EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

PROPOSAL to the ISOLDE and Neutron Time-of-Flight Committee

Interaction and Dynamics of *add*-atoms with 2-Dimensional Structures

(PAC studies of mono- and low- number of stacking layers)

IDA2DS-Collaboration

24 September 2013

V. S. Amaral[1], A. Gottberg[2,3], J. P. Araújo[4], S. Cottenier[5], J. G. Correia[6,3], J. N. Gonçalves[1], A. S. Fenta[1,3], L. Hemmingsen[7], K. Johnston[3], Y. Kadi[3,8], A. M. L. Lopes[9], S-W Hong[8], V. M. Pereira[10], L. M. C. Pereira[11], K. Potzger[12], D. Pribat[8], J. Roeder[3], K. Temst[11], C. Tenreiro[8,13], T. Trindade[1], A. Vantomme[11]

[1] Universidade de Aveiro, Departments of Physics and Chemistry, CICECO, Aveiro, Portugal
[2] CSIC, Madrid, Spain
[3] ISOLDE-CERN, Switzerland
[4] Universidade do Porto, Faculdade de Ciências, IFIMUP, Porto, Portugal
[5] Center for Molecular Modeling, University of Ghent, Belgium
[6] Campus Tecnológico e Nuclear, Instituto Superior Técnico, Universidade de Lisboa, Portugal
[7] Faculty of Life Sciences, University of Copenhagen, Denmark
[8] Sungkyunkwan University, Seoul, Korea
[9] Universidade de Lisboa, Centro de Física Nuclear, Lisboa, Portugal
[10] Graphene Research Centre, National University of Singapore, Singapore
[11] Instituut voor Kern- en Stralingsfysica (IKS), KU Leuven, Belgium
[12] Helmholtz-Zentrum Dresden-Rossendorf, Germany
[13] University of Talca, Chile

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Spokespersons:
V. S. Amaral (vamaral@ua.pt)
A. Gottberg (alexander.gottberg@cern.ch)

Local Contact:
K. Johnston (karl.johnston@cern.ch)

Abstract

The interaction and dynamics of add-atoms with graphene, graphene-derivate structures and, later, MoSi2, two-dimensional – single and few – atomic layers will be studied with the Perturbed Angular Correlation – PAC – technique. Graphene is also envisaged as new platform for growing semiconductor nanostructures devices, such as quantum dots and as a particularly powerful catalyst. Understanding nucleation of nanostructures and clusters on graphene and related phases in wet conditions as they are used in chemical methods in research and industry require complementary studies.
These systems shall therefore be studied systematically using radioactive probe atomsattaching via a transfer media (e.g., water in catalysis process) or being deposited with soft-landing techniques under vacuum and UHV conditions, as is proportionated by the ASPIC setup at ISOLDE. The hyperfine fields obtained under different environments are expected to reveal basic information on the rich atomistic and physical mechanisms associated with these materials, which are arousing an intensive research effort worldwide. Experiments aim to be performed under different conditions, which have been reported to affect intrinsic properties, such as, e.g., the substrate (if not freestanding), temperature, bias and illumination.

Requested shifts: 16 (6+10, over 2 years)

1 Motivation

Scientific

Graphene presents unique physical and structural properties, and it has unanimously turned over the attention of a large number of both, fundamental researchers and applied industry, as a strong candidate for a variety of electronic and energy-related devices and structures. It has recently been elected as the subject of one of the two Europe's first 10-year FET flagship projects with 1000 million € funding assured, and a R&D roadmap was elaborated [1]. Among the properties of graphene, outstands the tunable electronic transport properties, with exceptional quantum characteristics associated to the massless Dirac fermions [2-5]. Its stiffness, stretchability and impermeability, as well as optical absorption features are also distinctive. From a technological point of view, devices like ultrahigh frequency transistors, ultrafast photoactive structures, and transparent flexible electrodes for optoelectronics or photovoltaics were demonstrated and are being developed, combining also graphene with other 2D materials, such as atomically thin boron nitride or molybdenum disulfide. The growth of graphene (single or multiple) layers on metallic and semiconducting surfaces which can then be transferred, goes already beyond wafer dimensions (several cm^2) [6,7]. Moreover, the low electronic noise in graphene makes its properties very sensitive to the presence of adatoms or molecules (e.g. for sensors) and the manipulation of its properties by chemical functionalization is also focus of strong attention [8-10]. It is our purpose to tackle challenging properties associated with the adatoms interactions and dynamics at the two-dimensional surfaces, with characteristic electron densities, by using a selection of pure isotopes, (probe elements) and, complementing studies that are being undertaken with other techniques, maybe still reaching unexplored features. While focusing on graphene, other 2D surface systems will also be investigated, such as graphene-like dicalcogenides (e.g. MoS2-topological insulators) and ferroelectric/multiferroic single crystal surfaces.

Why nuclear techniques @ ISOLDE

In the context of condensed-matter physics, radioactive ion beams and associated nuclear techniques available at ISOLDE-CERN have been applied to modify (dope) and probe materials with the exceptional possibility to "see and feel" at the nanoscale, to determine the positions and function of atoms, electrons, electric and magnetic fields, at a certain element/isotope with extreme sensitivity (doses of ppm or less). The LOI132 "Radioactive Local Probing and Doping on Graphene" approved in 2011 allowed to initiate studies with these techniques on graphene and *graphene-derivated* structures using wet-chemical procedures to bind the radioactive probes, previously collected on ice. We believe that such data and experience has granted us a solid ground to proceed experiments on that line of interests while initiate new hyperfine Perturbed Angular Correlations (PAC) experiments with ions deposited with the soft-landing technique at surfaces and interfaces under vacuum and UHV conditions as these are uniquely proportionated by the ASPIC setup at ISOLDE, which is currently being refurbished [VITO-INTC].

The experimental work strategy is complemented by scanning probe and electron microscopies, optical spectroscopies (Raman) and other physical characterization studies. The electronic structure of the 2D systems and hyperfine parameters of the ad-atoms interacting with the surfaces are modeled, applying diverse computer codes based on ab-initio density functional methods (DFT). This approach consists today of a powerful predictive tool to guide materials research.

It is now timely to proceed to further hyperfine experiments in cleaner conditions, with ions deposited with the soft-landing technique at surfaces and interfaces under the unique UHV conditions of the ASPIC setup at ISOLDE.

Feasibility

The ISOLDE – unique – laboratory assures the variety of isotopes, which can be chosen as different elemental probes to be used with the PAC technique.

At the present stage we have successfully applied the methodology of ion implantation on ice (frozen solvent), for later wetting of the graphene surface and ion adsorption, as used for biophysics experiments [11]. This allows flexible means to incorporate probes, grafted (or not) to particular molecular species, which attach to the graphene surface allowing also functionalization studies in catalysis – like conditions. The next step is to use the radioactive soft-landing technique existing in the ASPIC facility (UHV surface purposes) after implantation of ions on a ultra-clean refractory metal foil and later evaporation onto the graphene sample's surface. First preparation experiments using an evaporator device (NOT UHV) have started already looking for optimized substrates and best conditions for evaporation at graphene layers of 199mHg atoms in 2012.

PAC experiments: To optimize and profit from the availability of radioactive isotopes, new digital PAC spectrometers equipped with $LaBr_3$ detectors have been installed at ISOLDE. With equivalent sub ns time resolution to BaF_2 scintillators but with much superior energy resolution, these new setups allow the clear separation and identification of gamma lines, even with poor feeding – as was demonstrated with the recent first time PAC experiment onto decay of ^{61}Cu/^{61}Ni.

On the essential experimental side of the sample preparation, the ASPIC facility provides the ideal sample preparation environment in UHV where these nuclear probes can be deposited via soft landing, onto the desired surfaces.

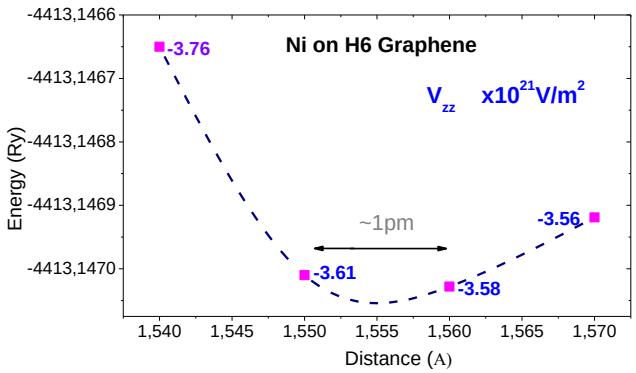
Samples preparation by transferable patterned CVD graphene at partner laboratories [6,7]. Single and double/multiple layer coverage on the sample surface (of mm2 area) is available and can also be monitored by spectroscopic techniques. Growth on Cu, Ni or Ag is available, graphene being then transferred to other substrates like Si/SiO2, PET. Highly homogeneous samples on SiC substrates and gated systems for voltage dependent studies will also be used. The film's synthesis by ion implantation with subsequent annealing will further be used. This is an alternative method with wide-open perspectives that can be further envisaged to incorporate radioactive probes within/under the layer, before and during the growth. The success of these procedures would determine adaptations of the future working program with clear impact on device production. Studies of low energy (< 5 keV) ion implantation through the graphene layer will also be performed, with subsequent annealing to move the probe ions into the interface.

Other 2D materials are available commercially (for preliminary studies).

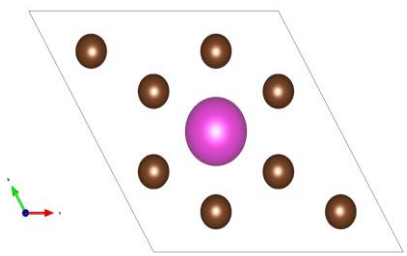
Ferroelectric/Multiferroic single crystals are available commercially (serving as substrates) and within collaborations.

Sample characterization: (before and post PAC measurements) using e.g. Raman spectroscopy (capable of distinguishing single, double or higher number of graphene layers on the substrates), optical microscopy for visual inspection of homogeneity, and atomic force microscopy. In situ characterization using Low Electron Energy Diffraction (LEED) for evaluating the lattice quality and Auger Electron Spectroscopy (AES) for investigating the chemical conditions are prepared at ASPIC.

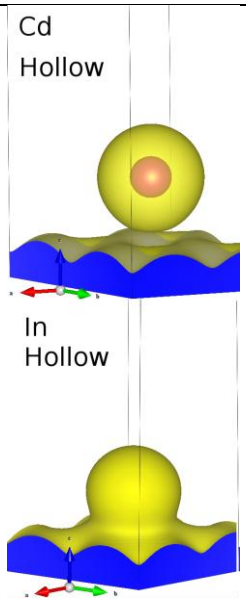
Theoretical Modelling: Several studies in the literature are dedicated to study the electronic structure of graphene and of ad-atoms interacting with it. Generally, computer codes based on ab-initio density functional methods (DFT) are used such as VASP and Wien2k. These powerful predictive tools also allow to study and predict the hyperfine parameters on the ad-atom. Studies of stability and electronic interactions were already conducted within the team.



Dependence of Energy and Vzz on z coordinate for Ni in H6 (hollow) position



View of the Hollow site Cd-adatom (most stable among Hollow, Top, and Bridge sites.). Cd is at 3.22 Å



Iso-surface charge density plots, for Cd and In, at the Hollow sites. Surfaces correspond to the same level of the electron density. In is more stable/closer.

The previous figures shows some of our results on the study of some ad-atoms on graphene, their stability and hyperfine parameters sensitivi. The following table compares our results for Cd, In and Hg adatoms, which all more stable when sitting at the Hollow position. In is the

T; H; B: *adsorption sites: Top (ad-atom on top of a C atom), Hollow (ad-atom above the center of an hexagon), Bridge (ad-atom above the center of a C-C bond);*

(lower energy site in bold)	Cd			In			Hg		
	T	**H**	B	T	**H**	B	T	**H**	B
V_{zz} (10^{21} Vm^{-2})	-0.03	**-0.02**	-0.31	8.48	**8.28**	8.97	-1.73	**-0.89**	-1.66
η	0.00	**0.01**	0.40	0.00	**0.00**	0.12	0.00	**0.00**	0.22
distance (Å)	3.27	**3.22**	3.26	2.77	**2.58**	2.76	3.20	**3.14**	3.19

most stable (higher bonding, closer to graphene surface)

The Collaboration-added value

This proposal joins together material science researchers using different methods and complementary techniques. There are two clearly identified binding aims within the IDA2DS Collaboration, i.e., the desired high quality scientific output must be accompanied by young people doing MSc and PhD thesis. While this is a general rule for any successfully research group, we point the exceptional particularity of the ISOLDE environment, world-wide recognized as the reference for providing radioactive isotopes dedicated to science, it is therefore able to further motivate people joining experiments with *unsuspected* problems and research thematic looking for *unsuspected* solutions. Those who came here are in many cases outside of the nuclear world, they are material and life science researchers, meeting for the first time radio-isotopes, nuclear techniques and nuclear-atomic interactions, the whole delivered on a true synergetic combination of efforts and results. Such environment is a unique opportunity to generate high-quality and original thesis, both at the R&D and scientific level – a unique environment for unique opportunities on people's training and careers.

The IDA2DS collaboration has defined a starting organizational structure as presented below:

SPOKESPERSONS:

V. Amaral, Coordination and organization of scientific studies

A. Gottberg, Coordination and organization of ASPIC work/beamtimes

CONTACT PERSON:

K. Johnston, ISOLDE SSP coordinator, interface with other SSP groups

SAMPLE'S MANUFACTURE AND CHARACTERIZATION

Samples are available through partners and their collaborations. Structural, electronic, optical and scanning probe characterizations are currently performed for complementary graphene-related studies.

J. P. Araújo, A. M. L. Lopes, S-W. Hong, K. Potzger, D. Pribat, K. Temst, C. Tenreiro, T. Trindade,

PERTURBED ANGULAR CORRELATIONS

J.G. Correia, A. M. L. Lopes, J. Röder

THEORY

S. Cottenier, Hyperfine calculations and DFT calculations

V. M. Pereira, Graphene Properties (electronic and other)

J. N. Gonçalves, DFT calculations

OBSERVERS

M. Stachura, link to bio β-NMR groups

M. Deicher, Saarbrucken has the ownership of the ASPIC equipment, link to BMBF

2 Case Studies

The opportunities for the application of radioactive ions in the study of graphene are numerous. The hyperfine properties of pure graphene were addressed theoretically, in the presence of a sea of 2D Dirac electrons, with a linear E(k) dispersion [12-14] and the role of spin coherence relaxation mechanisms with nuclei for spintronics and quantum information processing applications [14] was highlighted. However, the presence of a local / impurity probe was not considered.

We propose to use Perturbed Angular Correlations (PAC) to study the interaction of the add-atom probe element, namely the nucleus and the surrounding electrons, with the respective surface, by assessing the subsequent Electric Field Gradient and the Hyperfine Magnetic Fields.

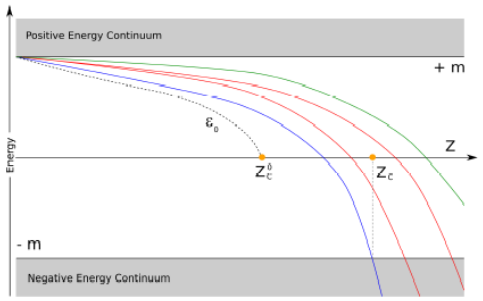
Based on the first results from LOI132, that are drafted below, the following developments will address the new topics of the physics of add-atoms that require the both dedicated sample preparation capabilities in UHV of ASPIC and in the liquid phase:

1- Studying the nucleation of nanostructures and clusters on graphene and related phases requires the use of wet chemical methods. Graphene and graphene-oxide have been investigated as new platforms for growing semiconductor nanostructures aiming at diverse devices, such as quantum dots. Fundamental studies that address their nucleation are lacking. We intend to monitor the nucleation of CdS nanophases on graphene sheets. This task will involve the controlled generation of CdS seeds, in situ, using wet chemistry methods developed in our laboratories. Radioactive ^{111m}Cd can be introduced into the CdS precursors to be merged into the nucleation process at the graphene surface. By probing the PAC spectra for distinct reaction times the local environment and crystalline quality of the CdS dots can be probed on the graphene surface.

2- Addressing the preparation of isotopically pure graphene layers on transition metal template coatings/substrates. Graphene synthesis by ion implantation was demonstrated (carbon implanted at 30 keV on metal (Ni) coatings/substrates, with subsequently segregation to the surface at lower temperature) [15,16]. This is an ideal case study, in particular to growth mono-isotopic graphene layers under UHV conditions.

3- Charge renormalization in graphene was predicted to change considerably the electron motion in a strong Coulomb field of an ad-atom impurity, leading to quantum relativistic atomic collapse and the supercritical instability already at charges Z~1-2 in contrast to the heavy nuclei charge (Z>170) for a free atom [17,18]. The crossover was very recently reported by a Scanning Tunnel Microscopy study in clusters of charged Ca dimers on electronically gated graphene on BN [19] thus, producing resonances in conductivity.

I. Diving states (Hydrogen atom in QED)

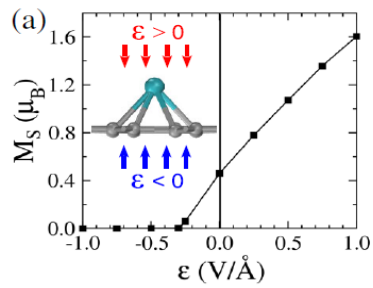


Gershtein, Popov, Zeldovich, Perolomov, Greiner, *et al.*
Electronic Structure Of Superheavy Atoms
Ya. B. Zeldovich *et al.*, Sov. Phys. Usp. 14 673 (1972)

It is our intention to probe such catastrophic charge renormalization phenomena using hyperfine field changes induced by radioactive ions of different valences soft-landed onto graphene.

4- The concept of topological insulators (TI), or quantum spin-Hall states was predicted initially to occur in graphene, but such new quantum states, with spin-filtered edge states (quantized conductance, with opposite spin electrons propagating in opposite directions), was first observed in HgTe quantum wells and in the surface states of Bi2Se3 and other materials with sufficiently strong spin-orbit coupling [20,21]. Recently, graphene as a viable candidate for TI was revived [22,23] by predicting that a few % of heavy add-atoms (In, Os, Ir,..) can produce a robust gapped topological insulator state. However, the mechanism is still controversial, either involving electron tunneling from graphene onto an add-atom or considering that despite their dilute character add-atoms form impurity states that hybridize with graphene. The role of adsorption sites, hybridization effects and intra-atomic charge transfer on the properties of transition metal adatoms has also been addressed recently in relation to their possible magnetic moments (paramagnetic or non-magnetic groundstates for Ni, Fe and Co), studied by scanning probe, X-ray absorption and circular dichroism [24]. Further, it is found that the electronic structure of add-atoms (e.g. Co) deposited on back-gated devices, could be tuned by applying a voltage and a screening cloud around a single atom as large as 10 nm could be observed [25,26]. Such tunability by external control and the emergence of extended screening effects are fundamental for electronic applications. Also, an unsuspected magneto-electric coupling effect has been predicted for transition metal adatoms on graphene (figure) , reacting on the appearance and the tuning of an adatom's magnetic moment [23]. These effects may lead to new concepts of multiferroic behavior, if graphene is backed by an active ferroelectric substrate, such as BaTiO3. This may also be used to study strain-dependent effects, such as migration and localization of atoms in defects and vacancies inside graphene [27, 28].

PRL **109,** 266801 (2012)



Magnetoelectric coupling is predicted to occur at the level of single adatom – Osmium/graphene

All these important findings inspire and urge the need for locally and internally probing the physics of the add-atom on graphene, with an electric and magnetic sensitive method, which we here propose by using the PAC technique within the UHV-ASPIC environment, using isotopes with different atomic numbers/valences, to vary local electronic conditions (In, Cd, Hg, Ag, ..). Each case requires the thorough comparison with DFT-predicted properties.
The proposed experiments will be performed under different voltage gating and temperature conditions.

5- The physics of add-atoms on other 2D materials, such as MoS2, and similar dichalcogenides with intrinsic spin-orbit coupling, is also poorly known despite its importance for understanding the electronic interactions or catalytic properties, and for helping the design of heterostructures with tuned properties, for which the first examples start to appear [20,21]. Again these are ideal subjects to be addressed with add-atoms probed by PAC under the UHV environment of ASPIC.

3 Experimental

This proposal opens an ambitious experimental research line on 2-Dimensional lattice structures, where the key feature is the measurement of hyperfine fields, which act as fingerprints of the interactions established between the 2D lattice and the probe atom - *our atomic scale "tip".* The PAC technique has been chosen since it is able to clearly characterize magnetic and quadrupole (charge density distribution) hyperfine fields, with a quality signal that is not degraded upon performing measurements as function of temperature. Our probing "tips" are add-atoms, which will become part of the system under study, either weakly or strongly bound; anyway, this is what happens in real life of devices – a panoply of existing interactions within the functionalized surface.
The PAC measurements occur without external interferences, others than the fact that each probe atom is binding to the surface. On the start of this project we shall keep, as well, a very low number of radioactive "tips", just enough to perform one PAC measurement per sample, per collection. Hence, we intend to use isotopes for what we can run with 10^{11} – $2{\cdot}10^{11}$ deposited atoms on samples that size typically for 25mm^2. These are ^{111m}Cd ($T_{1/2}$ = 48m), ^{111}In(2.7d)/^{111}Cd, ^{117}Cd(2.5h)/^{117}In and ^{199m}Hg($T_{1/2}$ = 42m).

Off-line PAC studies - all isotopes will be collected in the general-purpose SSP implantation chamber, either on solid substrates or on ice for aqueous preparations – at the biophysics chamber, at GLM in the ISOLDE hall, building 170. The respective measurements are done outside the ISOLDE hall, in the Solid State Lab in the new building 508, using sealed containers for transport. Closed glove boxes exist for handling samples and sample holders after collection.
On-line PAC UHV experiments are done in the ASPIC chamber at the new VITO beamline, former RB0/RB2 beamline.

We estimate a total of 16 shifts of beam time for this proposal in two years to allow establishing the procedures and obtaining first conclusive results. *Off-line* collections and experiments can run in shared beam time mode with other users. *On-line* PAC UHV with the shortest-lived isotopes needs the UHV-ASPIC line and exclusive beam time to setup the line (stable beam) and run with radioactive isotopes. Off-line experiments could be envisaged at ASPIC with the long lived ^{111}In(2.7d) isotope upon collection on evaporation substrates.

Table: Beamtime request

required isotope	ISOLDE beam	intensity [at/□C]	target	ion source	number of shifts
^{111m}Cd(48m)	^{111m}Cd	~ 7E8	Molten Sn	VADIS	6
^{111}In(2.8d)	^{111}In	~ 1E7	UC2	W-surface	2
^{199m}Hg(42m)	^{199m}Hg	~ 2E9	Molten Pb	VADIS	6
^{117}Cd (g.s.)(2.5h)	^{117}Ag (*)	~ 5.0E8	UC2	laser (Ag)	2

(*) The implantation of ^{117}Ag maximizes the ratio between ^{117}Cd/^{117m}Cd, what is needed to optimize the PAC measurements, which are performed onto the 89.73keV- 344.4keV cascade on ^{117}In obtained from decay of ^{117}Cd(g.s.).

Due to the nature of the sample preparation for PAC measurements, i.e., time collections of 15… 30 min per sample for ^{111m}Cd, ^{199m}Hg, each 4h, the beam time should be shared with other users, at least for wet conditions.

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[VITO-INTC] M. Deicher, M. Stachura et al, CERN-INTC-2013-013 ; INTC-O-017; http://cds.cern.ch/record/1551750?ln=en

Short report on LOI I132: Radioactive Local Probing and Doping on Graphene

Experiments were performed using radioactive ^{111m}Cd/^{111}Cd and ^{199m}Hg/^{199}Hg on graphene laying into Si/SiO_2 wafers and PET polymer sheet substrates. Additional experiments on related materials, like graphite, graphene oxide and carbon nanotubes suspensions were done for comparison. On these preliminary studies two different methods were used to deliver the isotopes to the sample's surfaces. The first method consisted on implanting the ions on ice that, once melted, was used to wet the samples until some ions bind to graphene. In the second method, direct implantation of radioactive ions through graphene samples standing on a Si/SiO_2 wafer, was followed by subsequent annealing up to 800 º C and 1100 º C, in order to promote the diffusion of ions from the substrate to the graphene interface. The aim was to study the process of recovery of the substrate and graphene itself after suffering the 50kV ion beam bombarding. From these experiments we got remarkable results regarding the determinant contribution of the *still surviving* graphene layer to the damage recovery of the implanted substrates. In spite of the tremendous effort of the technical teams, due to a serious fault in the separator system, restricted experiments could be performed in the last beam time assignment.

For Cd isotopes, the results present clear evidence of very severely attenuated signal making very difficult to assign to probes coordinated on solid. On the contrary, results with Hg present two fractions of local probe EFG (environments), one of them with low asymmetry common to both substrates and the more asymmetric with different values on Si or PET. On the other hand graphene oxide gives one fraction (~50%) with low attenuation and strong asymmetry, probably related to ions bound to oxygen.

Hereby, are shown results obtained at different temperatures, after wetting with melted ice containing ^{111m}Cd and ^{199m}Hg, the graphene samples laying at PET and Si substrates: Figure LOI-1 and Figure LOI-2 show the experimental PAC observable, the R(t) function, as measured in graphene on Si and PET substrates with ^{111m}Cd ^{199m}Hg. The different spectra show multiple Electric Field Gradients, which reveal that the substrate is able to influence the binding of Hg and Cd ions to graphene. Figure LOI-3 shows results on graphene oxide suspension with ^{199m}Hg.

Due to the temperature dependence of the R(t) spectra, we further believe that water molecules are interfering with the bonding, and consequently, with the places where the Cd and Hg metal ions sit. DFT first principle simulations are in progress, which model atomic configurations containing metal ions and water molecules on graphene, aiming to reproduce the experimental data and help on explaining the interaction of metal ions with graphene in, e.g., catalytic processes.

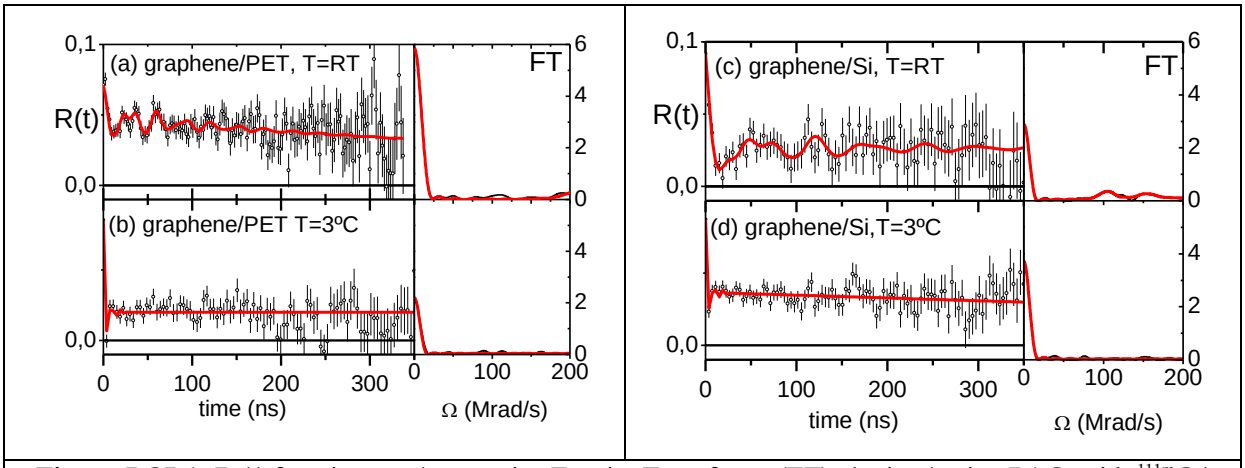

Figure LOI-1. R (t) functions and respective Fourier Transforms (FT) obtained using PAC, with ^{111m}Cd isotope, measured at room temperature (RT) and 3 º C. The samples analyzed were graphene on PET - a) and b), and graphene on Si - c) and d).

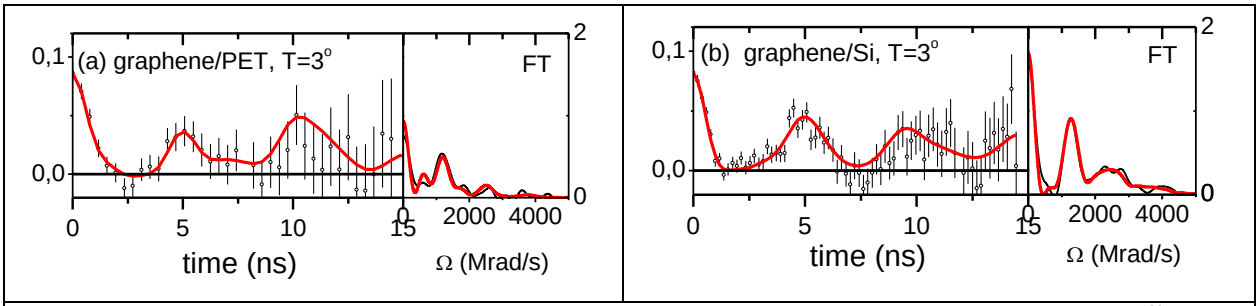

Figure LOI-2. R (t) functions and respective Fourier Transforms (FT) obtained using PAC, with ^{199m}Hg isotope, measured at 3 ºC. The samples analyzed were graphene on PET - a), and graphene on Si - b).

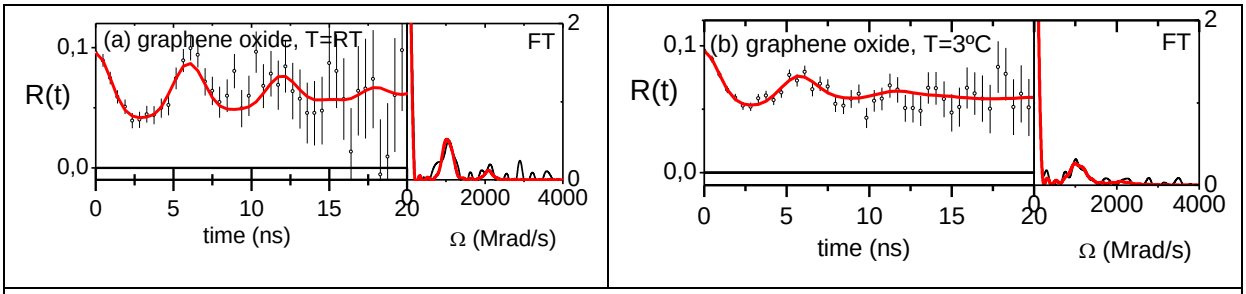

Figure LOI-3 - R (t) functions and respective Fourier Transforms (FT) obtained using PAC, with ^{199m}Hg isotope, on graphene oxide measured at room temperature (RT) and 3 º C.

Appendix

DESCRIPTION OF THE EXPERIMENTAL ENVIRONMENT

The experimental setup comprises:
(name the fixed-ISOLDE installations, as well as flexible elements of the experiment)

Part of the / Choose an item.	Availability	Design and manufacturing
SSP-GLM chamber	☒ Existing	☒ To be used without any modification
ASPIC UHV setup	☒ Existing	☒ To be used after integration into the VITO beam line
Existing equipment at the Solid State and Chemistry laboratories in building 508 - 6 detector PAC standard setups - Annealing furnaces - Glove boxes	☒ Existing ☐ New	☒ To be used without any modification ☐ To be modified ☐ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing

HAZARDS GENERATED BY THE EXPERIMENT

(if using fixed installation) Hazards named in the document relevant for the fixed SSP-GLM chamber and building 508 installations.

Additional hazards:

Hazards	***SSP-GLM***	***Building 508***	***ASPIC - UHV***
Thermodynamic and fluidic			
Pressure (bar) **Volume (l)**	Vaccum 10 l	Ambient	UHV 100 l
Vacuum	10^{-6} mbar at SSP chamber 10^{-5} mbar during ice collections	none	10^{-9} … 10^{-11} mbar
Temperature	77K due to implantations on ice.	Ambient 20 – 25 ^{o}C	(inside the chamber) from 77K – 1000K at the sample holder, during UHV experiments, Up to 150°C for two days prior to experiments for vacuum bake out.
Heat transfer			
Thermal properties of materials			
Cryogenic fluid	Liquid nitrogen. Ice is kept at a cold finger adapted to a metallic LN2 15 litres Dewar. The system is of current use since 2001, being set at the back of the SSP Chamber.	Liquid nitrogen, 1 Bar, few litres used during the PAC measurements on appropriate glass dewar.	Liquid nitrogen, 1 Bar, few litres used during the PAC measurements with appropriate transfer lines between chamber and LN2 container.
Electrical and electromagnetic			

Electricity	[220] [V], [current][A]	[220] [V], [current][A]	[220] [V], [current][A]
Static electricity			
Magnetic field	[magnetic field] [T]		
Batteries	☐		
Capacitors	☐		
Ionizing radiation			
Target material	[material]		
Beam particle type (e, p, ions, etc)	Isolde radioactive beams	none	Isolde radioactive 30-60 keV beams
Beam intensity	10^8 pmC	none	10^8 pmC
Beam energy	30-60 keV	none	30-60 keV
Cooling liquids	[liquid]		
Gases	[gas]	[gas]	[gas]
WORKING sources:	☒	☒	☒
• **Open source**	☒ Produced at ISOLDE: ^{111m}Cd (48m) *Max activity: 30MBq (1.2E11 atoms per sample)* ^{111}In(2.8d)/^{111}Cd, *Max activity: 1MBq (3E11 atoms per sample)* ^{199m}Hg($T_{1/2}$ = 42m) *Max activity: 33MBq (1.2E11 atoms per sample)* ^{117}Cd(2.5h)/^{117}In *Max activity: 12MBq (1.5E11 atoms per sample)*	☒ Produced at ISOLDE: ^{111m}Cd (48m) *Max activity: 30MBq (1.2E11 atoms per sample)* ^{111}In(2.8d)/^{111}Cd, *Max activity: 1MBq (3E11 atoms per sample)* ^{199m}Hg($T_{1/2}$ = 42m) *Max activity: 33MBq (1.2E11 atoms per sample)* ^{117}Cd(2.5h)/^{117}In *Max activity: 12MBq (1.5E11 atoms per sample)*	☒ Produced at ISOLDE: ^{111m}Cd (48m) *Max activity: 30MBq (1.2E11 atoms per sample)* ^{111}In(2.8d)/^{111}Cd, *Max activity: 1MBq (3E11 atoms per sample)* ^{199m}Hg($T_{1/2}$ = 42m) *Max activity: 33MBq (1.2E11 atoms per sample)* ^{117}Cd(2.5h)/^{117}In *Max activity: 12MBq (1.5E11 atoms per sample)*
• **Dose rate on 10 cm distance**	[dose][mSV] Samples are handled with tweezers at more than 10cm distance ^{111m}Cd : 0.5 miliSv/h ^{111}In : 8 microSv/h ^{199m}Hg : 0.5 miliSv/h ^{117}Cd : 0.1 miliSv/h	[dose][mSV] Samples are handled with tweezers at more than 10cm distance ^{111m}Cd : 0.5 miliSv/h ^{111}In : 8 microSv/h ^{199m}Hg : 0.5 miliSv/h ^{117}Cd : 0.1 miliSv/h	[dose][mSV] Samples are only handled inside the HUV chamber and, consequently, much lower dose rates are applying than the ones reported on the adjacent fields.
CALIBRATION Sealed sources	☒ [ISO standard]	☒ [ISO standard]	☒ [ISO standard]
• **Isotope**	22Na sources provided by RP services at CERN	22Na sources provided by RP services at CERN	22Na sources provided by RP services at CERN
• **Activities**	< 3E7 Bq	< 3E7 Bq	< 3E7 Bq
Use of activated material:			
• **Description**	☐		
• **Dose rate on contact and in 10 cm distance**	[dose][mSV]		
• **Isotope**			
• **Activity**			
Non-ionizing radiation			
Laser			
UV light			
Microwaves (300MHz-30 GHz)			
Radiofrequency (1-300MHz)			

Chemical			
Toxic			
Harmful	ethanol (ICSC: 0044)	Acetone (ICSC: 0087), ethanol (ICSC: 0044) and methanol (ICSC: 0057). Less than few centilitres per chemical, used on cleaning samples on ventilated fume hood on building 115. *The respective ICSC forms have been printed and will be handled during preparation and experiments.*	Acetone (ICSC: 0087), ethanol (ICSC: 0044)
CMR (carcinogens, mutagens and substances toxic to reproduction)	[chemical agent], [quantity]		
Corrosive	[chemical agent], [quantity]		
Irritant	[chemical agent], [quantity]		
Flammable	[chemical agent], [quantity]		
Oxidizing	[chemical agent], [quantity]		
Explosiveness	[chemical agent], [quantity]		
Asphyxiant	[chemical agent], [quantity]		
Dangerous for the environment			
Mechanical			
Physical impact or mechanical energy (moving parts)	[none]		
Mechanical properties (Sharp, rough, slippery)	[none]		
Vibration	[none]		
Vehicles and Means of Transport	[none]		
Noise			
Frequency	[frequency],[Hz] Ambient noise at the ISOLDE Hall, building 170		[frequency],[Hz] Ambient noise at the ISOLDE Hall, building 170
Intensity	Ambient noise at the ISOLDE Hall, building 170		Ambient noise at the ISOLDE Hall, building 170
Physical			
Confined spaces	[none]		
High workplaces	[none]		
Access to high workplaces	[none]		
Obstructions in passageways	[none]		
Manual handling	All samples and sample holders are manually	All samples and sample holders are manually	On-line experiment Activity stays inside the

	handled either by long tweezers to insert and extract the sample holder into and out of the SSP implantation chamber at GLM, or when manipulating the samples and sample holders inside glove boxes or fume houses on building 508.	handled either by long tweezers to insert and extract the sample holder into and out of the SSP implantation chamber at GLM, or when manipulating the samples and sample holders inside glove boxes or fume houses on building 508	vacuum chamber. Only short lived isotopes will be used. No alpha emitters.
Poor ergonomics	[none]		

0.1 Hazard identification

3.2 Average electrical power requirements (excluding fixed ISOLDE-installation mentioned above): *(make a rough estimate of the total power consumption of the additional equipment used in the experiment)*