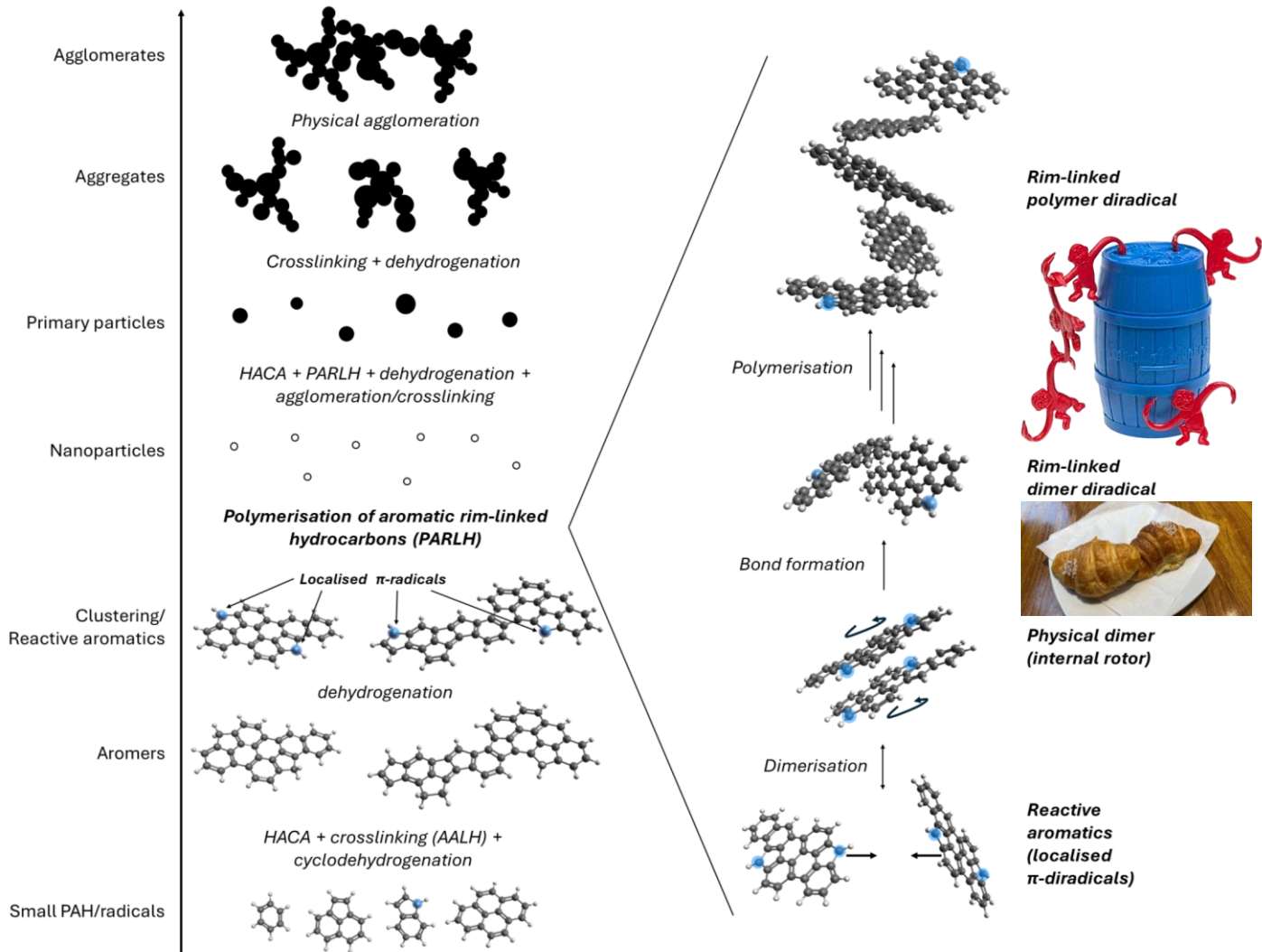
Condensation followed by bond formation – Physical + Chemical

π -Diradical aromatic soot precursors in flames. Journal of the American Chemical Society. 2021 Aug 2;143(31):12212-9.

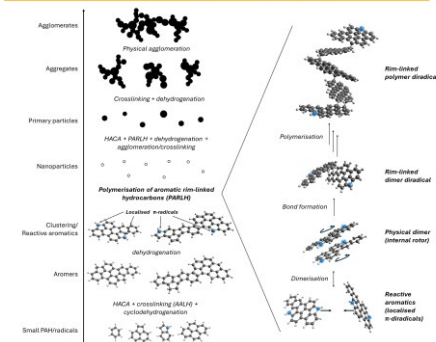


"We thus suggest that the activation of internal rotation creates "collisional events" between the edges of the rotating PAH that offer the opportunity for reaction to take place."
Frenklach and Mebel
2020

Physical condensation occurs first then internal rotors enable the reactive sites to find each other and react (not found for σ -diradicals).



Polymerisation of aromatic rim-linked hydrocarbons

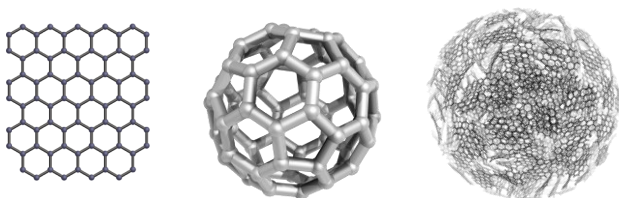
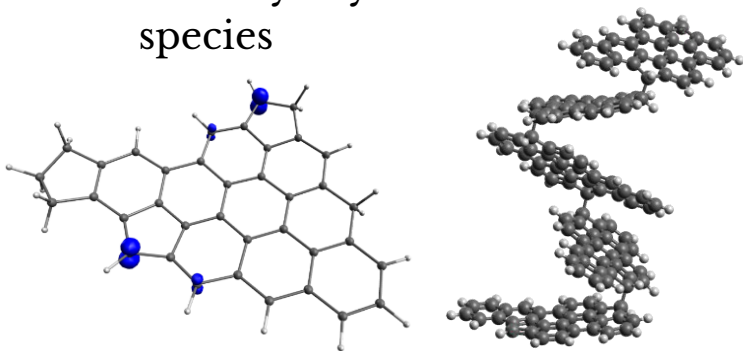


Dr Jacob Martin, Lecturer in Physics & Astronomy



Summary

1. Identify key reactive species
2. Control carbon nanostructures produced in pyrolysis



Methane pyrolysis for hydrogen production: carbon formation and nanostructure

Previous title: Character of n-radicals involved in carbon formation: A DFT study

Praveen K. Selvakumar,* Mauricio Di Lorenzo, Mark Paskevicius, Craig E. Buckley and Jacob W. Martin*, Physics and Astronomy, Curtin University, Perth, Australia, *p.selvakumar@postgrad.curtin.edu.au; jacob.w.martin@curtin.edu.au

Methane pyrolysis enables hydrogen production using renewable energy without carbon dioxide emissions but significant challenges remain;

1) How can the carbon nanostructure be controlled?
2) Can carbon reactor coking be eliminated?
3) Can the reactivity of catalysts be maintained?

Our focus has been on understanding the key reactive species present in carbon formation and developing methods to characterise the carbon nanostructures formed during methane pyrolysis.

Methane

reactive species?

Carbon materials

Hydrogen

Renewable energy

Luigi Piccaro, ChemSusChem (2022).

What are the carbon nanostructures produced?

We applied two techniques to differentiate the carbon structures produced in pyrolysis. Pulse heating to ultra-high temperatures inspired from laser heating of soot [5] and mild oxidation inspired from SEM imaging of graphite [6]. Samples were used from a commercial pyrolytic carbon and a carbon film from the University of Toronto.

1) Pulse heating to ultra-high temperatures using a custom furnace

Pyrolytic carbon commercially sourced

Carbon film produced from methane pyrolysis from Uni. Toronto

Heat treated in our custom graphite furnace to > 2800 °C one pulse 10 s

2) Mild oxidation before imaging in SEM resolves nanocarbons

Pyrolytic carbon

Carbon film

Clear edge structure

Contains carbon spherical particles and nanotubes

Loss of volatiles on shell surface attached to wall.

Hexagonal pitting

Two textures suggest particles held together by tar

Oxidation reveals shell structure of carbon sphere

3) Raman shows regions of higher crystallinity in carbon film

Regions of high crystallinity appear to be due to surface ordering. XRD did not reveal any fast graphitisation but only slow graphitisation for the pyrolytic carbon

What are the reactive species involved in formation?

The software package ORCA [1] was used to perform the electronic structure calculations and geometry optimisation at the B3LYP/6-311G(d,p) level of theory with the EPR-II on a range of reactive n-radicals. EasySpin [2] was used to compute the electron paramagnetic resonance spectroscopy.

1) Localisation of π -electron needed for thermally stable crosslinks

Pentagonal and methylene groups were found to concentration the π -electron to enable thermally stable crosslinks. But which are important for carbon formation?

2) EPR spectroscopy suggests unsaturated π -radicals

Electron paramagnetic spectroscopy (EPR) measures the magnetic interactions between the unpaired π -radicals and the hydrogens/protons through microwave absorption [4]. In a magnetic field the Zeeman effect splits spin up and down electrons, which are further split by hyperfine interactions with protons.

Experimental broadening seen in the literature for soot sampled from flames.

Computed EPR spectrum for π -radicals unsaturated (left) and saturated (right)

3) Pulsed EPR sup

Short microwave pulses can access forbidden transitions between hyperfine levels. Multiple sequences are needed to capture the weak signal through rephasing an ensemble in NMR.

Experimental HYSCORE spectrum of soot

Computed HYSCORE

Bending from strong orientational dependence of π -radicals

most closely reproduce experimental spectrum.

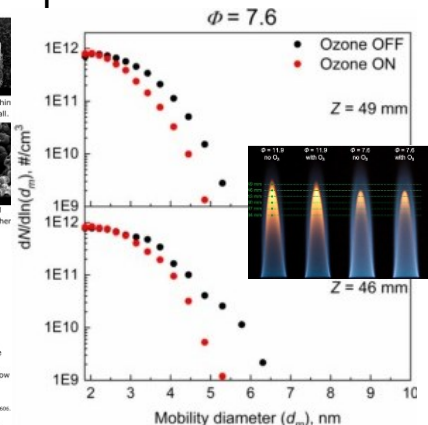
Praveen Selvakumar

REFERENCES

[1] T. Neese, F. Weig, Wiley Interdisciplinary Reviews: Computational Molecular Science 12.3 (2022): e1006.
 [2] S. Stoll, H. Pfeifer, and J. Schaefer, Journal of Magnetic Resonance 176, 1 (2006): 42-50.
 [3] S. Stoll, H. Pfeifer, and J. Schaefer, Journal of Magnetic Resonance 176, 1 (2006): 42-50.
 [4] S. Stoll, H. Pfeifer, and J. Schaefer, Journal of Magnetic Resonance 176, 1 (2006): 42-50.
 [5] S. Stoll, H. Pfeifer, and J. Schaefer, Journal of Magnetic Resonance 176, 1 (2006): 42-50.
 [6] S. Stoll, H. Pfeifer, and J. Schaefer, Journal of Magnetic Resonance 176, 1 (2006): 42-50.



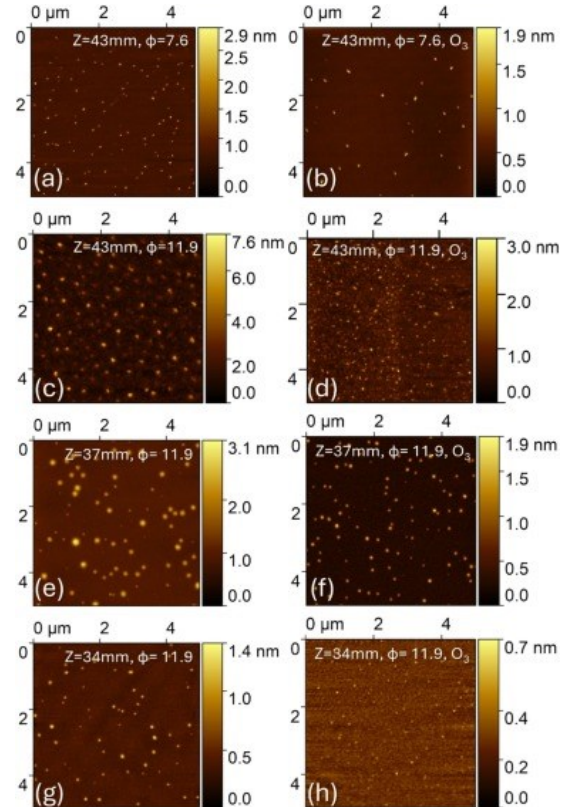
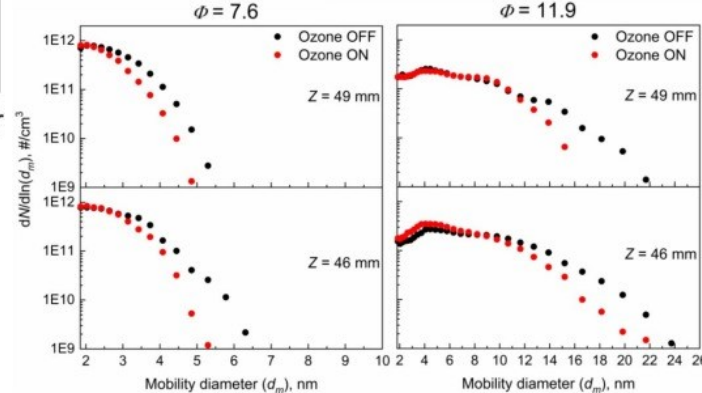
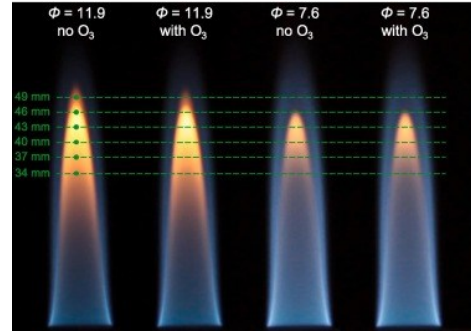
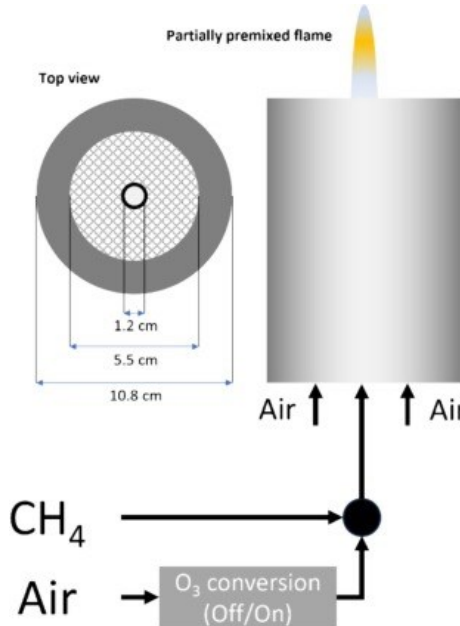
Luca Basta Poster Ozone injection



Ozone injection



Luca Basta
Poster



Basta, Luca, Alessia Pignatelli, Fabio Sasso, Francesca Picca, Mario Commendo, Patrizia Minutolo, Jacob W. Martin, and Andrea D'Anna. "The effect of ozone on soot formation in partially premixed laminar methane/air flames." *Fuel* 373 (2024): 132342.

