Properties of 2D Noble Gases

M. Längle[1,2] F. Castioni[1] D. Lamprecht[2,3] P. Nandi[4] K. Mustonen[2] T. Susi[2] J. Kotakoski[2] M. Kociak[1] L. Tizei[1]

[1]University Paris-Saclay, CNRS, Laboratoire de Physique des Solides, 510 Rue André Rivière, Paris, 91405, France
[2]University of Vienna, Faculty of Physics, Boltzmanngasse 5, Vienna, 1090, Austria
[3]Institute for Microelectronics, TU Vienna, Gusshausstrasse 27-29, Vienna, 1040, Austria
[4]Laboratory of Electron Nanoscopies (LENS), University of Barcelona, Carrer de Martí i Franquès, 1, 11, 08028 Barcelona, Spain

Using low-energy ion implantation, it is possible to create small 2D noble gas crystallites by trapping them between layers of 2D materials [1]. These encapsulated noble-gas systems represent a new model platform for two-dimensional (2D) condensed-matter physics.Noble gases are non-reactive due to their outer electron shell being filled. Their interactions are governed by the van der Waals interaction, making them easy-to-understand model systems for complex processes. One example of this is condensed noble gases on cryogenic surfaces, one of the first experimental 2D systems studied in the 1960s [2]. Studying this system directly, however, is experimentally challenging. Here, 2D materials come into play. Beyond their extraordinary intrinsic properties, they can be used as ultrathin, impermeable membranes [3] confining atoms and molecules in nanometer-scale volumes [4,5]. As such, they have also been used as imaging substrates in (Scanning) Transmission Electron Microscopy ((S)TEM) studies [6,7]. In this work, multilayers of different 2D materials were irradiated with ultra-low energy noble gas ions to implant them into the van der Waals gap between the layers. This trapping between 2D materials results in 2D crystals of dense noble gases under a pressure of up to 3 GPa exerted by the graphene.Atomic-resolution STEM combined with (monochromated) electron energy loss spectroscopy (EELS) at elevated and low temperatures is used to study this system. Noble gases should be relatively non-reactive; however, in a similar system, a Kr dimer within a 1D carbon structure, it was found that the Kr-Kr bond length indicates covalent bonding after ionization via the imaging electron beam [8], in line with a recent theoretical study on covalent bonding of ionized noble gas atoms [9].We have observed indications of non-van der Waals bonding in clusters, both using EELS and by studying the atomic arrangement, which raises the question of which mechanism governs the system. Additionally, encapsulation and temperature control allow us to investigate the melting of these clusters in 2D, where we observed a surprising process involving 1D liquid chains. The results suggest that inert atoms can be forced to bond chemically when confined at high pressures within atomically thin cavities under electron irradiation.Noble gases encapsulated between 2D materials constitute a versatile platform for exploring different phenomena in condensed-matter physics. By combining encapsulation in van der Waals materials with atomic-resolution STEM and EELS, we create a powerful playground for future 2D condensed-matter research.

[1] Manuel Längle, Kenichiro Mizohata, Clemens Mangler, Alberto Trentino, Kimmo Mustonen, E. Harriet Åhlgren, Jani Kotakoski, *Nature Materials* **23**, 762-767 (2024).

[2] Joshua Jortner, Lothar Meyer, Stuart A. Rice, und E. G. Wilson, *The Journal of Chemical Physics* **42**, 4250-4253 (1965).

[3] J. Scott Bunch, Scott S. Verbridge, Jonathan S. Alden, Arend M. van der Zande, Jeevak M. Parpia, Harold G. Craighead, and Paul L. McEuen, *Nano Letters* **8**, 2458-2462 (2008).

[4] Philipp Valerius, Charlotte Herbig, Moritz Will, Mohammad A. Arman, Jan Knudsen, Vasile Caciuc, Nicolae Atodiresei, and Thomas Michely, *Physical Review B* **96**, 235410 (2017).

[5] Herbig, Charlotte, und Thomas Michely, *2D Materials* **3**, 025032 (2016).

[6] Rasim Mirzayev, Kimmo Mustonen, Mohammad R. A. Monazam, Andreas Mittelberger, Timothy J. Pennycook, Clemens Mangler, Toma Susi, Jani Kotakoski, Jannik C. Meyer, *Science Advances* **3**, e1700176 (2017).

[7] Matthias Kühne, Felix Börrnert, Sven Fecher, Mahdi Ghorbani-Asl, Johannes Biskupek, Dominik Samuelis, Arkady V. Krasheninnikov, Ute Kaiser, Jurgen H. Smet, *Nature* **564**, 2018 (234-239).

[8] Ian Cardillo-Zallo, Johannes Biskupek, Sally Bloodworth, Elizabeth S. Marsden, Michael W. Fay, Quentin M. Ramasse, Graham A. Rance, Craig T. Stoppiello, William J. Cull, Benjamin L. Weare, Richard J. Whitby, Ute Kaiser, Paul D. Brown, and Andrei N. Khlobystov, *ACS Nano* **18**, 2024 (2958-2971).

[9] Araujo, Lucas, Felipe Fantuzzi, und Thiago M. Cardozo, *The Journal of Physical Chemistry Letters* **15**, 2024 (3757-3763).