

Use of Ambient Ionization High-Resolution Mass Spectrometry for the Kinetic Analysis of Organic Surface Reactions

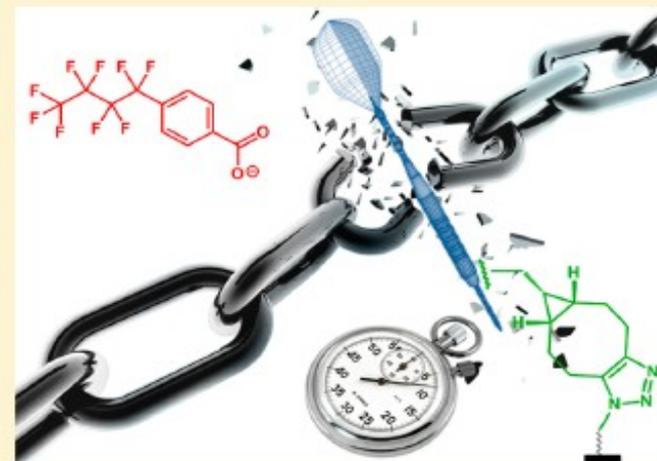
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Supporting Information

ABSTRACT: In contrast to homogeneous systems, studying the kinetics of organic reactions on solid surfaces remains a difficult task due to the limited availability of appropriate analysis techniques that are general, high-throughput, and capable of offering quantitative, structural surface information. Here, we demonstrate how direct analysis in real time mass spectrometry (DART-MS) complies with above considerations and can be used for determining interfacial kinetic parameters. The presented approach is based on the use of a MS tag that—in principle—allows application to other reactions. To show the potential of DART-MS, we selected the widely applied strain-promoted alkyne–azide cycloaddition (SPAAC) as a model reaction to elucidate the effects of the nanoenvironment on the interfacial reaction rate.



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Introduction

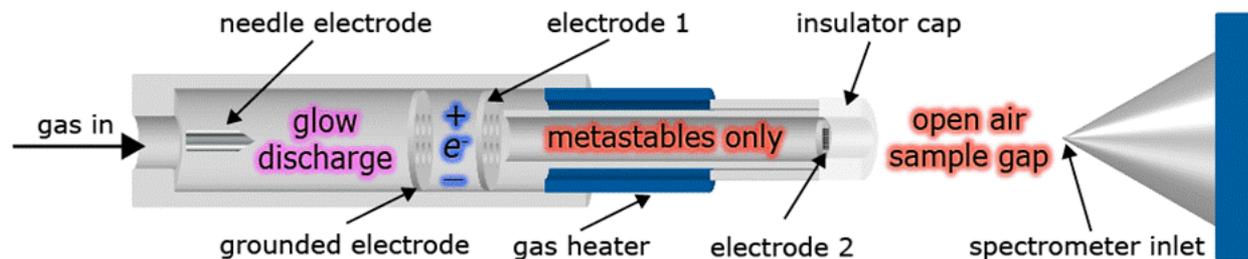
- Chemical reactions on solid surfaces play critical roles in many fields, such as the functionalization of devices used in catalysis, solar energy conversion, nanotechnology, and biosensing.
- The advancement of such devices is hampered by the absence of general, fast, and quantitative analytical techniques to probe the kinetics of organic reactions at the solid–liquid interface.
- Although interfacial reactions kinetics have been studied by different techniques in the past years, their applicability so far is limited as many of these techniques can only be used for specific functional groups, conducting surfaces, and/or require high vacuum.
- The development of rapid and easy to- use analytical techniques to measure the rates of interfacial reactions is of utmost interest.
- Ambient desorption/ionization (ADI) mass spectrometry techniques offer a viable alternative to overcome these limitations.

This paper?

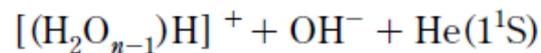
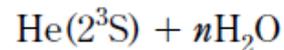
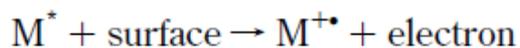
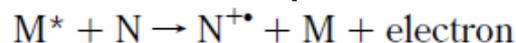
- *First time use of DART-HRMS as a general and fast analytical method to obtain quantitative kinetic insights into chemical reactions at the solid-liquid interface.*

DART? – Direct Analysis in Real Time

- is an atmospheric pressure ion source that instantaneously ionizes gases, liquids and solids in open air under ambient conditions.



Ionization process



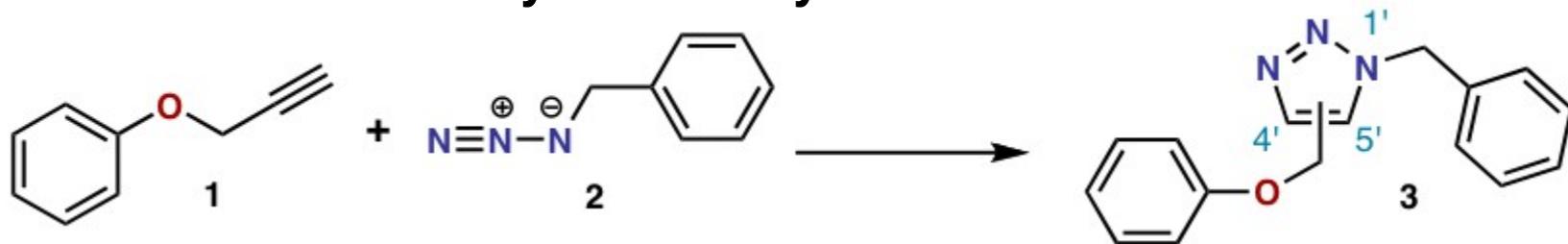
Why DART?

- ✓ DART is capable of generating ionized fragments from a very wide range of functional groups, including amides and esters.
- ✓ The effectiveness of this method has been shown for both solution and surface substrates for routine high-throughput analysis, as times vary from seconds to at most minutes.
- ✓ This technique has been successfully applied for the fast, qualitative analysis of monolayers on a wide variety of surfaces and recently for the study of gas-surface heterogeneous reactions.

This paper- kinetic analysis of an organic surface reaction

Strain promoted **alkyne-azide** cycloaddition (SPAAC) metal-free click reaction

Alkyne-azide cycloaddition reaction

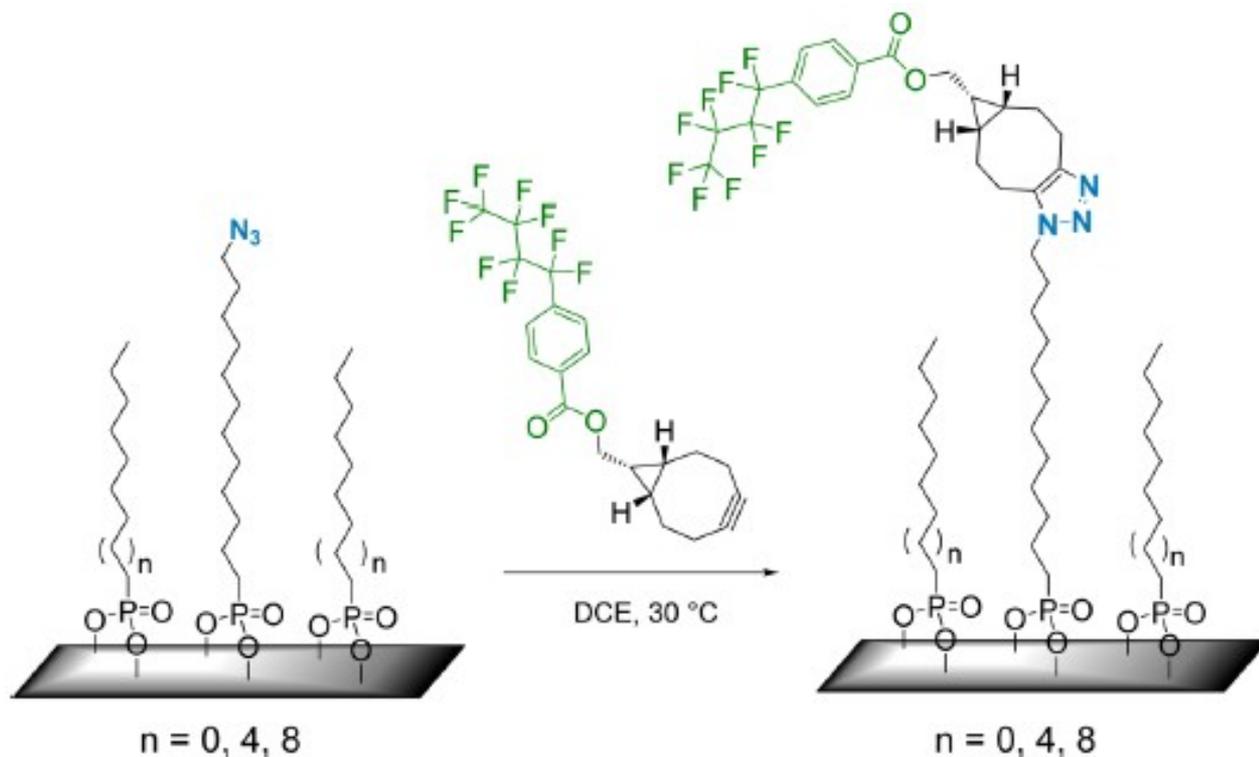


1,3-dipolar cycloaddition between an azide and a terminal or internal alkyne to give a 1,2,3-triazole.

American chemist K. Barry Sharpless has referred to this cycloaddition as "the cream of the crop" of click chemistry and "the premier example of a click reaction."

In chemical synthesis, "click" chemistry, more commonly called tagging, is a class of biocompatible reactions intended primarily to join substrates of choice with specific biomolecules.

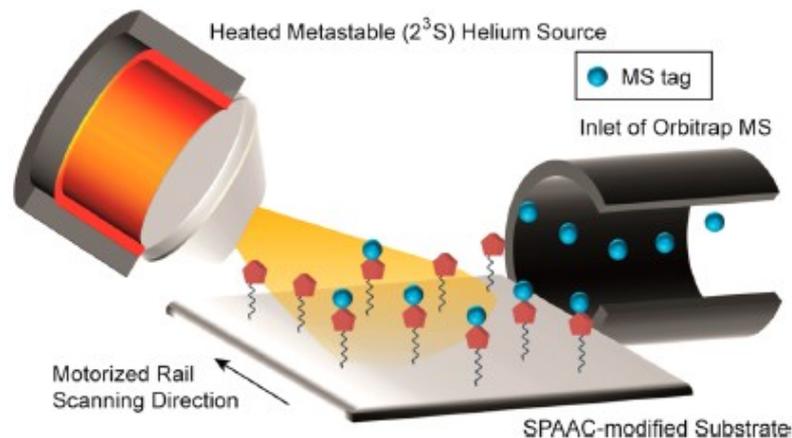
Reaction studied in this work



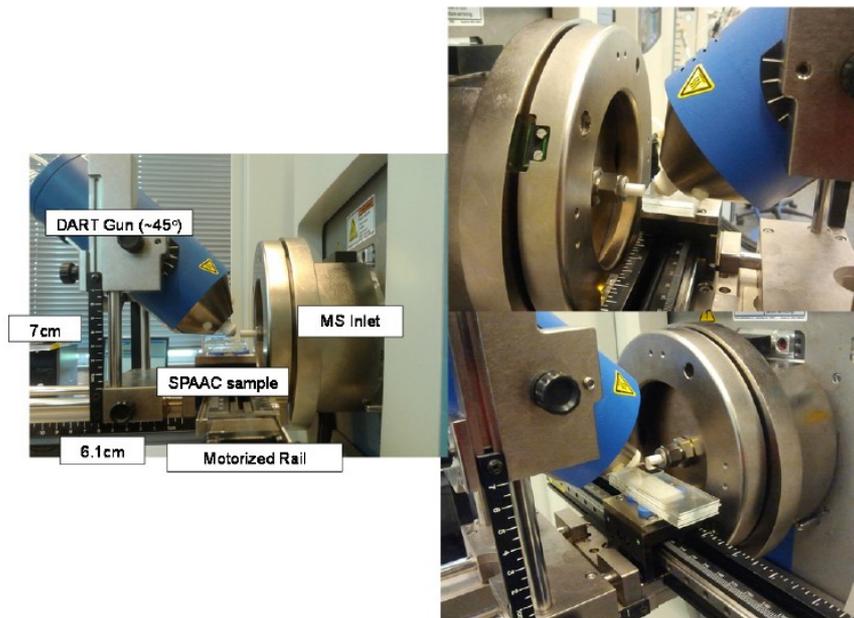
BCN derivative + Immobilized azides on an aluminium oxide surface

((1R,8S,9S)-bicyclo[6.1.0]non-4-yn-9-yl)methyl 4-(perfluorobutyl)benzoate

Instrumentation



Schematic representation of the DART setup used for monitoring the progress of chemical reactions on surfaces.



Pictures of DART setup for the kinetic analysis of organic surface reactions.

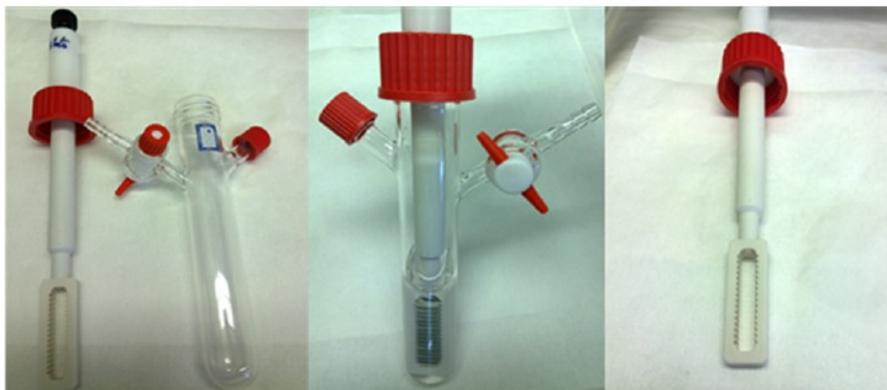


Image of the sample holder.

Analytical Instruments

- 1) Static Water Contact Angle (SCA) Measurements.
- 2) Infrared Reflection-Absorption Spectroscopy (IRRAS).
- 3) X-ray Photoelectron Spectroscopy (XPS) Measurements.
- 4) DART-HRMS Measurements.

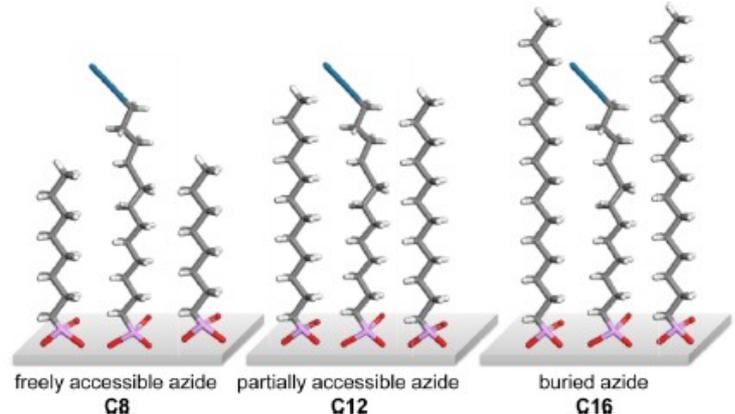
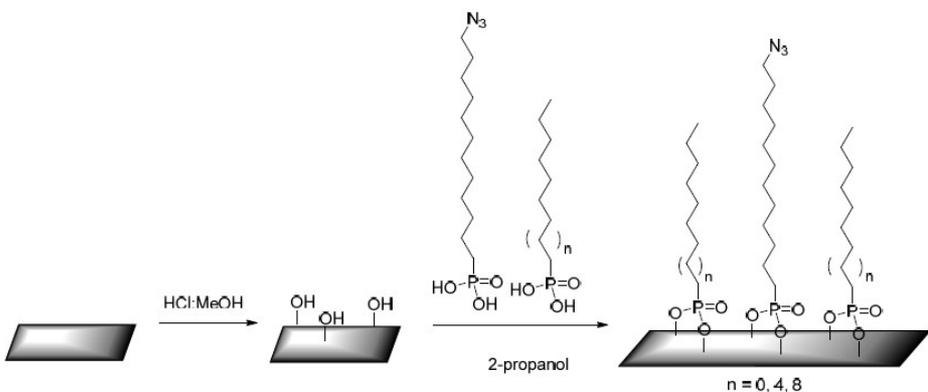
Results and discussion

Monolayer Formation and Characterization.

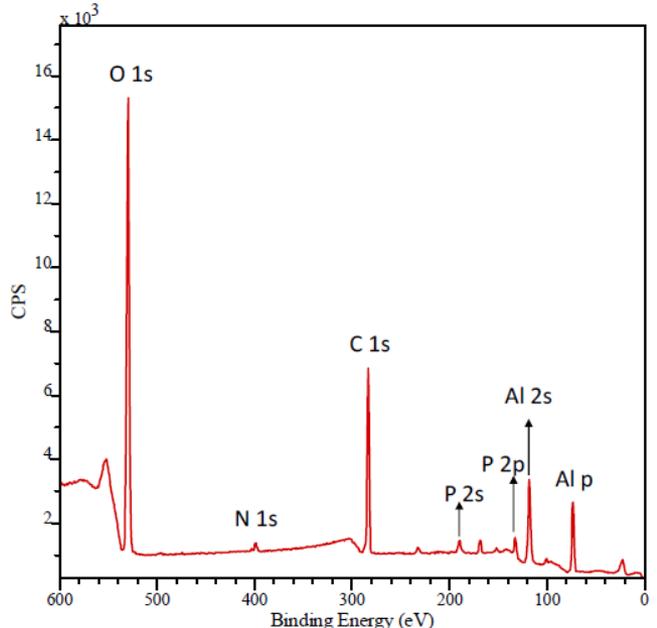
SPAAC Reaction Development.

DART-Based Reaction Rate and Activation Parameters Determination.

Monolayer Formation and Characterization.

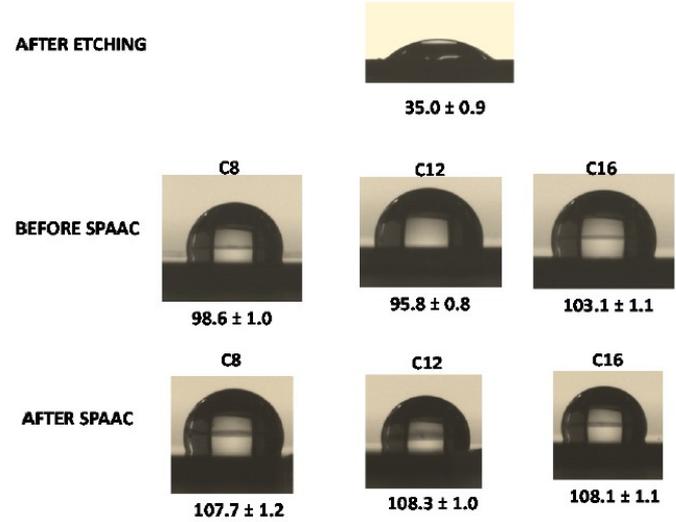


Preparation of mixed alkyl:azide monolayers.



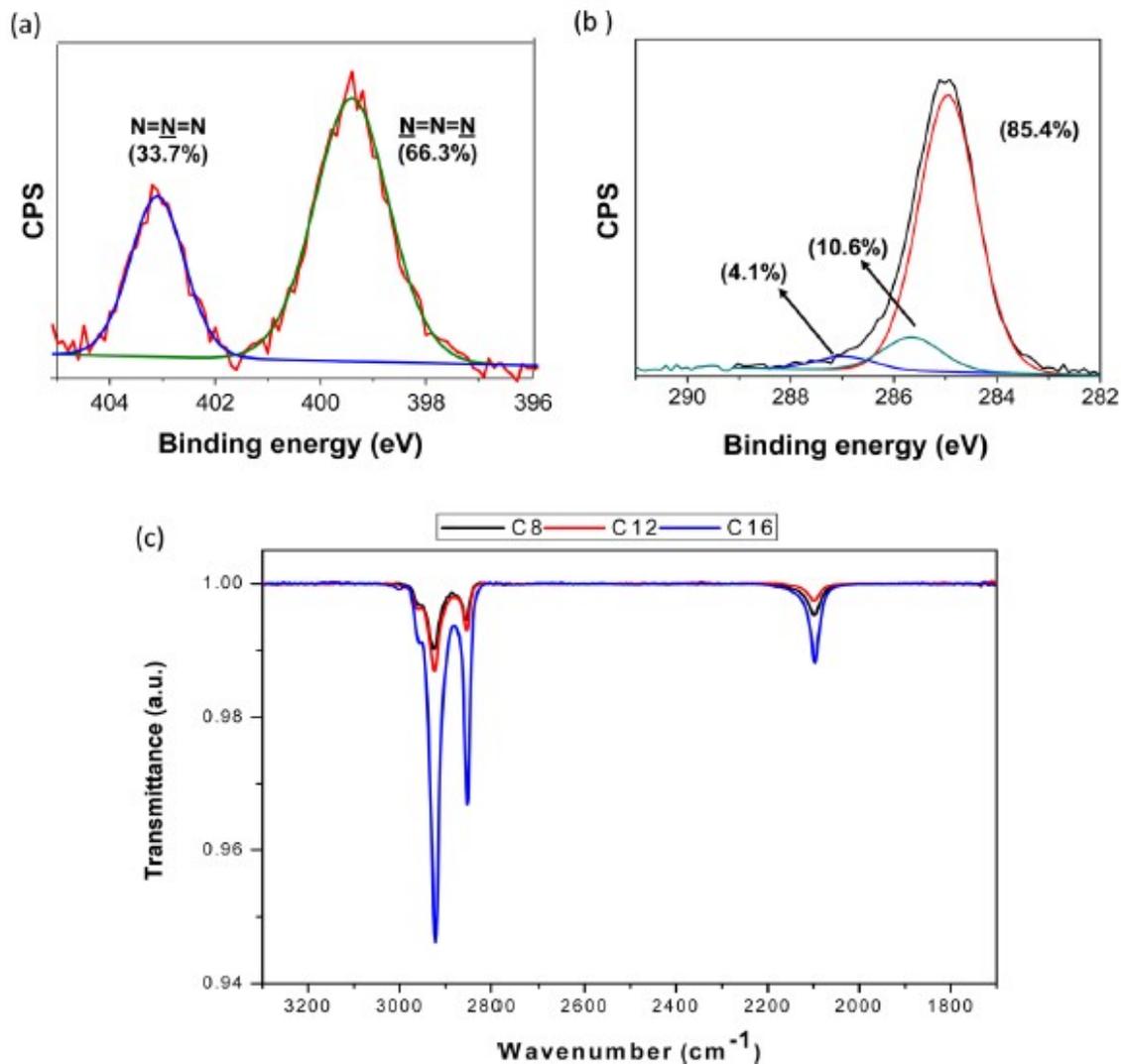
XPS spectrum (wide scan) of a 3:1 mixture of octylphosphonic and 12-azidododecylphosphonic acid monolayer onto oxidized aluminium.

Schematic model of the mixed monolayer used for the SPAAC with immobilized azide groups present in the three different nanoenvironments: freely accessible (C8), partially accessible (C12), and buried (C16).



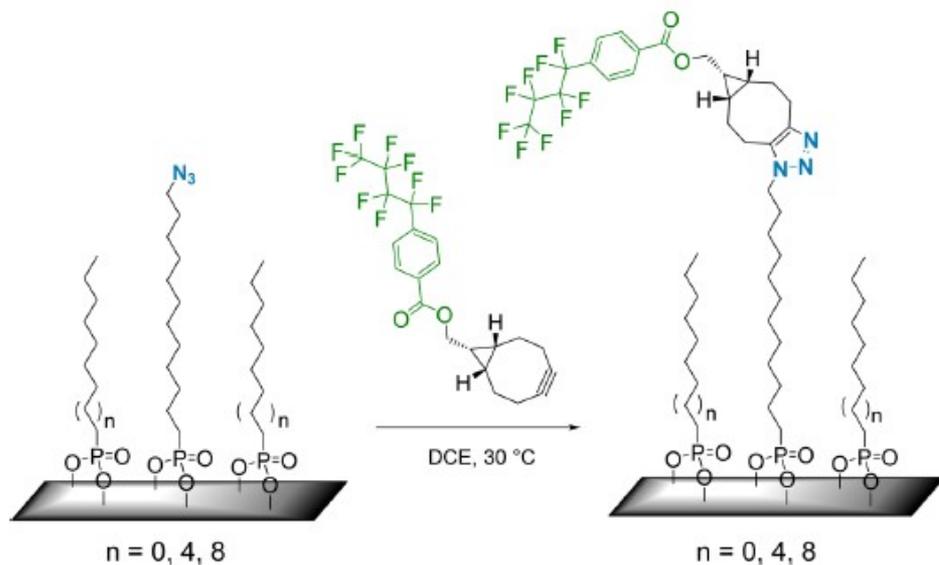
SCA for different functionalized surfaces.

Monolayer Formation and Characterization.

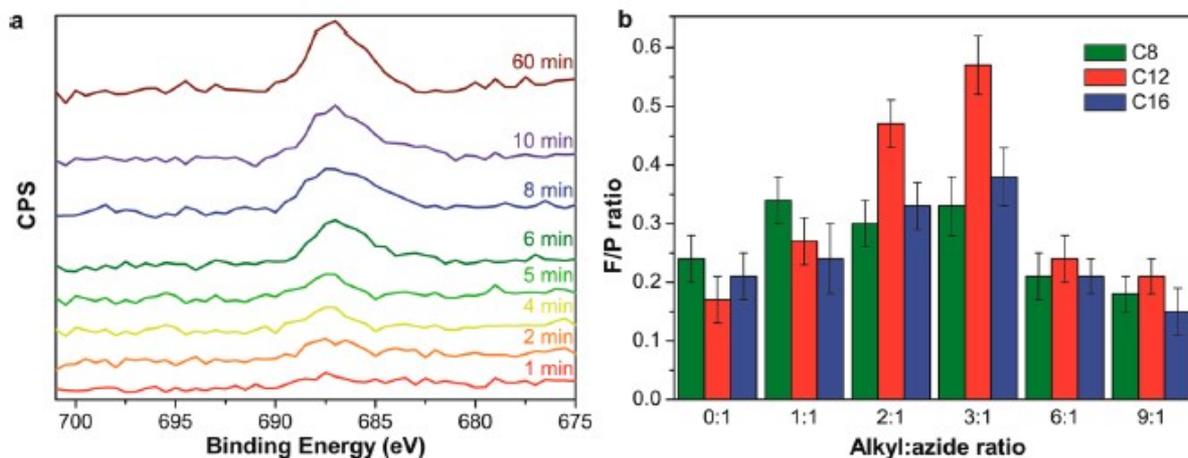


High-resolution XPS N 1s (a) and C 1s (b) spectra of a 3:1 mixture of octylphosphonic and 12-azidododecylphosphonic acid monolayer (C8) onto oxidized aluminum. (c) IRRAS spectra of 3:1 mixed monolayers of C8, C12, and C16 onto oxidized aluminum.

SPAAC Reaction Development.

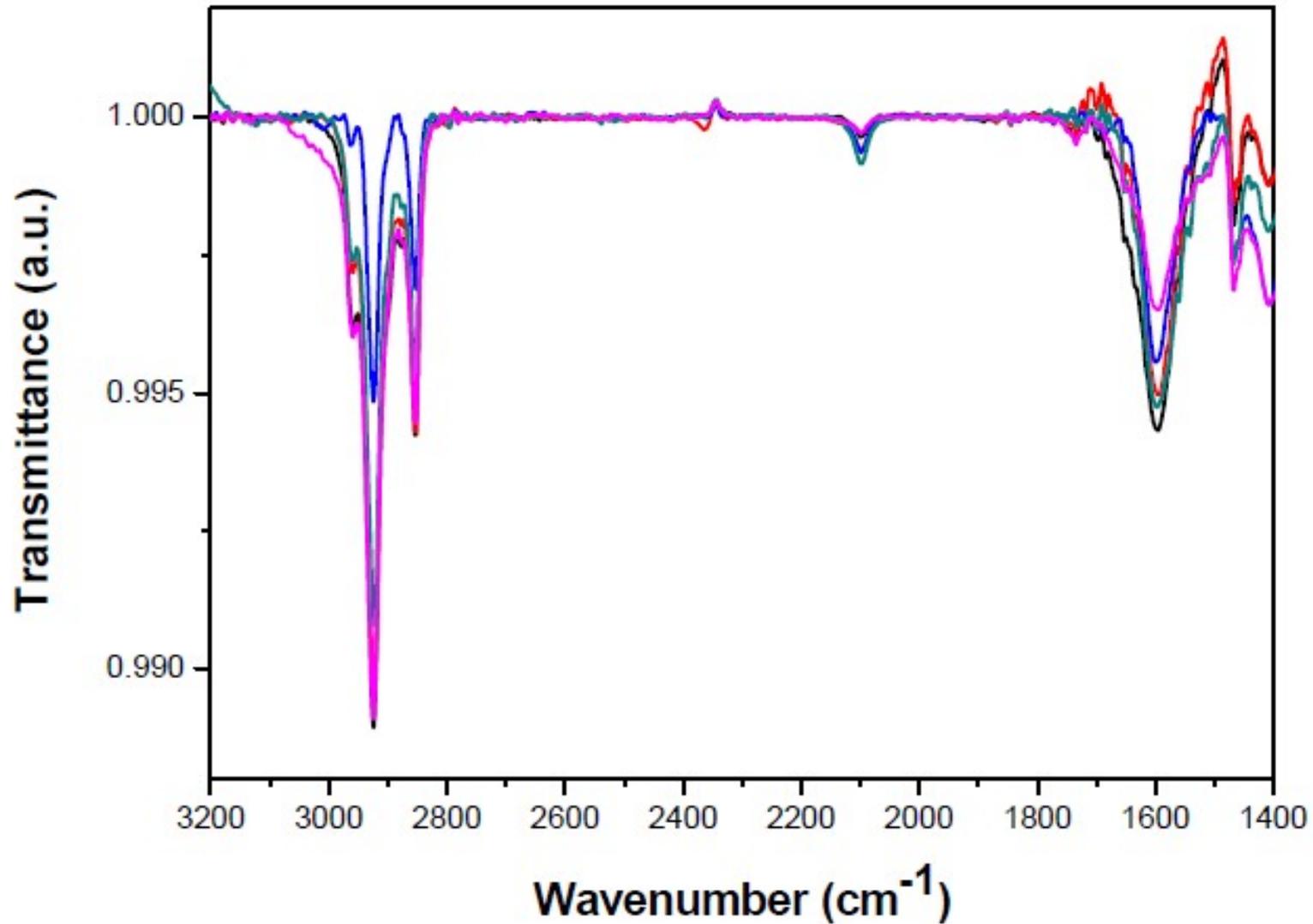


SPAAC Reaction of BCN Derivative 1 with Immobilized Azides Present in Three Different Nanoenvironments: Freely Accessible ($n = 0$, C8), Partially Accessible ($n = 4$, C12), and Buried ($n = 8$, C16)



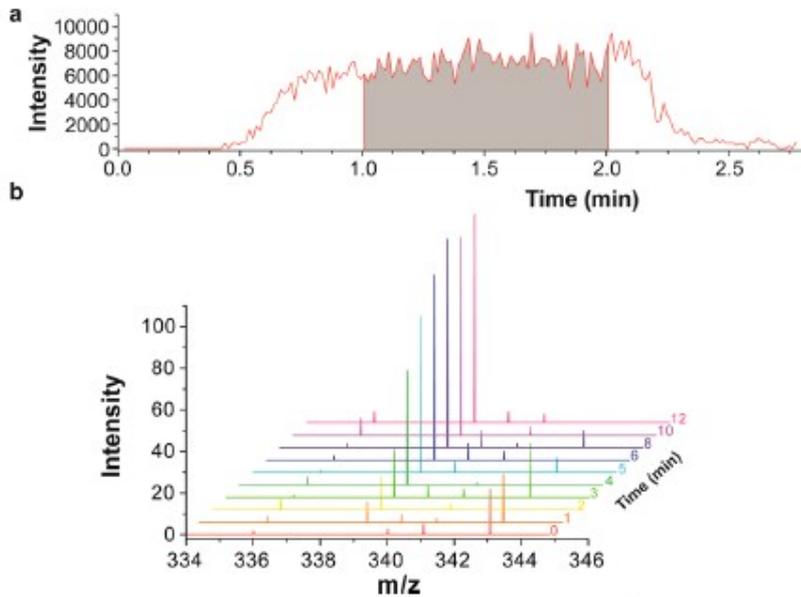
(a) XPS F 1s spectra after SPAAC at different reaction times. (b) F/P ratio for the three different mixed monolayers with varying C-alkyl environment after SPAAC reaction (60 min; as in rest of the paper: all results from 6-fold repetition).

SPAAC Reaction Development.



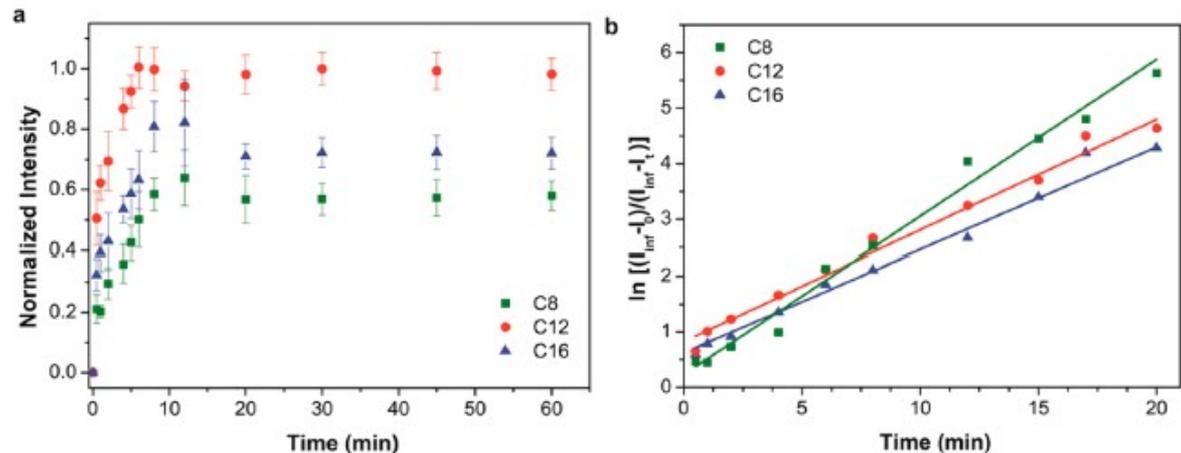
IRRAS spectra of 3:1 mixed monolayers of C8 after different SPAAC reaction times.

DART-Based Reaction Rate and Activation Parameters Determination.



(a) Extracted ion chromatogram (m/z 339.0052–339.0072) from the labile group ($[C_{11}H_4O_2F_9]^-$) and integrated peak area (in gray). (b) Mass spectra for the incorporation of BCN compound 1 to the azide-functionalized surface C12 at different times (from 0 to 12 min).

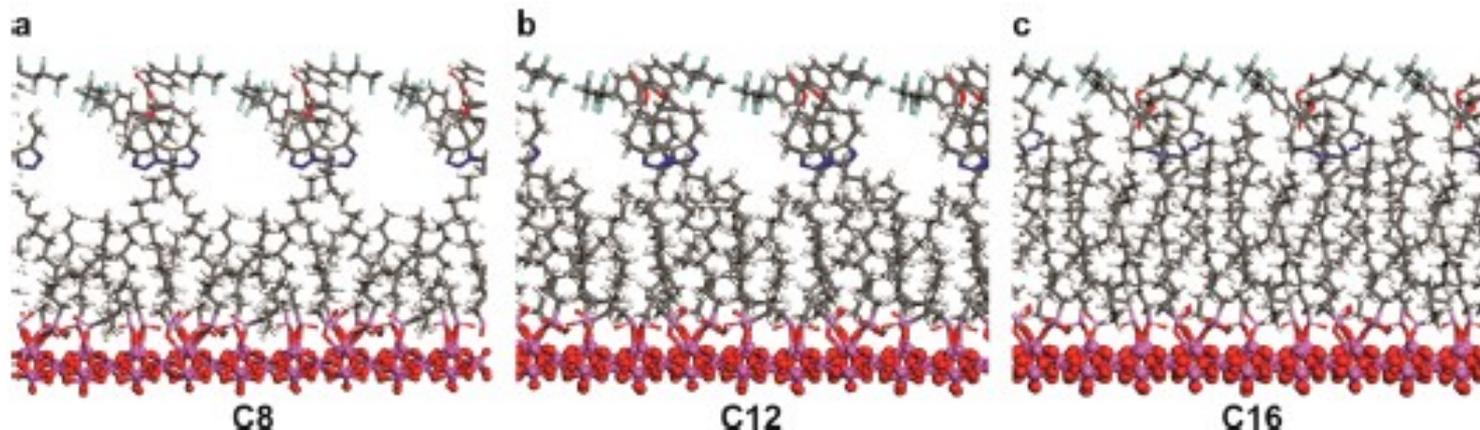
(a) Normalized intensity (with respect to C12) for the SPAAC reaction of BCN derivative 1 with immobilized azides in the three nanoenvironments at 30 °C (each data point from 6-fold repetition). (b) Plot showing $\ln[(I_{inf} - I_0)/(I_{inf} - I_t)]$ vs time, used to obtain the first-order rate constants.



DART-Based Reaction Rate and Activation Parameters Determination.

Monolayer	k'_{DART} ($\times 10^{-3} \text{ s}^{-1}$)	k'_{XPS} ($\times 10^{-3} \text{ s}^{-1}$)	ΔH^\ddagger (kJ mol^{-1})	ΔS^\ddagger ($\times 10^2 \text{ J K}^{-1} \text{ mol}^{-1}$)
C8	5.7 ± 0.4	5.3 ± 0.3	12 ± 1	-2.5 ± 0.3
C12	3.7 ± 0.3	3.3 ± 0.4	24 ± 2	-2.1 ± 1.0
C16	3.1 ± 0.3	2.8 ± 0.5	21 ± 3	-2.2 ± 1.0

First-Order Rate Constants and Activation Parameters (Determined by DART-HRMS) for the Interfacial SPAAC Reaction of BCN and Azido Moieties on the Three Nanoenvironments (Results from Sixfold Repetitions)



Schematic model of the mixed monolayer used for the SPAAC with immobilized azide groups present in the three different nanoenvironments: freely accessible (C8), partially accessible (C12), and buried (C16).

DART-Based Reaction Rate and Activation Parameters Determination.

T (°C)	k' ($\times 10^{-3} \text{ s}^{-1}$)		
	C8	C12	C16
20	3.7 ± 0.3	2.3 ± 0.3	2.7 ± 0.2
30	5.7 ± 0.4	3.7 ± 0.3	3.1 ± 0.3
40	5.6 ± 0.3	4.6 ± 0.4	4.5 ± 0.3
50	6.8 ± 0.4	6.5 ± 0.4	6.4 ± 0.5

First-order rate constants (determined by DART-HRMS) for the interfacial SPAAC reaction of BCN and azido moieties at self-assembled monolayers containing methylene spacers of varying lengths. For determining every rate constant, DARTHRMS measurements were performed on 6 independent surfaces.

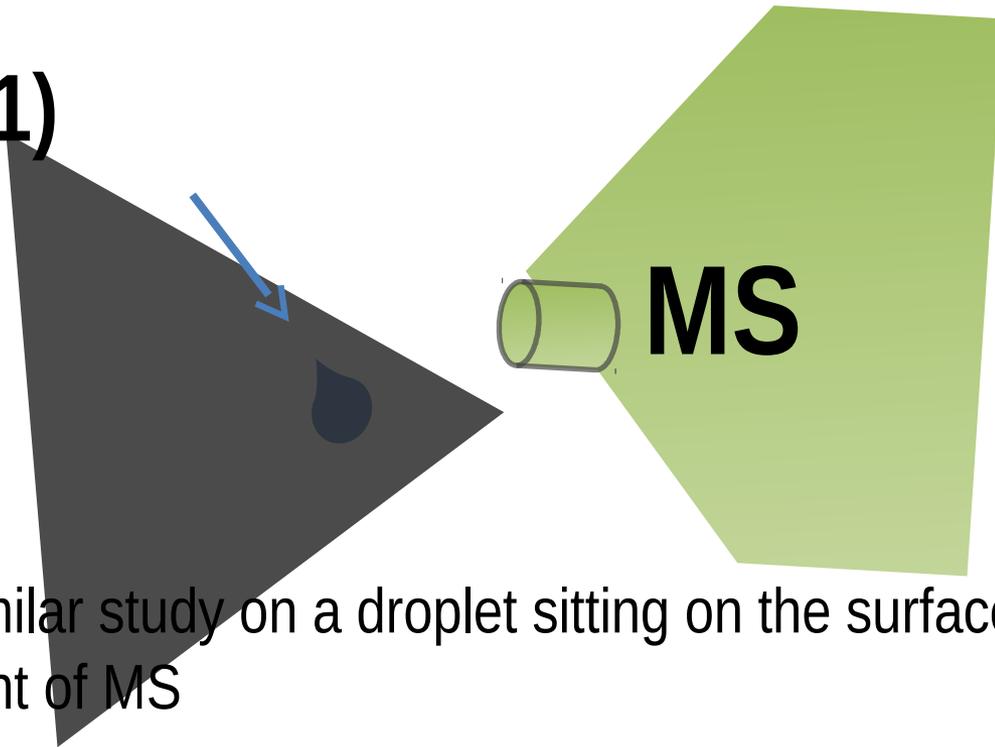
Comparison of the activation parameters for the interfacial SPAAC reaction of BCN derivative 1 with monolayers that present the azide group in a buried environment (C8), an accessible environment (C12 and C16).

Monolayer	ΔH^\ddagger [kJ mol ⁻¹]	ΔS^\ddagger [$\times 10^2$ J (K mol) ⁻¹]
C8	12 ± 1	-2.5 ± 0.3
C12	24 ± 2	-2.1 ± 1.0
C16	21 ± 3	-2.2 ± 1.0

Conclusion

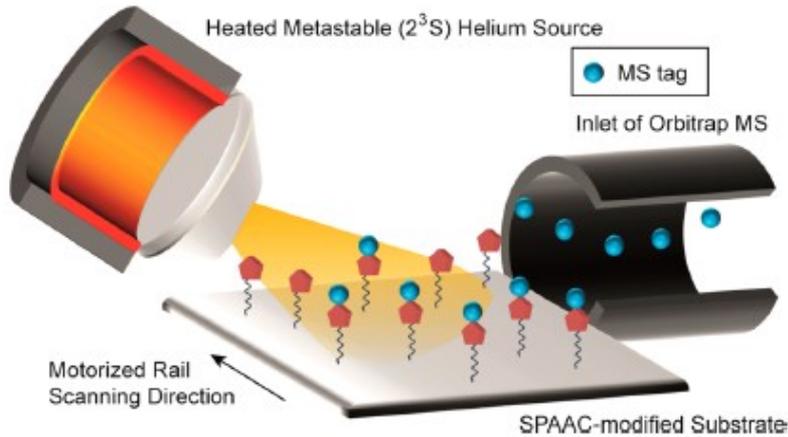
- ❖ The successful unravelling of the effects of the nanoenvironment on the rate of the commonly employed SPAAC highlights the power of DART-HRMS as a general and fast technique to study interfacial reaction kinetics in great detail.
- ❖ The tailor-made control over the nanoenvironment of the reactive moieties via tuning of the accessibility of the immobilized azide within the monolayer can steer both the reaction rates and the extent of the surface-bound SPAAC reaction.

1)



Similar study on a droplet sitting on the surface of a hydrophobic substrate in front of MS

2)



IM-MS study of different isomer interaction



Thank you