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Structural adaptations of electrosprayed aromatic oligoamide foldamers on Ag(111)

Dennis Meier,^{†a} Benedikt Schoof,^{†a} Jinhua Wang,^b Xuesong Li,^b Andreas Walz,^a Annette Huettig,^a Hartmut Schlichting,^a Frédéric Rosu,^c Valérie Gabelica,^d Victor Maurizot,^b Joachim Reichert,^a Anthoula C. Papageorgiou,^{*a} Ivan Huc^{*e,f} and Johannes V. Barth^{a,f}

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Aromatic foldamers are promising for applications such as molecular recognition and molecular machinery. For many of these, defect free, 2D-crystalline monolayers are needed. To this end, submonolayers were prepared in ultra-high vacuum (UHV) on Ag(111) via electrospray controlled ion beam deposition (ES-CIBD). On the surface, the unfolded state is unambiguously identified by real-space single-molecule imaging using scanning tunnelling microscopy (STM) and it is found to assemble in regular structures.

Aromatic foldamers adopt particularly stable and predictable conformations and constitute useful molecular platforms for applications in molecular recognition,^{1–6} transport through bilayer membranes^{7–9} or molecular machinery.^{10–12} They also feature interesting charge transport properties.^{13–16} In the case of oligoamides of 8-amino-2-quinoline-carboxylic acid (Q_n , Fig. 1a), helical conformations are extremely stable in solution due to hydrogen bonding (dotted blue lines in Fig. 1a). An unfolding is also hindered through repulsive interaction between the oxygen atoms of the peptide bonds and the quinolines' nitrogen (grey arrows in Fig. 1a). For example, an octamer shows no denaturation at 120 °C in dimethyl sulfoxide¹⁷ and its helix handedness inversion is kinetically locked in water.¹⁸ These helices also show strong resistance to mechanical extension.¹⁹ No experimental conditions have been

found to date under which unfolded (extended) or misfolded conformations would be significantly populated.

In the course of charge transport studies of these compounds, monolayers of thiol-functionalized helices on gold were produced.^{14–16} Despite having the expected thickness for upstanding helices, these monolayers did not show high order, presumably due to limited surface diffusion preventing epitaxial growth. On the other hand, various helical polymers have been found to self-assemble on surfaces, albeit with their helix axes parallel to the surface plane.^{20, 21} We endeavoured into constructing 2D-crystalline monolayers of the previously described oligoamide foldamers by a completely different approach, using an in-house developed ES-CIBD system (Fig. 1e).^{22, 23} This method exploits electrospray ionisation to bring molecular ions to the gas phase and transfer them to UHV. After mass filtering, the extracted ions are soft landed on a solid surface with controlled energy and dose.^{24–26} ES-CIBD allows for the deposition of objects that would be too fragile, reactive or large for the sublimation required by organic molecular beam epitaxy.^{27, 28} Here we report of pyr- Q_4 and pyr- Q_7 oligomers revealing the formation of ordered arrays on an atomically planar Ag(111) surface in a surprising unfolded[†] flat ribbon conformation (Fig. 1c,d) analysed by STM. Complementary ion mobility measurements indicate that the ions are helically folded in the gas phase and the unfolding occurs on the metal surface.

Pyr- Q_4 and pyr- Q_7 (Fig. 1a, synthesis in ESI) were designed with a pyrene foot expected to provide affinity to the surface yet without hampering mobility. As with the related aromatic foldamers, single crystal data show that pyr- Q_4 has a helical form (Fig. 1b, details in ESI). Fig. 1f,g show the mass spectra for the two foldamer species measured with a digital quadrupole mass filter (dQMF) as part of the ES-CIBD system prior to deposition (see ESI for experimental parameters). Pyr- Q_4 has only one peak at around 1230 Th, which corresponds to $[\text{pyr-}Q_4+\text{H}]^+$ (see compound characterisation along with synthesis details in ESI). Pyr- Q_7 has two major peaks at 1957 Th, $[\text{pyr-}Q_7+\text{H}]^+$, and 979 Th, $[\text{pyr-}Q_7+2\text{H}]^{2+}$. Only the singly charged

^a Physics Department E20, Technical University Munich, D-85748 Garching, Germany. E-mail: a.c.papageorgiou@tum.de

^b CBMN (UMR 5248), Univ. Bordeaux, CNRS, Bordeaux INP, F-33600 Pessac, France.

^c Institut Européen de Chimie et Biologie (UAR3033/US001), Univ. Bordeaux, CNRS, INSERM, F-33600 Pessac, France.

^d ARNA (U1212), Univ. Bordeaux, INSERM, CNRS, F-33600 Pessac, France.

^e Department of Pharmacy, Ludwig-Maximilians-University Munich, D-81377 Munich, Germany. Email: ivan.huc@cup.lmu.de

^f Cluster of Excellence e-conversion, D-85748 Garching, Germany

[†] These authors contributed equally to this work.

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cations were deposited (blue windows in Fig. 1e,f). It is proposed that the additional protons of $[\text{pyr-Q}_n + \text{H}]^+$ species will spill over to the silver surface at room temperature (r.t.)^{29,30} and form adsorbed pyr-Q_n and atomic H. The latter recombines to form gaseous H_2 .³¹

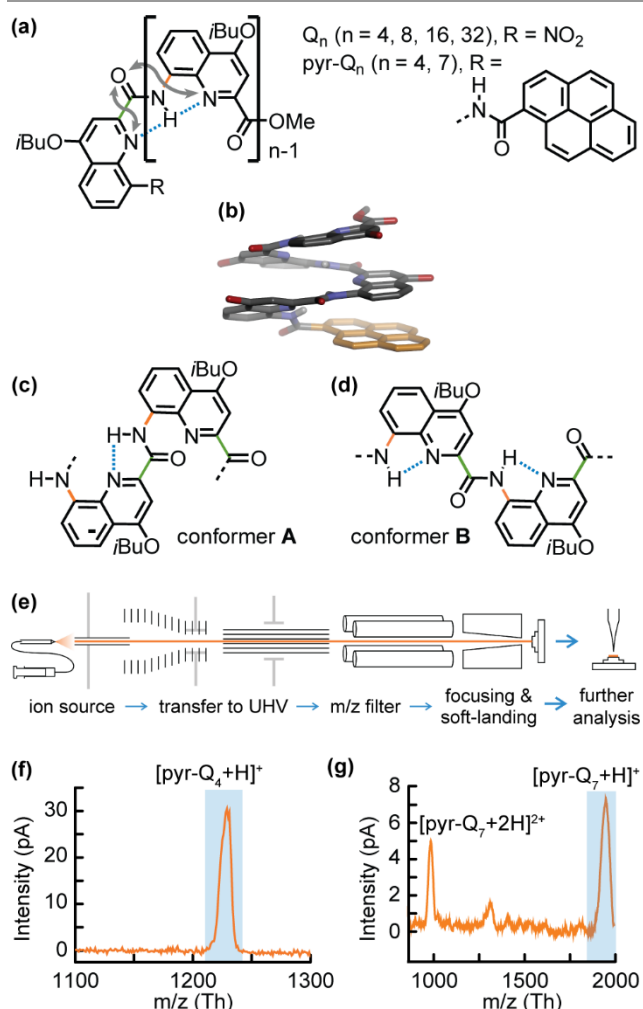


Fig. 1 (a) Chemical formula of Q_n and pyr-Q_n foldamers. Blue dotted lines point out hydrogen bonds and grey arrows show electrostatic repulsion. The aryl-amine and aryl-carbonyl bonds are coloured in green and orange, respectively. (b) Crystal structure of pyr-Q_4 (isobutyl groups and hydrogen atoms omitted for clarity). Ribbon structures of unfolded[†] molecule through either (c) rotation of the aryl-amine bonds (green) or (d) rotation of the aryl-carbonyl-bond (orange). (e) Schematic of the ES-CIBD system. Mass spectra prior to ES-CIBD of (f) pyr-Q_4 and (g) pyr-Q_7 . The m/z regions used for deposition emphasized with blue badges.

We started our investigation with the deposition of pyr-Q_4 . The mean landing energy was set to ~ 4.5 eV/z per molecule, as a trade-off of the ion current optimisation. The adsorbed pyr-Q_4 on Ag(111) was too mobile to image at r.t.. Fig. 2a depicts the structure of a highly-ordered island stabilised at 170 K. Its periodicity is characterised by a unit cell containing two molecules rotated by 180° and is described by the epitaxial matrix $\begin{pmatrix} 11 & 3 \\ 7 & 14 \end{pmatrix}$ (marked in blue in Fig. 2a). This corresponds to a submonolayer concentration of 0.21 molecules per nm^2 . A single molecule is identified by a constellation of five major protrusions (see blue and green dots in Fig. 2b) forming a zig-

zag like structure and four small protrusions (orange dots in Fig. 2b) at the side. The latter can be associated with the *iso*-butoxy (*i*BuO) side groups at the quinoline core. Therefore, the protrusions marked green can be associated with the quinoline units. Notably, the terminal related protrusion is larger, presumably due to the methyl ester end group at the quinoline. The protrusion marked blue can be assigned to the pyrene foot. Hence, the molecules appear adsorbed in an intact, unfolded[†] yet organized, flat ribbon state on the Ag(111) surface. The self-assembled structure seems to be driven by attractive van der Waals interactions between the *i*BuO side groups. Extended aromatic oligoamide ribbons were hitherto reported to form solely under a stretching force.¹⁹ Nevertheless, less stable polyacetylene helices have also been shown to unfold into ribbons on graphite.³² In fact, the conformational flexibility and unfolding of ribbons on surfaces may control their self-assembly, as exemplified recently by employing diene surface folding to form open chains and shape-persistent macrocycles.³³

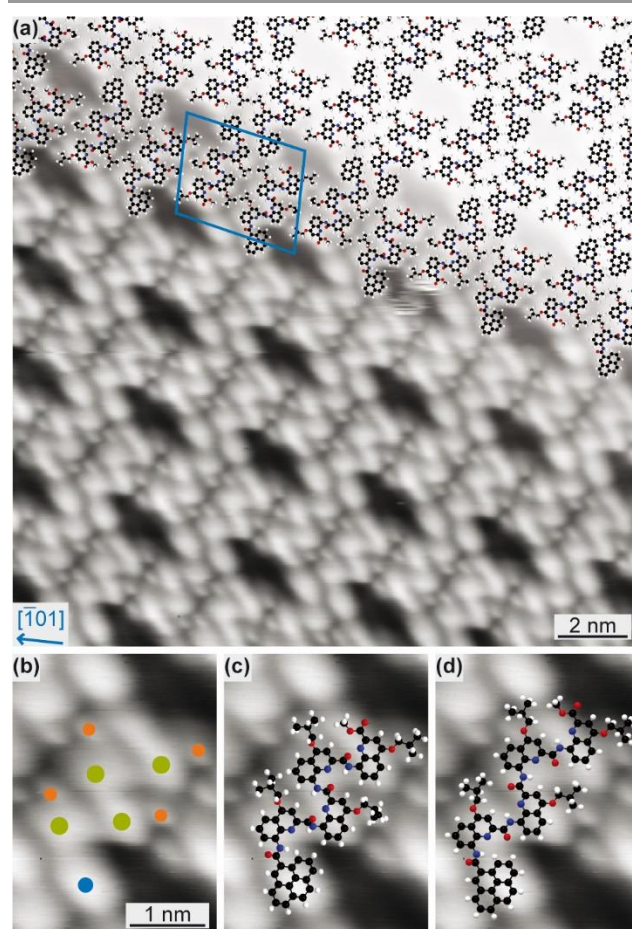


Fig. 2 STM of pyr-Q_4 on Ag(111). (a) Overview image (1500 mV, 100 pA, 170 K) partially overlaid with molecules. C, N, O and H atoms in black, blue, red and white, respectively. The unit cell is indicated in blue. A blue arrow shows a high symmetry direction of the Ag substrate. (b-d) High resolution STM image (1500 mV, 30 pA, 170 K). In (b) Blue, green and orange dots mark the moieties of a single molecule assigned to pyrene, quinoline and *i*BuO, respectively. Rotamer A and rotamer B are overlaid over the STM data in (c) and (d), respectively. Only rotamer A fits the STM data.

To further understand the extended flat conformation of the adsorbed molecules, we considered different planar geometries. Rotations of the aryl-amine bonds (orange in Fig. 1c) and /or of the aryl-carbonyl bonds (green in Fig. 1d) between the quinolines can give rise to planar, ribbon conformations. Due to the regularity of the structure, we assumed that the same rotation takes place between every quinoline unit. With these considerations, two conformations of the extended foldamer were examined: through rotations of either all aryl-amine bonds (rotamer **A**) or all aryl-carbonyl bonds (rotamer **B**). The latter produces the most stretched conformation whereas the former corresponds to a shorter ribbon-like structure. The geometries of these rotamers on the Ag(111) surface were optimised by molecular mechanics (ESI Fig. S4a,b). Comparison with the high-resolution STM data (Fig. 2b,c) reveals that only rotamer **A** fits the STM image. This is somewhat surprising given the strong repulsion between iminic N and the carbonyl (Fig. 1c) in rotamer **A** which is in principle even less favoured than rotamer **B**.³⁴ However, electrostatic repulsions may be screened by the image charges in the metal surface.³⁵

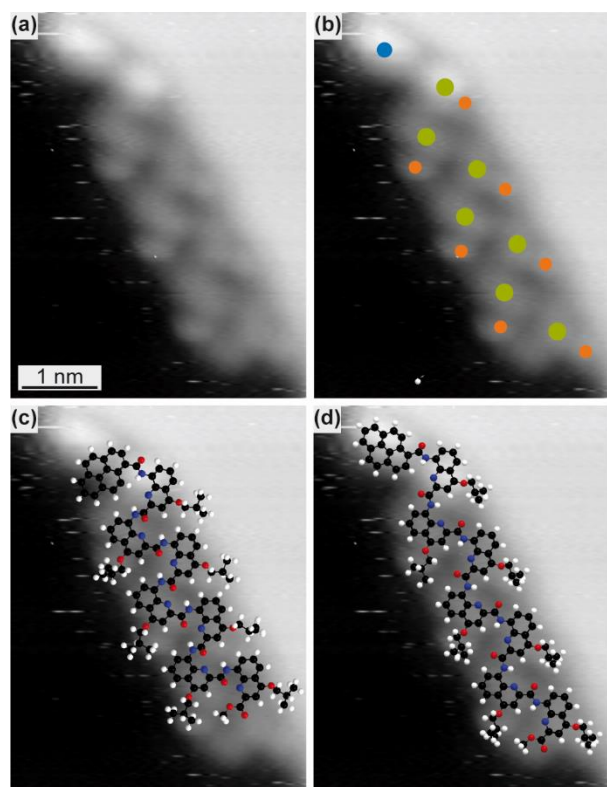


Fig. 3 (a) STM image (-1250 mV, -80 pA, 160 K) of pyr-Q₇ on the step edge of Ag(111) (b) Pyrene, quinoline, *t*BuO groups marked on the STM image in blue, green and orange, respectively. STM image overlaid with (c) rotamer **A'** obtained through rotation of all aryl-amine bonds and (d) rotamer **B'** obtained through rotation of all the aryl-carbonyl bonds.

For comparison, the single positively charged [pyr-Q₇+H]⁺ was deposited by similar spraying parameters and landing energy per charge (4.5 eV/z). At 160 K, the molecules were found immobilised exclusively at the step edges of the Ag(111) surface (see Fig. 3a). Individual molecules are distinguished by

eight major protrusions marked by green and blue dots in Fig. 3b. This corresponds well to the STM imaging of the extended pyr-Q₄ with five major protrusions (compare Fig. 2b and 3b). The protrusions assigned to the pyrene, quinoline, *t*BuO groups are marked by blue, green and orange dots, respectively (Fig. 3b). As for pyr-Q₄, the corresponding compact and extended rotamers **A'** and **B'** were considered and their geometries optimised on Ag(111) (ESI Fig. S4c,d). When the two simulated molecular structures are overlaid on the STM image (Fig. 3c,d), rotamer **B'** matches better (Fig. 3c) in contrast to rotamer **A** adopted by the smaller pyr-Q₄. It is therefore deduced that the unfolding occurs independently of the length of the foldamer and that different stereoisomers are expressed on the surface, presumably depending on the surface adsorption site (terrace vs. step edge).

Following this analysis, the question arises whether the unfolding occurs during the spraying or upon adsorption. To answer this, ion mobility spectroscopy (IMS) measurements were carried out on a series of Q_n helical molecules with *n* ranging from 4 (less than two helix turns) to 32 (almost 13 helix turns). These experiments allow one to estimate the size of ions in the gas phase after electrospray ionization. Fig. 4 shows a linear relation of the collisional cross section (CCS) of the different Q_n molecules and their mass. Calculated CCS values based on theoretically optimised structures are in excellent agreement with the experimental data (see ESI). The linear evolution of the CCS with the size of the foldamer indicates a perfectly cylindrical (*i.e.* compact helical) shape and therefore a conservation of the foldamers' compact helical conformation in the gas phase. Notably, no changes of the CCS are found with increasing charge state up to four for Q₃₂. Thus, also Q_n molecules with higher charge state are in a helical structure during electrospray ionisation. Additionally, the charge states of Pyr-Q₄ and pyr-Q₇ ions within the presented experiments further support a helical structure (see ESI section 4.1). It is thus reasonable to extrapolate that the pyr-Q_n molecules will retain their helical form following the electrospray ionisation and that the observed unfolding only occurred on the Ag(111) surface.

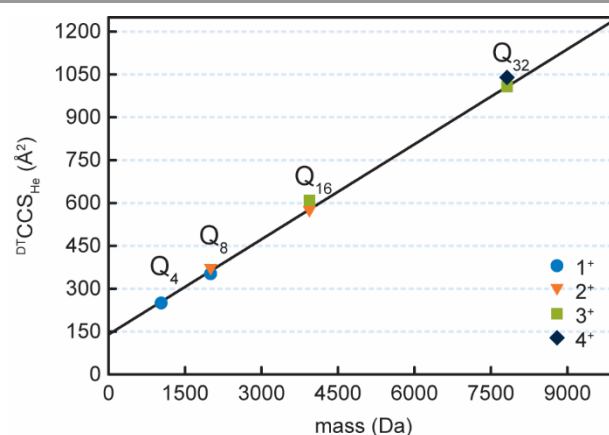


Fig. 4 Evolution of the collisional cross section ($^{DT}CCS_{He}$) as a function of the Q_n mass. The linear regression ($R^2 = 0.99$) indicates a perfectly cylindrical shape.

A variety of factors can account for the structural change after landing. These include the high affinity of the aromatic

units towards the metal surface, the screening of electrostatic repulsion by the metal surface (which eventually overrides intramolecular forces), deposition at r.t. and a kind of “reactive landing” caused by the impinging energy of 4.5 eV/z, which is considered to be “less soft”.²⁵ This shall be evaluated in follow up experiments.

In summary, we reported on the adsorption of flat extended pyr-Q₄ and pyr-Q₇ molecules on Ag(111) in UHV after deposition via ES-CIBD. Through IMS measurements, we determined that the electrospray ion beam contains helical molecules which unfold upon deposition on the metal surface. The insight provided by the present study is anticipated to be crucial in controlling the folding of biological and biomimetic molecules when integrated on metallic surfaces.

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Conflicts of interest

There are no conflicts to declare.

Notes and references

- † Unfolding often refers to a disordered conformation, as in proteins. In contrast, the unfolded flat ribbons observed here have a well-defined structure.
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